Radio-over-Fiber Systems with 1-bit Outphasing Modulation for 5G/6G Indoor Wireless Communication

HORI Shinichi, KASE Yuma, OSHIMA Naoki, KUNIHIRO Kazuaki

Abstract

We propose a radio-over-fiber (RoF) system with 1-bit outphasing modulation. The proposed RoF system does not require a power-hungry digital-to-analog converter in distributed antenna units and relaxes the operation speed of optical transceivers to reduce device cost. In the system, wide-band transmission with a signal bandwidth of 1 GHz was experimentally verified complying with the 3GPP standard for the adjacent channel leakage ratio (ACLR). Finally, the proposed RoF system has been shown to have a higher bandwidth efficiency compared with other systems. Therefore, the proposed RoF system provides a cost-effective in-building wireless solution for 5G and 6G mobile network systems.

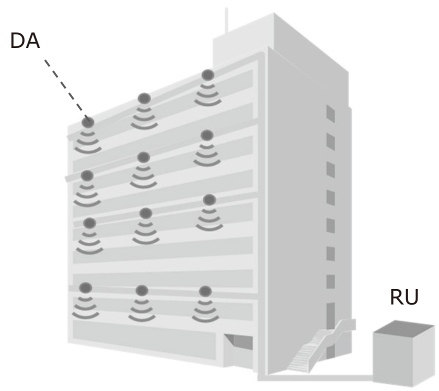
Keywords

Radio-over-fiber (RoF), Outphasing, In-building wireless, Beyond 5G, 6G

1. Introduction

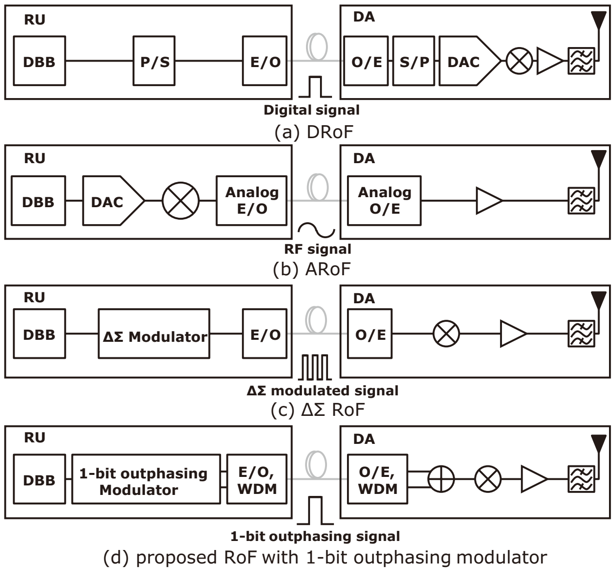
High-speed wireless communication using millimeter-wave technology has been used for 5G (fifth-generation mobile communication system) and is expected as a key technology in Beyond 5G/6G. When constructing an in-building wireless system with millimeter waves, it is necessary to consider its large propagation loss and high straightness. These make it difficult to propagate from base stations installed outdoors to indoor terminals. Since more than 80% of mobile communication traffic occurs in buildings[1], it is essential to improve the quality of service (QoS) in such environments with many obstacles. While high-density deployment of millimeter-wave distributed antenna units (DAs) in these areas is effective in improving QoS, miniaturization, low power consumption, and cost reduction of DAs are necessary for practical use. A radio-over-fiber (RoF) system shown in **Fig. 1** is a promising solution since it can provide the flexibility to install small and low-power DAs in indoor environments.

Current RoF systems are classified as digital RoF (DRoF), analog RoF (ARoF), and delta-sigma (ΔΣ) RoF, as shown in **Fig. 2**(a), (b), and (c), respectively. DRoF systems have been commercialized and widely used for indoor mobile network systems. Their DAs often require large power consumption and incur high cost because they are equipped with a high-performance digital-to-analog convertor (DAC) for wideband signal. ARoF



DA: distributed antenna unit, RU: radio unit

Fig. 1 Radio-over-fiber system for indoor wireless communication.



