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Quadrature-Phase-Shift-Keying Radio-over-Fiber Transmission for Coherent Optical and Radio Seamless Networks

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SUMMARY We propose a coherent optical and radio seamless network concept that allows broadband access without deployment of additional optical fibers within an optical fiber dead zone while enhancing network resilience to disasters. Recently developed radio-over-fiber (RoF) and digital coherent detection technologies can seamlessly convert between optical and radio signals. A millimeter-wave radio with a capacity greater than 10 Gb/s and high-speed digital signal processing is feasible for this purpose. We provide a preliminary demonstration of a high-speed, W-band (75–110 GHz) radio that is seamlessly connected to an optical RoF transmitter using a highly accurate optical modulation technique to stabilize the center frequencies of radio signals. Using a W-band digital receiver with a sensitivity of −37 dBm, we successfully transmitted an 18.6 Gb/s quadrature-phase-shift-keying signal through both air and an optical fiber.
key words: *radio over fiber, digital signal processing, coherent detection, millimeter-wave radio*

1. Introduction

The construction of directly interconnecting optical and radio networks has been of interest not only for enhancing network resilience but also because the implementation of such networks would help to foster more universal broadband connectivity. Particularly where passive optical access networks are used in rural areas, the "last-mile" issue becomes significant to broadband access if optical fibers cannot be deployed owing to geomorphic characteristics such as mountains, valleys, or rivers, or because the initial cost of installing fibers is too high. In such circumstances, high-speed radio connection is an attractive alternative candidate for extending the access area. Even where fixed wireless access solutions have already been installed, the conventional radio communication technology used may provide inadequate capacity to support future broadband services such as remote interactive healthcare using real-time, high-resolution video. Therefore, the enhancement of the network capacity and the support area of next-generation mobile backhauling networks will be necessary owing to the rapid spread of high-speed mobile service. Because of its installation ease and universal broadband connectivity, the use of high-speed radio transmission seamlessly connected to optical fiber access networks represents a promising solution to such problems. Furthermore, this technology will likely play an important role in disaster recovery. Following the 2011 Japanese earthquake and tsunami, conventional networks broke down [1], [2]. In future situations involving the disruption of fiber cables, high-speed radio could be used to quickly restore networks by providing both protection and temporal links to stations.

Millimeter-wave radio transmission is more attractive for high-speed radio rather than microwave transmission, as the achievable transmission capacity within the microwave frequency region is less than 5 Gb/s [3], [4]. In terms of atmospheric attenuation, the use of W-band (75–110 GHz) transmission appears to be suitable, as the attenuation within this band tends to be less than 1 dB/km [5]. Electronic transceivers based on the recently developed high-speed, millimeter-wave integrated circuit (MMIC) technology represent one potential high-speed, high-frequency radio transceiver solution; however, these have increased energy consumption owing to their bandwidth and use of high frequencies. Furthermore, a function of the conversion between optical and radio signals, which involves not only modulation format conversion but also the addition of preambles in order to compensate for transmission impairments, is indispensable in a radio access unit (RAU) (Fig. 1(a)).

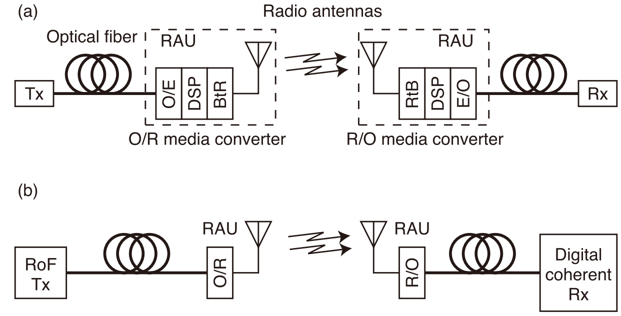

Fig. 1 Conceptual diagrams for (a) conventional optical-radio-optical transmission and (b) the proposed seamless conversion of radio and optical signal using an RoF transmitter and a digital coherent receiver. BtR and RtB indicate a baseband to radio signal converter and a radio to baseband signal converter, respectively.

