Experimental Evaluation of Remote Beamforming Scheme with Fixed Wavelength Allocation for Radio-over-Fiber Systems

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Abstract *Experiments are conducted to evaluate a remote beamforming scheme with fixed wavelength allocation for radio-over-fiber systems, which can control the beam direction of base station from the central station. The results confirm that the scheme can realize beamforming and beamscanning, and achieve almost ideal beam patterns.*

Introduction

One of the key technologies for future high-capacity wireless communications is radio-over-fiber (RoF), as it offers low attenuation, large bandwidth, and cost-effectiveness[1]. RoF systems for higher frequency bands, such as millimeter-wave band, are particularly attractive since higher frequency bands offer large bandwidth wireless signals while optical fiber supports long signal transmission distances. Therefore, the coverage area of higher frequency bands wireless communication can be extended cost-effectively by deploying a number of simple base stations (BSs) connected to a sophisticated central station (CS) via RoF link[2].

Beamforming plays an important role in higher frequency bands by compensating the significant free-space propagation loss. When deploying RoF systems, to maximize the cost-effectiveness by consolidating as many functions as possible at the CS, it is desired that the CS remotely controls the beam direction in order to keep the many BSs as simple as possible. A remote beamforming method for RoF systems that is based on the time delays caused by chromatic dispersion has been reported[3]. However, this conventional method, which controls the beam direction by controlling wavelength allocation, has four problems[5]. *(i) Wavelength utilization is inefficient.* Since each beam direction requires a wavelength allocation, the number of wavelengths required is much larger than the number of antenna elements. *(ii) BS control is required.* Since the wavelength assigned to a certain antenna element changes if the beam direction changes, the de-multiplexer (DEMUX) at BS must be tunable. A passive DEMUX that overcomes this problem has been reported[4]. *(iii) Optical fiber length information is necessary to determine the wavelength allocation.* The wavelength allocation must be back-calculated from fiber length, dispersion characteristics, and radio frequency (RF) carrier frequency. *(iv) When using high RF carrier frequency or long optical fiber, the required wavelength allocation may be impossible.* For instance, assuming a fiber length of 10 km, typical dispersion parameter of 17 ps/nm/km in C band, and RF carrier frequency of 60 GHz, the required wavelength tuning range is 0.05 nm.

We have proposed a remote beamforming scheme with fixed wavelength allocation to overcome all problems, (i)-(iv), detailed above[5]. This paper experimentally evaluate the proposed scheme under the condition of 10 GHz RF signals, 10 km single mode fiber (SMF), and four-element linear array antenna, and confirm its feasibility.

Proposed remote beamforming scheme

Fig. 1 shows the proposed remote beamforming scheme[5]. The scheme assigns wavelengths λ_1, λ_2,..., λ_n to antenna elements 1, 2,..., n, respectively, in a fixed manner. The wavelengths are allocated with sufficiently narrow spacing of $\Delta\lambda$. At the CS, the optical signals are intensity modulated by an RF signal and their RF phases are controlled. The RF phase of the modulated optical signal (wavelength of λ_i) is adjusted to $(i-1)\alpha$. This phase control can also be implemented on the RF signals before optical intensity modulation. These phase controlled optical modulated signals are multiplexed and transmitted to BS through the optical fiber. The transmitted modulated optical signals are de-

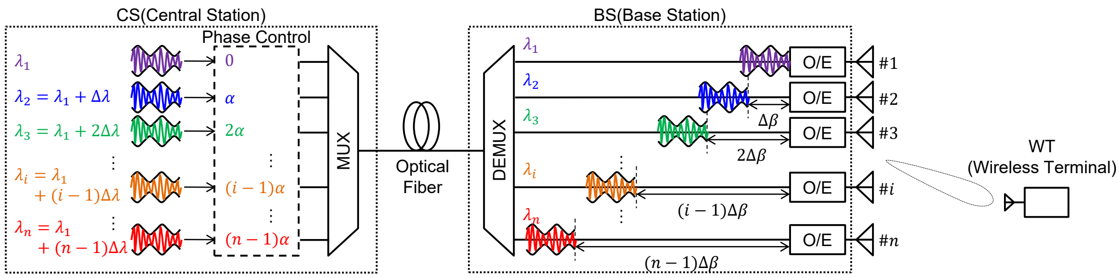

Fig. 1: Proposed remote beamforming scheme

multiplexed and photo-detected at BS. Since wavelength spacing $\Delta\lambda$ is sufficiently narrow, we can assume that the wavelengths $\lambda_1, \lambda_2, \ldots, \lambda_n$ have the same dispersion parameter D. Hence the RF phase delay difference between the adjacent modulated optical signals with λ_i and λ_{i+1} caused by chromatic dispersion can be determined according to Eq. (1), where c is the speed of light, L is the fiber length, and λ_{RF} is RF signal wavelength.

