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Proposal of the Radio High-Way Networks Using Asynchronous Time Division Multiple Access

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SUMMARY Air interfaces of the future mobile communication are widely spreading, because of the multimedia service demands, technology trends and radio propagation conditions. Radio-Highway Networks are expected to realize the universal, seamless and multi-air-interface capability for mobile access networks, and play an important role in the future multimedia radio communications. For the radio-highway networks, this paper newly proposes natural bandpass sampling - asynchronous time division multiple access (NBS-ATDMA) method, where radio signals are natural bandpass sampled at the radio base station and are *asynchronously* multiplexed on the optic fiber bus link and intelligently transmitted to its desired radio control station. We theoretically analyze the loss probability of the radio signal due to collision in the network and the carrier-to-noise power ratio of received radio signals at the radio control station. Moreover, in order to reduce the loss probability, two access control methods, carrier sense and pulse width control, are proposed, and it is clarified that these improve the number of base station connected to radio highway networks.

key words: *microcellular system, optmicrowave technique, radio-highway networks, asynchronous time division multiple access, optic-fiber bus link*

1. Introduction

In near future cellular radio communication systems, the cell number is tend to increase as the results of cell size reduction to improve the frequency reuse efficiency and low consumption power. At the same time, the radio signal air-interface format will be rapidly changed and diversified because the multimedia personal communications require various types of signal speed and radio signal access format. To solve these problems, it is proposed that the microcells in a wide area are connected by optical fibers, and radio signals are converted into optical signals with the same signal formats and transmitted to the remote control station [1]–[3]. We call this system fiber-and-radio extension link (FREx Link) [1] and furthermore we have proposed the Radio High-way Networks, which have a networking function of radio signals and offer more universal and flexible networks for the future multimedia mobile communications [4].

The concept of the Radio High-way Networks is illustrated in Fig. 1. Many radio base stations (RBS) and radio control stations (RCS) are connected in wide area by optical fibers and routing nodes (RN). The radio signal received at RBS is encapsulated into the optical intensity and transferred to the appropriate remote RCS via several optic RNs. This optic RN is constructed by the photonic switch and plays a role to switch optically enveloped signals to the appropriate control station. Optical envelopes received at RCS is de-capsulated to the radio signals just as same as the transmitted radio signals. In this way, radio signals are transferred in the network without any demodulation, and furthermore, the network can open and switch the radio free space of any cell to any remote cell or RCS according to the demand of a terminal by attaching the header signal to the radio burst signal and routing it to the destination like ATM [4]. We call this space as "Virtual Free Space" [4]. So the Radio High-way Networks are universally applicable for any types of air-interfaces and any new multimedia-personal services, and the system construction requires only one radio receiver installation in a RCS and no replace of RBSs and networks.

We have proposed the radio highway networks using optic-fiber bus-type intercell connection link and optical PAM/IM/TDMA (Pulse Amplitude Modulated radio / optical Intensity Modulation / Time Division Multiple Access) method [5]–[7], where a radio signal received at each RBS is transformed into optical PAM/IM signal by natural bandpass sampling [6], [8], [9] and the optical signals from many RBSs are multiplexed by TDMA method in optic-fiber bus link. As a multiplexing scheme, we have examined synchronous multiple access in [5]–[7]. However, in this approach, a strict time-synchronization of the whole network is

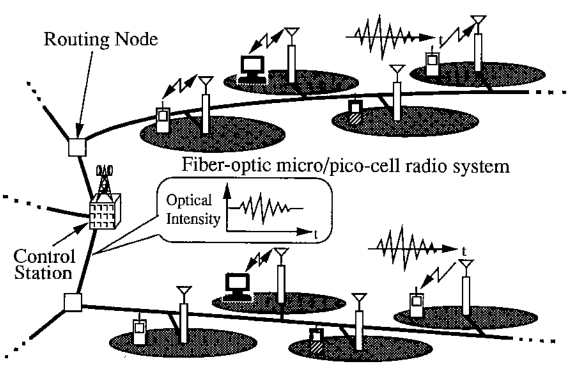

Fig. 1 Concept of the Radio Highway Networks.

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needed to keep the communication channel among RBSs, RNs and RCS and this will be a very severe problem as the total number of RBS increases.

In contrast, asynchronous TDMA method is effective on the convenience and flexibility of the radio highway networks because of its advantages such as no time synchronization among RBSs and RCS, and easy addition of some RBSs to the bus link without any change of systems. In this paper, we newly propose the Radio High-way Networks using natural bandpass sampling asynchronous time division multiple access (NBS-ATDMA) [10], where a radio signal is transformed into optical PAM/IM burst signals by use of photonic switch, and these bursts are asynchronously multiplexed like ATM in the fiber-optic bus link. Moreover, we propose two access control methods to reduce the loss probability of optical PAM/IM burst transferring radio signals.