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The radio-over-fiber (RoF) technology is a more promising solution for developing combined radio optical-fiber transmission networks. Using a photonic direct up-conversion technique, RoF can directly convert optical signals to radio signals [6]. A high-speed photomixer in the RAU acts as an optical-to-radio (O/R) converter, seamlessly converting high-speed optical signals from RoF transmitters (Tx) directly into radio signals [7]–[10]. In a conventional conversion system (as shown in Fig. 1(a)), a digital signal processing (DSP) unit is usually installed in a radio-to-optical (R/O) converter to compensate for the degradation of air-transmitted signals as well as in the O/R converter to form the signal form for radio transmission. The use of such a unit may increase the energy consumption of both O/R and R/O converters. On the other hand, the use of optical digital coherent detection techniques at the receiver (Rx) can completely compensate for transmission impairments such as media dispersion, eliminating the need to use DSP units altogether. As it is likely that an optical digital coherent Rx will soon be routinely implemented, the proposed method for seamless conversion between optical and radio signals is feasible for use in near-future optical networks (Fig. 1(b)).

In this study, we demonstrate high-symbol-rate RoF signal transmission, optically over fibers and via radio transmission through air. In this method, a quadrature-phase-shift-keying (QPSK) modulation at 10 Gbaud provides a data transmission capacity of nearly 20 Gb/s. In Sect. 2, the details of the proposed coherent optical and radio network concept are discussed and an energy consumption comparison with a conventional scheme is made. Following this, the experimental setup is described in 3.1, and results, including discussion of how to extend the transmission distance and how to apply protection links, are presented in Sects. 3.2 and 3.3.

2. Coherent Optical and Radio Seamless Network Concept

Figure 2 shows a schematic drawing of a coherent optical/radio seamless network composed of an RoF Tx, several RAUs, and a digital coherent Rx [10], [11]. During normal operation, called the "baseband operational mode," the RoF Tx transmits a high-speed optical baseband signal to the Rx over an optical fiber (Fig. 2(a)). It is anticipated that the total capacities of around 1 Tb/s or more will be needed in future metro area networks owing to the spread of 40/100 Gigabit Ethernet (GbE) implementation. In this situation, the RoF Tx might play a role as a conventional optical baseband transmitter, while the digital coherent Rx could be used to demodulate optical signals.

If the optical link between the Tx and the Rx is broken through an optical fiber cut, the operational mode of the RoF Tx will change to the "RoF operation mode," which is suitable for radio transmission (Fig. 2(b)). In the RoF operation mode, the RoF Tx generates an RoF signal consisting of a baseband signal for data modulation and an optical local oscillator (LO) signal for direct photonic upconversion

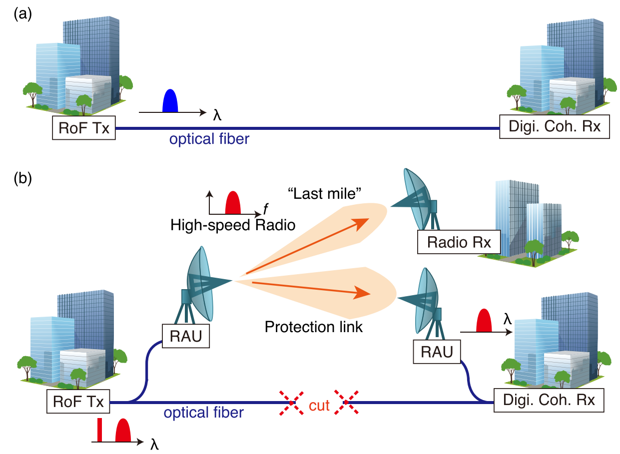

Fig. 2 Conceptual schematics for (a) a typical optical fiber network case (i.e., "baseband operation mode") and (b) a protection link mode ("RoF operation mode") using high-speed radio at a fiber cut. Schematic spectra are also shown.

[6]. This generated RoF signal is then transmitted to the RAU, which consists of a simple O/R converter such as a photomixer. The RAU converts the received radio signal to an optical signal without changing the signal format, and the optical signal is then transmitted. Thus, this RAU represents an alternative link that can act as the protection link for a cut optical fiber. The use of high-speed radio together with optical fiber transmission will generate protection links for enhancing network resilience. However, because of its wide transmission bandwidth, the total available capacity of an RoF link is not very large; thus, the use of millimeter-wave signals is required for high-capacity transmission.

