URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Millimeter-wave signal generation and its radio-over-fiber link transmission based on optical SSB modulation in 105-GHz band

Kohei Fujiwara[(1)], Atsushi Kanno[(2)], and Kouichi Tokita[(1)]
(1) Tokyo Metropolitan Industrial Technology Research Institute, Tokyo, Japan
(2) National Institute of Information and Communications Technology, Tokyo, Japan

Abstract

The development of a system facilitating the convergence of millimeter-wave and optical systems is highly desirable to realize 5G/beyond 5G mobile communication. However, such broad-bandwidth signals cannot be easily transmitted using a long optical fiber owing to the optical fiber chromatic dispersion effect. This paper reports upon the realization of a high-speed millimeter-wave radio-over-fiber signal transmission by using an optical single-sideband (SSB) modulation scheme. The combination of an optical intensity modulator and optical filter can provide the optical SSB signals with an automatic bias controller. The IEEE802.11ad-compliant packet streams are successfully transmitted and converted into 105 GHz millimeter-wave signals. The system can generate and transmit a packet in 16-QAM under an error vector magnitude of 4.8% at a frequency of 104.77 GHz.

1 Introduction

The use of a millimeter-wave radio system is a promising solution to provide a high-speed wireless link in fifth generation (5G) mobile communication systems, which involve a data rate of more than 1 Gbit/s. In such a case, the backend network, particularly, the optical fiber system, should have a broader bandwidth than that of a traditional digital system. For example, a digital-based optical connection system, such as a common public radio interface, can provide a bandwidth of approximately 100 MHz by using 12 Gbit/s optical transceivers. However, the signal conversion between the high-speed radio and high-capacity digital optical link via digital signal processing induces a processing latency, additional footprint, and additional power consumption. The analog radio-over-fiber (RoF) technology can be used to configure a massive telecommunication network for a high-speed communications system in the millimeter-wave (MMW) band without any digital conversions required between the radio and optical domains at an antenna site. This feature can help realize robust and low-cost antenna units, and such a configuration is applicable for typical terrestrial mobile wireless communication systems as well as high-speed train communication systems. In particular, for a train communication system, the optical fiber networks can be easily installed along the railway tracks. In addition, in a bullet train system, the transmission distance in the optical domain is 10–30 km, and thus, it is not necessary to install optical repeaters in the network. Thus, the MMW-RoF system can be applied to train communication systems.

The train wireless link system based on the MMW-RoF technology is a distributed prediction-based train tracking system [1, 2, 3], in which a central station predicts the train location information and activates the nearest radio station from the train. The stations are located at 1-km intervals along a train track. Furthermore, the MMW-RoF technology itself involves a hybrid system: Its architecture is split into an optical part and an electronics part [4]. A baseband signal is transmitted using an optical fiber over a long distance with the minimum transmission loss; subsequently, a radio signal is converted directly from an optical signal to a radio signal in a photo diode (PD). In previous work, we have already proposed and demonstrated an MMW-RoF system in the 90-GHz-band for a bullet train or Maglev [5]. This system is used for the backhaul of an in-car Wi-Fi service provided to the passengers, which monitors and diagnoses the train and railway status [3]. The proposed setup is based on a single-sideband (SSB) optical modulation technique [6] with an automatic bias controller (ABC) for an optical modulator [7]. In addition, an extremely low distortion front-end circuit in the W-band is used to transmit an IEEE802.11ad [8] packet in 16-QAM and 64-QAM under the error vector magnitudes (EVMs) of 4.8% and 5.5%, respectively, at a frequency of 97.5 GHz [5]. To realize the effective transmission of a high-speed signal, a broader bandwidth or higher frequency is desirable. However, the transfer of a broad-bandwidth signal in a single mode fiber (SMF) leads to signal deterioration owing to the effect of the wavelength-dependent dispersion. Thus, we employ the SSB optical modulation instead of a conventional double-sideband (DSB) method to mitigate this effect [7].

In this study, we demonstrate the MMW-RoF system based on the SSB optical modulation with the ABC, and discuss the feasibility of its application to future telecommunications systems for high-speed trains.

