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Proposal of Fiber-Optic Radio Highway Networks Using CDMA Method

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SUMMARY This paper proposes fiber-optic radio highway network using code division multiple access (CDMA) method which is universally applicable for various type of personal radio services and radio air interfaces. The proposed system can asynchronously open the radio-free space among any microcells. The outage probability and the number of connectable radio base stations are theoretically analyzed and compared with these in using conventional subcarrier multiplexing (SCM) method. Analysis results show that the reduction effect of the optical signal beat noise, due to spread spectrum of optical signal, improves the number of the active RBSs in CDMA radio highway network.

key words: *CDMA, radio highway, fiber-optic bus link, optical beat noise*

1. Introduction

Recently, fiber-optic microcellular systems, where microcells in wide area are connected by optical fibers and radio signals are transmitted over fiber-optic link among radio base stations (RBS) and a control station (CS), has been studied and demonstrated [1], [6]. This system can instantaneously open radio free spaces among several users and several control stations according to user's demand. We have called this "Virtual Radio Free Space" and proposed "Fiber-Optic Radio Highway Network" [7], [8]. This network can operate any types of air interfaces and requires no restoration of a great number of radio base stations to start any new multimedia personal services for global area. Figure 1 illustrates the concept of Fiber-Optic Radio Highway Network which can realize the universal and seamless capability for multi-air-interfaces such as microcellular radio systems, B-ISDN ATM based high-speed radio distribution system called FTTA (Fiber-To-The-Air) system [4], [5], CATV radio distribution systems and so on. In radio highway network, RBS is equipped only with an electric-to-optic converter (E/O) and an optic-to-electric converter (O/E), and all of the complicated functions such as RF modulation and demodulation, frequency assignment, spectrum delivery swithing are performed at the CS.

As an configuration of radio highway, we have proposed the choice of the fiber-optic link with bus topology [1], [6]. In the fiber-optic bus link, since all RBSs of microcells share a fiber, the number of the fiber can be reduced. So, the fiber-optic bus link provides a cost effective approach for the implementation of radio highway network.

As multiplexing scheme for fiber-optic radio communication system using subcarrier multiplexing (SCM) have been discussed [1], [4], [9]–[12]. SCM is the excellent in simplicity and flexibility, however, optical beat noises drastically deteriorate the received carrier-to-noise ratio (CNR) performance at the CS, if there is no strict control of optical wavelength of many lasers in RBSs connected to the bus link [1], [11], [12]. In bus link system using SCM, moreover, a radio frequency used in one cell can't be reused in other cells, because optical receiver of the CS receives simultaneously all optical signals modulated by radio signals at many RBSs.

On the other hand, time division multiplexing (TDM) method has been proposed and investigated [6]. In radio highway using TDM method, timewise sampled radio signals are multiplexed and transmitted over fiber-optic bus link, therefore, no beat noise arises and a radio frequency used in one cell can be reused in other cells. However, in TDM radio highway, it will be difficult to perform time-synchronization of whole system.

In this paper, as an alternative candidate of asynchronous multiplexing scheme, we have newly proposed the Radio High-way Network using CDMA method [8]. CDMA offers several potential advantages to radio highway networks, for example, CDMA makes efficient

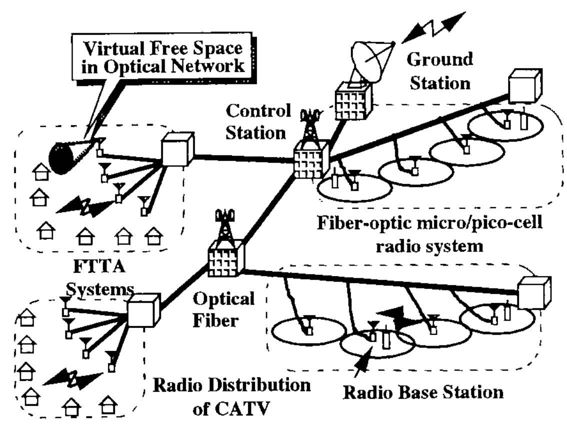

Fig. 1 Concept of Radio Highway Network.

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use of the channel by providing asynchronous access to each user and it is easy to add new RBS to the network without scheduling. Therefore, CDMA which allows multiple users to share the entire channel, is more suitable for radio highway networks than TDMA dedicating a portion of the channel to each user.