For "last mile" situation including quick deployment of broadband connection such as a temporal link to temporal stations at a disaster recovery and within an optical fiber dead zone, a radio Rx should be set at these stations with the "RoF operation mode" Tx. This radio Rx is comprised of the RAU and the optical Rx without an optical front end: receiver antenna, a receiver front end including an analog-to-digital converter (ADC), and a DSP. Because the DSP configuration is a similar to the optical Rx, a number of components and resulting energy consumption would be reduced rather than that for the protection link. Especially in the optical dead zone, an optical fiber may be deployed in future due to the demand of higher capacity connection. To prepare for this, the feature of both the "baseband operation mode" and the "RoF operation mode" should be implemented for the RoF Tx in advance.

The key feature of the proposed RoF transmitter is its use of frequency-locked, two-tone optical generation in order to stabilize the transmitted radio signals' center frequencies within parameters allowed by radio regulations. An advantage of this two-tone generation method, i.e., the "optical frequency quadrupler," stems from its simple and robust configuration, which is based on a single synthesizer, laser, and optical modulator and lacks movable structures [12]–[14]. The quadrupler forms optical two-tone signals by means of separation of quadruple of the synthesizer's incident frequencies. In testing, the phase noise of the generated signal was observed to follow a theoretical degradation curve of $20 \log m$, where m is the number of multiplications [12], [15]. The optically synthesized frequency quadrupler is thus considered to be suitable both in terms of its frequency stabilization characteristics and its advantageous phase noise degradation curve.

3. Demonstration

To simply verify the proposed concept, a demonstration of combined multi-level and high-speed RoF signal generation, radio transmission, and reception in the W-band was conducted, as shown in Fig. 2(b). All the experiments described here were performed in a large-scale anechoic chamber.

3.1 Experimental Setup

Figure 3 shows the experimental setup of the proposed system [11]. An RoF signal was generated using an optical two-tone generator with a separation of 92.5 GHz [14]. An arrayed waveguide grating (AWG) separated this signal into an upper-sideband (USB) signal for baseband modulation and a lower-sideband (LSB) signal for use as an optical reference component that served as an optical LO. The data-modulated USB component signal was then reshaped by an optical bandpass filter (OBPF) with a bandwidth of 50 GHz to suppress unnecessary side lobe components. The LSB component was passed through a polarization controller (PC) to maximize parallel polarization relative to the USB. These two components were then re-coupled with an optical 3-dB coupler to form the desired RoF signal. This signal was directed into a 20-km-long standard single-mode fiber (SMF) for optical transmission. At the O/R conversion RAU, the transmitted signal was boosted by means of the EDFA, and the boosted RoF signal was then directed into an OBPF with a 1 nm bandwidth in order to suppress amplified spontaneous emission, after which the amplified RoF signal was converted from an optical to a radio signal by means of a uni-traveling carrier photodiode (UTC-PD). The radio signal was amplified using an electrical power amplifier (PA) operating in the W-band and finally transmitted through air over a distance of between 5 and 10 m. The gain of the RAU and Rx antennas was 24 dBi.

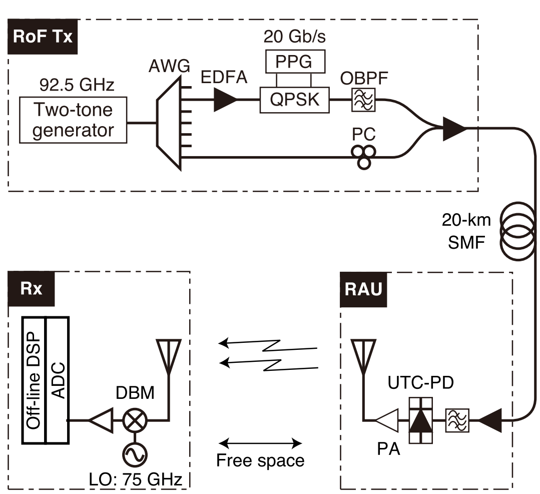

Fig. 3 Experimental setup for 10-Gbaud W-band QPSK RoF transmission.