In Sect. 2, the concept and configurations of the Radio High-way Networks using NBS-ATDMA are shown, and in Sect. 3, the analytical model is shown. In Sects. 4 and 5, the burst loss probability and the carrier-to-noise are theoretically analyzed taking into account the collision among bursts, respectively. In Sect. 6, numerical results are shown and discussed.

2. System Configuration

Figure 2 illustrates the configuration of proposed Optical Fiber Radio-Highway Networks using NBS-ATDMA method. Many RBSs and the RCS are connected with a fiber-optic bus link including RNs where optical signals are switched and transfered to the appropriate RCS. The radio signal received at RBS directly modulates a laser diode (LD) and we obtain intensity-modulated (IM) optical signal. Before modulating, a digital header signal is attached to recognize the start point of the burst frame, the base station number, and the destination RCS address. Then this IM optical signal is asynchronously fed into optical bus link by photonic switch. This photonic switch not only connects a RBS to the optic bus link but also performs the natural bandpass sampling of the optical IM signal to produce pulse amplitude modulated radio (PAM)/optical intensity modulation (IM) signal format, and this format enables us to multiplex optical IM signals launched from many RBSs by asynchronous time division multiple access (ATDMA).

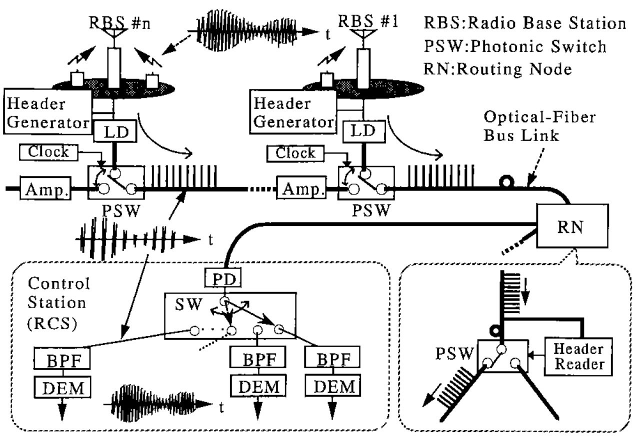

Fig. 2 Configuration of the Radio Highway Network using NBS-ATDMA.

Figure 3 illustrates an example of the waveform of natural bandpass sampled radio signal, that is, a radio PAM signal and its spectrum are shown. At the RCS receiver, the radio signal can be reproduced from the radio PAM signal by use of the bandpass-filtering, if we use the appropriate sampling frequencies [7]. In general, the sampling frequency should be more than double of the maximum frequency of the radio signal. However we can reduce this sampling frequency to the double of modulating speed because the radio signal is the band limited signal. In the proposed system, therefore, the photonic switch operates at the double speed of modulating speed of the received radio signal. Therefore, since the obtained PAM signal contains the radio carrier frequency, this radio highway network can be independent of the frequency of received radio signals if their frequencies are below the modulating bandwidth of the optical modulator and all of their bandwidths are the same among RBSs. On the other hand, the pulse width of PAM signal is an arbitrary value regardless of the frequency or the bandwidth of received radio signals, but for the TDMA system, it must be selected so as to obtain the desired CNR under the laser peak power constrained.

The intermediate RN is composed of a simple photonic switch which operates according to the header signal of optical PAM/IM burst signal. At the RN, each of the burst signals multiplexed by ATDMA method is switched to its own destination RCS. At the RCS received optical PAM/IM signal is detected by a photo detector (PD), and after bandpass-filtering, we can obtain the original radio signal.

When multiplexing the optical PAM/IM signal over the optic link, we can use synchronous time-division-multiplexing or asynchronous one. In TDMA system, the synchronous method is generally used, however in order to realize this, the network must provide

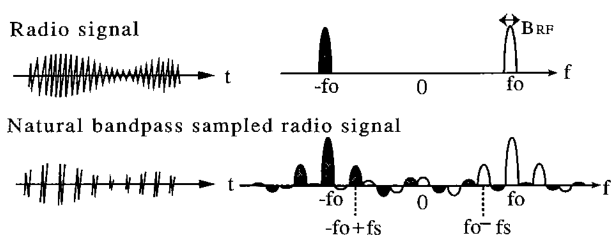

Fig. 3 Spectrum of natural bandpass sampled radio signal.

time synchronizing signals to all RBSs, RNs, and RCSs, and this realization will become more difficult as the network size increases. On the other hand, the asynchronous method is simple and improve the flexibility and the extensibility of the radio-highway network.

In the asynchronous system, it will be difficult to perform routing switch control at the RN, however if at each RBS the digital header is attached to each burst signal, we can perform both the routing switch control and the demultiplexing at the RCS easily. Another problem is the signal loss due to the collision among the PAM/IM bursts. This problem will be discussed in more detail in the next section.

