PAPER

Proposal of Direct Optical Switching CDMA for Cable-To-The-Air System and Its Performance Analysis

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SUMMARY For Cable-To-The-Air network providing a seamless access network in both indoor and outdoor, direct optical switching CDMA scheme is newly proposed to multiplex any types of radio signals. In two types of connection methods, optical switch connection and optical coupler connection systems, the received carrier-to-interference-plus-noise power ratios are theoretically analyzed. It is clarified that in the optical switch connection connection system, by introducing the additional optical gain at each radio base station, the carrier-to-interference-plus-noise power ratios for all radio base stations and the connected number of radio base stations can be improved compared with the OC connection system.
key words: *microwave photonics, radio over fiber system, CATV, optical CDMA*

1. Introduction

A future CATV system needs a broadband transmission link to offer interactive multimedia services including voice, high quality video, video-on-demand, high speed data and so on. Fiber optic transmission systems have been introduced into trunk networks to provide high transmission quality. On the other hand, radio access links for broadband communications have a variety of features such as the portability of set-top box (STB) and the flexible construction of access links [1].

The wired local loop system will be used for radio signal delivery to construct the indoor wireless network. However, mobile wireless communications or mobile computing should be operated as anytime and anywhere as possible, so we must provide the same communication environments both for inside such as in-house, office, in-shop and so on, and for outside such as street, in-car, station and so on. In addition, future mobile communications providing multimedia services should have two important capabilities: one is the globally enhanced seamless connection capability among a huge number of cell, and the other is the flexibility and universality for diversified and various radio signal formats.

To solve above problems, we have proposed Fiber-To-The-Area (FTTA) system [2]. The same concept of FTTA can be applied to CATV system. In this paper, we first call such a system Cable-To-The-Air (CATA) system. The CATA system is a broadband wireless local loop, but by using progressive microwave/millimeter wave photonics techniques, radio signals from subscribers are transmitted among radio base stations (RBS) and a head end (HE) with radio signal formats kept over an optical fiber. Figure 1 illustrates a concept of CATA system, where radio signals are encapsulated into the envelope of optical signal through fiber-optic links. Since a RBS is only equipped with an E/O converter and an O/E converter, and all of complicated functions such as RF modulation /demodulation and spectrum delivery switching are performed at the HE, CATA can accommodate various types of radio interfaces such as mobile communications, video broadcasting, in-house radio network and so on, and moreover it can provide the same wireless communication environment for both indoor and outdoor. CATA also has a great flexibility for any changes or additions of radio services. For example, at first, CATA provides a video-on-demand (VOD) service, and later it can immediately offer any new mobile communication services or new video standards with no restoration of new STB and only with additional equipments at the HE.

A bus type optical link or a passive double star link is preferable for CATA because it provides more reduction in conduit and optical fiber lengths as well as more robust and flexible interconnection architecture than a star link [3]. Therefore, we should consider effective multiple access methods for various types of radio signals over an optical link. In the downlink of CATA system, for example, video distribution can be provided by conventional multiplexing methods such as SCMA and FDMA. On the other hand, the uplink traffic is not so large in spite of many potential subscribers, but there exist various types of radio signals which have different frequencies, different data rates and different multiple access methods. Thus, CDMA will be a strong candidate as a multiple access in the optical link because of its asynchronous access property, greater flexibility and transparency for various radio air interfaces than SCMA, TDMA and FDMA.In this paper, we newly propose direct optical switching (DOS)-CDMA scheme for CATA system.

Reference [4] has proposed radio highway networks us-

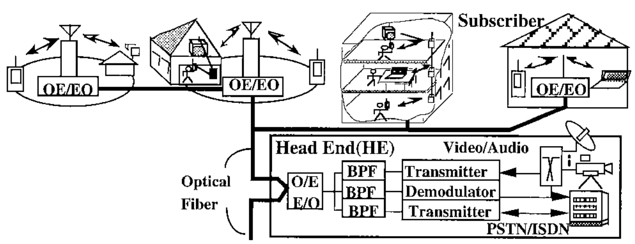

Fig. 1 Concept of CATA system.

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ing an electrical CDMA scheme where radio signals are multiplexed by the spread spectrum in the electrical stage. In CATA system, however, the optical CDMA scheme is more suitable in order to obtain higher processing gain and broader bandwidth than the conventional electrical CDMA scheme. Up to this time, various optical CDMA methods have been studied mainly for digital optical LAN. As optical spread-spectrum methods, the optical pulse coding using fiber delay line [5], [6], the time spreading using optical phase mask [7] have been proposed. However, the optical pulse coding and the time spreading can not be applied for multiplexing radio signals in the optical domain in CATA system. Furthermore, those methods have no flexibility in assigning code sequences. Reference [8] has proposed the coherent optical phase modulation, but the correlator for this method has a considerable complexity, moreover needs narrowband optical filters with the extremely fine accuracy of its passband.

The proposed DOS-CDMA scheme can be performed only with an optical switch(OSW) at the transmitter and also an OSW, a photodetector(PD), and an electrical bandpass filter(BPF) at the receiver. So any types of radio signal can be converted into optical intensity-modulating (IM) / CDMA signals. When applying DOS-CDMA scheme for a bus type optic-fiber link, an OSW spreading the signal spectrum can be also used to launch them into the fiber link. In the DOS-CDMA scheme, multiplexing is performed by randomizing positions of optical pulses by driving an OSW with a pseudo random code sequence. This is quite different from Random Access Discrete Address (RADA) scheme using the quantized pulse position modulation (PPM) [9].

The remainder of this paper is composed as followings: In Sect. 2, we describe the principle of DOS-CDMA scheme and the configuration of CATA. We also propose two types of connection methods, the optical coupler(OC) connection type CATA system and the OSW connection type CATA system where an OSW is used not only to spread the spectrum of optical signals but also to launch them into fiber-optic bus link. In Sect. 3, we theoretically analyze the carrier to interference-plus-noise ratio (CINR) of the radio signal regenerated at the HE for OC connection system and OSW connection system considering the chip pulse erasure at the OSW. In Sect. 4, we show some numerical results and compare them between two types of connection methods.

