High-Stability, High-Signal-Quality Radio-over-Fiber System for IEEE802.11ad Packet Transmission Based on Optical Single-Sideband Modulation in W-band

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Abstract To address the communication needs of high-speed trains such as bullet trains, which require high-speed millimeter-wave wireless links, we developed a high-stability radio-over-fiber system to transmit IEEE802.11ad packets using optical single-sideband (SSB) modulation. The system comprises an optical SSB modulator with automatic bias control and a low-distortion millimeter-wave amplifier stage and is capable of generating and transmitting IEEE802.11ad packets with 16-QAM modulation under an error vector magnitude of 5.8% at frequency of 97.57 GHz over a 45.5-km-long single-mode fiber.

key words: radio-over-fiber, W-band, IEEE802.11ad
Classification: Optical hardware

1. Introduction

In recent years, the number of tourists coming to Japan has increased considerably, with more than 30 million foreign tourists visited the country in 2018 [1]. As an integral part of the rising tourism economy, high-speed trains are convenient and popular intercity transportation systems. During transportation, Internet connectivity is a key service for pass- engers; to meet this requirement, mobile communication providers are attempting to cover the nation’s railway network, including all track sections that run through tunnels. However, efficient wireless signal delivery for high-speed trains with passing speeds of up to 300 km/h via conventional fourth-generation (4G) mobile communication systems such as Long-term Evolution is difficult owing to the frequent hand-off processes involved in the changing of radio base stations. Fifth-generation (5G) mobile communication systems represent a promising solution [2] to the delivery of signals to/from high-speed vehicles in low-latency, high-throughput environments.

For the reasons described above, it would be useful to develop a novel railway communication system (RCS) for passenger services based on a combination of optical and millimeter-wave (MMW) radio techniques. As trains move linearly along a railway track, a large number of transceivers should be deployed along the track at intervals of several kilometers to configure a hand-off-free system [3]. In general, a mobile communication system employs cell coverage over a two-dimensional field. In this regard, a 5G centralized radio access network configured using a star network topology can be effective in achieving high throughput and seamless linking. Accordingly, an RCS should be configured using network link technology. However, as implementation cost is critical, digital processing circuits cannot be used in all RCSs. In addition, RCSs will face problems in terms of digital processing time and handling. Analog radio-over-fiber (RoF) technology is capable of directly converting optical signals into radio signals and can handle enhanced modulation bandwidth signals with a modulation bandwidth of several gigahertz; these characteristics make it a potential “silver bullet” for solving the problems faced by RCSs [4, 5, 6, 7, 8]. Previously, we demonstrated and confirmed that RoF technology in the MMW band [9] can be implemented using IEEE802.11ad packets [10].

The mechanism of RCSs is based on the use of MMW-RoF technology [4, 8, 11] to provide distributed prediction-based train tracking and information transferring capability that ensures hand-over-free access to provide the backhaul for in-car passenger Wi-Fi service while monitoring and diagnosing train and railway conditions [12, 13, 14, 15]. In such a system, a central station predicts train location information and switches the optical route radio stations located at 1-km intervals along the train track. Separately installed signal processing units comprising modulators and demodulators and remote radio access units based on photodiodes (PDs) and power-amplifiers as radio front-end parts are connected to each other within the RCS to enable the transfer of information via optical fiber.

This architecture makes it easy to configure an RoF system as a distributed antenna system. To transfer high-speed signals, it is necessary to broaden bandwidth or increase frequency. To mitigate the degradation of broadband signal transferability that occurs in a single-mode fiber (SMF) as a result of...
wavelength-dependent dispersion [16, 17, 18], SSB optical modulation[16, 17] is used instead of a conventional double-sideband (DSB) method. Previously, we succeeded in developing an SSB optical modulation scheme for IEEE802.11ad packets transmission with 16-QAM modulation at an error vector magnitude of 4.8% in the W-band under the back-to-back condition [9]. We have also developed an automatic bias control (ABC) to stabilize the SSB optical modulator from changes in the ambient environment [20]. In this letter, we demonstrate an MMW-RoF system based on ABC for SSB optical modulation and discuss the feasibility of its application in a future RCS for high-speed trains.

2. Advantages of analog RoF system with SSB optical modulation

In general, high-speed radio telecommunication requires a wide modulation bandwidth. The MMW band is quite appropriate for this purpose. For example, the IEEE802.11ad standard for the industrial, scientific, and medical (ISM) radio band at 60 GHz can be used to achieve high-speed data wireless local access network transference with a 2.16-GHz bandwidth [10]. However, as the atmospheric attenuation at 60 GHz is approximately 16 dB/km [21], this band is not suitable for transmission lengths beyond 1 km. In Japan, the frequency bands at 71–76, 81–86, 92–100, and 102–109.5 GHz are allocated for radio telecommunication purposes [22]. As the atmospheric attenuation in the 96-GHz frequency band is only approximately 0.5 dB/km [21], we selected this band to experimentally demonstrate the validity of our RCS approach with the 2.16-GHz modulation bandwidth of the IEEE802.11ad packets. However, the free-space propagation loss in the MMW band is still greater than that in the microwave band because of the shorter wavelengths involved, making direct wireless transmission on the order of kilometers difficult. As RoF is compatible with high-speed RCS communication (as discussed in the preceding section), this problem can be overcome through the application of a hybrid analog MMW-RoF system. An example of an MMW-RoF system, in which the architecture is split into an optical component and an electric component, is illustrated in Fig. 1. In this system, optically modulated signals and local signals are mixed in an optical combiner to produce mixed optical signals. These are then injected through a PD into MMW signals, which are finally amplified to obtain sufficient output power for operation.