3. Consideration on Burst Collision

In the proposed system, the PAM/IM bursts produced from radio signals at RBSs are multiplexed asynchronously in the optic link, thus radio burst signals may be lost due to collision when several RBSs transmit radio burst signals at just the same timing. Figure 4 illustrates the collision of the PAM/IM bursts. When the collision between two burst signals occurs at the photonic switch of a certain RBS, we lose the burst signal from the RBS located farther than this RBS because the multiplexing of radio signals is performed by photonic switch. For example, the burst from jth RBS is successfully transmitted and one from kth RBS ($j < k$) is lost. Consequently, the throughput of the burst signal decreases, hence, the quality of the received radio signal is deteriorated at the RCS. In order to reduce the burst loss probability, we consider two countermeasures: the carrier sense control at the RBS and the pulse width control of PAM signal.

With respect to carrier sense control, we consider the following three types of asynchronous TDMA method:

1) with no control
Each RBS transmits the PAM/IM burst signals as soon as a radio signal is received regardless of the burst signals from the other RBSs on the bus link.

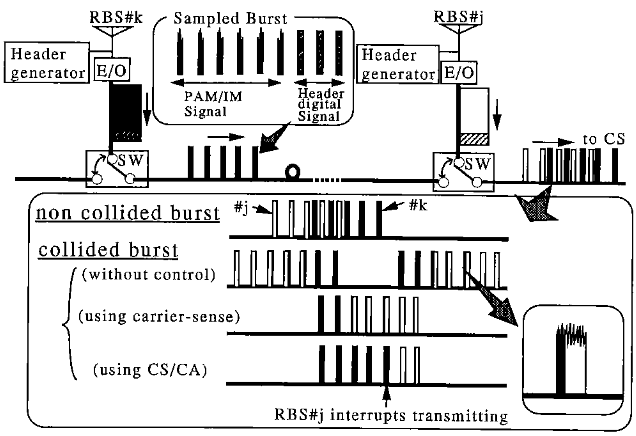

Fig. 4 Collision of signal bursts.

2) with carrier-sense control (CS)
Each RBS senses the PAM/IM signals on the optic bus link when receiving a radio signal. Owing to this carrier sense, the RBS can start to transmit the PAM/IM burst signal at the different timing even if the farther RBS's signals are already passing through the photonic switch. This control method is, however, unable to avoid the collision in case that the signals of farther RBSs come on the switch during the transmission.

3) with carrier-sense control and collision avoidance (CS/CA)
Each RBS not only senses optical signals at the start point of the sampling as same as method 2., but also continues to perform it during the transmission of the RBS's own signal to avoid the collision with the signals of farther RBSs. If the RBS detects such a collision, the RBS interrupts transmitting its own signal. Hence, the farther RBS on the optic bus link has the higher priority of transmitting the PAM/IM burst than the nearer RBS.

Another technique to decrease the probability of the burst collision is the pulse width narrowing in the PAM/IM signal, which means the broadband transmission utilizing the wide band characteristic of optic-fibers and photonic switches positively. The improvement effect of these techniques are discussed in Sect. 6

4. Theoretical Analysis of Burst Loss Probability

In this section, we analyze the burst loss probability due to the collision, theoretically. We number RBSs from one which is the nearest to the RCS. Concerning the radio signal model, we assume that one radio carrier is used to multiplex all users in the TDMA format in each cell. We also assume that the length of the TDMA radio burst signal is fixed value, H, and that the interval between two successive burst signals has the exponential distribution with the mean a. According to these assumptions, the mean traffic per RBS is given by

$$A_{RBS} = H/(a+H) \qquad \text{[erl/RBS]}. \qquad (1)$$

Let A_{kj} denote the event that the PAM/IM burst signal from the jth RBS doesn't be lost due to collision with the burst signal from the kth RBS ($k \neq j$) when the jth RBS receives a radio signal at time t_0 and transmits it into the optic bus link. In this paper, "collision" means that when two bursts overlap, the PAM pulses included in them overlap. Thus the probability of the event A_{kj}, $P(A_{kj})$, is given by

$$P(A_{kj}) = 1 - P_{over} \cdot p_c$$

P_{over}: the probability that bursts overlap

p_c: the probability that the PAM pulses overlap.

In the following analysis, we will first derive $P(A_{kj})$, and next we will derive the throughput, $P_{through_j}$, which is the probability that certain burst signal from the jth RBS successfully reach the RCS without any collision with other bursts. Since the traffics in all cells are mutually independent, $P(A_{kj})$ $(k = 1, 2, \ldots, M)$ is independent for all k and, $P_{through_j}$ is given by

$$P_{through_j} = \prod_{k=1}^{M} P(A_{kj}), \tag{2}$$

where M is the total number of RBSs connected to bus link. From $P_{through_j}$, therefore, the burst loss probability of the jth burst signal, P_{loss_j}, is

$$P_{loss_j} = 1 - P_{through_j}. \tag{3}$$

Now, to derive $P(A_{kj})$ we consider two cases (a) and (b) as shown in Fig. 5: one is the case that the jth RBS starts to transmit just during the transmission of the other kth RBS (Fig. 5 (a)). For example, for $k < j$, the kth RBS is just transmitting a burst signal when the burst signal from jth RBS reaches at the kth photonic switch, and for $k > j$, the jth RBS starts to transmit a PAM/IM burst signal while the burst from kth RBS is passing through the jth photonic switch . Another is the case that the jth RBS starts to transmit in the presence of no other burst on the bus link (Fig. 5 (b)).