DBB: digital baseband, P/S: parallel-to-serial convertor,
S/P: serial-to-parallel convertor, WDM: wavelength division multiplexing

Fig. 2 Block diagram of RoF systems.

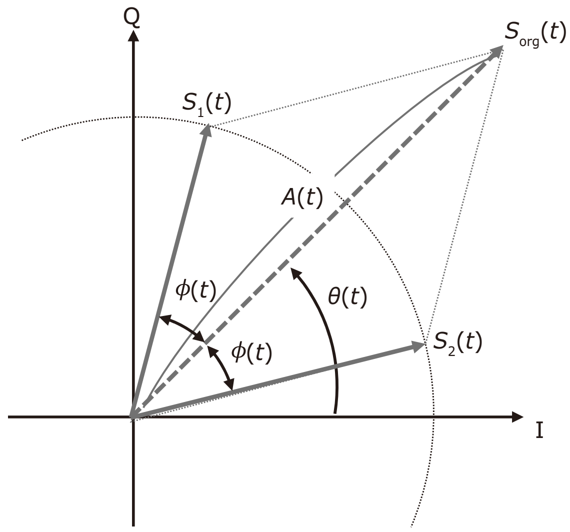


Fig. 3 Principle of outphasing with vector separation.

DAs have the advantage of low power and small footprint because they do not require a DAC with large power consumption. ARoF systems require specific high-linear electrical-to-optical (E/O) and optical-electrical (O/E) convertors to avoid signal degradation due to distortion, leading to high cost. In contrast, ΔΣ RoF systems enable the implementation of low-cost RoF systems with small DAs since they do not require high-linear E/O and O/E devices or a power-hungry DAC in the DAs[2)3)]. However, for wideband communication using millimeter waves, the sampling rate of the ΔΣ modulator needs to be increased, meaning a higher device speed is required for the optical transceiver, which drives up costs.

We propose a RoF system with 1-bit outphasing modulation, as shown in Fig. 2(d), to enable the use of low-cost optical devices.

2. Operation Principle of 1-bit Outphasing Modulation

Outphasing is a technique for transforming the original signal vector $S_{org}(t)$ with amplitude and phase modulations into a pair of outphasing signal vectors $S_1(t)$ and $S_2(t)$ with only phase modulation, as shown in **Fig. 3**[4)]. The amplitude $A(t)$ and phase $\theta(t)$ are generated from the I/Q signal by polar coordinate conversion, as shown in the following equation,

$$\begin{cases} A(t) = \sqrt{I^2(t) + Q^2(t)} \\ \theta(t) = \tan^{-1}(Q(t)/I(t)) \end{cases}. \quad (1)$$

The $S_1(t)$ and $S_2(t)$ are generated in accordance with Eqs. (2a) and (2b), respectively,

$$S_1(t) = \frac{A_{\max}}{2}\cos\left(2\pi f_c t + \theta(t) + \phi(t)\right), \quad (2a)$$

$$S_2(t) = \frac{A_{\max}}{2}\cos\left(2\pi f_c t + \theta(t) - \phi(t)\right), \quad (2b)$$

$$\phi(t) = \cos^{-1}\left(\frac{A(t)}{A_{\max}}\right), \quad (2c)$$

where, f_c and A_{max} indicates carrier frequency and the maximum value in $A(t)$, respectively. The principle of outphasing indicates that $S_{org}(t)$ is reconstructed by combining $S_1(t)$ and $S_2(t)$, as expressed with the following equation:

$$S_{org}(t) = A(t)\{\cos\left(2\pi f_c t + \theta(t)\right)\}. \quad (3)$$

In the proposed RoF system, $S_1(t)$ and $S_2(t)$ are converted into rectangle wave signals $S_{1b}(t)$ and $S_{2b}(t)$ by comparing their amplitude with the value of zero. These are called 1-bit outphasing signals afterward.