$$\Delta\beta = \frac{2\pi c \Delta\lambda D L}{\lambda_{RF}} \tag{1}$$

Since the total RF phase difference between the adjacent modulated optical signals with λ_i and λ_{i+1} caused by the phase control at CS and the fiber transmission is $\alpha - \Delta\beta$, the RF phase difference between the adjacent antenna elements is also $\alpha - \Delta\beta$. It follows that beamforming can be carried out on direction θ, defined by Eq. (2), where d is the spacing of adjacent antenna elements.

$$\frac{2\pi d}{\lambda_{RF}} \sin\theta = \alpha - \Delta\beta \tag{2}$$

In practical RoF systems, as the accurate fiber length L is unknown, the relative RF phase delay difference $\Delta\beta$ and beam direction θ are also unknown. However, since the scheme uses fixed wavelength allocation, the relative RF phase delay difference $\Delta\beta$ is constant, so beam direction θ depends on just the RF phase shift α, which can be controlled at the CS. Therefore, beamscanning can be carried out by controlling the value of α, even though the absolute beam direction is initially unknown. To determine the beam direction, first beacons are transmitted from BS to wireless terminal (WT) while scanning the value of α, and WT feedback determines the best value of α. The scheme requires BS to simply convert optical signals into electric signals and vice versa.

Simulations for experimental setup

We confirm the feasibility of the proposed remote beamforming scheme by experiments under the condition shown in Tab. 1. Since the proposed scheme assumes that the wavelength spacing is sufficiently narrow, the permissible wavelength spacing for the experimental condition is determined by simulations. The wavelength spacing is calculated in "GHz" not "nm," since the laser diodes (LDs) and DEMUXes used in the experiments support dense wavelength division multiplexing (DWDM) with 50 GHz grid in C band.

We evaluate beam patterns by calculating array factor (AF) of each wavelength spacing $\Delta\lambda$. The parameters used are based on the experimental condition shown in Tab. 1. The AFs normalized by the maximum peak of the ideal AF are shown in Fig. 2(a). The level of main lobe

Tab. 1: Experimental condition and simulation parameters

RF Carrier Frequency	10 GHz
Array Antenna	Four-element linear array with $\lambda_{RF}/2$ spacing
Optical Fiber	10 km SMF (ITU-T G.652.B)
First Wavelength λ_1	196.30 THz ≈ 1527.22 nm

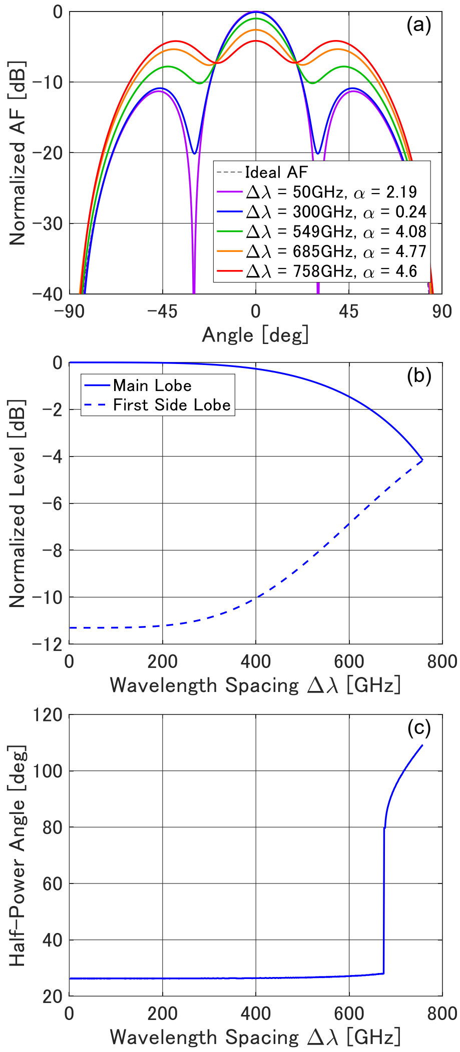

Fig. 2: (a) Normalized AFs, (b) Levels of main and first side lobes of AF, (c) Half-power angle of AF

decreases while those of side lobes increase as the wavelength spacing widens, and multiple maximum peaks are confirmed if $\Delta\lambda \geq 758$ GHz. The beam collapse at large wavelength spacing is caused by invalidating the assumption that the wavelengths have the same dispersion parameter. Fig. 2(b) shows the levels of main and first side lobes of the normalized AF. The level of main lobe equals to that of first side lobe at $\Delta\lambda =$ 758 GHz; the level is -4.17 dB. Fig. 2(c) shows the half-power angle of the normalized AF. The half-power angle increases sharply at $\Delta\lambda =$ 685 GHz, because of the increase in the side lobes levels.