Although various CDMA optical fiber networks have been studied [13], [15], in these conventional studies the connectable number of station or the received CNR in the fiber-optic bus link like radio highway network, have not been investigated. In this paper, we clarify the outage probability of received CNR and the number of connectable RBSs in proposed CDMA radio highway and further, compare them with conventional SCM system. For fiber-optic bus link especially, we must consider the influence of optical signal beat noises. Banat and Kavehrad investgate the reduction effect of optical beat noise due to using spread spectrum optical carrier in SCM/WDMA networks [16], however in thier investigation the spread spectrum technique has not been taken as a multiplexing method.

In Sect. 2, the concept and configurations of the proposed system are described. In Sect. 3, the CNR and the outage probability of the proposed system are theoretically analyzed, taking into account the signal beat noise reduciton due to optical spectrum spreading in CDMA. In Sect. 4, it is clarified that the proposed method can improves the outage probability compared with the conventional SCM method.

2. Radio Highway Networks Using CDMA Method

Figure 2 shows the configuration of the proposed Radio Highway Network using CDMA method. Radio highway network connects among L microcells and a CS with a fiber-optic bus link. At each RBS composed only of a LD and a few equipment, radio signals from subscribers are received, multiplied by a pseudo-random noise (PN) and encapsulated into the envelope of optical signal by direct intensity modulation (IM) of LD. We assume that the chip rate of PN sequence is much higher than the bandwidth of the radio signal. Moreover, an AGC (Aotumatic Gain Control) circuit is equipped at each RBS in order to keep average radio signal power constant, therefore this CDMA system can avoid near-far problem due to fading or distance change between the mobile terminal and the RBS. The optical direct sequence spread spectrum signal is launched into a fiber-optic bus link. In the bus link, many optical spread spectrum signals from many RBSs are multiplexed by CDMA method and transmitted to the CS.

At the CS with L correlators, all received optical spread spectrum signals (CDMA/IM signals) are detected by a photodiode (PD) and multiplied by the PN sequence matching the one used in the transmitter of RBS. Finally, the desired radio signal of each RBS is separated out from the interference background of the undesired signals by bandpass filtering.

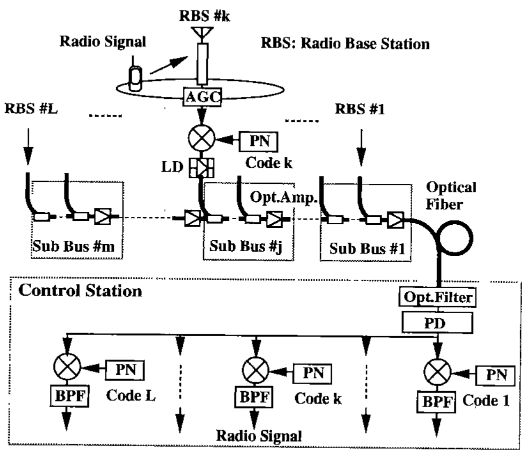

Fig. 2 Configuration of Radio Highway using CDMA method.

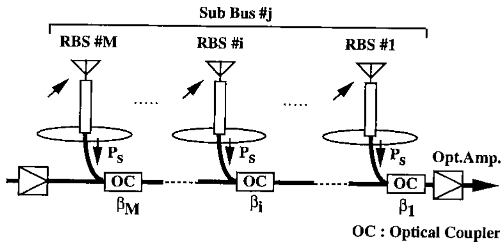

Fig. 3 Configuration of sub-bus link.

To compensate the losses of couplers and fibers of the bus link, some optical amplifiers are equipped at equal interval called sub-bus link, into which M RBSs launch signal lights through optical couplers. Figure 3 shows the configuration of a sub-bus link. A number of optical signals enter from the left end of the sub-bus link. Each signal is launched from different RBS included into the previous sub-bus links. We assume that all these optical signals have the same power of P_s. Furthermore, assuming that the optical signal power launched by each of M RBSs in this sub-bus link is P_s, the set of optical coupling coefficients $(\beta_1, \beta_2, \cdots, \beta_M)$ to equalize all optical signal powers transmitted from RBSs included in all sub-bus links at this sub-bus output are given by [6]

$$\beta_i = \frac{\beta_{i+1} 10^{-\alpha_L/10}}{1 + \beta_{i+1} 10^{-\alpha_L/10}} \quad (i = 1 \cdots M-1),$$
$$\beta_M = 1/2, \tag{1}$$

where α_L is the total loss of an optical coupler and a fiber.

