Optical Subcarrier Multiplexing Transmission for Base Station With Adaptive Array Antenna

Ichiro Seto, Hiroki Shoki, *Member, IEEE*, and Shigeru Ohshima, *Member, IEEE*

***Abstract*—We propose utilizing a radio-over-fiber technique of optical subcarrier-multiplexing transmission for radio base stations (BSs) with adaptive array antennas. The proposed system can be constructed at low cost since only one optical transmitter and receiver is required for a center station and a BS. Moreover, relative phases among antenna branches are insensitive to equivalent length fluctuation of an optical fiber.**

***Index Terms*—Land mobile radio equipment, microwave antenna arrays, optical fiber communication, phase-locked loop, subcarrier multiplexing.**

I. Introduction

RECENTLY, there has been great interest in wireless communication infrastructure including the adaptive-array-antenna (also known as the smart antenna) technique [1]–[4]. Combining array-antenna output/input signals with proper weights can provide advantages; notably, efficient utilization of frequency resources, array gain, and spatial filtering. The adaptive array antennas require plural antenna branches and signal processing units so that base-station (BS) structures become large and complicated. However, widespread introduction of BSs to wireless local area networks is predicated on reducing the size and the cost. For this purpose, the radio-over-fiber (ROF) technique has attracted a great deal of attention [5], [6]. This technique makes it possible to process complicated operations in a center station (CS), such as modulation/demodulation and weight controllers. Among several optical-fiber links for transmitting antenna output signals from the CS to the BS or antenna input signals from the BS to the CS, optical-fiber-parallel (OFP) transmission [7], [8] and wavelength-division-multiplexing (WDM) transmission [9], [10] have been proposed. These transmissions require as many optical transmitters/receivers as antenna branches. Therefore, it is difficult for CSs and BSs to be constructed at low cost. Moreover, in OFP transmission, the skew of plural optical fibers becomes variable [11] and causes different arrival times of transmitted optical signals since equivalent optical-fiber lengths fluctuate corresponding to ambient temperature. This is a serious obstacle to the operation of spatial filtering on adaptive array antennas with remote weight-control/modification via optical fibers.

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The authors are with the Research and Development Center, Toshiba Corporation, Kanagawa 212-8582, Japan.

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In this paper, we propose utilizing an ROF technique of optical subcarrier multiplexing (SCM) transmission for a BS with an adaptive array antenna. The proposed system transmits antenna input/output signals as an SCM signal via an optical fiber, with a clock reference. The proposed system can be constructed at low cost since only one optical transmitter/receiver is required for a CS and a BS. Moreover, the proposed system is insensitive to equivalent length fluctuation of an optical fiber under various ambient temperatures. It is because a phase-locked loop (PLL) technique is utilized for frequency conversions with the SCM signal in order that relative phases among antenna branches may be maintained. In Section II, we show the proposed system configuration and the principle of maintaining relative phases among antenna branches via an optical fiber. In Section III, we show optical link characteristics of carrier-to-noise ratio (CNR) per antenna element and phase fluctuation variance due to PLL techniques, with numerical calculations. In Section IV, optical SCM transmission for two-array antennas under some ambient temperatures is demonstrated.

II. System Configuration and Principle

A. System Configuration

The optical SCM transmission for an adaptive array antenna is constructed as shown in Fig. 1. The proposed system is based on transmitting an optical SCM signal consisting of a clock reference and antenna output/input signals, which are frequency-converted into different intermediate frequencies (IFs). The image of the SCM signal spectra is also shown in Fig. 1. The clock component is set on a lower frequency than the signal components. On the optical reception side, each received signal component is frequency-converted again to the same frequency. In the case of the downlink and uplink, the frequencies of the signal components are up-converted and down-converted, respectively. A PLL technique is utilized and the local-oscillator (LO) signals for frequency conversions in the CS and BS are in-phase with the common clock reference so that relative phases among antenna branches may be maintained. The proposed system provides the most advantage of cost and size for wireless communications using several-gigahertz frequency. It is because monolithic-microwave integrated-circuit (MMIC) technology can be applied to PLLs, which is as many as antenna branches.