2. DOS-CDMA CATA system

2.1 Principle of DOS-CDMA System

DOS-CDMA uses on-off type switching spectral spreading. Each radio signal received at each RBS is transmitted to a HE by analog type optical PAM scheme, and the multiple access among many RBS's is performed by DOS-CDMA scheme. The regeneration of radio signal is based on the bandpass natural sampling theory [10], [11]. Figure 2 shows the system model of DOS-CDMA system to illustrate the principle of the spectrum spreading process at the RBS transmitter and the correlating process at the HE receiver. At a RBS, a received radio signal is converted into an optical intensity-modulating (IM) signal by modulating LD directly and next sampled at an OSW, which is driven with a certain code sequence, $c_k(t)$, and the output signal of OSW is transmitted to a receiver through optical fiber. At the output of OSW in the transmitter, we can obtain optical pulse amplitude modulation (PAM)/IM signal whose pulses are positioned according to the code pattern of $c_k(t)$. At the receiver, many PAM/IM signals from many RBS's are correlated with the code sequence, $c_k(t)$, at an OSW, then directly detected at a PD and interpolated at a BPF to regenerate the desired radio signal. The radio signal which is contaminated by all other radio signals, is fed into a demodulator in order to obtain the information data.

The radio signal $g_k(t)$ at the k-th RBS is represented by

$$g_k(t)=\mathrm{Re}\{a_k(t)e^{j2\pi f_{rf}t}\}, \tag{1}$$

where f_{rf} is radio frequency and $a_k(t)$ is the complex envelope with its bandwidth B_{rf}. Optical on-off switching spectrum spreading is performed at the OSW driven by a code sequence, $c_k(t)$, whose frame period is T_F(sec) and its pulse amplitude is 1 or 0. The intensity of the optical PAM/IM signal at the output of the OSW is given by

$$P_k(t)=P_s\{1+g_k(t)\}c_k(t), \tag{2}$$

where P_s is the transmitted peak optical power. The $P_k(t)$ is a bandpass natural sampled signal converted from a radio signal because an optical switching is a window-type sampling. Therefore, a radio signal can be conveyed by optical carrier with its signaling format kept and regenerated from the pulsed signals by the interpolation at a BPF if we choose sampling period of less than or equal to half of the inverse of radio signal bandwidth $\leq 1/(2B_{rf})$ [10], [11]. In the proposed DOS-CDMA system, since we choose a pseudo random sequence as a code sequence which drives the OSW at the transmitter, the durations between optical pulses become various values according to the kind of code sequence, but each pulse is surely repeated with its frame period of T_F.

Therefore, in order to regenerate the radio signal after interpolation, we should choose T_F of less than or equal to $1/(2B_{rf})$. From the viewpoint of simplicity, using T_F of much less than $1/(2B_{rf})$ is not effective, because we require a much faster speed for OSW. Hence, in this paper, we set T_F to be the maximum value, that is, $1/(2B_{rf})$.

To improve the quality of the regenerated radio signal

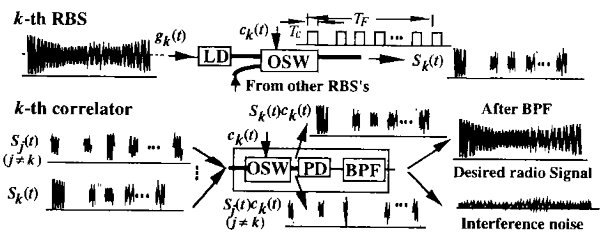


Fig. 2 Principle of spectrum spreading and correlating process in DOS-CDMA system.

in DOS-CDMA system, we have to choose a code sequence with the highest possible autocorrelation and the lowest possible cross-correlation. In the DOS-CDMA using optical IM/direct detection (DD) scheme, we have to use a uniphase code as a code sequence, while bipolar codes like maximum length or Gold code, are used in conventional radio CDMA system. References [5] and [6] have reported that a prime code sequence is the best code as a uniphase orthogonal code which can provide the highest autocorrelation and the lowest cross-correlation of various orthogonal codes. So in the proposed DOS-CDMA system, we employ the prime code sequence as a spread spectrum (SS) code.

A set of prime codes has the preferable feature for IM/DD CDMA system that there are very few coincidences of 1's among code sequences. Prime codes with length p^2 are derived from prime sequences obtained from a Galois field, $GF(p)$, where p is a prime number[12]. Therefore, the chip width T_c is given by T_F/p^2. Table 1 shows an example of prime sequences and prime code sequences for a prime number p of 7. Each prime sequence element s_{mn} is obtained by the product of the corresponding m and n modulo p. Letting $c_m=(c_{m0},c_{m1},\ldots,c_{mj},\ldots,c_{m(p-1)})$ denote the m-th prime code sequence, a j-th code element, c_{mj}, is given by

$$c_{mj}=\begin{cases}1 & ;\, j=s_{mn}+np \\ 0 & ;\, \text{otherwise}\end{cases} \tag{3}$$

When an OSW correlator is driven with the k-th prime code sequence, $c_k(t)$, at the receiver, the optical PAM/IM signal transmitted from the k-th RBS is extracted out of all CDMA signals. Then the output current of the PD is composed of a desired signal component, $S_k(t)$, interference components, $I(t)$, and additive noise components, $N(t)$. $S_k(t)$ and $I(t)$ are given by

$$S_k(t)=\alpha P_r g_k(t)c_k(t), \tag{4}$$

$$I(t)=\alpha P_r \sum_{j=1, j\neq k}^{M} g_j(t)c_j(t)c_k(t), \tag{5}$$

respectively where α, P_r and M are the responsivity of PD, the received peak optical power at the correlator, and the total number of RBS's, respectively. Here, we derive the carrier to interference power ratio (CIR) in the DOS-CDMA system. We derive the power spectral density (PSD) of signal component, $S_k(t)$, by calculating the autocorrelation of $S_k(t)$ from Eq.(4). The PSD of $S_k(t)$, $S_k(f)$, is given by