We should note that, at $\Delta\lambda = 50$ GHz, which is the narrowest wavelength spacing in the experimental condition, the beam pattern is

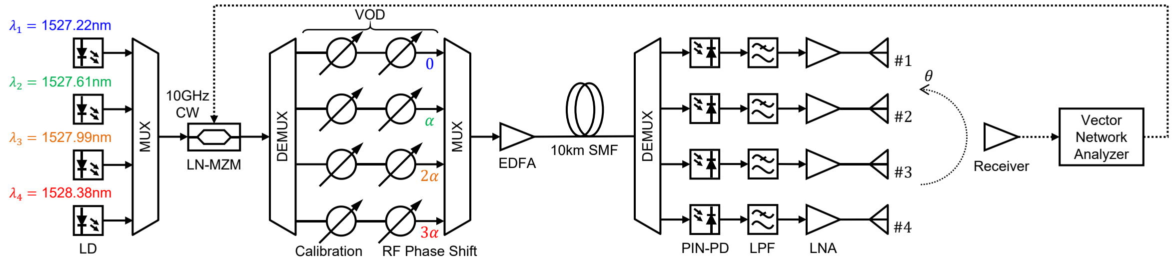

Fig. 3: Experimental setup

virtually equivalent to the ideal AF. Therefore, we set the wavelength spacing $\Delta\lambda$ to 50 GHz in the experiments.

Experiments and results

Fig. 3 shows the experimental setup, based on the experimental condition shown in Tab. 1. Four optical signals with 50 GHz ≈ 0.4 nm spacing are intensity modulated by a 10 GHz RF signal. The modulated optical signals are phase controlled by VODs. Two cascaded VODs are used for each optical signal, since one cancels out the optical path difference among the four optical signals while the other controls the RF phase. The phase controlled optical signals are multiplexed, amplified by EDFA, and transmitted through 10 km SMF. After fiber transmission, the optical signals are de-multiplexed and photo-detected by PIN-PDs. The detected RF signals are transmitted from the antenna elements after passing through LPFs and LNAs. The four-element array antenna as transmitter and lens horn antenna as receiver are separated by 6.3 m. Beam pattern is measured for each RF phase shift α = 0°, -36°, -72°,…, -324°.

Fig. 4(a) shows the 10 measured beam patterns. The beam patterns are normalized by the maximum peak of the beam pattern of α = -144°, which is the closest to the front and shows the highest gain. The maximum peaks of the beam patterns decrease as the beam direction diverges from the front, because of the directivity of the antenna element. Fig. 4(b) shows the measured beam pattern of α = -144° and ideal beam pattern of the same beam direction of θ = 3°. The ideal beam pattern is calculated by both array factor and element factor. The measured beam pattern of α = -144° is substantially coincident with the ideal beam pattern, therefore, it is confirmed that the proposed scheme can form the beam desired. Moreover, the beam direction changes continuously with RF phase shift α, which confirms that the proposed scheme with its continuous scanning RF phase shift α at CS can realize continuous scanning of beam direction at BS without information of optical fiber length.

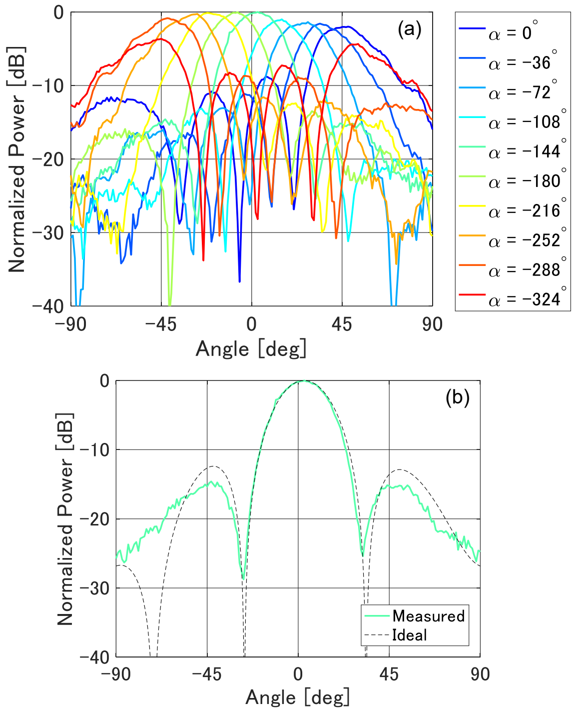

Fig. 4: (a) Measured beam patterns, (b) Measured beam pattern of α = -144° and ideal beam pattern.

Conclusion

Experiments evaluated our proposed remote beamforming scheme under the condition of 10 GHz RF signals, 10 km SMF, and four-element linear array antenna. The results confirmed that the proposed scheme can carry out beamforming and beamscanning, and achieved almost ideal beam patterns.

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