Experimental Evaluation of Remote Beamforming Scheme with Fixed Wavelength Allocation in IF-over-Fiber Systems

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Abstract:
Radio over fiber (RoF) technology, especially intermediate frequency over fiber (IFoF), is attracting much attention as one way to realize high frequency band systems. Such systems require beamforming to attain the desired link budget. Furthermore, highly accurate beamforming permits the adoption of space division multiplexing (SDM), with its greater system capacity. Since beamforming should be controlled by the central station to achieve simple base stations, we proposed a novel remote beamforming scheme with fixed wavelength allocation. This paper introduces experiments conducted on modulated signals to evaluate the characteristics of the scheme’s beamforming gain and signal to interference ratio (SIR).

Keywords: IFoF, High frequency bands, Beamforming

Classification: Wireless communication technologies

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1 Introduction

Large capacity wireless communication systems using high frequency bands are very attractive, but one problem is the coverage reduction created by the higher propagation loss. Radio over fiber (RoF) technology is one interesting solution to this problem. The coverage of high frequency band systems can be expanded effectively by RoF technology because the functions of the wireless base station are apportioned among central station (CS) and base station (BS), and multiple simple BSs are connected to one CS via RoF links. Using analog RoF simplifies the BS compared to digital RoF because it renders analog-digital and digital-analog converters unnecessary. IF over fiber (IFoF) [1], which performs analog RoF transmission after down converting the radio frequency (RF) signal to an intermediate frequency (IF), necessitates frequency conversion but is expected to be more cost effective than RoF. The reason being that IFoF can solve the problems of RoF which are the performance and cost of electric-optic and optic-electric conversion (E/O and O/E) devices supporting high frequency band signals [2] and single sideband (SSB) modulation to suppress the power fading induced by chromatic dispersion [3]. IFoF can employ E/O and O/E devices whose electro-optical bandwidths suit the low frequency bands. Furthermore, SSB modulation becomes unnecessary because low frequency band signal transmission has negligible power fading.

However, high frequency band systems require beamforming to attain the desired link budget. In addition, high beamforming accuracy would further increase system capacity by performing space division multiplexing (SDM) with low interference waves. To perform beamforming of simple BSs that have no signal processing function, remote beamforming must be performed in the CS. Remote beamforming techniques [4] have been proposed but most suffer from poor wavelength utilization, control in BS is required, information of optical fiber length is necessary, and beam control is difficult in high frequency bands or with long optical fiber links. Therefore, we proposed a novel remote beamforming scheme with fixed wavelength allocation [5]. The proposed scheme can solve the problems of the existing method in RoF / IFoF systems, because the proposed scheme can perform beamforming without BS control and fiber length information, with higher wavelength utilization.

A previous study experimentally verified the characteristics of the proposed remote beamforming scheme using continuous wave (CW) signals. In case of CW signal transmission, beamforming can be realized even if signals have $2n\pi$ phase difference. However, beamforming cannot be performed unless the phase difference is controlled so as to be within $2\pi$ in actual wireless communication systems. In addition, phase fluctuations which depend on the transmission
characteristics of the optical fiber occur for each frequency in the signal band, when modulated signals are transmitted via RoF. Since the phase fluctuations change with the wavelength used for optical fiber transmission, the signal characteristics after synthesis may degrade due to the phase fluctuation in the signal band in the proposed beamforming scheme which assigns a different wavelength to each antenna element. This paper uses modulated signals to verify the feasibility of the proposed remote beamforming scheme; it shows that the proposed scheme is effective even if, (1) the phase difference of $2n\pi$ is unacceptable, (2) phase fluctuations occur in the signal band for each wavelength. We evaluate the beamforming gain with a 4 element linear array, and the signal to interference ratio (SIR) when different modulated signals are transmitted in the same frequency channel.

2 Proposed beamforming scheme in IFoF
The proposed remote beamforming scheme assigns $n$ wavelengths $\lambda_i (i = 1, 2, \cdots, n)$ to $n$ antenna elements. If the wavelengths are assigned with sufficiently narrow and equal intervals ($\Delta \lambda$), the dispersion of each wavelength and the relative phase delay difference ($\Delta \beta$) between adjacent wavelengths due to chromatic dispersion during fiber transmission can be considered equal. $\Delta \beta$ is defined by the speed of light ($c$), wavelength interval, dispersion parameter of fiber ($D$), fiber length ($L$) and IF signal wavelength ($\lambda_{IF}$).

$$\Delta \beta = \frac{2\pi c \Delta \lambda DL}{\lambda_{IF}}$$ (1)

At CS, $(i - 1)\alpha$ is added to the phase of the $i$-th element signal for controlling beam direction. $(i - 1)\alpha$ is added to received signals from each antenna element in the case of uplink, or transmitting signals corresponding to antenna elements in advance in the case of downlink. The phase of the $i$-th element signal after $(i - 1)\alpha$ addition and fiber transmission is $(i - 1)(\alpha - \Delta \beta) + \varphi$, and the phase difference between adjacent element signals becomes $\alpha - \Delta \beta$ at all antenna elements, where $\varphi$ is initial signal phase. Thus the beam is formed on direction $\theta$ defined by Eq. (2)

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

where $d$ is the spacing of adjacent antenna elements. Since the signal phase difference is preserved even though analog IFoF systems use frequency conversion, the proposed scheme explained in [5] can be applied to analog IFoF.