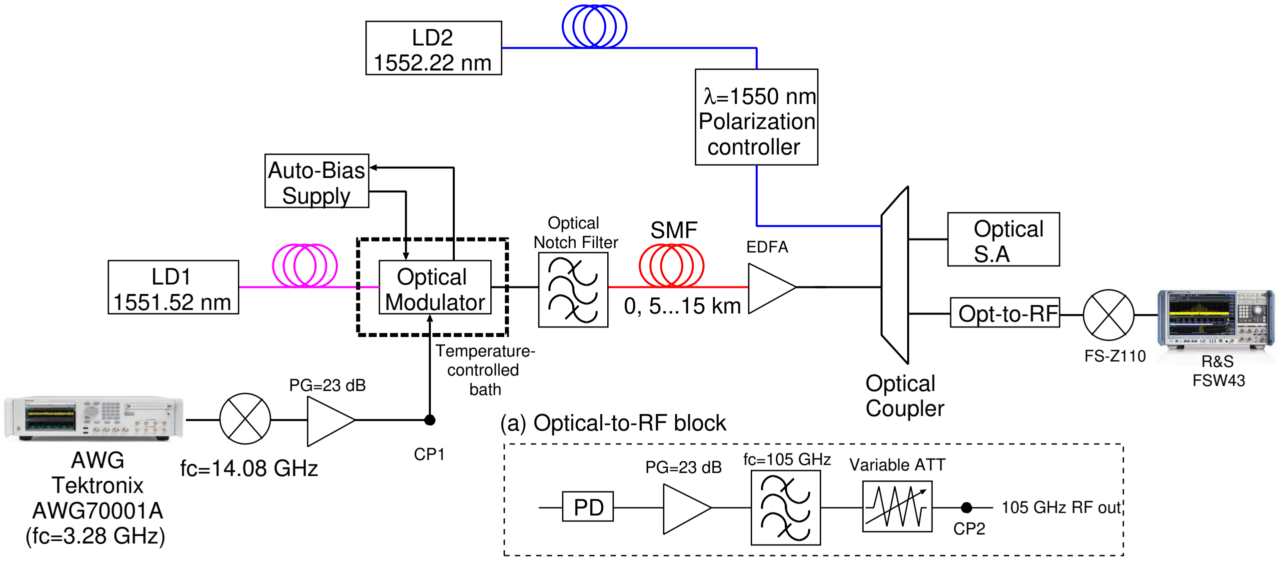

Figure 1. Experimental setup of the MMW-RoF system in 105-GHz band.

2 Experimental Setup

The experimental setup is shown in Figure 1. The baseband signal of the IEEE802.11ad standard for 16-QAM of the modulation code scheme (MCS) 12 is generated on a Tektronix AWG70001A arbitrary waveform generator at a center frequency of 3.28 GHz. The baseband signal is up-converted to 14.08 GHz in an IF up-converter. The signal is amplified by a preamplifier with a gain of 29.5 dB and injected into an optical modulator. In the optical modulator, the baseband signal and 1551.52 nm fiber laser (LD1) are mixed to obtain an optical double-sideband (DSB) signal by optimizing the bias voltages with an ABC [4]. The SSB optical signal is obtained by passing the optical DSB signal through an optical notch filter to suppress the other sideband. The optical SSB signal is then transferred via an SMF and injected into an erbium-doped fiber amplifier with an automatic gain control. The length of the SMF is changed in steps of 5 km from 0 to 15 km. The optical SSB signal is optically mixed with a 1552.22-nm fiber laser (LD2), which acts as an optical local oscillator in an optical coupler. Therefore, the MMW signal frequency can be adjusted by tuning a wave length of the LD2. LD1 and LD2 have a laser linewidth of approximately 15 Hz.

One output from the coupler is input to an optical spectrum analyzer to monitor the optical SSB spectrum. The other output is injected into a PD in the optical-to-RF part shown in Figure 1 (a) to convert an MMW signal. To maintain the input level for a down-converter (FS-Z110) and the signal-to-noise power ratio, a WR-10 waveguide variable attenuator (VAT) is prepared to adjust the input signal level from the optical-to-RF part. In addition, a waveguide bandpass filter with a center frequency of 105 GHz and a 3-dB passband of 9.5 GHz is installed between the low-noise amplifier and the VAT. The output signal is evaluated using a Rohde & Schwarz FSW43 signal and spectrum analyzer and a FS-Z110 down-converter, by using the IEEE802.11ad signal analysis option. The difference in the frequencies of the sideband of the SSB signal and LD2 is the frequency of the IEEE802.11ad signal in the W-band.

3 Experimental Result

A typical optical spectrum in the back-to-back setup (SMF length of 0 km) for the SMF is shown in Figure 2. The difference in the wavelength of the LD2 and IF spectra is equivalent to the center frequency of the MMW signal output from the PD. The ratio of the upper-sideband and the carrier is obtained by 18 dB, approximately.