For the case (a), let z_i denote the time interval between the start point of the burst from the jth RBS, t_0, and that of ith burst from the kth RBS. Here z_1 is composed of two portion, x_0 and y_0 as shown Fig. 5. For the case (b), z'_i is defined as same as case (a). The probabilities of the case (a) and (b), p_a and p_b, are derived from the probability that a certain RBS is transmitting the PAM/IM burst signal at an arbitrary time. Since this probability is the mean traffic per RBS, A_{RBS}, p_a and p_b are given by $H/(a+H)$ and $a/(a+H)$, respectively.

4.1 $P_{through_j}$ in the Case of No Control

Let $P_{over}(i)$ denote the probability that a burst signal from the jth RBS overlap i burst signals from kth RBS.

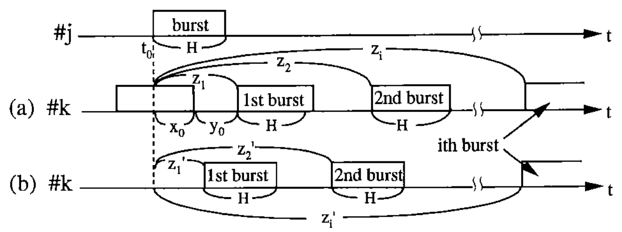

Fig. 5 Collision among bursts.

Taking into account fixed burst length H, $P_{over}(i)$ is given by

$$P_{over}(0) = p_b \int_H^{\infty} p_{z'_1}(z'_1)dz'_1, \tag{4}$$

$$P_{over}(1) = p_a \int_H^{\infty} p_{z_1}(z_1)dz_1 + p_b \int_0^H p_{z'_1}(z'_1)dz'_1, \tag{5}$$

$$P_{over}(2) = p_a \int_0^H p_{z_1}(z_1)dz_1, \tag{6}$$

$$P_{over}(i) = 0 \qquad (i \geqq 3), \tag{7}$$

where $p_{z_i}(z_i)$ and $p_{z'_i}(z'_i)$ are the pdf (probability density function) of z_i and z'_i , respectively. x_0 is uniform distributed in the interval $0 \leqq x_0 \leqq H$ and y_0 is an exponential distributed variable with mean a. Then since x_0 and y_0 are mutually independent, the pdf of $z_1 = x_0 + y_0$, $p_{z_1}(z_1)$, is derived from the convolution of $p_{x_0}(x_0)$ and $p_{y_0}(y_0)$ as

$$p_{z_1}(z_1) = \begin{cases} \frac{1}{H}(1 - e^{-\frac{z_1}{a}}) & (0 \leqq z_i \leqq H) \\ \frac{1}{H}e^{-\frac{z_1}{a}}(e^{\frac{H}{a}} - 1) & (z_i > H) \\ 0 & (z_i < 0). \end{cases} \tag{8}$$

On the other hand, z'_1 is an exponential distributed variable with mean a, and the pdf of z'_1 is given by

$$p_{z'_1}(z'_1) = \begin{cases} \frac{1}{a}e^{-\frac{z'_1}{a}} & (z'_1 \geqq 0) \\ 0 & (\text{otherwise}). \end{cases} \tag{9}$$

Substituting Eqs. (8) and (9) into Eqs. (4)–(6),

$$P_{over}(0) = \frac{1}{1+\frac{H}{a}} e^{-\frac{H}{a}}, \tag{10}$$

$$P_{over}(1) = \frac{2}{1+\frac{H}{a}}(1 - e^{-\frac{H}{a}}), \tag{11}$$

$$P_{over}(2) = \frac{\frac{H}{a}}{1+\frac{H}{a}} \left\{1 + \frac{a}{H}(e^{-\frac{H}{a}} - 1)\right\}. \tag{12}$$

Now, the burst signal is composed of optical PAM/IM burst signal format with sampling interval T_s and pulse width τ_j. So two burst signals doesn't collide till their optical pulses overlap each other. Since the sampling time can be modeled as an uniform distributed random variable in the interval $[-\frac{T_s}{2}, \frac{T_s}{2}]$, the probability that a pulse in the burst from kth RBS overlaps with one from jth RBS, $p_{c_{jk}}$, is given by

$$p_{c_{jk}} = \begin{cases} \frac{\tau_j + \tau_k}{T_s} & (\tau_j + \tau_k \leqq T_s) \\ 1 & (\tau_j + \tau_k > T_s). \end{cases} \tag{13}$$