B. System Principle

We shall explain the operation principle along the two antenna branches on the downlink. For simplicity, we ignore delay

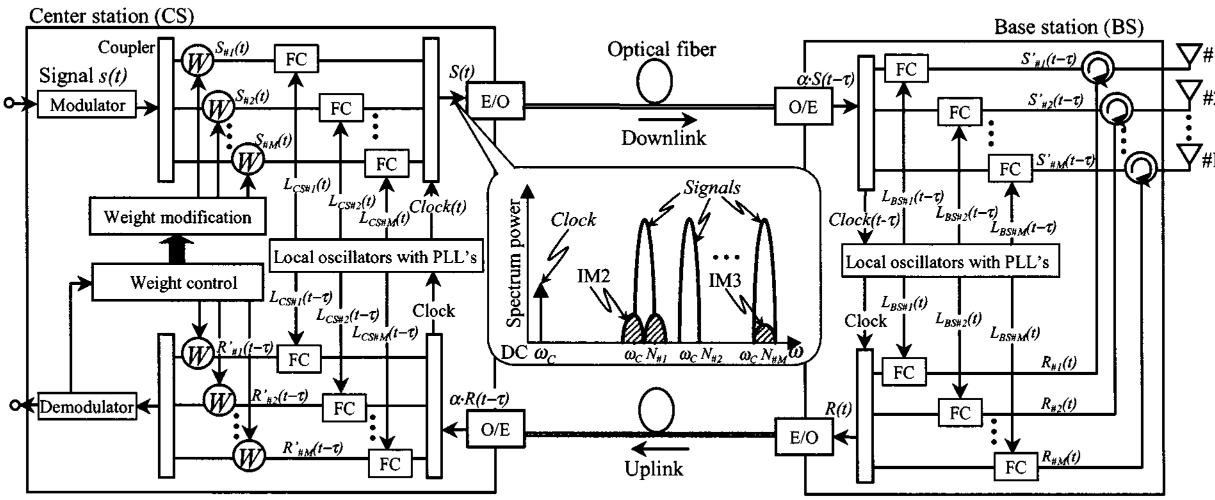


Fig. 1. System configuration of the proposed optical SCM transmission for an adaptive array antenna including spectrum image of the SCM signal with the IM2 distortion between the clock and the signal components and the IM3 distortion among the signal components.

times and losses, which are dependent on individual electrical components. At the CS, the weight-modified signal $S_{\#M}(t)$ can be expressed as follows:

$$S_{\#M}(t) = s(t) \cdot A_{\#M} \cdot e^{j\phi_{\#M}}, \qquad \text{where } M = 1 \text{ or } 2. \tag{1}$$

ϕ and A represent the weights of phase and amplitude for the signal, respectively. $s(t)$ is the signal modulated with data for subscribers. Here, we focus on variation of the relative phase $\Delta\phi = \phi_{\#1} - \phi_{\#2}$. It is assumed that the LO signal $L_{\mathrm{CS}}(t)$ and the clock reference $clock(t)$, whose angular frequency is represented as ω_C, are precisely in phase-lock. The relations of angular frequencies ω_{CS} of the LO signals and the clock reference are written as

$$\omega_{\mathrm{CS}\#M} = \omega_C \cdot N_{\#M}. \tag{2}$$

N is the multiplying ratio in the PLL. The frequencies of the signals $S_{\#1}(t)$ and $S_{\#2}(t)$ are up-converted to the IFs by mixing the LO signals. The SCM signal $S(t)$, after coupling the up-converted signals and the clock reference, can be written as

$$S(t) = s(t) \cdot A_{\#1} \cdot e^{j(\omega_{\mathrm{CS}\#1} t + \phi_{\#1})} + s(t) \cdot A_{\#2} \cdot e^{j(\omega_{\mathrm{CS}\#2} t + \phi_{\#2})} + \cdots + e^{j\omega_C t}. \tag{3}$$