In this paper, it is also assumed that to overcome the whole loss of a sub-bus link, Λ, an optical amplifier is equipped at the output of the sub-bus link. The optical amplifier model is shown in Fig. 4 [9]. The gain element is an ideal noiseless amplifier with power gain G_a. The input amplifier noise, $\nu(t)$, is modeled by zero-mean white gaussian noise process whose double-sided

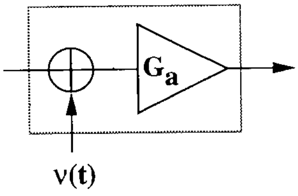

Fig. 4 Model for optical amplifier.

power spectral density(PSD), N_{sp} is given by

$$N_{sp} = \frac{n_{sp}}{2\eta_a}(1 - {G_a}^{-1})h\nu, \tag{2}$$

where $h\nu$ is the photon energy, n_{sp} is the spontaneous emission factor and η_a is the quantum efficiency of the amplifier.

3. Theoretical Analysis of Received CNR

The analysis model for radio highway using CDMA method is shown in Fig. 5. Assuming all subscribers on radio cell are multiplexed by TDMA method to simplify the discussion, we theoretically analyze the received carrier-to-noise ratio (CNR) of the radio signal reproduced at the CS. The radio signal $g_k(t)$ received at the k-th RBS is written by

$$g_k(t) = Re[a_k(t)e^{j2\pi f_c t}], \tag{3}$$

where $a_k(t)$ is a complex baseband information signal with bandwidth B_w. By using AGC at each RBS, the normalized power of $g_k(t)$ can be assumed to be constant($\overline{|a_k(t)|^2} = 1$).

Next, the radio signal is multiplied by the PN sequence $c_k(t)$ having the value ± 1. The spread spectrum radio signal is given by

$$s_k(t) = c_k(t)g_k(t), \tag{4}$$

whose bandwidth B_{ss} is given by

$$B_{ss} = G_p B_w \tag{5}$$

where G_p is the spread-spectrum processing gain.

When LD is directly-intensity-modulated by the radio spread spectrum signal $s_k(t)$ with optical modulation index of 1, the intensity of the optical signal is given by

$$I_k(t) = P_s(1 + c_k(t)g_k(t)), \tag{6}$$

where P_s is the average transmitted optical power.

At the CS, all optical IM signals from K RBSs are detected by a photodiode (PD). When the K of L RBSs receive a radio signal and transmit optical signal, the intensity of received optical signal is written by

$$I_r(t) = \sum_{k=1}^{K} P_r(1+c_k(t)g_k(t)) \quad (K = 1, 2, \cdots, L), \tag{7}$$

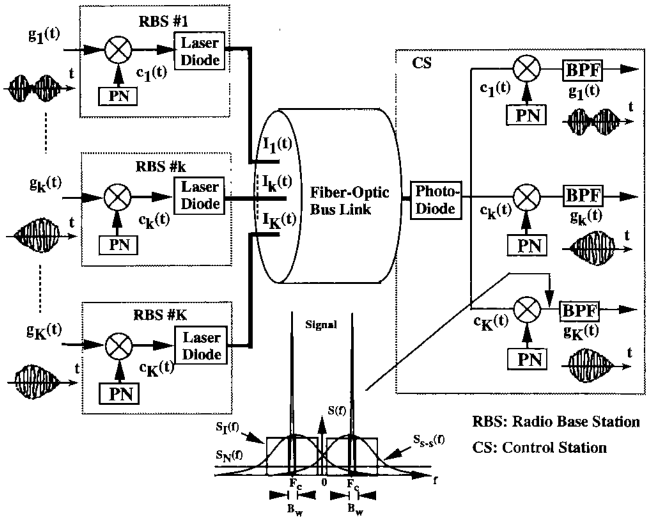

Fig. 5 Analysis model for radio highway using CDMA method.

