Power-Fading-Free Analog-RoF Transmission using IF/LO Frequency Optimization

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***Abstract*— We propose a novel frequency-tuning technique for analog-RoF system to suppress chromatic-dispersion-induced power fading. By controlling the frequency of IF and LO signals properly, 28-GHz analog-RoF transmission up to 20 km was successfully confirmed.**

Keywords— Radio-over-fiber, Chromatic dispersion

I. Introduction

5th Generation (5G) mobile communication service has been introduced widely and the focus of the research is moving to Beyond-5G. One of the key technologies that will support high-speed mobile communications after 5G is a millimeter wave (mmWave). Since the path loss of mmWave is larger than the sub-6GHz radio signal, it is necessary to install vast numbers of antennas densely to ensure the line of sight to the users. To accommodate these densely deployed antennas, both characteristics of a large capacity of mobile fronthaul (MFH) link and a simple configuration of antenna equipment need to be satisfied. Analog-Radio over Fiber (A-RoF) is considered as an attractive candidate of the MFH transmission technology for mmWave-based mobile systems to meet such requirements [1]-[2]. A-RoF can eliminate the bandwidth expansion of MFH link by transmitting radio signals as an analog waveform over a fiber, not as a digitized waveform information. A-RoF can also simplify the configuration of antenna sites by putting all the functionalities of radio signal processing into a central office, which resulting in the smaller size and lower power consumption of antenna site equipment. One of the problems of A-RoF system especially for higher frequency radio signals such as mmWave is the signal degradation caused by the power fading effect induced by chromatic dispersion (CD) [3]. When a conventional double sideband (DSB) intensity modulation (IM) is used, power fading occurs because there is a phase difference between an upper sideband (USB) and a lower sideband (LSB) due to CD, and received RF power is attenuated significantly at specific fiber lengths where the phase difference of USB and LSB is in opposite phase. Several techniques have been proposed to solve the power fading problem of A-RoF system by using special optical modulators, such as the combination of IM and phase modulator [4], single sideband optical modulator [5], and dual-electrode Mach-Zehnder modulator [6]. However, these kinds of special modulators will increase the system costs.

In this paper, we propose a novel technique to suppress power fading with a conventional DSB intensity modulator, in which a mmWave is transmitted as two separate components: an intermediate frequency (IF) signal and a local oscillator (LO) signal. By setting the center frequencies of IF and LO signals around half of the mmWave frequency, and by keeping the sum of the center frequencies equal to that of mmWave, mmWave can be extracted as a beat component at the output of a photodetector (PD) after A-RoF transmission while avoiding the effect of power fading. After explaining the principle of our proposed method using theoretical equations, transmission experiments were conducted using a conventional intensity modulator. It was confirmed that the proposed method can effectively suppress the power fading, and no degradation was observed after 28 GHz A-RoF transmission for different fiber lengths up to 20 km.

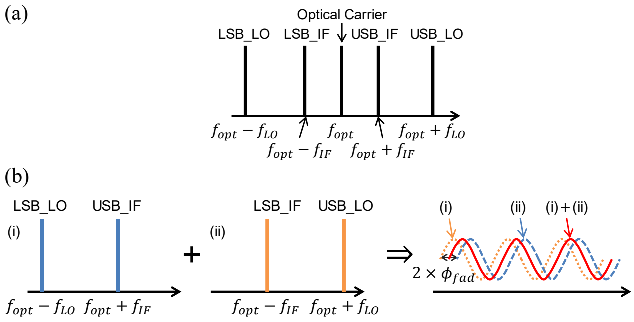

Fig. 1. Explanatory diagram of the proposed method. (a) Optical spectrum of A-RoF signal. (b) Output signal from PD output around f_{RF}.

II. Principle Explanation

Fig. 1 shows an explanatory diagram of the proposed method, where f_{RF}, f_{IF}, f_{LO} , and f_{opt} are the center frequencies of RF, IF, LO signals, and an optical carrier, respectively. When IF and LO signals are combined and input to the intensity modulator, the optical spectrum of A-RoF signal is shown in Fig. 1 (a). If we set the frequency of IF and LO signals to be $f_{RF} = f_{IF} + f_{LO}$, RF signal can be obtained at the output of the PD as the sum of the beat components of USB_LO and LSB_IF, and USB_IF and LSB_LO, with phase difference of $2 \times \varphi_{fad}$ caused by CD as shown in Fig. 1 (b). The relationship between the output power Pout of the RF signal and the phase φ_{fad} can be derived as in (1) and (2) by extending the small-signal analysis in [3] to the case where two modulation signals with different frequencies are simultaneously input to the modulator. Note that λ_{opt} is a wavelength of optical carrier, D is a dispersion coefficient, L is a fiber length, and a chirp parameter of the modulator is