Therefore, when i bursts from kth RBS overlap with a burst from jth RBS, the probability that no optical pulse overlaps between the jth and kth RBS's bursts is given by $(1 - p_{c_{jk}})^i$ and furthermore, averaging it with respect to i, $P(A_{kj})$ is given by

$$P(A_{kj}) = \begin{cases} \sum_{i=0}^{\infty} \left(1 - p_{c_{jk}}\right)^i P_{over}(i) & (k < j) \\ 1 & (k \geq j). \end{cases} \quad (14)$$

Substituting Eq. (14) into Eq. (2) gives

$$P_{through_j} = \prod_{k=1}^{M} \sum_{i=0}^{\infty} \left(1 - p_{c_{jk}}\right)^i P_{over}(i). \quad (15)$$

4.2 $P_{through_j}$ in Using CS

As a result of each RBS's carrier sense, the burst signal of jth RBS is lost only when it reaches the photonic switch of the kth RBS which is nearer to the RCS ($k < j$) and just transmitting its own burst (see Fig. 5 (a)). Hence, $P(A_{kj})$ is given by

$$P(A_{kj}) = \begin{cases} \left(1 - p_{c_{jk}}\right) p_a + p_b & (k < j) \\ 1 & (k \geq j), \end{cases} \quad (16)$$

and substituting Eq. (16) into Eq. (2) gives

$$P_{through_j} = \prod_{k=1}^{j-1} \left[\left(1 - p_{c_{jk}}\right) p_a + p_b\right]. \quad (17)$$

4.3 $P_{through_j}$ in Using CS/CA

In case using CS/CA, the burst signal of jth RBS is lost when it collide with burst signals of the further kth RBS's ($k = j+1, \ldots, M$), unlike the case of using only carrier sense. The jth RBS stops to transmit its own burst in order to avoid the collision with burst signals of the further RBSs. Therefore, the burst signal of jth RBS is lost when it collides with the 1st burst signal of the further kth RBS in the cases shown in Fig. 5 (a) and 5 (b). So $P(A_{kj})$ is given by

$$P(A_{kj}) = \begin{cases} p_b \int_H^{\infty} p_{z_1'}(z_1')dz_1' + p_a \int_H^{\infty} p_{z_1}(z_1)dz_1 \\ \quad + \left(1 - p_{c_{jk}}\right) \left[p_a \int_0^H p_{z_1}(z_1)dz_1 \right. \\ \quad \left. + p_b \int_0^H p_{z_1'}(z_1')dz_1'\right] & (k > j) \\ 1 & (k \leq j), \end{cases} \quad (18)$$

and substituting Eq. (18) into Eq. (2) gives

$$P_{through_j} = \prod_{k=j+1}^{M} P(A_{kj}). \quad (19)$$

5. Theoretical Analysis of Received CNR

In this section, we theoretically analyze the received carrier-to-noise ratio (CNR) of the radio burst signals at the RCS. In this paper, it is assumed that an optical amplifier is equipped just before every photonic switch and before RCS in order to make up for the fiber transmission loss and the switch insertion loss, and that the power spectral density (psd) of the amplified spontaneous emission (ASE), N_{sp}, is given by [11]

$$N_{sp} = \frac{n_{sp}}{\eta_a} \frac{G_a - 1}{G_a} h\nu \quad (20)$$

where G_a, n_{sp}, η_a and $h\nu$ are the amplifier gain, the spontaneous emission factor, the quantum efficiency of the amplifier and the photon energy, respectively. In the following analysis, furthermore, we ignore the nonlinearity of LD and the noise generated in the Radio link.

When the kth RBS receives a radio signal, $g_k(t)$, and transmits the PAM/IM signal without any collision with other bursts over the optic bus link, the photodetector output current, $i_{out}(t)$, at the RCS is written by

$$i_{out}(t) = \sum_k \sum_{l=-\infty}^{\infty} \alpha P_r(1 + g_k(t))p(t - lT_s + t_k) + n(t), \quad (21)$$

where $p(t)$, t_k, P_r and α are a rectangular pulse with the unit amplitude and the pulse width of τ_k, the start time of sampling, the average received optical signal power and the responsivity of PD, respectively. In this paper, G_a[dB] is assumed to equal to the transmission loss between RBSs, L[dB], including the fiber loss and the insertion loss of the photonic switch. Thus, the RCS receives each RBS's optical signal with the same power P_r, which equals to the transmitting optical power P_t. And $1/T_s$ is the sampling frequency which is given by the double of the bandwidth of radio signal, B_{RF},

$$1/T_s = 2B_{RF}. \quad (22)$$

The white noise photocurrent $n(t)$ is given by

$$n(t) = i_{RIN}(t) + i_{shot}(t) + i_{th}(t) + i_{s-sp}(t) + i_{sp-sp}(t), \quad (23)$$