$$S_k(f)=(\alpha P_r)^2\frac{1}{p^2}\left(1+\frac{1}{p}-\frac{1}{p^2}\right)\Big\{G_k(f)+\frac{p-1}{p^2+p-1} \times \sum_{i=-\infty, i\neq 0}^{\infty} \mathrm{sinc}^2(\pi i/p^2)G_k(f-2iB_{rf})\Big\}, \tag{6}$$

where $G_k(f)$ is the power spectrum of $g_k(t)$ and $\mathrm{sinc}(x)$ is $\sin(x)/x$. Figure 3 shows the normalized both-side PSD of signal component. The first term of $S_k(f)$ is the desired signal component around f_{rf} and $-f_{rf}$, and the second terms is the frequency shifted components caused by bandpass sampling. Images of these shifted components cause the distortion in the desired signal as the self-interference if they overlap over the signal components as shown in Fig. 3 (a). We can perfectly remove the self-interference components by setting the value of the radio frequency f_{rf} at $(j+1/2)B_{rf}$ or j/T_c (j is an integer) as shown in Fig. 3 (b). Without such special values of f_{rf}, however, the self-interference component may not deteriorate the signal quality because its power is much low compared with that of the carrier signal component. We examine the carrier signal to self-interference power ratio (CSIR) and Fig. 4 shows the some numerical results for the f_{rf} of 1.93 GHz and B_{rf} of 900 KHz. In the small value of p, the sinc function causes the up and down in CSIR, but as p increases, CSIR tends to be a saturated value of more than 30 dB which is a enough value to obtain the radio signal quality in DOS-CDMA. As p increases, the saturated value of CSIR is determined by the relation between f_{rf} and B_{rf}.

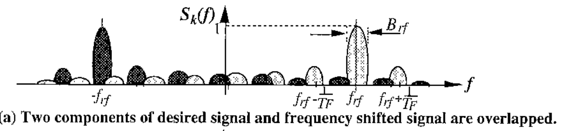
Table 1 Prime sequences and code sequences for $p=7$.

Prime sequences for p=7

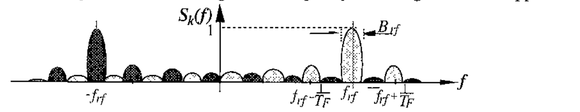
m	s_{m0}	s_{m1}	s_{m2}	s_{m3}	s_{m4}	s_{m5}	s_{m6}
0	0	0	0	0	0	0	0
1	0	1	2	3	4	5	6
2	0	2	4	6	1	3	5
3	0	3	6	2	5	1	4
4	0	4	1	5	2	6	3
5	0	5	3	1	6	4	2
6	0	6	5	4	3	2	1

Prime code sequences for p=7

m	c_{m0}	c_{m1}	c_{m2}	c_{m3}	c_{m4}	c_{m5}	c_{m6}
0	1000000	1000000	1000000	1000000	1000000	1000000	1000000
1	1000000	0100000	0010000	0001000	0000100	0000010	0000001
2	1000000	0010000	0000100	0000001	0100000	0001000	0000010
3	1000000	0001000	0000001	0010000	0000010	0100000	0000100
4	1000000	0000100	0100000	0000010	0010000	0000001	0001000
5	1000000	0000010	0001000	0100000	0000001	0000100	0010000
6	1000000	0000001	0000010	0000100	0001000	0010000	0100000



(a) Two components of desired signal and frequency shifted signal are overlapped.



(b) Two components of desired signal and frequency shifted signal are not overlapped.

Fig. 3 Normalized both-side PSD of signal component.

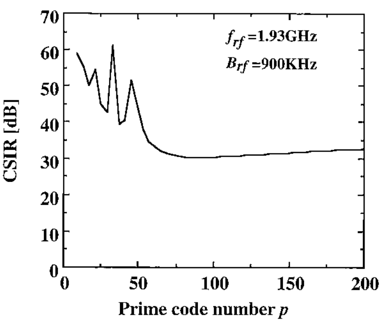


Fig. 4 Relationship between CSIR and p.

Table 2 Average variance of cross-correlation, σ_c^2.

p	σ_c^2	p	σ_c^2
7	0.272	31	0.322
11	0.298	47	0.326
13	0.303	71	0.328
23	0.318	97	0.329

Therefore, in following analysis, we will ignore the self-interference components.

From Eq. (6), the carrier power of the regenerated radio signal, C_0, is given by

$$C_0=(\alpha P_r)^2\frac{1}{p^2}(1+\frac{1}{p}-\frac{1}{p^2}). \tag{7}$$

Let σ_c^2 denote the average variance of the cross-correlation of the prime code. Then, the carrier to interference power ratio, CIR_0, is given by [5], [6]

$$CIR_0=C_0/I_0=\frac{p^2}{\sigma_c^2(M-1)}. \tag{8}$$

Table 2 shows σ_c^2 for different values of prime number p calculated by using computer simulation. Table 2 shows that σ_c^2 is a little increased as p increases but has a saturated value of 0.329 for p=97.

2.2 Configuration of DOS-CDMA CATA System

Figure 5 illustrates the configuration of the proposed DOS-CDMA CATA system. From the viewpoint of a cost effective configuration, the CATA system adopts a bus type fiber-optic link. M radio zones are connected to the bus link, where the radio signals from radio terminals in each zone are multiplexed by DOS-CDMA scheme and transmitted to the HE. The RBS in each zone equips only a LD, an optical switch (OSW) and an automatic gain controller (AGC).

As mentioned in Sect. 2.1, after the direct-intensity-modulation of LD, the optical on-off switching spread spectrum (SS) is performed at the OSW, and in the bus type fiber link, many optical SS signals are multiplexed by CDMA. At the receiver, received optical powers are different among the received CDMA signals from M RBS's because the optical loss between each RBS and HE is different. Also, intensity modulation indices are different among the received CDMA signals because radio signal received by RBS has various amplitudes due to fading and the different distance between terminal and RBS. These differences cause the near-far problem in CDMA system. For this reason, a RBS is equipped with an AGC to keep the amplitude of radio signals constant, and also equipped with an OA to compensate optical loss between two RBS's.