Fig. 4 illustrates the waveforms of $S_{org}(t)$, a pair of $S_{1b}(t)$, $S_{2b}(t)$, and the conventional ΔΣ modulator output signal $S_{\Delta\Sigma}(t)$. The period of $S_{org}(t)$ is expressed as $1/f_c$, and those of $S_{1b}(t)$ and $S_{2b}(t)$ are also $1/f_c$. Thus, their pulse width is $1/(2f_c)$, which means the required transition speed required of an optical transceiver is twice the f_c. However, the transition speed of $S_{\Delta\Sigma}(t)$equals the sampling rate f_s, which is much higher than twice the f_c, because this waveform is updated with the clock of f_s. The lower transition speed enables the use of low-cost commercially available optical devices for millimeter-wave communications[5)6)]. This is an advantage of the proposed RoF system over conventional ΔΣ RoF systems.

Moreover, the proposed system is less affected by timing jitter depending on pulse patterns. The proposed system basically has the uniform pulse pattern in which high and low levels are alternately switched around a time interval of $1/(2f_c)$, while ΔΣ RoF systems have random pulse patterns, as shown in Fig. 4.

3. Circuit Configuration

In section 3, we describe the circuit configuration for the RoF system with 1-bit outphasing modulation. **Fig. 5** illustrates a block diagram of the proposed RoF system. In the radio unit (RU), the in-phase and quadrature (I/Q) of a digital baseband signal is given to the outphasing modulator and transformed to a pair of outphasing signals at an intermediate frequency f_{IF} by digital signal processing. The output signals are input to the DACs and transformed into analog signals, $S_1(t)$ and $S_2(t)$, through anti-alias filters. These are then transformed into $S_{1b}(t)$ and $S_{2b}(t)$ at the comparators. These signals are transferred to a DA through an optical fiber cable. The wavelength division multiplexing (WDM) enables the RU to be connected to a DA through a single fiber. In the DA, $S_{1b}(t)$ and $S_{2b}(t)$ are combined to reconstruct the original signal at f_{IF}. This combined signal is up-converted to a desired high-frequency band, e.g., a millimeter-wave band, then transmitted to the air after amplification and filtering.

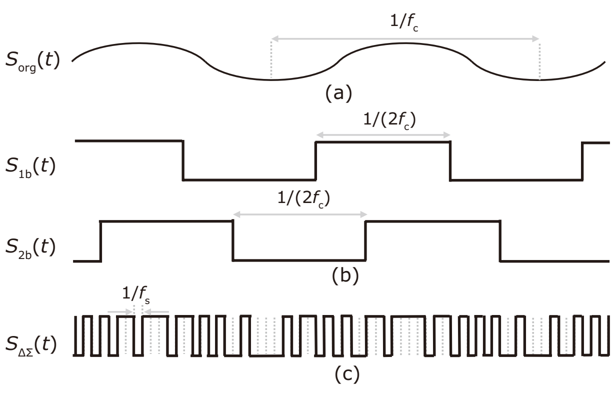


Fig. 4 Waveforms of (a) S_{org}(t), (b) pair of S_{1b}(t) and S_{2b}(t), and (c) conventional $S_{\Delta\Sigma}$(t).

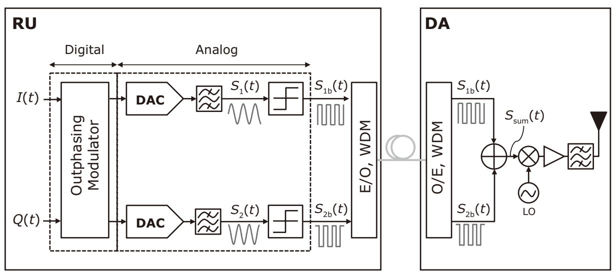


Fig. 5 Block diagram of proposed RoF system.

4. Experimental Results

Fig. 6 shows the experimental setup to demonstrate the proposed RoF system. We used two types of 5G NR signals with 64QAM modulation at f_{BW} of 100 MHz and 400 MHz, respectively. A pair of output signals from the outphasing modulator, $S_1(t)$ and $S_2(t)$, was generated in an arbitrary waveform generator (AWG). The generated signals were input to a quad small form-factor pluggable plus (QSFP+) module, which has maximum transmission rate of 10 Gbps per channels and 1,310 nm wavelength. The input signals were transformed into $S_{1b}(t)$ and $S_{2b}(t)$ during of E/O conversion. They were then transmitted to the receiver side through a 50 m single mode fiber (SMF) assuming the indoor environment. On the receiver side, the received signals were combined and measured using a spectrum analyzer. For reference, we also measured in case where the signals output from the AWG are directly input to the combiner without fiber transmission.