The above SCM signal is converted into an optical signal and transmitted to the BS via the optical fiber. We assume that the arrival time of the signal $S(t)$ from the CS to the BS via the optical fiber is τ. The arrival time fluctuation or fading loss due to fiber dispersion against each signal component of the SCM signal $S(t)$ can be ignored because all these components are on the same wavelength from a laser diode (LD) and have IFs of less than several gigahertz. Therefore, the received signal at the BS can be simply expressed by $\alpha * S(t-\tau)$. The parameter of α represents fiber loss. The LO signals $L_{\mathrm{BS}}(t)$ and the received clock reference $\alpha * clock(t-\tau)$ can be kept in phase-lock so that $L_{\mathrm{BS}}(t)$ having the angular frequency of ω_{BS} are also delayed with τ. The LO signals of the BS can be written as

$$L_{\mathrm{BS}\#M}(t-\tau) = e^{j\omega_{\mathrm{BS}\#M}(t-\tau)}. \tag{4}$$

Here, their angular frequencies are as follows:

$$\omega_{\mathrm{BS}\#M} = \omega_C \cdot N'_{\#M}. \tag{5}$$

After mixing $\alpha * S_{\#M}(t-\tau)$ and $L_{\mathrm{BS}\#M}(t-\tau)$, the two antenna output signals can be expressed as follows:

$$S'_{\#1}(t-\tau) = \alpha \cdot s(t-\tau) \cdot A_{\#1} \cdot e^{j\{\omega_{\mathrm{FC}}(t-\tau) + \phi_{\#1}\}} \tag{6}$$

and

$$S'_{\#2}(t-\tau) = \alpha \cdot s(t-\tau) \cdot A_{\#2} \cdot e^{j\{\omega_{\mathrm{FC}}(t-\tau) + \phi_{\#2}\}} \tag{7}$$

where

$$\omega_{\mathrm{FC}} = \omega_{\mathrm{CS}\#1} + \omega_{\mathrm{BS}\#1} = \omega_{\mathrm{CS}\#2} + \omega_{\mathrm{BS}\#2}. \tag{8}$$

ω_{FC} is the converted angular frequency for the two weight-modified signals due to the frequency conversions. The phase rotation $\theta_r(\tau)$ depending on the arrival time τ is in common with all antenna branches, and is given by

$$\theta_r(\tau) = -\omega_{\mathrm{FC}} \cdot \tau. \tag{9}$$

Different phase rotations depending on the IFs via the optical fiber are cancelled due to the frequency conversion with the LO signals $L_{\mathrm{BS}\#M}(t-\tau)$. Therefore, the relative phase $\Delta\phi$ among antenna branches can be maintained independently of the arrival time τ. On the other hand, each signal component passes through the same optical link as the SCM signal so that each signal component of the SCM signal suffers the same link loss α. Therefore, the relative amplitudes among signal components can also be maintained between the CS and BS.

TABLE I
CALCULATION PARAMETERS OF OPTICAL COMPONENTS

Parameters	Estimate value
PD responsibility η	0.8 A/W
Electric quantity e	1.602×10^{-19} C
Receiver current noise Ith	6.5 pA/Hz$^{(1/2)}$
Relative intensity noise of a LD	-150 dB/Hz
Output power of a LD	6.0 dBm
Fiber loss α	0.5 dB/km
Connector loss	0.5 dB/point × 2
Optical power margin	3.0 dB

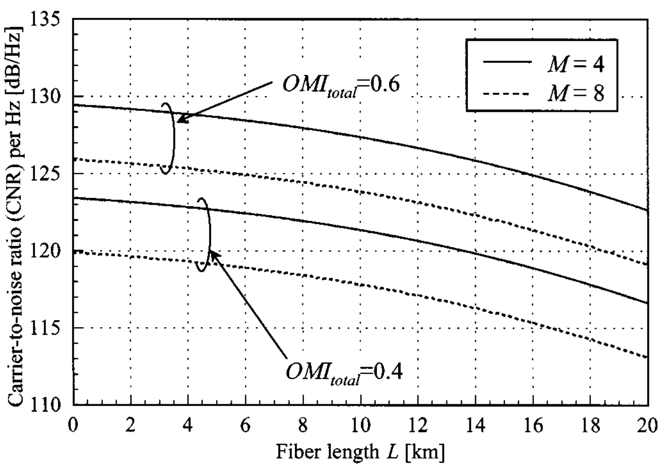


Fig. 2. Calculated CNR performance per antenna element versus fiber length as functions of the number of antenna elements M and total OMI of the SCM signal $\mathrm{OMI}_{\mathrm{total}}$.