where $i_{RIN}(t)$, $i_{shot}(t)$, $i_{th}(t)$, $i_{s-sp}(t)$ and $i_{sp-sp}(t)$ are the relative intensity noise current, the shot noise current, the receiver thermal noise current, the beat noise current among ASEs and optical signal and beat noise current among ASEs, respectively. These noise powers in the bandwidth of the radio signal, B_{RF}, are given by

$$< i_{RIN}^2 > = RIN\,(\alpha P_r)^2 B_{RF}, \quad (24)$$

$$< i_{shot}^2 > = 2e\alpha(P_r + m_k N_{sp} W)B_{RF}, \quad (25)$$

$$< i_{th}^2 > = (4kT/R)B_{RF}, \quad (26)$$

$$< i_{s-sp}^2 > = 4\alpha^2 m_k N_{sp} P_r B_{RF}, \quad (27)$$

$$< i_{sp-sp}^2 > = 2\alpha^2 (m_k N_{sp})^2 (W - f_0) B_{RF}, \quad (28)$$

where RIN, m_k, W, k, T, and R are the psd of the relative intensity noise of the transmitting LD, the number of optical amplifier between the kth RBS and the RCS, the bandwidth of optical filter at the RCS, Boltzmann constant, the noise temperature and the load resistance, respectively.

After demultiplexing of the kth PAM signals from the output current $i_{out}(t)$ by the distributor and filtering by the ideal bandpass filter with the center-frequency of f_0 and the bandwidth of B_{RF}, we can obtain the reproduced radio signal, $\hat{g_k}(t)$, which is given by

$$\hat{g_k}(t) = (\tau_k/T_s)\alpha P_r g_k(t). \tag{29}$$

Therefore the carrier power of $\hat{g_k}(t)$ is given by

$$< i_k^2 > = \frac{1}{2}\left(\frac{\tau_k}{T_s}\right)^2 (\alpha P_r)^2. \tag{30}$$

On the other hand, after demultiplexing and filtering, the noise power $n_{PAM}(t)$ is equal to $\frac{\tau_k}{T_s}$ times the power of $n(t)$ [5]. From Eqs. (24)–(28) and (30), consequently, the received CNR of the reproduced radio signal at the RCS is given by

$$\left(\frac{C}{N}\right)_{RCS} = \frac{< i_k{}^2 >}{\frac{\tau_k}{T_s}\left[< i_{RIN}^2 > + < i_{shot}^2 > + < i_{th}^2 > + < i_{s-sp}^2 > + < i_{sp-sp}^2 >\right]}$$
$$= \frac{\frac{1}{2}\frac{\tau_k}{T_s}(\alpha P_r)^2}{\left[RIN(\alpha P_r)^2 + 2e\alpha\{P_r + m_k N_{sp} W\} + \frac{4kT}{R} + 4\alpha^2 m_k N_{sp} P_r + 2\alpha^2 (m_k N_{sp})^2 (W - f_0)\right]\frac{1}{2T_s}}. \tag{31}$$

6. Evaluation of Performance

In this section, the burst loss probability and the CNR are calculated and compared among three types of transmission control (with no control, using CS, and using CS/CA). Parameters used for calculation are shown in Table 1.

6.1 The Performance in Case of No Control

Figure 6 shows burst loss probabilities versus the pulse width of the PAM/IM signal for different values of average traffic A_{RBS}. In this figure, the abscissa is the pulse width normalized by the sampling interval T_s, which represents the pulse duty cycle, and assuming 10 RBSs are connected on the optic-fiber bus link, numerical results of P_{loss} of 10th RBS's burst are shown. It is seen that burst loss probability is much improved as pulse duty decreases for any values of A_{RBS}.

Figure 7 indicates required pulse duty cycle for 10th RBS's burst signals to satisfy $P_{loss} = 10^{-3}$ as a function of average traffic, and also shows the received CNR at the RCS in using the value of the pulse duty. For comparison, the required pulse duty and received

Table 1 Parameters used in calculation.

RIN	-152 dB/Hz	f_0	1 GHz
α	0.8 [A/W]	R	50 Ω
n_{sp}	2.0	T	300 [K]
η_a	0.5	L	5 dB
W	1THz	P_t	10 dBm

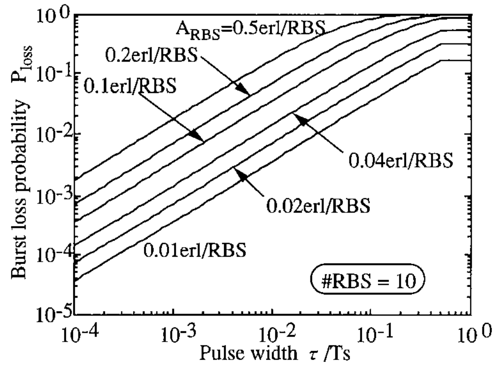

Fig. 6 Burst loss probability versus pulse duty.