At the HE, optical CDMA signals from RBS's are at first power-split into each of M receivers, then matched with one of different prime codes at each OSW correlator and detected at PD. Finally, the desired radio signal of each RBS is regenerated by the interpolation in BPF and then fed to a demodulator. In the conventional bus type fiber optic link, each node is usually connected to a bus link with a passive optical coupler (OC). In this case, there are the insertion loss

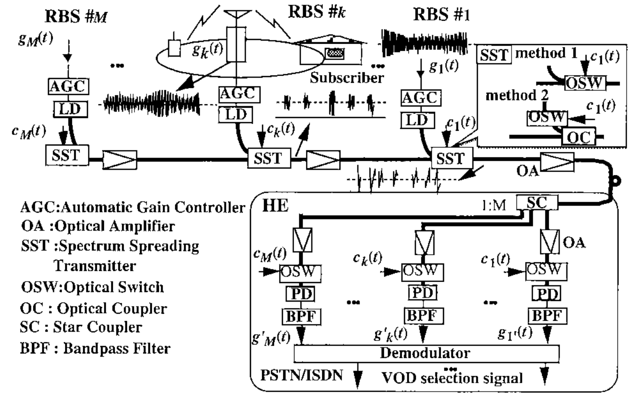


Fig. 5 Configuration of DOS-CDMA CATA system.

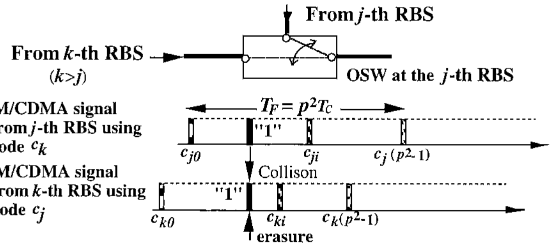


Fig. 6 Collision between two IM/CDMA signals.

and the coupling loss in a coupler. In the proposed DOS-CDMA CATA system where OC connection is used, the optical signal beat noise is caused by the interference between two lights arriving at the PD at the same time. On the other hand, we can use an OSW not only to perform switching-spread-spectrum of the optical IM signal but also to launch them into the bus link. In this paper, we propose a configuration of CATA system using OC and OSW connection. These two connection methods at a RBS are shown in Fig. 5. In the case of OSW connection, when an IM/CDMA signal from RBS's that are further away from the HE arrives at the OSW of the those which are closer and transmitting their signals, the signal collision at the OSW of each RBS will cause the erasure of some chip pulses in DOS-CDMA signal as shown in Fig. 6. The detail will be discussed in Sect. 3.

3. Theoretical Analysis of Carrier-to-Interference-Plus-Noise Ratio Performance

In this section, we theoretically analyze the carrier-to-interference-plus-noise power ratio(CINR) of the regenerated radio signal at the HE. We derive them for both OC connection and OSW connection in DOS-CDMA CATA system.

3.1 OC Connection

At the k-th correlator, the received peak power, P_{r_k}, can be written as

$$P_{r_k}=10\log_{10}P_s-k(L_f+L_{oc})+kG -10\log_{10}M+G_M[\mathrm{dB}], \tag{9}$$

where L_{oc}[dB], L_f[dB], G[dB] and G_M[dB] are the coupling loss plus the insertion loss of an OC, the fiber loss between RBS's, the gain of OA at the RBS and the gain of OA at the output of 1:M star coupler(SC), respectively[13]. It is assumed that an OA equipped at each RBS has the gain G of L_f+L_{oc} and G_M is equal to $10\log_{10}M$.

From Eq.(9), therefore, P_{r_k} is given by

$$P_{r_k}=P_s\ (k=1,2,..,M). \tag{10}$$

At the HE, each correlator receives M optical signals with the same modulation index of 1 and the same received power, $P_r=P_s$, thereby the carrier power and the CINR of the regenerated radio signal are C_0 and CIR_0 given by Eqs.(7) and (8) in the case of $P_r=P_s$, respectively. At the output of BPF, we consider additive noise currents composed of relative intensity noise, shot noise, receiver thermal noise, beat noise among amplified spontaneous emissions (ASE) of an optical amplifier and optical signal, beat noise among ASE's and optical signal beat noise. Considering that the average number of coincidences of 1's between any prime code sequence pair in the interval of the code frame period, T_F, is one, that will be analyzed in Sect. 3.2, the total noise power, N_c, is written by

$$N_c=N_{RIN}+N_{shot}+N_{th}+N_{s-sp}+N_{sp-sp}+\langle N_{s-s}\rangle \tag{11}$$

and each power is given by

$$N_{RIN}=\zeta_{RIN}\left(\frac{\alpha P_s}{p^2}\right)^2(p^2+M-1)B_{rf}, \tag{12}$$

$$N_{shot}=2e\{\frac{\alpha P_s}{p^2}(p+M-1)+\alpha M(N_{sp}+N_{spM})W\}B_{rf}, \tag{13}$$

$$N_{th}=4k_BTB_{rf}/R_L, \tag{14}$$

$$N_{s-sp}=4\alpha M(N_{sp}+N_{spM})\frac{\alpha P_s}{p^2}(p+M-1)B_{rf}, \tag{15}$$

$$N_{sp-sp}=2\alpha^2M^2(N_{sp}+N_{spM})^2(W-f_{rf}), \tag{16}$$

where e, ζ_{RIN}, W, k_B, T and R_L are the electric charge, the PSD of the relative intensity noise, the bandwidth of optical filter at the HE, Boltzmann constant, the noise temperature and the load resistance, respectively. The PSD's of the ASE, N_{sp} and N_{spM}, are given by

$$N_{sp}=\frac{\eta_{sp}}{\eta_a}\cdot\frac{10^{G/10}-1}{10^{G/10}}h\nu, \tag{17}$$

$$N_{spM}=\frac{\eta_{sp}}{\eta_a}\cdot\frac{M-1}{M}h\nu, \tag{18}$$

respectively, where η_{sp}, η_a and $h\nu$ are the spontaneous emission factor, the quantum efficiency of the OA and the photon energy, respectively [14].