III. OPTICAL LINK CHARACTERISTICS FOR ADAPTIVE ARRAY ANTENNAS

A. CNR Performance

We calculate the CNR performance for each antenna element in the adaptive array antenna providing one channel band. The CNR performance in optical SCM transmissions mainly depends on the number of the array antenna elements M, total optical modulation index $\mathrm{OMI}_{\mathrm{total}}$ for the SCM signal and average received optical power P_{in}. The parameter $\mathrm{OMI}_{\mathrm{total}}$ corresponds to the product of OMI per signal component multiplied by M since each signal component carries the identical data. Taking into account shot noise, receiver thermal noise, and the relative intensity noise (RIN), the CNR is given by [12]

$$\mathrm{CNR} = \frac{(\mathrm{OMI}_{\mathrm{total}}/M \cdot \eta \cdot P_{\mathrm{in}})^2}{2 \cdot BW \cdot (2 \cdot e \cdot \eta \cdot P_{\mathrm{in}} + I_{th}^2 + \eta \cdot P_{\mathrm{in}}^2 \cdot \mathrm{RIN})}. \tag{10}$$

Optical component parameters used in calculations are tabulated in Table I. The maximum CNR per hertz for each antenna element versus the optical fiber length L (in kilometers), is shown in Fig. 2. For example, for a CDMA signal with 3.84 Mc/s [13], a CNR of 59.1 dB per antenna element can be provided within $L = 8$ km in the case of $M = 8$ and $\mathrm{OMI}_{\mathrm{total}} = 0.6$. The dynamic range on the uplink for each antenna element can be estimated by this maximum CNR value or a third-order intermodulation (IM3) distortion. Using a typical distributed feedback (DFB)-LD for analog transmissions, the proposed system offers sufficiently large dynamic ranges for such applications as wireless access networks and cellular phone systems employing CDMA [14]. The number of antennas, fiber distance, and signal bandwidth are limited dominantly by whether the proposed system keeps CNR specifications.

B. Phase Fluctuations Due to PLL

The greatest difficulty for the proposed system is phase fluctuations of LO signals, which cause deformation of radiated beam pattern on the optical reception side. Since the received clock reference suffers additive noise via the optical link, these phase fluctuations will occur depending on PLL designs. A larger CNR value of the clock reference for the PLL inputs is desirable with increasing the OMI for the clock reference $\mathrm{OMI}_{\mathrm{clock}}$ at the optical transport side. However, as $\mathrm{OMI}_{\mathrm{clock}}$ is increased, the CNR performance for the signal components is degraded since the available OMI for the signal components is reduced. Moreover, increasing $\mathrm{OMI}_{\mathrm{clock}}$ produces a second-order intermodulation (IM2) distortion within the signal component bands due to nonlinear performance of an LD. This occurrence of IM2 causes signal distortion, such as decreasing CNR performance and available signal component bandwidth. Therefore, a tradeoff exists between the phase fluctuations of the LO signals and the dynamic range for each antenna element. $\mathrm{OMI}_{\mathrm{clock}}$ is required to be an optimum level while satisfying both the specifications.

In the case that the PLL provides N-times frequency multiplication against the reference component, the phase fluctuation of the LO signals are generally governed by the phase of the reference component, the phase of the VCOs in the PLLs, and the additive noise of the reference component. In order to estimate the effect of the additive noise and the required $\mathrm{OMI}_{\mathrm{clock}}$, these phase noise of the reference component and the VCOs are assumed to ideally be time-invariant. According to [15], the variance of the phase of the LO signal due to additive noise $\overline{\theta}_n^2$ can be written as