and

$$P_r = P_s / F_{loss}, \tag{8}$$

where P_r is the average received optical power and F_{loss} is the fiber loss between the CS and the optical amplifier in the 1st sub-bus (see Fig. 2). The output current of PD is given by

$$i_{out}(t) = \alpha \sum_{k=1}^{K} P_r c_k(t) g_k(t) + n(t), \tag{9}$$

where α is the responsibity of PD and $n(t)$ is the additive noise current, which is given by

$$n(t) = i_{RIN}(t) + i_{shot}(t) + i_{th}(t) + i_{s-sp}(t) + i_{sp-sp}(t) + i_{s-s}(t), \tag{10}$$

where $i_{RIN}(t)$, $i_{shot}(t)$, $i_{th}(t)$, $i_{s-sp}(t)$, $i_{sp-sp}(t)$ and $i_{s-s}(t)$ are the relative intensity noise current, the shot noise current, the receiver thermal noise current, the beat noise current among ASEs and optical signals, the beat noise current among ASEs and the optical signal beat noise current, respectively. The output of the k-th correlator to recover the spread spectrum signal of the k-th RBS is given by

$$i_k(t) = i_{out}(t) \times c_k(t) = \alpha P_r g_k(t) + \alpha P_r \sum_{\substack{i=1 \\ i \neq k}}^{K} g_i(t)c_i(t)c_k(t) + n(t)c_k(t). \tag{11}$$

The first term in (11) represents the reproduced radio signal received from the k-th RBS, the second term is the interference noise and the third term is the additive noise. Finally, by bandpass filtering the desired radio signal of k-th RBS is separated out from the interference background of the undesired signals.

Now, we derive the CNR of $i_k(t)$. By using Eqs. (3) and (11), the signal power is given by

$$C = (\alpha P_r)^2/2. \quad (12)$$

Let $i_I(t)$ represent the interference noise, that is,

$$i_I(t) = \alpha P_r \sum_{\substack{i=1 \\ i \neq k}}^{K} s_i(t)\gamma_{ik}(t), \quad (13)$$

where $\gamma_{ik}(t) = c_i(t)c_k(t)$ $(i, k = 1, 2, \cdots K; i \neq k)$. When $R_\gamma(\tau)$ and $R_g(\tau)$ represent the autocorrelation functions of the γ_{ik} and the radio signal $g_k(t)$, respectively, the autocorrelation of $i_I(t)$ is given by

$$R_I(\tau) = (K-1)(\alpha P_r)^2 R_\gamma(\tau) R_g(\tau). \quad (14)$$

$R_\gamma(\tau)$ and $R_b(\tau)$ are given by [17]

$$R_\gamma(\tau) = e^{-2|\tau|f_{PN}}, \quad (15)$$

$$R_g(\tau) \cong \frac{1}{2}\cos(2\pi f_c \tau). \quad (16)$$

Therfore $R_I(\tau)$ becomes

$$R_I(\tau) = \frac{1}{2}(K-1)(\alpha P_r)^2 R_g(\tau) e^{-2|\tau|f_{PN}}, \quad (17)$$

where f_{PN} is the chip rate of PN sequence given by

$$f_{PN} = B_{ss} \quad (18)$$

Since from Eq. (14) the PSD of $i_I(t)$ is given by

$$S_I(f) = \frac{1}{4}(K-1)(\alpha P_r)^2 \left(\frac{f_{PN}}{f_{PN}^2 + \pi^2(f-f_c)^2} + \frac{f_{PN}}{f_{PN}^2 + \pi^2(f+f_c)^2} \right), \quad (19)$$

the interference noise power at the output of BPF, I, is given by

$$I = \left[\int_{f_c - \frac{B_w}{2}}^{f_c + \frac{B_w}{2}} + \int_{-f_c - \frac{B_w}{2}}^{-f_c + \frac{B_w}{2}} \right] S_I(f) df = \frac{1}{2}(K-1)(\alpha P_r)^2 G_p^{-1}. \quad (20)$$

Since the additive noise (the third term in (11)) can be modeled by zero-mean white noise with the same PSD as the $n(t)$, its power at the output of the BPF, N, is given by

$$N = N_{RIN} + N_{shot} + N_{th} + N_{s-sp} + N_{sp-sp} + N_{s-s}, \quad (21)$$

where N_{RIN}, N_{shot}, N_{th}, N_{s-sp} and N_{sp-sp}, are the power of relative intensity noise, shot noise, receiver thermal noise, beat noises among ASEs of optical amplifiers and optical signals and beat noises among ASEs, respectively. These are given by