Fig. 7 shows the measured spectrum of $S_{sum}(t)$ at f_{IF} of 2 GHz and f_{BW} of 400 MHz. The measured ACLR was −36 dB, in compliance with the 3GPP standard.

We measured the error vector magnitude (EVM) by a signal analyzer. **Fig. 8** shows the results of the EVM measurement versus f_{IF}. The solid lines indicate the EVM

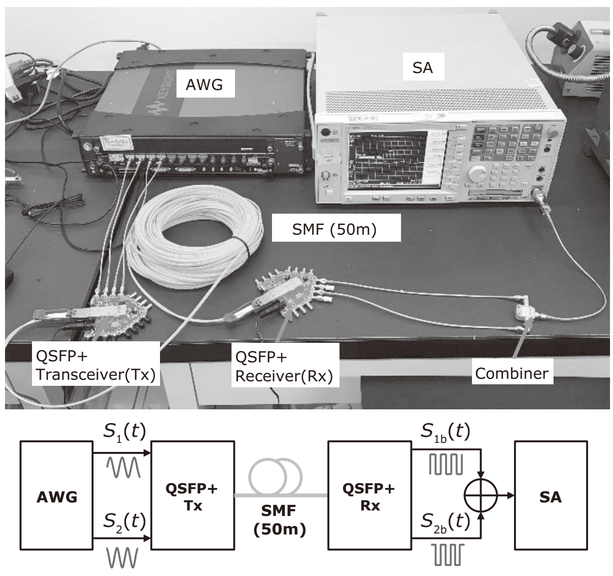
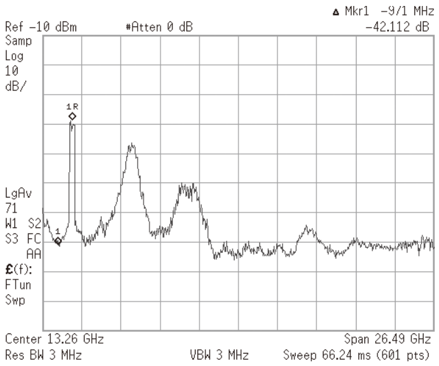
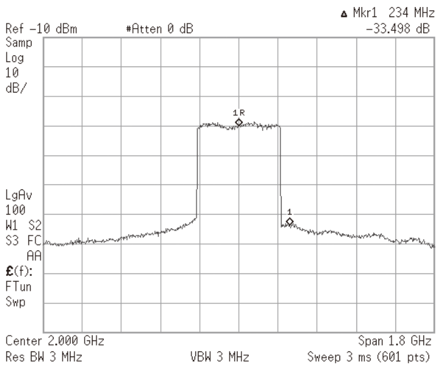


Fig. 6 Experimental setup for evaluating proposed RoF system.



(a) 26.49 GHz span



(b) 1.8 GHz span

Fig. 7 Measured spectrum at f_{IF} of 2 GHz and f_{BW} of 400 MHz.

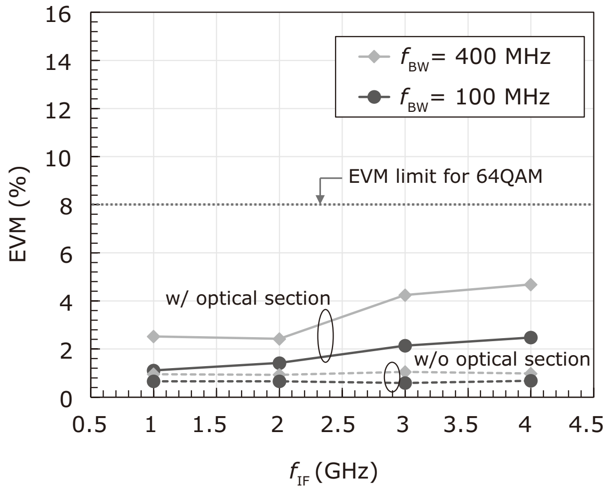


Fig. 8 Measured EVM vs. f_{IF}.