$$\begin{aligned}\overline{\theta}_n^2 &= \int_0^{\infty} N^2 \cdot |H(j2\pi f)|^2 \cdot S_n(f)\, df \\ &= N^2 \cdot B_L \cdot \frac{1}{CNR_{\mathrm{clock}}}\end{aligned} \tag{11}$$

where $Sn(f)$ is the spectral density of the additive noise, which is defined by the ratio between noise power per hertz and clock reference power as $1/CNR_{\mathrm{clock}}$. The integral of the square of the transfer function $H(j2\pi f)$ defines the noise bandwidth of the loop and commonly is given the symbol B_L. The phase fluctuation of the LO signal θ is characterized by twice the root-mean-square (rms) average of the probability distribution function as

$$\theta = \sin^{-1}(2 \cdot \overline{\theta}_n). \tag{12}$$

Here, we calculate the phase fluctuation θ under the parameters tabulated in Table I. We assume that the frequency of the clock reference is 10 MHz, the IF of the signal component is 500 MHz, and the radio frequency is 2.0 or 5.8 GHz for cellular

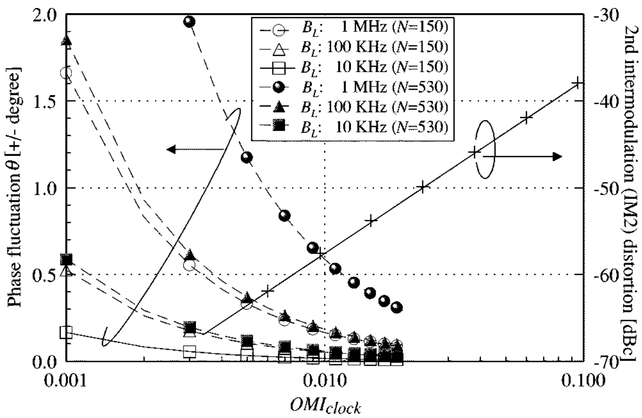
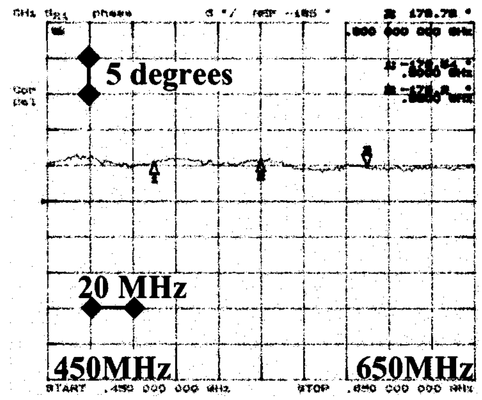


Fig. 3. Calculated phase fluctuation of a PLL against $\mathrm{OMI_{clock}}$ of the clock component as functions of the multiplying ratio N and the loop bandwidth B_L, and measured IM2 distortion around the signal component of the SCM signal against $\mathrm{OMI_{clock}}$ of the clock component as a function of $\mathrm{OMI_{total}}$ of the signal components.

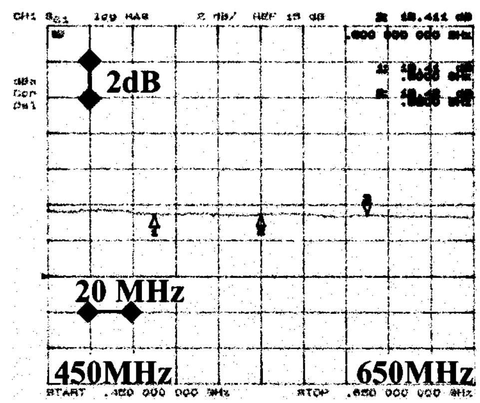
phone systems or the intelligent transportation system (ITS). The frequency multiplying ratio N is set at 150 or 530. The fiber length L is assumed to be 20 km. The phase fluctuation θ against $\mathrm{OMI_{clock}}$ as a function of the loop bandwidth B_L can be shown as in Fig. 3. Fig. 3 also shows the measured IM2 performance of a commercial DFB-LD for a signal component with a 500-MHz frequency and $\mathrm{OMI_{total}}$ of 0.80. Assuming that the requirements for the phase fluctuation of the LO signals θ and the dynamic range are within $\pm 0.5^\circ$ and 60 dB, respectively, we judge the optimum $\mathrm{OMI_{clock}}$ range to be from 0.004 to 0.008 with a B_L of 100 kHz. When the radio signal is millimeter wavelength, the phase fluctuation θ can be similarly calculated. However, the requirement for the loop bandwidth B_L is stricter because the multiplying ratio N becomes so large. In that case, a higher frequency of the clock reference is desirable and other PLL structures are also of interest [16].