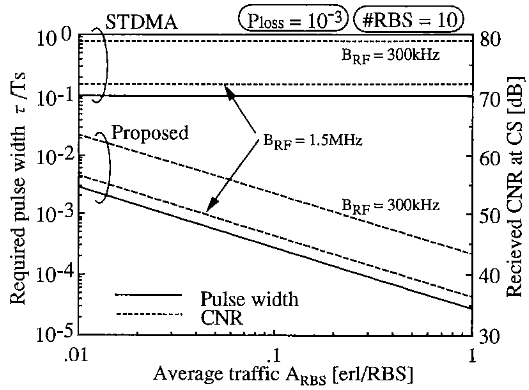

Fig. 7 Required pulse width and received CNR as a function of average traffic.

CNR at RCS of synchronous time division multiple access method (STDMA) are also shown. It is seen that the received CNR in the proposed system gets worse than that in STDMA because we must use hundreds or thousand times smaller pulse width than in STDMA in order to satisfy the quality of $P_{loss} = 10^{-3}$. However, even under the condition of $\tau/T_s = 10^{-4}$ and $A_{RBS} = 0.4erl/RBS$, the received CNR of more than 40 [dB] is obtained at the RCS.

Figure 8 shows burst loss probability and received CNR versus the RBS number which is numbered from RCS for the case of τ/T_s of 10^{-3}. In case of no control, P_{loss} and CNR get worse as the RBS is farther from the RCS (as the RBS number increases), because of the use of photonic switch to multiplex optical radio signals at each RBS. However, we can easily add some RBSs without any troublesome change of the whole system only if we can put up with a little deterioration of burst loss probability and received CNR.

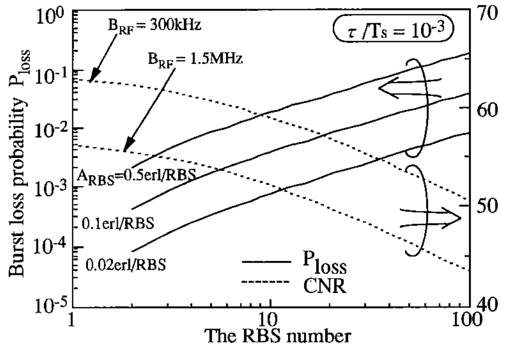

Fig. 8 Burst loss probability and received CNR versus the RBS number.

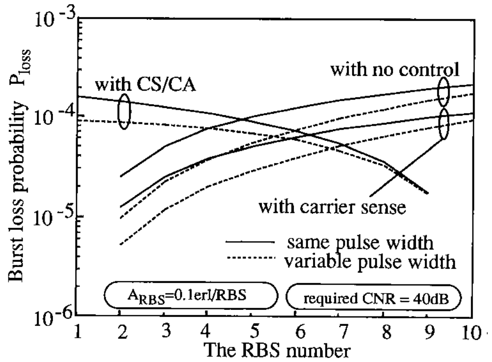

Fig. 9 Burst loss probability and received CNR versus the RBS number with variable pulse width and control.

6.2 Improvement Effect on P_{loss} Due to CS, CS/CA and Variable Pulse Width

Figure 9 shows the relationship between the burst loss probability and the RBS number for three types of transmission control at each RBS (with no control, CS, and CS/CA) when 10 RBSs are connected to bus link. In this figure, the solid lines shows P_{loss} for the case that all RBSs have the same pulse width which is determined for the radio signal from the farthest RBS to attain the required CNR of 40 dB at the RCS. As shown in Fig. 8, the burst signal of RBS nearer to the RCS has a better received CNR at the RCS, in other words, for nearer RBS the narrower pulse width is sufficient to obtain the desired CNR. Thus, it is expected to reduce the loss probability due to such pulse width reduction. So, with the dashed lines this figure also shows the burst loss probability for the case that each RBS sets the pulse width at the value required to attain required CNR at the RCS (variable pulse width).

It is seen from the figure that we can reduce burst loss probability to the half of with no control by using carrier sense. On the other hand, the characteristic of P_{loss} of the system with CS/CA is reverse to those of the systems with no control and with CS because the further RBS has the higher priority to transmit burst signals in using CS/CA.

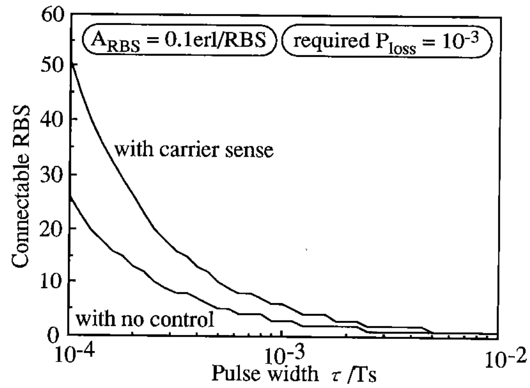

Fig. 10 Maximum number of connectable RBS versus pulse width in the network with CS or with no control.