$$N_{RIN} = KRIN(\alpha P_r)^2 B_w, \quad (22)$$

$$N_{shot} = 2e\alpha\{KP_r + mN_{sp}WG_a/F_{loss}\}B_w, \quad (23)$$

$$N_{th} = \frac{4kTB_w}{R}, \quad (24)$$

$$N_{s-sp} = 4\alpha^2 KP_r mN_{sp}B_w G_a/F_{loss}, \quad (25)$$

$$N_{sp-sp} = 2\alpha^2(mN_{sp}G_a/F_{loss})^2(W - f_c), \quad (26)$$

where RIN, m, e, k, R, T, W and N_{sp} are the PSD of relative intensity noise, the number of opitcal amplifier, electron charge, Boltzman constant, load resistance, noise temperature, the bandwidth of optical filter and the PSD of ASE, respectively. N_{s-s} is the optical signal-signal beat noise. Assuming that i-th RBS has a LD with the center frequency of f_{oi} and furthermore, assuming that the optical spread spectrum signal at f_{oi} has the single mode gaussian shaped spectrum with the full width half maximum, $\Delta\nu_i$, given by

$$\Delta\nu_i = \sqrt{\Delta\nu^2 + B_{ss}{}^2}, \quad (27)$$

where $\Delta\nu$ is the spectral linewidth of the unmodulated optical carrier, the PDS of optical signal-signal beat noise is given by

$$S_{s-s}(f) = \alpha^2 \sum_{i=1}^{K} \sum_{\substack{j=1 \\ j \neq i}}^{K} P_r{}^2 \left[\frac{1}{2\sigma_{ij}\sqrt{2\pi}} e^{-\frac{(f-\delta f_{ij})^2}{2\sigma_{ij}{}^2}} + \frac{1}{2\sigma_{ij}\sqrt{2\pi}} e^{-\frac{(f+\delta f_{ij})^2}{2\sigma_{ij}{}^2}} \right], \quad (28)$$

where

$$\delta f_{ij} = f_{oi} - f_{oj}, \qquad \sigma_{ij}{}^2 = \sigma_i{}^2 + \sigma_j{}^2,$$
$$\sigma_i = \frac{\Delta\nu_i}{2\sqrt{2\log 2}} (i = 1, 2, \cdots L). \quad (29)$$

Hence, N_{s-s} is given by

$$N_{s-s} = \alpha^2 \left[\int_{-f_c - B_w/2}^{-f_c + B_w/2} + \int_{f_c - B_w/2}^{f_c + B_w/2} \right] S_{s-s}(f) df = \alpha^2 \sum_{i=1}^{K} \sum_{\substack{j=1 \\ j \neq i}}^{K} P_r{}^2 \left[erfc\left\{ \frac{-2(f_c + \delta f_{ij}) - Bw}{2\sqrt{2}\sigma_{ij}} \right\} - erfc\left\{ \frac{-2(f_c + \delta f_{ij}) + Bw}{2\sqrt{2}\sigma_{ij}} \right\} + erfc\left\{ \frac{-2(f_c - \delta f_{ij}) - Bw}{2\sqrt{2}\sigma_{ij}} \right\} - erfc\left\{ \frac{-2(f_c - \delta f_{ij}) + Bw}{2\sqrt{2}\sigma_{ij}} \right\} \right]. \quad (30)$$

From Eqs. (12), (20) and (21), the received CNR of the radio signal is given by

$$\left(\frac{C}{N}\right)_{CDMA} = \frac{C}{I+N}. \tag{31}$$

From the viewpoint of simplicity of the system configuration, we assume no control of each optical carrier frequency, f_{oi} $(i = 1, 2, \cdots, L)$ at each RBS. Therefore, the optical carrier frequencies are mutually independent random variables with mean of f_o and uniform probability density function (p.d.f) in the range $|f_{oi} - f_o| \leqq \frac{\Delta f}{2}$, and the p.d.f of $\delta f_{ij} = f_{oi} - f_{oj}$ is given by

$$p(\delta f_{ij}) = \begin{cases} \frac{1}{(\Delta f)^2}(\Delta f - |\delta f_{ij}|) & |\delta f_{ij}| \leqq \Delta f \\ 0 & \text{otherwise} \end{cases}$$
$$(i, j = 1, 2, \cdots, L; i \neq j). \tag{32}$$

In this case, since the signal beat noise power, N_{s-s}, is a random variable, $(C/N)_{CDMA}$ given by Eq. (31), is also a random variable.