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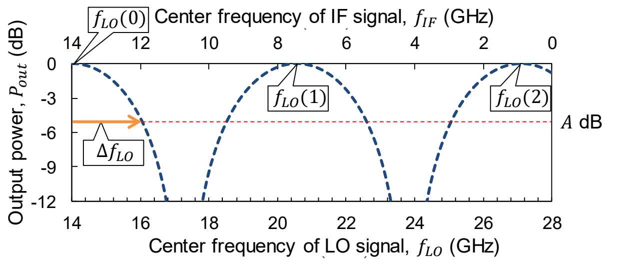

Fig. 2. Power fading when f_{RF} = 28 GHz, λ_{opt} = 1550 nm, D = 17 ps/nm/km, and L = 20 km.

ignored for simplicity of derivation.

$$P_{out} \propto \left|\cos \varphi_{fad}\right|^2 \tag{1}$$

$$\varphi_{fad} = \pi\lambda_{opt}^2 DL\,(f_{LO}^2 - f_{IF}^2)\,/\,2 \tag{2}$$

From (1) and (2), the power fading depends on f_{IF} and f_{LO} and can be controlled by them while keeping f_{RF} constant. As an example, Fig. 2 shows the calculation results of P_{out} when f_{RF} was set to 28 GHz, which is commonly used in mmWave band of 5G, and f_{IF} and f_{LO} were changed. Note that L, λ_{opt}, and D were set to 20 km, 1550 nm, and 17 ps/nm/km, respectively. From Fig. 2, power fading is minimized at several frequency combinations. When the power fading is minimized, 2 × φ_{fad} in Fig. 1(b) is an integer multiple of 2π and the sum of beats is maximum. Thus, when n is defined as an integer, the optimal f_{LO} and f_{IF} are derived as (3) and (4), respectively, by substituting $\varphi_{fad} = n\pi$ into (2). As a reference, calculation results of (3) are shown in Fig. 2.

$$f_{LO}(n) = \frac{1}{2}\left(f_{RF} + \frac{cn}{\lambda_{opt}^2 DLf_{RF}}\right) \tag{3}$$

$$f_{IF}(n) = f_{RF} - f_{LO}(n) \tag{4}$$

From (3), the optimal f_{LO} when $n \neq 0$ depends on various parameters such as L and λ_{opt}. On the other hand, the optimal f_{LO} is always f_{RF} / 2 when $n = 0$. Hence, power fading can be avoided using constant f_{LO}, regardless of various parameters. However, f_{IF} is the same value as f_{LO} when $n = 0$ as shown in (4), these frequencies must be shifted to avoid interference. When the allowable transmission loss at a particular length is A dB, the upper limit of frequency that can be shifted from optimum frequency while keeping the loss below A dB is derived as in (5).

$$\Delta f_{LO} = \frac{1}{2}\cdot\frac{c\cdot\arccos\left(10^{-A/20}\right)}{\pi\lambda_{opt}^2 DLf_{RF}} \tag{5}$$

As is clear from (5), Δf_{LO} is in inverse proportion to L. Therefore, if Δf_{LO} is calculated for the envisaged maximum transmission distance L_{max} and the frequency is shifted within the range below Δf_{LO}, the radio signal can be transmitted with a loss below A dB for the transmission distance below L_{max}.

III. Transmisson Experiments

To evaluate the effect of our proposed method, a transmission experiment was performed when f_{RF} was set to 28 GHz. The experimental setup was depicted in Fig. 3(a). A distributed feedback laser diode (DFB-LD) with the wavelength of 1550.0 nm was input to a lithium niobate Mach-Zehnder modulator (LN-MZM), and intensity modulated to generate A-RoF signal. As modulation signals, the LO signal generated by a signal generator (SG) and the IF signal generated by an arbitrary waveform generator (AWG) with level adjustment by a RF amplifier (AMP), variable attenuator (vATT) and BPF for IF signal (IF BPF) were used. Since the proposed method does not use the optical carrier in demodulation, a bias voltage was adjusted to suppress the optical carrier so that subsequent erbium-doped fiber amplifier (EDFA) can amplify LSB and USB without being saturated by the optical carrier. The IF signal output from the AWG was a 3GPP-compliant 5G signal with a bandwidth of 380.16 MHz, a modulation scheme of 64QAM Orthogonal Frequency Division Multiplexing (OFDM). In order to avoid the overlap of f_{IF} (0) and f_{LO} (0), f_{LO} (0) was shifted to 15 GHz for this experiment so that A is less than 1 dB under transmission distance below 20 km. Similarly, the center frequency f_{IF} (0) was shifted to 13 GHz. The modulated A-RoF signal was amplified by an EDFA and transmitted through a single-mode fiber (SMF) for different length of L from 1 to 20 km, which is a typical maximum length of optical access network [7]. A variable optical attenuator (voATT) was adjusted so that a received optical power of the PD was -5 dBm. The RF signal around 28 GHz was extracted from the output signal of the PD using BPFs for RF signal (RF BPF), amplified by the AMP, and input to a signal analyzer (SA) to evaluate an error vector magnitude (EVM). As a reference, EVM was measured before the LN-MZM input and before the SMF transmission. For comparison, EVM for general DSB A-RoF signal was also measured using the similar setup as depicted in Fig. 3(b). A 28 GHz RF signal was generated by up-converting 2.1 GHz 5G signal from the AWG, and intensity modulated using LN-MZM. The results of power fading and EVM are shown in Fig. 4. As a result, in the case