The optical signal beat noise, $\langle N_{s-s}\rangle$, is due to an interference between two optical carriers. In this analysis, it is assumed that the k-th RBS uses a LD with its center frequency of f_k and its single mode gaussian shaped spectrum, and also assumed that f_k is a random variable with a uniform probability density [4]. The PSD of optical signal-signal beat noise is given by

$$S_{s-s}(f)=\left(\frac{\alpha P_s}{p^2}\right)^2\sum_{j=1}^{M}\sum_{\substack{k=1\\k\neq j}}^{M}\{\frac{1}{2\sigma\sqrt{2\pi}}e^{-\frac{(f-\Delta f_{jk})^2}{2\sigma^2}}+\frac{1}{2\sigma\sqrt{2\pi}}e^{-\frac{(f+\Delta f_{jk})^2}{2\sigma^2}}\}, \tag{19}$$

$$\text{where } \Delta f_{jk}=f_j-f_k, \tag{20}$$

$$\sigma=\Delta\nu/(2\log 2), \tag{21}$$

$$\Delta\nu=\sqrt{\Delta\nu_{LD}+\left(p^2B_{rf}\right)^2}, \tag{22}$$

where $\Delta\nu_{LD}$ is the full width half maximum(FWHM) of the LD, and $\Delta\nu$ is the FWHM after spread spectrum by prime codes with the prime number p. The PSD of the optical signal beat noise, $S_{s-s}(f)$, appears in the radio frequency band after the photodetection, but its frequency location depends on the frequency difference among LD's of M RBS's. So we treat its power N_{s-s} as a random variable and derive its average power $\langle N_{s-s}\rangle$. Assuming that optical carrier frequencies at RBS's, f_j (j=1,2,..., M) are mutually independent random variables with their mean of f_0 and a uniform probability density function in the range of $|f_j-f_0|<\Delta F/2$, then the power of optical signal beat noise falling in bandwidth B_{rf}, N_{s-s}, is given by

$$\begin{aligned}N_{s-s}&=\left(\int_{-f_{rf}-B_{rf}/2}^{-f_{rf}+B_{rf}/2}+\int_{f_{rf}-B_{rf}/2}^{f_{rf}+B_{rf}/2}\right)S_{s-s}(f)df\\&=\left(\frac{\alpha P_s}{p^2}\right)^2\sum_{j=1}^{M}\sum_{\substack{k=1,\\k\neq j}}^{M}\left[erfc\left\{\frac{-2(f_{rf}+\Delta f_{jk})-B_{rf}}{2\sqrt{2}\sigma}\right\}\right.\\&\quad-erfc\left\{\frac{-2(f_{rf}+\Delta f_{jk})+B_{rf}}{2\sqrt{2}\sigma}\right\}+erfc\left\{\frac{-2(f_{rf}-\Delta f_{jk})-B_{rf}}{2\sqrt{2}\sigma}\right\}\\&\quad\left.-erfc\left\{\frac{-2(f_{rf}-\Delta f_{jk})+B_{rf}}{2\sqrt{2}\sigma}\right\}\right].\end{aligned} \tag{23}$$

We can obtain the average power of optical signal beat noise falling in bandwidth B_{rf}, $\langle N_{s-s}\rangle$, by ensemble averaging N_{s-s} with the pdf of $\Delta f_{jk}(j,k=1,2,..,M,j\neq k)$.

Finally, the CINR of the regenerated radio signal in the OC connection system is given by

$$CINR_c=C_0/(N_c+I_0). \tag{24}$$

3.2 OSW Connection

In the case of OSW connection, some optical chip pulses in CDMA signal from k-th RBS may be lost at the OSW of other RBS's which are located between the k-th RBS and the HE, therefore, we have to take into consideration the chip pulse erasure in the CINR analysis. First, we theoretically derive the average number of 1's in the prime code sequence successfully reaching the HE and next analyze the CINR.

At the OSW of each RBS, an optical IM signal converted from a radio signal is spectrum-spread and simultaneously launched into the fiber-optic bus link. If an IM/CDMA signal from the k-th RBS arrives at the OSW of the j-th ($k>j$) RBS which is transmitting its own signal, a signal collision occurs and causes the erasure of some chip pulses from the k-th RBS. Figure 6 illustrates the collision between two IM/CDMA signals. When the collision between two IM/CDMA signals occurs at the OSW of the j-th RBS, we lose IM/CDMA signal from the k-th RBS located farther than the j-th RBS because the multiplexing of IM/CDMA signals is performed by using OSW.

Here, we examine the number of coincidences of 1's between any two prime code sequences in the code frame period, T_F. For the 0-th prime code sequence, c_0, the number of coincidences of 1's with any other sequences, $c_n(n\neq 0)$, is always one in the code frame period T_F, and this property is kept for all shifted versions of $c_n(n\neq 0)$. On the other hand, between any other two code sequences, c_m and c_n $(m\neq 0, n\neq 0, m\neq n)$, the number of coincidences of 1's yields none, one, or two. In other words, the peak of the cross-correlation function is 1 between c_0 and $c_n(n\neq 0)$ sequences, and 1 or 2 between c_m and c_n $(m\neq 0, n\neq 0, m\neq n)$. Let N_{mni} the number of the shifted versions of c_m sequences which has i coincidences of 1's with c_n sequences. For a prime number $p=2q-1$, we can find N_{mni},

$$N_{0ni}=\begin{cases}0 & ;i=0,2\\ 4q^2-4q+1=p^2 & ;i=1 \text{ for } n=1,2,..,p\text{-}1\end{cases}, \tag{25}$$

$$N_{mni}=\begin{cases}q^2-q & ;i=0,2\\ 2q^2-2q+1 & ;i=1 \text{ for } m,n=1,2,..,p\text{-}1, m\neq n\end{cases}. \tag{26}$$

In the code frame period T_F, therefore, the average number of coincidences of 1's is one for any prime code sequence pair. In actual DOS-CDMA CATA system, a code sequence comes into collision with another sequence asynchronously, so we have to consider the partial collision between two chip pulses. For the simplicity of analysis, however, we assume the full chip pulse is lost even in this case.