The received signal was down-converted using a W-band double-balanced mixer (DBM) with a radio frequency bandwidth of 75–110 GHz, an LO of 75–110 GHz, and an intermediate frequency (IF) of DC–35 GHz. The DBM was connected to a free-running electrical LO operated at a frequency of 75 GHz. An electrical power of the LO was fixed about 10 dBm in all the experiments, that is no adaptive power optimization between the LO and the W-band signals. The regenerated IF component was amplified using a pre-amplifier for optimization of the reception range of an ADC. The electrical signal was acquired by means of a real-time oscilloscope working as the ADC with a sampling rate and bandwidth of 80 GSa/s and 30 GHz, respectively. The resulting digitized signal was separated into its in-phase and quadrature (IQ) components by a digital signal processor, and these components were demodulated using phase noise suppression, frequency domain equalization, and symbol decision in a manner similar to the procedure used for off-line optical digital coherent detection. Figure 4 shows the optical spectrum at the input port of the UTC-PD, where a clear 92.5-GHz separation between the optical reference and the 10-Gbaud QPSK baseband components is observed. The small peak structure near the 1550.3 nm wavelength corresponds to a residual carrier component from the two-tone generator and the AWG. However, owing to its low peak power and frequency separation of 46.25 GHz from the desired optical signals, this component could not affect the converted radio signal and can be filtered out before radiating over the air by the bandwidth limitation of amplifier and antenna. It should be noted that these transmissions were performed under far-field transmission conditions; a Fraunhofer distance of $2D^2/\lambda$ (where D and λ indicate the diameter of the antenna and the wavelength of the radio signal, respectively), which marks the traditional boundary value between near- and far-field, was approximately 0.5 m, which was much smaller than the transmission distances of

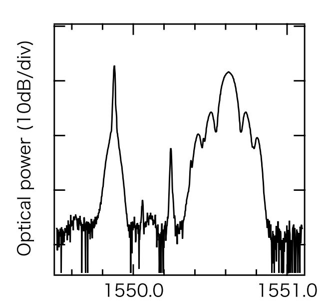

Fig. 4 Optical spectrum of the 10-Gbaud 92.5-GHz RoF signal transmitted into the RAU.

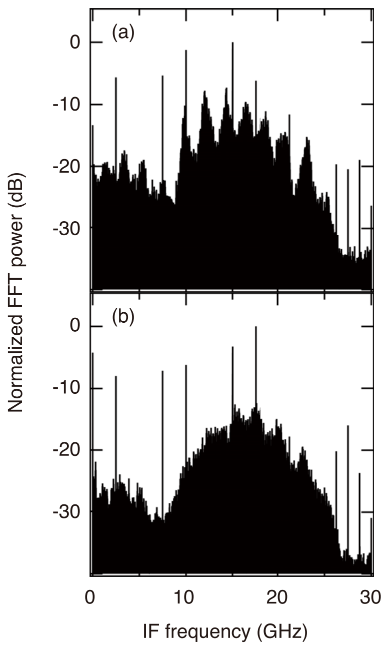

Fig. 5 Normalized FFT power spectra of received IF signals at the ADC (a) with a transmitter power amplifier and (b) without the amplifier (for reference).

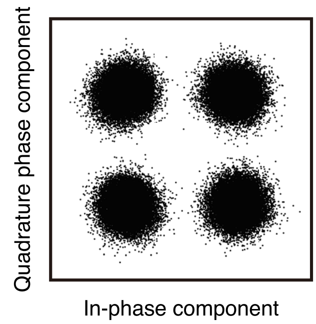

Fig. 6 Constellation map of a received radio signal at a transmitter power of +9 dBm over 10-m transmission.

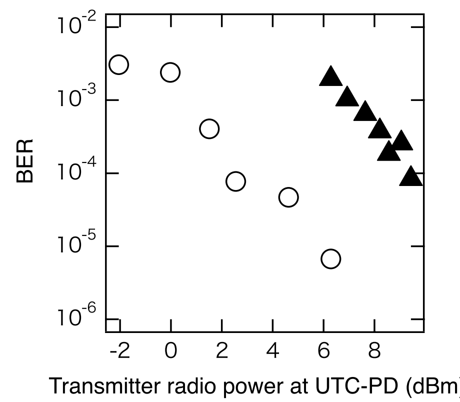

Fig. 7 Observed bit error rate dependence on transmitter radio power over 5-m (open circles) and 10-m (filled triangles) transmission.