In this paper, to examine the performance of the proposed system, we will derive the outage probability of CNR, P_o, that is, the probability that CNR falls to less than the required CNR, γ_a. The P_o is defined as

$$P_o = \text{Prob}\left[\left(\frac{C}{N}\right)_{CDMA} \leqq \gamma_a\right] \tag{33}$$

Since the optical signal beat noise power, N_{s-s}, is a sum of K independent random variables as shown in Eq. (30), the p.d.f. of the N_{s-s} can be modeled to be gaussian as the number K increase by the central limit theorem. So, the additive noise power, N, also has a gaussian p.d.f. given by

$$p_N(N) = \frac{1}{\sqrt{2\pi}\sigma_N}\exp\left\{-\frac{(N - m_N)^2}{2\sigma_N^2}\right\}, \tag{34}$$

where m_N and ${\sigma_N}^2$ are the average and variance of N, respectively, which are derived from Eqs. (21), (30) and (32).

From Eqs. (33) and (34), the outage probability P_o becomes

$$P_o = \frac{1}{2}erfc\left(\frac{\frac{C}{\gamma_a} - I - m_N}{\sqrt{2}\sigma_N}\right). \tag{35}$$

4. Outage Probability Performance

Some numerical results of the outage probability in the proposed Radio Highway using CDMA method are discussed below with parameters indicated in Table 1. For comparision, results in using SCM method are also shown. In calculation of the power of optical signal-signal beat noise for SCM system, we assume that $\Delta\nu$ (Eq. (27)) is nearly equal to $\Delta\nu$ because the bandwidth of the radio signal B_w is much smaller than the spectral linewidth of the unmodulated optical carrier $\Delta\nu$.

Table 1 Parameters used in calculation.

RIN	-152 dB/Hz	η_a	0.5
T	300 K	R	50 Ω
λ	1.53 μm	n_{sp}	2.0
α	0.8 A/W	W	1 THz
B_w	300 kHz	α_L	3.0 dB
f_c	1.9 GHz	G_a	19.7 dB
F_{loss}	1 dB	Δf	1 THz
$\Delta\nu$	10 MHz	P_s	10 dBm

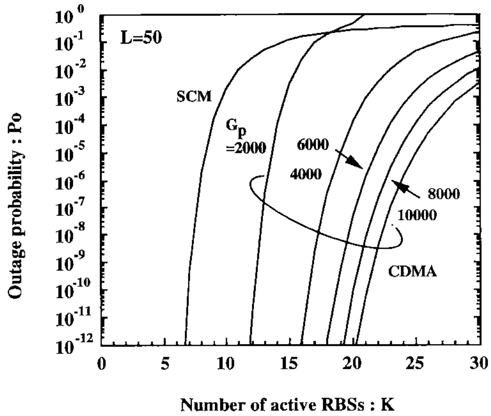

Fig. 6 Number of active RBSs K versus outage probability P_o.

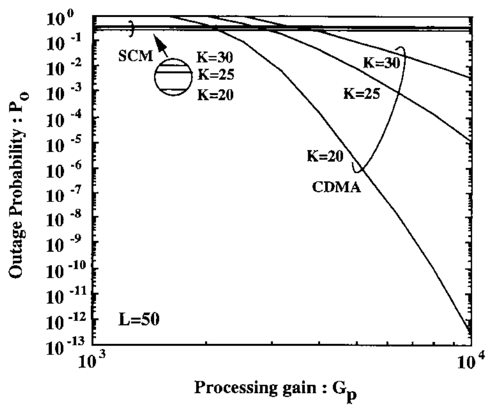

Fig. 7 Processing gain G_p versus outage probability P_o.

Figure 6 shows the relationship between the number of active RBSs and the outage probability, P_o for different values of the processing gain G_p in the case of γ_a of 20 dB. It is seen that as the number of active RBSs increases, the outage probability increase suddenly due to signal-signal beat noises for both methods, however, the outage probability of CDMA system is much less than SCM system and improved as the processing gain G_p increases. This is bacause the power of optical beat noise in CDMA system decreases due to the spectral spreading.