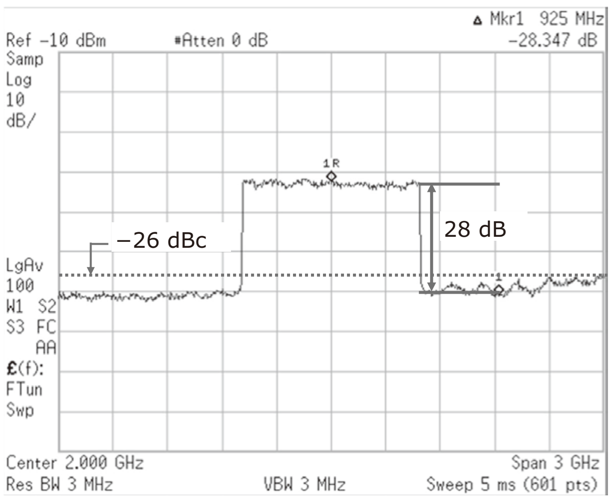


Fig. 9 Measured spectrum at f_{IF} of 2 GHz and f_{BW} of 1 GHz.

with the optical section, and the dotted lines indicate the EVM without the optical section as a reference. The circle plots indicate the EVM at f_{BW} of 100 MHz and the diamond ones are that at f_{BW} of 400 MHz. According to the 3GPP standard, the upper limit of EVM for 64QAM is defined as 8%[7)], and all cases in this measurement reached this limitation. The EVM was 3% or less for f_{IF} of 1 and 2 GHz, 4.24% for 3GHz f_{IF} and 4.68% for 4 GHz f_{IF} in compliance with 64 QAM 3GPP standard. This means that an appropriate f_{IF} should be chosen according to the system requirement of EVM.

Fig. 9 shows the measured spectrum of $S_{sum}(t)$ with 1 GHz bandwidth (10 x 100 MHz) OFDM signal at f_{IF} of 2 GHz for Beyond 5G/6G. The measured SNR was more than 28 dB, and the difference between the mean powers of the desired and adjacent channels is 26 dBc or more. This means the ACLR complied with the 3GPP standard for 37 to 52.6 GHz band.

5. Discussion

We discussed the performance of the proposed RoF system in terms of device cost, by comparing it with conventional RoF systems. **Table** shows the performance comparison of our proposed RoF system and conventional ΔΣ RoF systems. The device speed required for the optical transceiver is twice the f_{IF} in our proposed RoF system while it is equal to the sampling rate in the ΔΣ RoF systems. The bandwidth efficiency is defined as the ratio of f_{BW} to device speed required for each optical transceiver per channel[2)]. Our proposed RoF system has the highest bandwidth efficiency, complying with the 3GPP standard for ACLR.

Table Proposed and conventional RoF systems.

	[2]	[3]	Proposed	
Modulation scheme	ΔΣ	ΔΣ	1-bit outphasing modulation	
f_c or f_{IF} (GHz)	0.96	25	2	2
f_s (GHz)	5	100	-	-
SNR (dB)	30	29.1	33.4	28
EVM (%)	2.8	3.76	2.85	5.7
f_{BW} (MHz)	252	500	400	1,000
Device speed (Gb/s)	5	100	4	4
No. of channels	1	1	2	2
Bandwidth efficiency (MHz/Gbps)	50.4	5	100	125
Complying with the 3GPP standard for ACLR	No	Yes	Yes	Yes

6. CONCLUSION

We proposed a 1-bit outphasing modulation RoF system. Our system has the highest bandwidth efficiency complying with the 3GPP standard. This indicates that our system can be applied to 5G/6G indoor mobile networks at low cost.

7. Acknowledgments

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