C. Phase and Magnitude Deviations Over a Frequency Band for Signal Components on an Optical Link

Antenna input signals or weight-modified signals are transmitted on different frequencies as the SCM signal. When forming beam patterns with array antennas, the phase and amplitude deviations over a frequency band for the signal components must be in agreement. If these deviations are not in good agreement, the beam patterns of modulated signals cannot be ideally formed, along with phase and amplitude weights. Fig. 4 shows the typical response characteristics of phase and magnitude from a driver before a DFB-LD to a preamplifier after a photodiode (PD) versus frequencies from 450 to 650 MHz. The phase response was adjusted by electrical delay. Both characteristics were found to be flat responses over this frequency band. Due to the small variation, within 1° or 0.1 dB, the beam pattern forming was not affected by passing through the optical link as the SCM signal. In regard to optical link responses, it is important to use an available frequency band for the SCM signal.



(a)



(b)

Fig. 4. Response characteristics of magnitude and phase from a 450- to 650-MHz band by passing through an optical link. (a) Phase response. (b) Magnitude response.

IV. Experiments

A. Setup

We measured the relative phase stability between two-array antenna branches against the equivalent optical-fiber-length fluctuation. Fig. 5 shows our experimental setup for the downlink. At the CS, two phase shifters were introduced for weight modification to divided 70-MHz sinusoidal signals. Applying the two LO signals from the two frequency synthesizers (FSs) containing PLLs, which were in phase-lock to the 10-MHz clock reference, the frequencies of the weight-modified signals were up-converted into the IFs of 520 and 550 MHz, respectively. A 1.3-μm DFB-LD was directly modulated by the SCM signal that is composed by the two up-converted signals and the clock reference. The OMI for each signal component and the clock component were 0.10 and 0.01, respectively. The output from the LD was transmitted through a 4-km single-mode fiber (SMF). At the BS, the received signal with a p-i-n PD was separated into each component. The clock reference was applied to the PLLs in two FSs in order that the LO signals and the received clock references could be in phase-lock. Due to the large value of OMI for the clock component in the CS, the phase fluctuation of the LO signals in the BS could be ignored. Finally, the frequencies of the two received signal components were up-converted into the equal 1.91 GHz with the two LO signals. We measured the relative phase between the two radio signals #1 and #2 on a sampling oscilloscope.