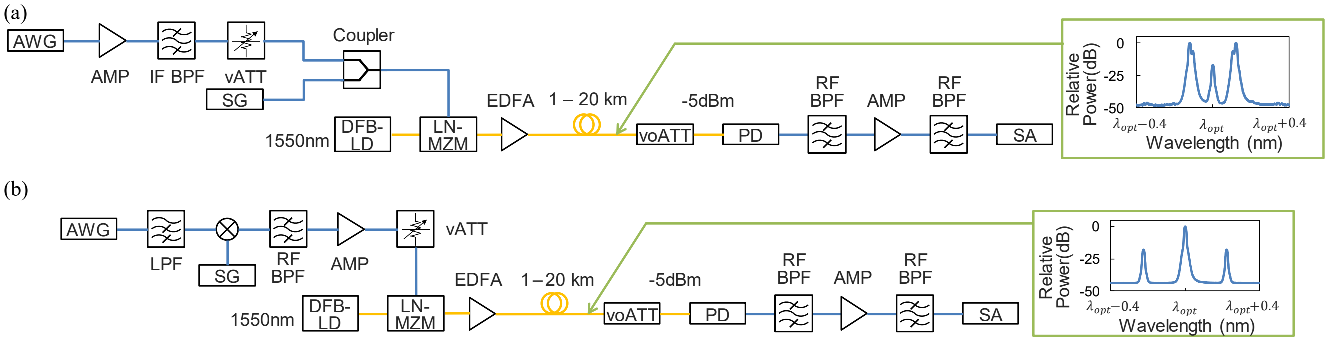

Fig. 3. Experimental system for EVM evaluation. (a) Proposed method. (b) DSB transmission.

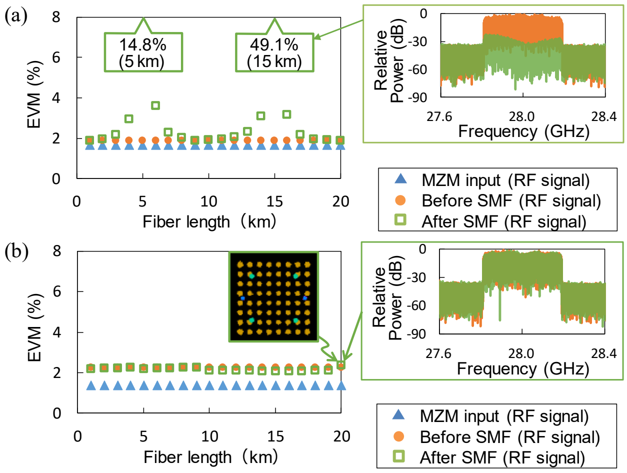

Fig. 4. Results of EVM at each measurement point. (a) DSB transmission. (b) Proposed method.

of DSB transmission, a signal-to-noise ratio (SNR) was degraded due to power fading, and EVM around 5 and 15 km was significantly higher than the upper limit of 8% for 64QAM specified in 3GPP [8]. On the other hand, the proposed method has almost no impact on SNR, and EVM differences before and after transmission were less than 0.2 percent point at any transmission distance. From the above, it is verified that the proposed method can effectively suppress the CD-induced power fading and can keep the signal quality even with the general intensity modulator at any transmission length from 1 to 20 km.

IV. Conclusion

In this paper, we proposed a novel A-RoF transmission method to suppress CD-induced power fading with the conventional DSB intensity modulator, in which RF signal was transmitted as two separate components, IF and LO signals, with their center frequencies set around half of RF signal frequency and with keeping the sum of the center frequencies equal to that of RF signal. Theoretical formulation and the transmission experiment showed that the proposed method can effectively suppress the power fading, and no degradation was observed after A-RoF transmission for different fiber lengths. The result showed the applicability of A-RoF transmission scheme as a MFH technology for Beyond-5G.

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