From above results, when an IM/CDMA signal from a RBS comes to another OSW, one chip pulse is erased due to the collision on the average. Moreover the IM/CDMA signal transmitted from the k-th RBS may lost from 1 to (k-1) chip pulses because it passes through (k-1) OSW's to the HE. Hence, letting χ_k denote the average number of chips successfully reaching the HE, χ_k, is given by

$$\chi_k=p-(k-1). \tag{27}$$

This is a worst case estimation because the same chip pulse comes into collision with different chip pulses of more than two RBS's. The k-th received peak power, P_{r_k}, at the output of the SC is given by

$$P_{r_k}=10\log_{10}P_s+kG'-kL_f-10\log_{10}M$$
$$+G_M[\mathrm{dB}](k=1,2,..,M). \tag{28}$$

It is assumed that G_M is equal to $10\log_{10}M$ as the same with the case of OC connection. For easy discussion, we consider $G'=G_c+G_a$ [dB]. G' is the gain of OA at each RBS to compensate the optical loss caused by the chip pulse erasure. We set the value of G_c to keep the carrier power of the radio signal from the farthest M-th RBS equal to that in OC connection at the correlator and G_a[dB] is an additional gain. The gain G_c satisfies the following equation:

$$P_{r_M}\frac{\chi_M}{p^2}=P_s\frac{1}{p}. \tag{29}$$

Consequently, the desired G_c is derived as

$$G_c[\mathrm{dB}]=\frac{10}{M}\log_{10}(\frac{p}{\chi_M})+L_f \tag{30}$$

and the received peak power, P_{r_k}, at the k-th correlator is given by

$$P_{r_k}=P_s\left(\frac{p}{\chi_M}\right)^{k/M}g_a{}^k, \tag{31}$$

where $G_a=10\log_{10}g_a$.

The carrier power of the k-th radio signal regenerated at HE can be written as

$$C_k=C_0\left(\frac{\chi_k}{p}\right)^2\left(\frac{p}{\chi_M}\right)^{2k/M}g_a{}^{2k}(k=1,2,..,M). \tag{32}$$

On the other hand, IM/CDMA signals from RBS's located farther than the k-th RBS never reach at the k-th correlator because they are erased at the OSW of the k-th RBS during the interval of 1's in $c_k(t)$ as shown in Fig. 6. Thus, we consider only the IM signals from RBS's nearer than the k-th RBS as the interference, then the interference power contaminating the k-th radio signal regenerated at HE can be written as

$$I_k=\frac{\sigma_c^2}{p^2}\sum_{j=1}^{k-1}C_j. \tag{33}$$

Hence, the CIR of k-th radio signal in the OSW connection system is given by

$$CIR_k=\frac{C_k}{I_k}=\varepsilon_k CIR_0(k=1,2,..,M), \tag{34}$$

$$\varepsilon_k=\frac{M-1}{\sum_{j=1}^{k-1}\left(\frac{p}{\chi_M}\right)^{2(j-k)/M}\left(\frac{\chi_j}{\chi_k}\right)^2 g_a{}^{2(j-k)}}, \tag{35}$$

where CIR_0 is the CIR obtained in the OC connection system(Eq.(8)).

In the OSW connection system, since IM/CDMA signals from RBS's located farther than the k-th RBS never reach the k-th correlator, relative intensity noise, shot noise, beat noise among ASE of an OA and optical signal and beat noise among ASE's are different from those in the OC connection system as the followings:

$$N'_{RIN}=\zeta_{RIN}\left(\frac{\alpha P_{r_k}}{p^2}\right)^2(\chi_k^2+k-1)B_{rf}, \tag{36}$$

$$\begin{aligned}N'_{shot}=2e[&\frac{\alpha P_{r_k}}{p^2}(\chi_k+k-1)\\&+\alpha\{N'_{sp}\sum_{j=1}^{k}(\frac{g'}{l_f})^j+MN_{sp_M}\}W]B_{rf},\end{aligned} \tag{37}$$

$$\begin{aligned}N'_{s-sp}=4\alpha\{&N'_{sp}\sum_{j=1}^{k}(\frac{g'}{l_f})^j+MN_{sp_M}\}\\&\times\frac{\alpha P_{r_k}}{p^2}(\chi_k+k-1)B_{rf},\end{aligned} \tag{38}$$

$$N'_{sp-sp}=2\alpha^2\{N'_{sp}\sum_{j=1}^{k}(\frac{g'}{l_f})^j+MN_{sp_M}\}^2(W-f_{rf}), \tag{39}$$

where $G'=10\log_{10}g'$, $L_f=10\log_{10}l_f$ [dB] and N'_{sp} are given by Eq.(17) substituted $G=G'$. Note that in OSW connection, no optical signal beat noise occurs that is different from OC connection. Therefore, the total noise power at the k-th correlator output, N_{swk}, is

$$N_{swk}=N'_{RIN}+N'_{shot}+N_{th}+N'_{s-sp}+N'_{sp-sp}, \tag{40}$$

and the CINR of the k-th regenerated radio signal, $CINR_k$, is given by

$$CINR_k=\frac{C_k}{I_k+N_{swk}}(k=1,2,..,M). \tag{41}$$

4. Numerical Results of Performance and Discussion

In this section, some numerical results of CINR in the DOS-CDMA CATA system for both OC and OSW connections are shown and discussed. Parameters used for calculation are shown in Table 3.

Figure 7 shows the CIR of the k-th RBS for p=23 and M=20. In the case of G_a=0dB, the CIR in the OSW connection system is degraded compared with the OC connection system as k comes near to M because the coefficient ε_k (Eq.(35)) which expresses the CIR reduction effect due to the erasure of chip pulse becomes less than 1 as k comes near to M. On the other hand, the CIR of the nearer RBS to the HE in the OSW connection system is more improved compared with the OC connection system because IM/CDMA signals from RBS's located farther than the k-th RBS never reach the k-th correlator, therefore the interference power is reduced. However, Eqs.(34) and (35) show that by increasing the additional gain, G_a, the CIR_k can be improved for any k-th radio signal. Figure 7 shows that as the G_a increases, the CIR_k is improved and we can obtain almost the same CIR for all radio signals from M RBS's. On the other hand, the additional gain is not effective to improve the CIR in the OC connection system because the radio signals from the nearer RBS to the HE suffer interferences with amplified large power while the CIR of the radio signal from the farther RBS can be improved as shown in Fig. 7.