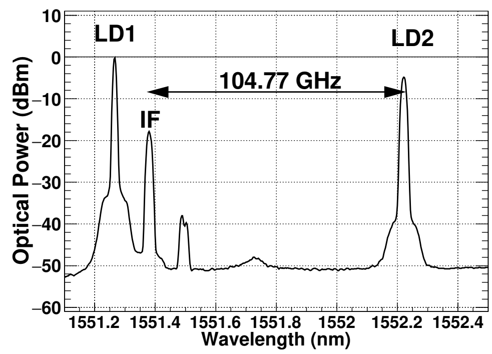

Figure 2. Typical optical spectrum of the SSB optical modulation from PD.

Next, the output MMW signal up-converted from the 14.08 GHz baseband signal of the MCS12 was examined. The typical output spectra and constellations at each check point (CP) are shown in Figure 3. The EVMs of the 14.08-GHz baseband signal at CP1, as shown in Figure 1, and the 104.77 GHz MMW signal at CP2 were 1.5% and 4.8%, respectively.

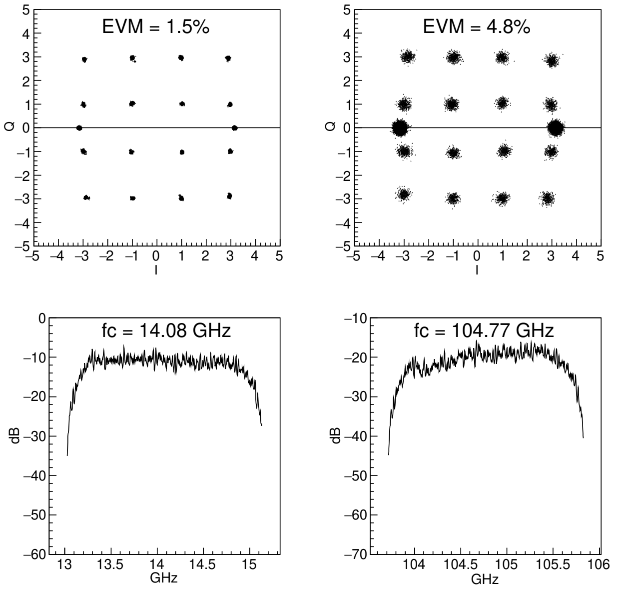

Figure 3. Typical constellations and spectra of 16-QAM on an MMW-RoF system. Left: IF signal input to optical modulator at CP1, Right: MMW signal at the output of the optical to the RF part at CP2.

To evaluate the stability of the optical modulator with the ABC, a heat-cycle test was performed in a temperature-controlled bath. The optical modulator was placed into the temperature-controlled bath, and the temperature was changed by 1 °C/min from 0 to 70 °C for 20475 s. The results of the optical SSB modulation, EVM, and output power in the stability evaluation are shown in Figure 4. The optical SSB modulation was stabilized with the ABC; subsequently, the EVM was maintained at 5.0 ± 0.1% in the heat-cycle test.

To evaluate the effect of varying the length of the SMF, the difference in the EVM and output power was observed, as shown in Figure 5. The stability of the EVM and output power was confirmed, even at the maximum length of 15 km. The EVM values in different of optical SSB modulation schemes are compared, as presented in Table 1. In a previous work [6], we employed the IQ modulation with bias control to generate an optical SSB signal. It was confirmed that even in the case of different modulation schemes and frequencies, a high quality MMW signal could be obtained using the proposed MMW-RoF setups.

Table 1. Comparison of EVM in different of optical SSB modulation schemes.

Modulation Scheme	MCS	RF frequency	EVM
IQ modulation w/ Bias control	12	97.57 GHz [6]	4.1%
DSB modulation w/ Notch Filter	12	104.77 GHz [This work]	4.8%