5–10 m. All the experiments described here were performed in a large-scale anechoic chamber.

3.2 Results

Normalized power spectrum of the received radio signal at a transmitter power of 9 dBm, as estimated using a fast Fourier transform (FFT) of the time-domain signals acquired by the ADC, is shown in Fig. 5(a): this is just a periodigram, which is the modulus-squared of the discrete Fourier transform of the time series with the appropriate normalization. The main spectral lobe structure's center at 17.5 GHz (which corresponds to a radio central frequency of 92.5 GHz at an LO frequency of 75 GHz) is clearly shown, along with some parasitic peaks. These may have been caused by the leakage of clock and LO signals to the ADC and to the receiver components, as no corresponding peaks can be seen in the optical spectrum (Fig. 4). For comparison, the spectrum obtained without the PA is shown in Fig. 5(b); from this figure, it can be seen that the parasitic peak behavior appears similar for both spectra. It can also be seen that the frequency response of the PA shows a slight relative power degradation at each IF frequency. It is further apparent that the power fluctuation of the PA spectrum shows an additional periodic modulation with a power of approximately 5 dB in the main lobe structure. This was possibly caused by interference between the UTC-PD and the PA, as these represented the only difference in the setup between the cases. It should be noted that the vertical axis in the figure were normalized by the parasitic peaks around the center frequency to show the relative power spectra for comparison of the effect with the PA. The PA with a noise figure (NF) larger than 8 dB and a gain flatness ±5 dB around the full W-band could degrade a signal-to-noise ratio (SNR) rather than the signal without the PA, however, the transmitter power about 10 dBm can extend the transmission distance. This issue would be mitigated by the development and improvement of the low-NF PA.

Figure 6 shows the observed constellation map of the received radio signal at a transmitter power of approximately 9 dBm. An estimated error vector magnitude (EVM) is about 23%, which corresponds to −12.8 dB. The clear separation and lack of IQ imbalance seem to indicate an error-free transmission. Degradation of the SNR could broaden the symbol mappings in the constellation map. The degradation could be caused by the W-band PA with the large NF and a poor frequency response described above. In addition, nonlinear response of the optical modulator might cause the degradation of an error vector magnitude. This issue can be solved by optimization of the operation condition because a full-swing voltage operation in transmission function of the modulator suppresses optical output signal fluctuation.

The observed bit error rates (BERs) associated with transmissions of 5 and 10 m between the RAU and the Rx are shown in Fig. 7. An observed BER will depend on the transmitter power as measured at the output port of the UTC-PD. Theoretically, the estimated EVM for the

BER of 1×10^{-4} is about -11.5 dB, which corresponds to the SNR of 14 dB under the white Gaussian noise assumption. [16]. The observed penalty between this value and the obtained EVM of -12.7 is about 1.3 dB. The degradation could be caused by the PA described above. Over both transmission distances, the obtained BERs were within a forward error correction (FEC) limit of 2×10^{-3}. Instead of not employing the FEC on the transmission payload in these experiments, we try to estimate the net data rate if a practical FEC code would be deployed [17]. In this scenario, we assumed combined Reed-Solomon (RS) and Boss-Chaudhuri-Hocquenghem (BCH) super FEC codes standardized in ITU-T G.975.1 sub-clause I.4 [18]. An RS(1023,1007)/BCH(2047,1952) requiring an overhead about 7% corrects a 2.23×10^{-3} BER before the FEC to a 1×10^{-13} BER after the FEC with a coding gain of 8.3 dB. Thus, an 18.6 Gb/s radio transmission with a 7% FEC overhead was successfully performed.

There was a measured power penalty between the two distances of approximately 6 dB, caused by the free-space propagation loss. Using the Friis transmission equation $P_r/P_t = G_r G_t(\lambda/4\pi R)^2$ (where P_r, P_t, G_r, G_t, and R indicate the power delivered to a transmitter antenna, the power available at the receiver, the transmitter and receiver antenna gains, and the transmission distance, respectively), an estimated difference of propagation losses of 6 dB is obtained at an antenna gain of 24 dBi, which agrees well with the observed penalty. This agreement confirms that transmission occurred under far-field conditions. Although attenuation caused by atmospheric oxygen is important, it has a value of approximately 1 dB/km; thus, in this experiment, the total atmospheric attenuation should have been less than 0.1 dB.