The MMW-RoF technology does have limitations in terms of usable modulation bandwidth for optical transmission via SMF. In general, an SMF with conventional DSB modulation will experience a chromatic dispersion effect of 17 ps/nm/km as a result of refractive changes in wavelength, which generates a phase-variation-induced transmission between the upper and lower sidebands. The dependency of the relative RF throughput of a fiber can be expressed in terms of this chromatic dispersion effect, the transmission distance, and the MMW modulation bandwidth frequency as follows [18, 19]:

\[
P_{RF} \propto \cos^2 \left\{ \pi c L D \left( \frac{f_m}{f_0} \right)^2 \right\}
\]

where \(D\) is the fiber dispersion parameter, \(c\) is the velocity of light in vacuum, \(L\) is the fiber transmission length, \(f_m\) is the modulation bandwidth frequency, and \(f_0\) is the optical carrier center frequency. Fig. 2 shows the relative RF power throughputs calculated using this expression for 2.16, 15, and 20 GHz modulation signals, with SMF transmission losses of 0.2 dB/km.

At transmission length of up to 50 km, the loss in the 2.16 GHz modulation signal is dominated by the transmission loss without a significant chromatic dispersion effect. By contrast, the chromatic dispersion in the 15-GHz signal generates specific dips at fiber lengths of approximately 16 and 49 km. These results illustrate the inapplicability of modulation signal generation and transmission at wider modulation bandwidths, such as those used under the DSB scheme.

In our setup, a baseband signal is transmitted using SMF over a long distance with minimum transmission loss and distortion using SSB suppressed-carrier modulation (SSB-SC). Following transmission, this signal is converted directly from an optical signal into a radio signal using a PD and is then amplified using an extremely low distortion front-end circuit.

3. Experimental setup

The experimental setup is shown in Fig. 3. The baseband
signal is generated on a Rohde & Schwarz SMW200A vector signal generator [23] using the SMW-K141 option [24] for IEEE802.11ad standard signal generation at a center frequency of 14.08 GHz. The baseband signal is modulated at 16-QAM under the modulation code scheme (MCS) at 12, and 64-QAM at a symbol rate of 1.76 GHz. The signal is amplified by a preamplifier with a 29.5-dB gain and is then injected into an optical IQ modulator via a 90-degree hybrid coupler. In the optical IQ modulator, the baseband signal is mixed with a 1551.52-nm fiber laser (LD1) signal to obtain the SSB-SC signal by optimizing the bias voltages with the ABC. The resulting SSB-SC optical signal is transferred via an SMF to an erbium-doped fiber amplifier (EDFA) for injection with automatic gain control (AGC). In the MMW-RoF system, a nonlinear distortion is predominantly generated in a PD caused by an over drive, therefore, the input level control in the EDFA is essential. The amplified optical signal is then passed through a 1550-nm optical tunable filter with a pass-bandwidth of 1 nm and, finally, the filtered optical SSB signal is optically mixed with a 1552.42-nm fiber laser (LD2), which serves as an optical local oscillator in an optical coupler. Both LD1 and LD2 have laser linewidths of approximately 15 Hz. The frequency difference of both IF and LD2 is corresponding to 97.57 GHz, it is the wavelength difference of 0.90 nm, approximately. Therefore, the LD1 and LD2 are set to 1551.52 nm and 1552.42 nm, respectively.

Two types of configuration were assessed:
1) In the first, an optical SSB-SC signal was transmitted using an IF-over-fiber (IFoF) setup from the optical IQ modulator to the EDFA via a section of fiber (SMF-1) with changing length;
2) In the second, a photo-mixed signal was transmitted from the optical coupler to the optical-to-RF component via a section of fiber (SMF-2) with varying length. The EDFA is operated in the condition of between 20 and 25-dB gain with the AGC.

In each case, the length of the SMF was changed in 5-km steps from 0 to 45.5 km. During the experiments, one of the outputs from the coupler was given as an input to an optical spectrum analyzer to monitor the optical spectrum of the SSB-SC optical modulation, while the other output was injected into a PD in the optical-to-RF component shown in Fig. 3 (a) for conversion into an MMW signal. To maintain good distortion characteristics and signal-to-noise power ratio, a WR-10 waveguide variable attenuator used to adjust the input signal level from the PD and a band-pass filter with a center frequency of 98.5 GHz and a pass band of 5 GHz was installed between the first and final amplifiers. The band-pass filter comprised a microstrip-line-to-waveguide transducer [25, 26, 27] and a coupled line filter on a printed circuit board. The output signal was observed using a Rohde & Schwarz FSW43 signal and spectrum analyzer [28] with a FS-Z110 harmonic mixer [29] using the SMW-K141 IEEE802.11ad analysis option [30]. The frequency difference between the side band of the SSB-SC signal and LD2 was equivalent to the frequency of the IEEE802.11ad signal in the W-band. The MMW signal frequency could be adjusted by tuning the wavelength of LD2 and the signal could be amplified using the optical-to-RF section, as shown in Fig. 3(a).