Figure 7 shows the relationship between the spread-spectral processing gain G_p and the outage probability for different values of the number of active RBSs K. For K of 20, 25 and 30, while the outage probability of

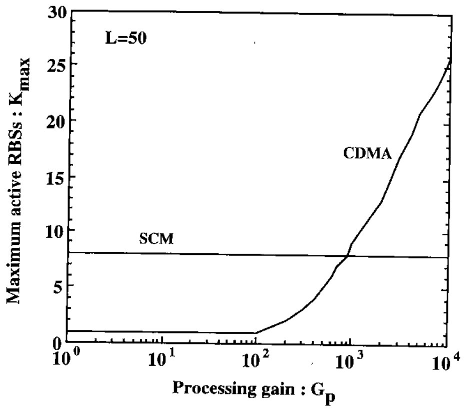

Fig. 8 Processing gain G_p versus maximum active RBSs K_{max}.

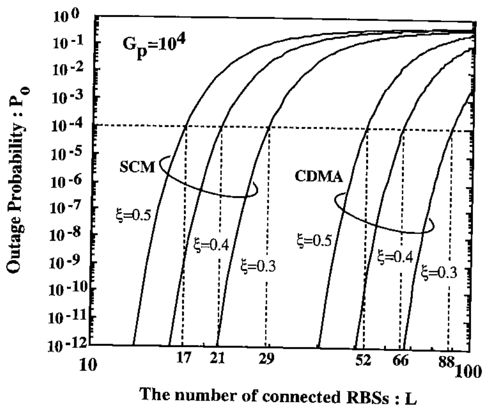

Fig. 9 The number of connected RBSs L versus outage probability P_o.

SCM system cannot achieve 10^{-1}, the outage probability of CDMA system is improved as the spread-spectral processing gain G_p increases because of the optical beat noise reduction.

Figure 8 shows the relationship betweeen the spread-spectral processing gain G_p and the number of maximum active RBSs, K_{max}, required to obtain the outage probability P_o of less than 10^{-4} at the CS. This figure shows that as the spread-spectral processing gain G_p increases, the number of maximum active RBSs of CDMA system is improved because of the optical beat noise reduction. For example, while SCM system can support only 8 active RBSs with the outage probability less than 10^{-4}, CDMA system with $G_p = 10^4$ can support 26 active RBSs with the same outage probability.

Figure 9 shows the relationship between the number of connected RBSs, L, and the outage probability. The system utilization rate $\xi = \frac{K}{L}$ is varied as a parameter. It is seen that the number of connectable RBSs in CDMA system is effectively improved compared to SCM system. The results shows that for the same values of ξ, the connectable number L to obtain the outage probability of 10^{-4} in CDMA system is about three times larger than SCM system.

5. Conclusion

In this paper, we have proposed the Fiber-Optic Radio High-way Networks using CDMA method, which is effective for the universal and seamless global radio networks. The CNR and the outage probability have been theoretically analyzed. It is clarified that compared with the conventional SCM method, CDMA method can improve the number of the active RBSs due to the reduction effect of the optical beat noise. For example, by using CDMA with $G_p = 10^4$, three times of active RBSs can access to the Radio Highway with the outage probability of 10^{-4} compared with the conventional SCM method.

In this analysis, we have not considered different values of laser linewidth $\Delta\nu$ or practical spectrum of modulated optical carrier. Further study for them will be required to realize this system.

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Appendix

When the coupling coefficients of k-th optical coupler is β_k and the total loss of optical coupler and fiber is α_L [dB], the optical signal power transmitted from i-th RBS at the output of the sub-bus link, P_{r_i}, is given by

$$P_{r_i} = P_s 10^{-i\alpha_L/10} \prod_{k=1}^{i-1} (1-\beta_k)\beta_i \quad (i = 1, 2, \cdots, M). \qquad \text{(A· 1)}$$

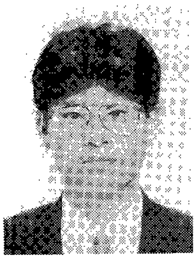
The optical signal transmitted from any RBS located in previous sub-bus links, which suffers the whole loss Λ_s of sub-bus link, has the output power $P_{through}$ given by

$$P_{through} = P_s \Lambda_s, \qquad \text{(A· 2)}$$

where

$$\Lambda_s = 10^{-M\alpha_L/10} \prod_{k=1}^{M} (1-\beta_k). \qquad \text{(A· 3)}$$

Consequently, we can find the set of coupling coefficients to make all optical signal powers transmitted from RBSs equal at the output of this sub-bus link, i.e., $P_{r_1} = P_{r_2} = \cdots = P_{r_M} = P_{through}$, as Eq. (A· 1).



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