The proposed scheme offers high wavelength utilization efficient beamforming without BS control because of its fixed wavelength allocation. In actual systems, $\alpha$ for the desired direction beam cannot be calculated, because the relative phase delay difference $\Delta \beta$ is unknown when optical fiber length is unknown. However, the adequate beam can be identified by scanning $\alpha$ (sweeping the beam direction), and receiving feedback from the opposing device. Thus, beamforming can be realized without information of optical fiber length. $\alpha$ adjustment can be performed in both the optical and RF / IF domains. In the experiments, $\alpha$ is adjusted in the optical domain.
3 Experimental evaluations

To confirm the feasibility of the proposed remote beamforming scheme in analog IFoF systems, we conduct two receiving beamforming experiments in the uplink as an example. The beamforming gain evaluation compares average received power with and without the proposed beamforming, while the SIR evaluation examines the received power ratio between the desired signal and the interference signal when different signals are transmitted concurrently in the same frequency channel.

3.1 Experimental parameters

The experimental setup and parameters are shown in Fig. 1 and Tab. I, respectively. In the beamforming gain experiment, only one directly facing transmitter (Tx1) is used. In the SIR experiment, two transmitters (Tx1 and Tx2) transmit different signals concurrently in the same frequency channel. The intention is that only the signal from the desired direction (Tx1) is received while the interference signal

| Table I. Simulation parameters |
|-------------------------------|
| RF / IF | 40 GHz / 10 GHz |
| Training signal band width | 160 MHz |
| Tx-Rx distance | 5 m |
| Tx setting | Tx1: 0°, Tx2: 2.6° |
| Tx antenna | Antenna gain: 31.5 dBi, HPBW: 3° |
| Rx array structure | 4 element linear array |
| Rx antenna | 6×5 subarray |
| Wavelength / interval | 1500 nm band / 50 GHz grid |
| Optical fiber length | 10 km SMF |

![Fig. 1 Experimental setup](image-url)
from the other direction (Tx2) is suppressed. These experiments use orthogonal frequency division multiplexing (OFDM) signals with two modulations (QPSK and 16QAM). Tx1 is set directly in front of Rx and Tx2 is offset by about 2.6°. Rx antenna is a linear array with four antenna elements; each element is a 6×5 subarray that attains the array gain needed to compensate the propagation loss.

Fig. 1(a)(b) show the structure and actual setup used in the experiments. Received signals are amplified (AMP) and then down-converted in the mixer (MIX). IF signals are input to low pass filtered (LPF) and converted into optical signals with different wavelengths by a lithium niobate Mach-Zehnder modulator (LN-MZM); they are then wavelength division multiplexed (WDM). The multiplexed optical signals are transmitted to CS through single mode fiber (SMF) after being amplified by an erbium doped fiber amplifier (EDFA), and demultiplexed into each wavelength by demultiplexer (DEMUX). SMF length assumes the average optical fiber length in most access areas. Demultiplexed signals are input to variable optical delays (VODs). The two VODs cancel the error of each path and suitably weight each wavelength. In the experiments, α for forming the front direction (0°) beams is calculated in advance by computer simulation. Signals output from VODs are converted into electric signals by pin photodiodes (pin PDs). The IF signals converted in the pin PD are input to LPF, and converted into IQ signals in the MIX. Output IQ signals have the relative phases needed to control beamforming. These signals are recorded in a digitizer after being synthesized. In the SIR evaluation, recorded signals are demodulated after averaging 100 OFDM symbols offline, to eliminate the influence of reception noise and clarify the influence of the interference signal. Channel estimation is carried out based on training signals which are only desired signals received beforehand; frequency domain equalization (FDE) is carried out using the estimated channel.

Fig. 1(c) shows reception beam patterns determined in preliminary simulations. The red line is for the case of using the same configuration and parameters as in this experiment, it includes the effect of chromatic dispersion. As the ideal, the black dashed line also shows beam pattern for the same array configuration used to the experiment. These beam patterns almost perfectly match, and it is expected that beams comparable to ideal can be realized by the proposed fixed wavelength beamforming scheme.

3.2 Experimental results

Experimental results are obtained by analyzing the recorded data. Fig. 2(a) plots the frequency spectra. Red lines and blue lines are the results with and without proposed beamforming, and solid lines and dotted lines represent difference of modulation method (QPSK and 16QAM), respectively. The flutter in the 16 QAM spectra is due to the characteristics of the experimental setup. Using the proposed beamforming improved the relative received levels for both QPSK and 16QAM, and it can be confirmed that the average relative received level is improved by about 6 dB. This result is consistent with the theoretical beamforming gain possible with four antenna elements, which confirms that the proposed beamforming
scheme can obtain beamforming gain close to ideal.

Fig. 2(b)(c) show constellations of received signals. Symbols show the signal point constellation at each subcarrier of the received signal. Red dots are the results for beamforming and averaging, and black cross symbols are ideal signal points of QPSK and 16QAM. The signal points of the received signals cluster around the ideal signal points, because the interference signal is suppressed by beamforming. EVM values are about 10.8 % and 10.3 %. If we consider only interference signals as causing the error because of symbol averaging, SIR of about 19.4 dB and 19.7 dB can be derived from the EVM values.

These results confirm that the proposed remote beamforming scheme with fixed wavelength allocation can perform beamforming even in modulated signal transmission, and it is possible to obtain beamforming gain close to the ideal value as it well suppresses interference waves.

4 Conclusion

This paper experimentally confirmed the feasibility of our remote beamforming scheme with modulated signal transmission in analog IFoF. Modulation signal transmission experiments were carried out, and it was confirmed that about 6 dB beamforming gain can be obtained by the proposed beamforming with four antenna elements. In addition, we demonstrated received beamforming with two Txs transmitting different signals in the same frequency channel; the interference signal was well suppressed by the proposed beamforming and SIR of about 20 dB was achieved for the case of 40GHz RF, 10GHz IF and 5 m Tx-Rx distance. These results show that the proposed remote beamforming scheme is effective even with modulated signal transmission in analog IFoF systems.

![Experimental results](image-url)