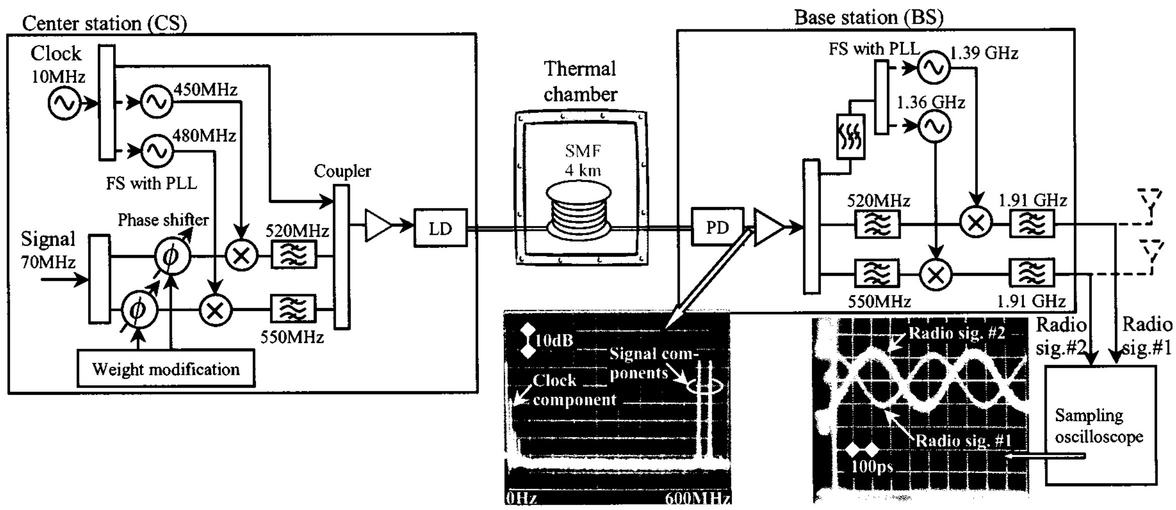


Fig. 5. Experimental setup with two-array antenna branches for the downlink.

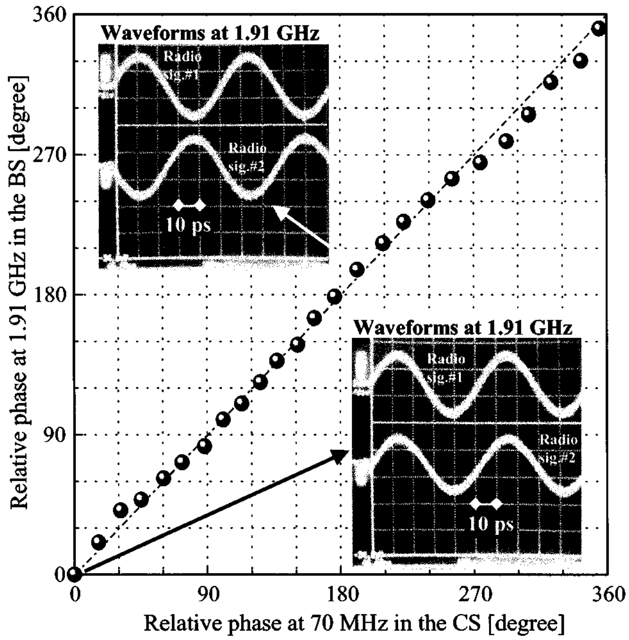


Fig. 6. Measured relative phases of the BS versus relative phases of the CS.

In this experimental setup, no amplifiers were introduced on both the antenna branches, except for the LD driver and the preamplifier of the PD. This is because we did not want to include unstable factors under the extended time measurements against various ambient temperatures.

B. Results

Fig. 6 shows the relative phase of the 1.91-GHz radio signals in the BS versus that of the 70-MHz weight-modified signals in the CS. It was found that the relative phase could be maintained via the optical fiber. The proposed system can provide remote phase-weight control for adaptive array antennas. The coefficient of optical fiber elasticity against temperature typically ranges from $+10^{-6}$ and $+10^{-5}$ per centigrade degree. We measured the arrival time of optical signals via the 4-km optical fiber while ambient temperatures around the optical fiber were changed in the thermal chamber. The arrival times were 19717.2 ns at 0 °C and 19723.5 ns at 40 °C, respectively. The delay time from 0 °C to 40 °C was 6.3 ns so that the relative phase rotation between the signal components of the SCM signal on the 520- and 550-MHz frequencies, which is a 30-MHz frequency interval, was estimated to be 68.04° via the optical fiber. Fig. 7 shows the relative phase fluctuations after the frequency conversion in the BS versus ambient temperatures. It is found that relative phase fluctuations were secured within $\pm 1.72°$ against the ambient temperatures of 0 °C$\sim$40 °C. We think these fluctuations were mainly caused by measurement errors because the CNR of the measured signals was low due to the fact that amplifiers were not included. If this effect is taken into account, it is predicated that the relative phase was stably maintained against equivalent length fluctuation of the optical fiber.