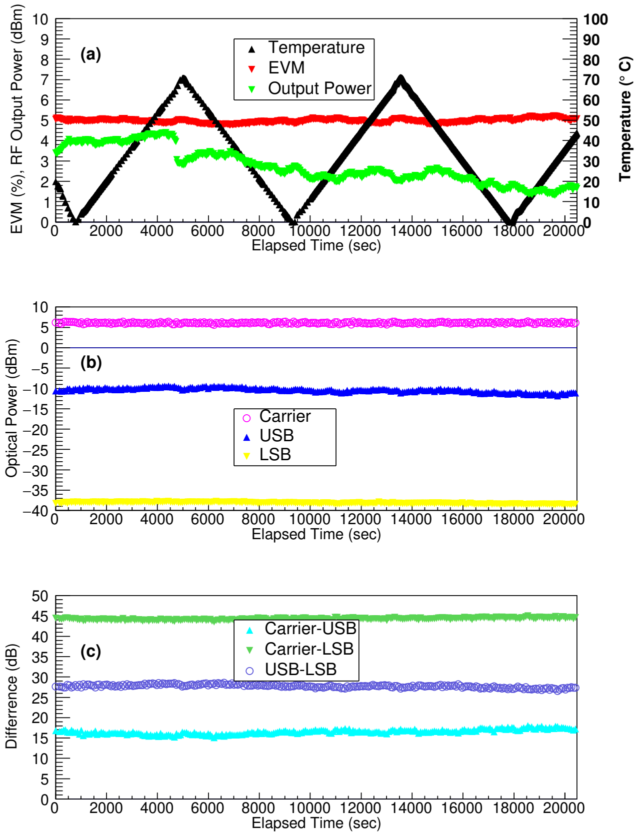

Figure 4. Time variation of the EVM, output power, and optical SSB modulation in the temperature-controlled bath. (a) EVM and output power, (b) optical power, (c) difference in the carrier and upper- and lower-sidebands, and difference in the upper- and lower-sidebands.

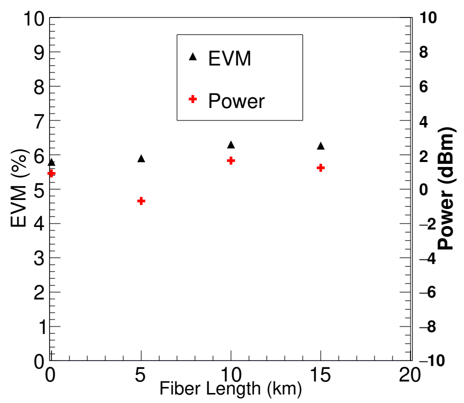

Figure 5. Relationship among the SMF length varying from 0 to 15 km, EVM and channel power at 104.77 GHz on 16-QAM.

4 Conclusion

In this work, an IEEE802.11ad-compliant packet of MCS12 of 16-QAM was successfully generated and transferred. The signal was modulated by an optical modulator with an ABC on an MMW-RoF system based on an optical SSB modulation scheme. In the proposed MMW-RoF system, the MMW signal exhibited an EVM of 4.8% at a center frequency of 104.77 GHz. The findings indicate that for a distributed optical network in the new generation wireless link for a high-speed train, the proposed MMW-RoF configuration can enable low distortion in signal transport along killometer-order distances.

5 Acknowledgments

This work was conducted as a part of the program entitled "Research and development to expand radio frequency resources," funded by the Ministry of Internal Affairs and Communications, Japan.

References

[1] Report ITU-R M.2442-0 (2018/11), "Current and future usage of railway radiocommunication systems between train and trackside," available at `https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2442-2019-PDF-E.pdf`

[2] APT Report on Broadband Railway Communication Systems Using Radio Over Fiber Technologies, APT/ASTAP/REPT-28, Edition: June 2019.

[3] A. Kanno, P. T. Dat, T. Umezawa, N. Yamamoto, T. Kawanishi, N. Iwasawa, N. Iwaki, K. Nakamura, K. Kawasaki, N. Kanada, N. Yonemoto, Y. Sato, M. Fujii, K. Yanatori, N. Shibagaki, and K. Kashima, "High-Speed Railway Communication System Using Linear-Cell-Based Radio-Over-Fiber Network and Its Field Trial in 90-GHz Bands," *J. Lightw. Technol.*, **38**, 1, 2020, pp. 112–122.

[4] C. Lim, A. Nirmalathas, and M. Bakaul, et. al.: "Fiber-Wireless Networks and Subsystem Technologies," *J. Lightw. Technol.*, **28**, 4, 2020, pp. 390–405 (2010).

[5] K. Fujiwara, A. Kanno, and K. Tokita, "IEEE802.11ad Packet Transmission Based SSB Optical Modulation on Radio-Over-Fiber in the 90-GHz band," Proceedings of 2018 48th European Microwave Week Conference, Madrid, Spain, September 2018, pp. 712–715.

[6] G. H. Smith, D. Novak, and Z. Ahmed, "Technique for optical SSB generation to overcome dispersion penalties in fibre-radio systems," *Electron. Lett.*, vol. **33**, 1, 1997, pp. 74–75.

[7] A. Kanno, N. Yamamoto, K. Fujiwara, and K. Tokita,: "Automatic bias control for radio-over-fiber-based train communication network system with single-sideband modulation," Proceedings of SPIE, vol. 10945, Broadband Access Communication Technologies XIII, February. 2019, 109450G.

[8] IEEE Std 802.11ad-2012. available at `http://standards.ieee.org/findstds/standard/802.11ad-2012.html/`