It is also seen from Fig. 9 that using variable pulse width is more effective to improve P_{loss} for the nearer RBS.

Comparing among three transmitting control methods, it is found that the CS method with variable pulse width is the best choice in order to minimize the worst P_{loss}. And from another viewpoint of system's simplicity, the method without any carrier sense and only with variable pulse width is effective for radio highway networks.

Figure 10 shows the maximum number of connectable RBS versus pulse width in case of required burst loss probability of 10^{-3} in the network with no control or with carrier sense when all RBSs use the same pulse width. It is seen that the network with carrier sense can connect double number of RBS as with no control for any values of pulse width. On the other hand, received CNR decreases as the total number of RBS increases. But even when 50 RBSs are connected to bus link using pulse duty of 10^{-4}, the CNR of more than 36 [dB] can realized under the condition of $B_{RF} = 1.5$ MHz.

7. Conclusion

In this paper, we have newly proposed natural bandpass sampling asynchronous time division multiple access method for Optical Fiber Radio High-way Networks, and two concrete methods to improve the performance of the proposed system are also proposed. We have analyzed the burst loss probability and the CNR performance of the proposed system. Following results are obtained:

1. We can multiplex and transfer radio signals without any time synchronization among RBSs and CS with very low burst loss probability of 10^{-3} and high received CNR at CS of more than 40 [dB] by natural bandpass sampling of radio signals with small pulse width using photonic switch.

2. Using carrier sense control reduce the burst loss

probability to half of that in case of no control and the carrier sense control can double the number of connectable RBS compared with no control.

3. Variable pulse width can further improve the burst loss probability and this is more effective for the nearer RBS.

In this paper, we have proposed Radio-Highway Networks using NBS-ATDMA. From a practical viewpoint, however, we will have a number of problems to be solved for realizing this network, such as attaching methods of the header signals to radio burst signals, the analysis considering radio link noise, LD nonlinearity and multi carrier/interference signal, and a consideration on the down link. These problems should be further studied.

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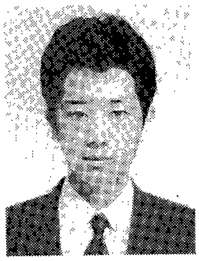
References

[1] S. Komaki, K. Tsukamoto, S. Hara, and N. Morinaga, "Proposal fiber and radio extension link for future personal communications," Microwave and Optical Technology Letters, vol.6, no.1, pp.55–60, Jan. 1993.
[2] J. Namiki, M. Shibutani, W. Domon, T. Kanai, and K. Emura, "Optical feeder basic system design for microcellular mobile radio," IEICE Trans. Commun., vol.E76-B, no.9, pp.1069–1077, Sept. 1993.
[3] H. Ogawa, "Microwave and millimeter-wave fiber optic technologies for subcarrier transmission systems," IEICE Trans. Commun., vol.E76-B, no.9, pp.1078–1090, Sept. 1993.
[4] S. Komaki, K. Tsukamoto, M. Okada, and H. Harada, "Proposal of radio high-way networks for future multimedia-personal wireless communications," 1994 IEEE International Conference on Personal Wireless Communications (ICPWC'94), Bangalore India, pp.204–208, Aug. 1994.
[5] K. Tsukamoto, H. Harada, S. Kajiya, S. Komaki, and N. Morinaga, "TDM intercell connection fiber-optic bus link for personal radio communication systems," 1994 Asia-Pacific Microwave Conference (APMC'94), Tokyo Japan, pp.1039–1042, Dec. 1994.
[6] H. Harada, S. Kajiya, K. Tsukamoto, S. Komaki, and N. Morinaga, "TDM intercell connection fiber-optic bus link for personal radio communication system," IEICE Trans. Commun., vol.E78-B, no.9, pp.1287–1294, Sept. 1995.
[7] H. Harada, K. Tsukamoto, S. Komaki, and N. Morinaga, "Optical TDM scheme for fiber-optic millimeter-wave radio system," IEICE Trans. Commun., vol.J77-CI, no.11, pp.1–10, Nov. 1994.
[8] A. Kohlenberg,"Exact interpolation of band-limited functions," J. Appl. Phys., vol.24, no.12, pp.1432–1436, Dec. 1987.
[9] A.S. Andrawis and I. Jacobs, "A new compound modulation technique for multichannel analog video transmission on fiber," IEEE Journal of Lightwave Technology, vol.LT-11, no.1, pp.49–54, Jan. 1993.
[10] Y. Shoji, S. Kajiya, K. Tsukamoto, and S. Komaki, "A consideration on asynchronous multiple access scheme for optic fiber radio-highway networks," IEICE Technical Report, RCS95-29, May 1995.
[11] S.S. Wagner, "Optical amplifier applications in fiber optic local networks," IEEE Trans. Commun., vol.COM-35, no.4, pp.419–426, April 1987.



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