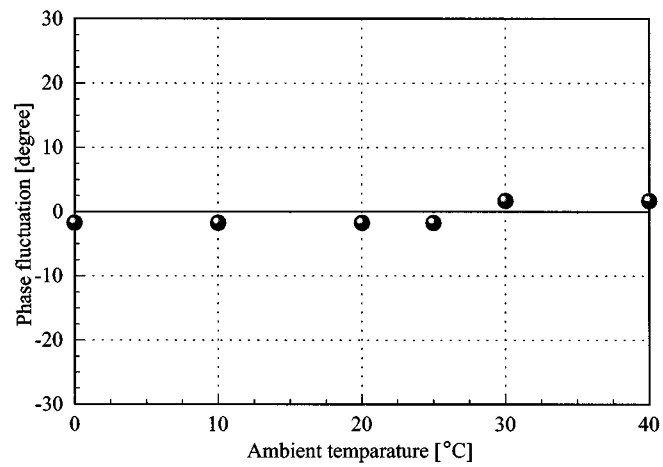


Fig. 7. Measured phase fluctuation between the two-array antenna branches versus ambient temperature around the 4-km optical fiber.

V. Discussion

The allowable fluctuations of phase and amplitude for an adaptive array antenna depend on the number of antenna elements M, antenna arrangements, or system applications. Following [17] and [18], these phase and amplitude fluctuations are approximately 6.0° or 1.0 dB, respectively, for keeping the signal-to-interference ratio of 20 dB. In the proposed system, the phase fluctuation can be secured within $\pm 0.5^\circ$ and no amplitude fluctuation occurs in principle even though a BS and an optical fiber are established outside. We think that sufficient stabilities of phase and amplitude can be provided for the applications of spatial filtering. However, for all practical purposes of BSs outside, it is expected that all electrical components, especially amplifiers on antenna branches or lines connecting antenna elements and a BS box can also cause fluctuations of phase and amplitude under various ambient temperature. The demand for calibration techniques [18], [19] for adaptive array antennas will be increased and become important.

VI. Conclusions

We have proposed utilizing an ROF technique of SCM transmission for radio BSs with adaptive array antennas. The proposed system has two advantages. Firstly, in a CS and BS, only one pair of an optical transmitter/receiver and an optical fiber for a downlink or an uplink is required, which is independent of the number of antenna elements. This allows the system cost to be greatly reduced. Secondly, relative phases among antenna branches can be maintained via an optical fiber provided a clock reference is common to both a BS and CS with PLL techniques.

According to the numerical calculations, with careful design of the optical modulation index of the clock reference $\mathrm{OMI}_{\mathrm{clock}}$, a sufficient level of the dynamic range, which is more than 60 dB, can be secured. The phase fluctuations of antenna input/output signals via the optical fiber can be secured within $\pm 0.5^\circ$. Experimental results showed that the relative phase between antenna branches was insensitive to equivalent optical-fiber-length fluctuation due to ambient temperature.

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Ichiro Seto received the B.E. and M.E. degrees from Keio University, Kanagawa, Japan, in 1991 and 1993, respectively.

In 1993, he joined the Research and Development Center, Toshiba Corporation, Kanagawa, Japan, where he is mainly engaging in research and development of optical communication systems.

Mr. Seto is a member of the Institute of Electrical, Information and Communication Engineers (IEICE), Japan. He was the recipient of the 2001 IEICE Young Engineering Award.

Hiroki Shoki (M'88) received the B.E., M.E., and D.E. degrees from Hokkaido University, Sapporo, Japan, in 1982, 1984, and 1992, respectively.

In 1984, he joined the Research and Development Center, Toshiba Corporation, Kanagawa, Japan, where he has been engaged in the research of satellite antennas, microstrip antennas, and smart antennas.

Dr. Shoki is a member of the Institute of Electrical, Information and Communication Engineers (IEICE), Japan. He was the recipient of the 1991 IEICE Young Engineering Award.

Shigeru Ohshima (M'99) received the B.S. and M.S. degrees in electronics engineering from the Tokyo Institute of Technology University, Tokyo, Japan, in 1976 and 1978, respectively.

In 1978, he joined the Toshiba Corporation, Kanagawa, Japan, where he has been engaged in research and development of optical components and optical communication systems.

Mr. Ohshima is a member of the Institute of Electrical, Information and Communication Engineers (IEICE), Japan. He was the recipient of the 1985 IEICE Young Engineering Award.