Figure 8 shows CIR of the farthest M-th RBS as a function of prime code number p for M of 20, 40 and 80. The upper abscissa is the switching speed of OSW. When G_a is 0dB in the OSW connection system, the coefficient ε_M is less than 1 as p comes near to M, thus the CIR_M of the farthest M-th RBS is degraded compared with OC connection system. This is due to the erasure of chip pulse of the M-th radio signal. However, this penalty can be reduced and the CIR_M comes to the same as that in the OC connection system as p increases more than M. It is also found from Fig. 8 that by introducing additional gain(G_a>0 dB), the CIR_M of the farthest M-th RBS is more improved than that in the OC connection system as G_a increases for any p and M. This is because as p increases more than M, Eq.(35) shows that ε_M comes near to $(M-1)/\sum_{j=1}^{M-1} g_a^{2(j-M)}$ which is more than 1 and yields the same value regardless of M.

Here, we have to consider the limitations in G_a and p to realize the OSW connection system.

Table 3 Parameters used for calculation.

responsivity of PD	α	0.8A/W	radio signal frequency	f_{rf}	1.93GHz
PSD of relative intensity noise	ζ_{RIN}	-152dB/Hz	radio signal bandwidth	B_{rf}	900KHz
bandwidth of optical filter	W	1THz	coupling and insertion loss of OC	L_{oc}	3dB
noise temperature	T	300K	fiber loss between RBS's	L_f	0.5dB
load resistance	R_L	50 Ω	FWHM of the LD	$\Delta\nu_{LD}$	10MHz
quantum efficiency of OA	η_a	0.5	difference of center frequency of the LD	ΔF	1THz
spontaneous emission factor	η_{sp}	2.0			

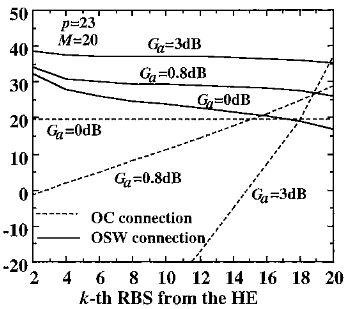


Fig. 7 CIR of the k-th RBS from the HE out of 20 RBS's.

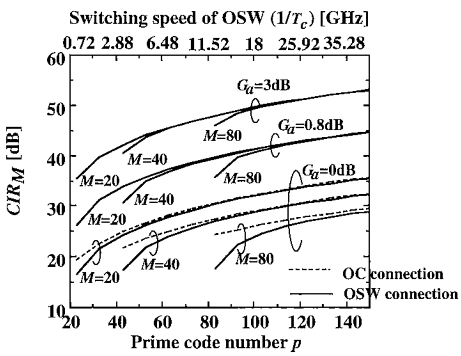


Fig. 8 CIR of the farthest M-th RBS versus p.

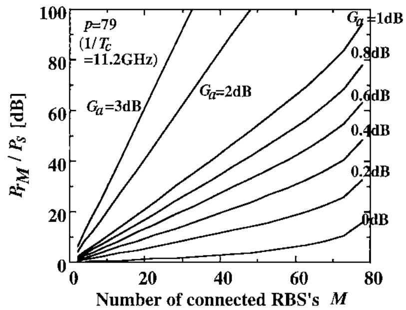


Fig. 9 Relationship between P_{rM} / P_s and M for p=79 in the OSW connection system.

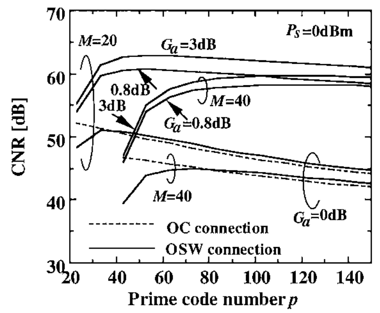


Fig. 10 CNR versus p for P_S=0 dBm and M of 20 and 40.

Regarding p, the achievable switching speed of the OSW gives the limitations of the prime code number, p. If we use the OSW with its speed of almost 10GHz, we can increase the p up to about 80. The possible additional gain, G_a, is limited by the optical peak power limitation in the optical fiber. Figure 9 shows the received peak power from the farthest M-th RBS, P_{rM} normalized by the transmitted peak power in the case of p=79 ($1/T_C$=11.2 GHz). For example, in the case that the limitation of P_{rM} / P_s is 20 dB, the upper limits in numbers of connected RBS's in OSW connection system are 63, 41, 30, 23 and 19 for G_a= 0.2, 0.4, 0.6 , 0.8 and 1 dB's respectively. G_a can be increased up to 0.8 dB for P_{rM} / P_s = 20 dB and M=20. Thus it is seen from Fig. 8 that for M=20, the CIR in the OSW connection system can be more improved by about 8 dB than that in the OC connection system by introducing the G_a of 0.8 dB.

Figure 10 shows CNR as a function of prime code number p for P_S of 0dBm and M of 20 and 40. When G_a is 0 dB, CNR's for both OC and OSW connection systems are dominated by the beat noise among ASE of an OA and the optical signal, N_{s-sp} and N'_{s-sp}, respectively for small p but affected by the receiver thermal noise, N_{th}, as p comes to large because the carrier power decreases in proportion to $1/p^2$. As p comes near to M, the CNR in the OSW connection system is degraded by the erasure of chip pulse compared with the OC connection system. However, the CNR's of both OC and OSW connection systems are similar as p increases more than M because the erasure of chip pulse can be neglected and N_{s-sp} and N'_{s-sp} are dominated by the OA at the output of SC. On the other hand, when G_a is more than 0 dB, the CNR in the OSW connection system is dominated by N'_{s-sp} caused

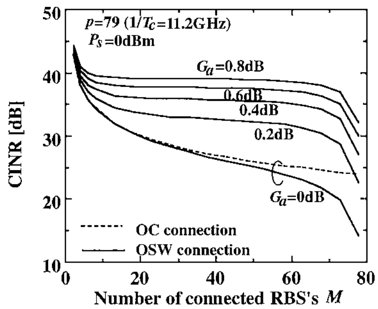


Fig. 11 CINR versus M for p=79($1/T_c$=11.2 GHz).

by the OA at the RBS, thus, the CNR is more improved than that in OC connection system as G_a increases. For example, it is seen from Fig. 10 that for P_S =0 dBm, M=20 and p=79, the CNR in the OSW connection system with G_a of 0.8dB can be more improved by 11 dB than that in the OC connection system.