3.3 Discussion

The reduction in energy consumption of the proposed RAU based on its utilization of RoF Tx is of interest, since RAUs with low energy consumption should be in high demand in the future. However, there are currently no commercially available media converters for optical and radio conversions within the W-band. Therefore, the energy consumption of the 60-GHz band radio media converters must be approximated. Some reports have indicated that the energy consumption of a radio transmitter and receiver together would be less than or around 300 mW at a total output power of approximately 1 mW [19], [20]. On the basis of this result, the total converter energy consumption can be estimated to be a several Watts as shown in Fig. 1(a). On the other hand, the energy consumption of a UTC-PD used for O/R conversion is approximately 10 mW at an output radio power of about 1 mW [21]. As the DSP unit used at the Rx in the proposed system is the same as that used in a conventional optical link, the total energy consumption will be decreased by using an RoF Tx with a digital coherent Rx.

The interchangeability of the DSP unit with respect to optical and radio signal reception is another important issue. In a typical optical coherent receiver, the DSP unit carries out the functions of carrier frequency offset (CFO) compensation, transmission dispersion compensation, and symbol deciding using a phase noise suppression feature. From the viewpoint of the radio Rx DSP unit, dispersion compensation and symbol decision blocks should be implemented, given that radio signals transmitted over the optical fiber experience a degree of degradation from fiber dispersion. Using direct photonic upconversion of frequency-stabilized RoF signals, however, a radio carrier frequency can be stabilized, allowing for the exclusion of CFO at the optical coherent receiver's DSP unit [14]. Thus, the CFO can be excluded from the DSP of the optical coherent receiver. In this manner, additional reduction in DSP energy consumption might be attained.

Receiver sensitivity is a key concern in evaluating the potential to extend the transmission distance. Using the transmission equation, the estimated receiver power is approximately -37 dBm with a BER of 10^{-3} which corresponds to a transmitter power of 6.93 dBm at a transmission distance of 10 m. Therefore, high power amplification at the RAU and use of a high-gain antenna are strongly indicated in order to significantly extend the transmission distance. A Cassegrain-type antenna with a gain greater than 50 dBi is commercially available [22]. In addition, a high-power, W-band amplifier with an output power of 5 W has been reportedly developed [23], [24]. Finally, the use of MMIC devices such as an integrated power amplifier has facilitated transmission distances of several kilometers for a 120-GHz on-off-keying radio with a data rate of 10 Gb/s [25]. It therefore seems likely that the antenna and amplifier requirements related to the extension of the transmission distance will be solvable. The amplifier component described above can be used in conjunction with the RAU proposed here. Based on a transmitter power of 10 dBm, an antenna gain of 50 dBi, and the receiver sensitivity observed here, as well as accounting for atmospheric attenuation, an estimated transmission distance of approximately 3.8 km with a BER of 10^{-3} is obtained. It should be noted that this receiver sensitivity at the Rx is estimated in the absence of a W-band low-noise amplifier. Given that a typical low-noise W-band amplifier has a gain of 20 dB, the use of these would increase the sensitivity by 10–20 dB. Furthermore, applying an IQ mixer to the Rx can drastically reduce common-mode noises while increasing the sensitivity. Thus, enhancement of receiver functionality will also extend the transmission distance.

4. Conclusion

In this paper, we proposed a coherent optical and radio seamless network concept based on an RoF transmission system and digital coherent detection technologies. The proposed RoF Tx enables the generation of dual-purpose signals with stabilized central frequencies for conventional optical and radio transmission. The use of a DSP unit at the Rx, instead of at the RAUs, would help to compensate for transmission impairments, thus reducing the total energy consumption of the system. To demonstrate the concept, 18.6 Gb/s W-band radio transmission following 20-km optical fiber transmission was successfully performed using a receiver sensitivity of −37 dBm. Extension of the transmission distance by several kilometers can be achieved by using a high-gain antenna such as a Cassegrain-type antenna and a high-power amplifier at the RAU in conjunction with a low-noise amplifier at the Rx. Such a transmission extension would be sufficient to implement the "last mile" of a broadband access network using radio transmission and would additionally serve as a protection link for critical disaster recovery.

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