3.1 Principle of automatic bias control
An optical IQ modulator with a 90-degree hybrid coupler configuration was used to generate the optical SSB. Although this configuration is more complex than that of a con-
ventional Mach-Zehnder modulator, it enabled adjustment of the carrier intensity by controlling the IQ bias [18, 20]. However, because the IQ modulator was sensitive to the ambient environment, the modulation could be easily disrupted. Therefore, to improve the optical SSB-SC modulation, therefore, we developed an ABC comprising analog and digital converters [20].

Normally, ABC is obtained by arranging nested Mach-Zehnder modulators at a quadrature point of the transfer function, with the main Mach-Zehnder interferometer also placed at a quadrature point. To reduce the carrier component, the bias set point for the IQ modulators should be set at a point at which there is a voltage difference of one-tenth of the $V_r$ of the modulator from a minimum transmission point. This procedure was performed based on the detected change in output power from an integrated PD inside the IQ modulator via an adjustment of the bias voltages in the ABC. To obtain this condition, the sideband component was enhanced with the desired suppression of the carrier component, as discussed in the next section.

4. Results and discussion

A typical optical spectrum in a back-to-back setup of SMF-1 and SMF-2 is shown in Fig. 4. Fig. 4 shows multiplexed IF and RF signals that are optimized for RF signal quality. The wavelength difference between the LD2 and IF spectra is equivalent to the center frequency of the RF signal output from the PD. Given the performance limitation of the ABC, the suppression ratio of the other sideband is approximately 16 dB. Our ABC worked imperfectly to suppress the carrier components in the experiments; however, the millimeter-wave band-pass filter can suppress the converted carrier component.

Figs. 5 and 6, respectively, show the 16-QAM and 64-QAM constellations and spectra of the IF output from the PD and the W-band RF output from the optical-to-RF part via a 10-km-long SMF under the first experimental configuration (in which the length of SMF-1 between the modulator and the EDFA was changed).

With the RF center frequency set to 97.57 GHz, IF and RF EVMs at the 16-QAM of 7.2 and 4.3%, respectively, were obtained at the 14.08 GHz IF out and CP2 checkpoints; at 64-QAM, the corresponding EVMs were 7.1 and 4.2%, respectively. The IF signal from the PD was measured using a direct connection to the spectrum analyzer via a coaxial cable. The baseband signal supplied to the 90-degree hybrid coupler had EVMs at the CP1 checkpoint of 3.4 and 3.6% at 16-QAM and 64-QAM, respectively, indicating that the baseband signal had been frequency-converted into an RF signal with minimum distortion and with an obtained signal-
Table I. Comparison of EVM values at each output with back-to-back (0 km) SMF-1 and SMF-2.

|            | Baseband (14.08 GHz) | RoF IF out (14.08 GHz) | RoF RF out (97.5 GHz) | RoF RF out (97.57 GHz) |
|------------|----------------------|------------------------|-----------------------|------------------------|
| 16-QAM     | 3.4%                 | 6.2%, 4.8%             | 4.8%, 4.1%            | 4.1%                   |
| 64-QAM     | 3.6%                 | 6.2%, 5.5%             | 5.5%, 4.0%            | 4.0%                   |

Fig. 7. Relationship between SMF-1 length over the range of 0 to 45.5 km and EVM (left) and channel power (right) at an IF of 14.08 GHz and an RF of 97.57 GHz with 16-QAM.

Fig. 8. Relationship between SMF-1 length over the range of 0 to 45.5 km and EVM (left) and channel power (right) at an IF of 14.08 GHz and an RF of 97.57 GHz with 64-QAM.

Fig. 9. Relationship between SMF-2 length over the range of 0 to 45.5 km and EVM (left) and channel power (right) at an RF of 97.57 GHz with 16-QAM and 64-QAM.

5. Conclusion

In this study, we verified that optical SSB-SC modulation with ABC on an MMW-RoF system could generate IEEE802.11ad MCS12 packets under both 16-QAM and 64-QAM. Furthermore, using the IFoF setup, we were able to transfer a 16-QAM, 97.57-GHz RF signal at a maximum length of 45.5 km with an EVM of 5.8%. Low distortion transmission has been successfully performed with the proposed configuration shown in Fig.1. Overall, we confirmed that the proposed MMW-RoF configuration is capable of being used in a next-generation MMW-RCS for high-speed trains. In subsequent research, we plan to evaluate the stability of SSB-SC optical modulation with ABC under temperature cycle testing in a thermostat chamber and to shift the system to higher operational frequencies.

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