It is seen from Figs. 8 and 10 that the CINR is dominated by the CIR for any p. By introducing additional gain, the CINR in the OSW connection system can be more improved than that in the OC connection system. It is found that for M=20, the CINR in the OSW connection system can be more improved by about 8 dB than that in the OC connection system by introducing the G_a of 0.8 dB.

Figure 11 shows CINR as a function of the number of connected RBS's, M, for p=79 ($1/T_c$=11.2 GHz) and P_S=0 dBm. In the OSW connection system, when G_a=0 dB and M comes near to p, the CIR is worse than the OC connection system. However, the CINR of the OSW connection system is more improved than that in OC connection system as G_a increases. In the OC connection system, the number of connected RBS's is determined by the required CINR. On the other hand, in the OSW connection system, the number of connected RBS's is determined by both the required CINR and the peak power limitation. It is seen from Figs. 9 and 11 that when the required CINR is 30dB and the required P_{rM} / P_s is 20 dB, the numbers of connected RBS's in the OSW connection system are 63, 41, 30 and 23 for G_a= 0.2, 0.4, 0.6 and 0.8 dB's respectively, while the number of connected RBS's in the OC connection system is 18. Thus it is found that in the OSW connection system with G_a=0.2 dB, three times of RBS's can be connected to CATA system compared with the OC connection system.

5. Conclusion

In this paper, we have proposed Cable-To-The-Air system using novel direct optical switching CDMA scheme (DOS-CDMA CATA system) which can provide seamless wireless access network in both indoor and outdoor. We have also proposed the configuration of DOS-CDMA CATA system by using OC and OSW connections. The carrier-to-noise-plus-interference power ratio has been theoretically analyzed. Following results have been obtained:

1. In the OSW connection system, by introducing the addi-

tional optical gain at each RBS, the CIR's for all RBS's can be almost the same as the prime code number increases more than the number of connected RBS's.

2. In the OSW connection system with the additional gain, the CINR's for all RBS's and the number of connected RBS's can be improved compared with the OC connection system. For example, by using the OSW connection system with G_a=0.2 dB, three times of RBS's can be connected to CATA system with the CINR of 30 dB and the P_{r_M} / P_s of 20 dB for p=79 compared with the OC connection system.

Thus the OSW connection is effective DOS-CDMA CATA system where an OSW is used not only to spread the spectrum of optical signals but also to launch them into fiber-optic bus link.

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References

[1] T.Yoshida, "A high speed wireless access link-solution of last mile problems," Proc. of Microwave workshops and exhibition (MWE), pp.195-200, Sept. 1993.
[2] S.Komaki, K.Tsukamoto, S.Hara, and N.Morinaga, "Proposal of fiber and radio extension link for future personal communications," Microwave and optical technology letters, vol.6, no.1, pp.55-60, Jan. 1993.
[3] H.Yanikomeroglu and E.S.Sousa, "Antenna interconnection strategies for personal communication systems," IEEE J. of Select. Areas Commun., vol.15, no.7, pp.1327-1336, Sept. 1997.
[4] S.Kajiya, K.Tsukamoto, and S.Komaki, "Proposal of fiber-optic radio highway networks using CDMA method," IEICE Trans. Electron., vol.E79-C, no.1, pp.111-117, Jan. 1996.
[5] P.R.Prucnal, M.A.Santoro, and T.R.Fan, "Spread spectrum fiber-optic local area network using optical processing," IEEE J. of Lightwave Tech., vol.LT-4, no.5, pp.547-554, May 1986.
[6] W.C.Kwong, P.A.Perrier, and P.R.Prucnal, "Performance comparison of asynchronous and synchronous CDMA techniques for fiber-optic local area networks," IEEE Trans. Commun., vol.39, no.11, pp.1625-1634, Nov. 1991.
[7] J.A.Salehi, A.M.Weiner, and J.P.Heritage, "Coherent ultrashot light pulse code-division multiple access communication systems," IEEE J. of Lightwave Tech., vol.7, no.3, pp.478-491, March 1990.
[8] S.Benedetto and G.Olmo, "Performance evaluation of coherent optical CDMA," Electronics Letter, vol.27, no. 22, pp.2000-2002, Oct. 1991.
[9] T.L.Duffield, "A comparison of modulation techniques for quantized voice communications," IEEE Trans. Commun., vol.18, no.5, pp.543-550, Oct. 1970.
[10] A.Kohlenberg, "Exat interpolation of band-limited functions," J. of applied physics, vol.12, no.12, pp.1432-1436, Dec. 1953.
[11] H.Harada, S.Kajiya, K.Tsukamoto, and S.Komaki, "TDM intercell connection fiber-optic bus link for personal radio communication systems," IEICE Trans. Commun., vol.E78-B, no.9, pp.1287-1294, Sept. 1995.
[12] A.A.Shaar and P.A.Davies, "Prime sequences:Quasi-optimal sequences for or channel code division multiplexing," Electronics Letter, vol.19, no.21, pp.888-889, Oct. 1983.
[13] K.Tsukamoto, T.Fujii, and N.Morinaga, "Multiaccess coherent optical communication system using common optical carrier with star configuration," IEICE Trans., vol.J77-B-I, no.5, pp.267-274, May 1994.
[14] T.Fujii, K.Tsukamoto, and N.Morinaga, "Transmission characteristics anlysis of optical fiber bus link with optical amplifier for microcellular communication systems," IEICE Tech. Report, RCS92-76, Oct. 1992.

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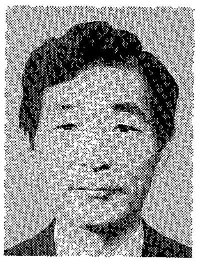

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