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Bidirectional Radio-Over-Fiber Link Employing Optical Frequency Multiplication

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Abstract—We propose a bidirectional radio-over-fiber link consisting of an optical downlink transmission employing the optical frequency multiplication principle, a remote local oscillator (LO) generation, a remote down-conversion of the radio-frequency uplink signals, and an optical uplink transmission employing intensity modulation-direct detection. Experiments demonstrate the optical up-conversion of 64-level quadrature amplitude modulated radio signals to 17.8 GHz after transmission over 4.4 km of multimode fiber, 12.5 and 25 km of single-mode fiber in the downlink; the uplink performance is evaluated in terms of down-conversion loss employing the optically generated LO.

Index Terms—Broad-band wireless access, optical fiber communications, radio-over-fiber (RoF) systems.

I. INTRODUCTION

RADIO-OVER-FIBER (RoF) distribution antenna systems have been long recognized as a flexible, bandwidth-efficient, and cost-effective option for fiber-based wireless access infrastructure, especially in in-building and corporate environments [1]. They enable the consolidation of the radio access control and signal processing at a centralized control station (CS) and the delivery of the radio signals transparently to simplified antenna sites (AS) via optical fiber. When deployed in current cellular access networks, direct modulation of a laser diode with the radio-frequency (RF) signal is the most common method to reduce cost and complexity, rather than external modulation [2]. Also for the popular wireless local area network systems, experiments with transmission over multimode fiber (MMF) have been carried out [3].

In emerging broad-band wireless systems operating at carrier frequencies beyond 5 GHz, the main challenge of RoF techniques is the generation and delivery of high-quality microwave signals to the AS, while maintaining the link simplicity. Some methods propose the delivery of a microwave local oscillator (LO) together with the radio signals [intermediate frequency (IF)] in order to perform up-conversion at the AS, either electronically [4] or optically [5]. These schemes rely on the transmission of the microwave LO over single-mode fiber (SMF) links, and have to cope with the carrier suppression effect induced by the fiber chromatic dispersion [6], [7].
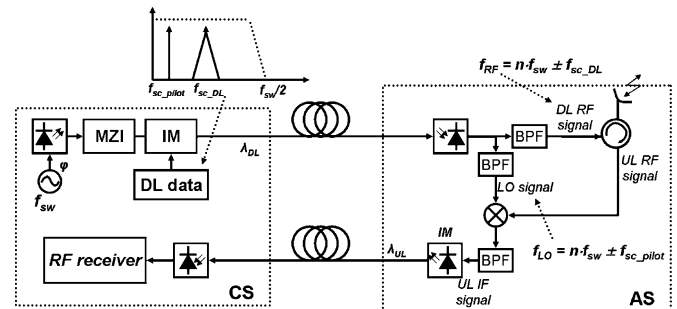
Fig. 1. Bidirectional RoF link employing OFM.

The optical frequency multiplication (OFM) principle proposed in [8] is a cost-effective method to optically generate microwave frequencies and deliver wireless signals to a remote AS. The OFM technique is based on harmonic generation and frequency-modulation–intensity-modulation conversion. With this dispersion tolerant method, high-frequency microwave carriers can be generated at the AS by remotely distributing radio signals at relatively low frequencies from the CS [9], [10].

II. BIDIRECTIONAL RoF LINK DESIGN

The proposed bidirectional RoF link is depicted in Fig. 1. It consists of an optical downlink transmission employing the OFM principle, a remote LO generation, a remote down-conversion of the RF uplink signals, and an optical uplink transmission employing intensity modulation (at the AS)-direct detection of the light source (at the CS).

At the CS, the downlink light source λ_{DL} is frequency modulated by a sinusoid signal with sweep frequency f_{sw}, and passed through a Mach–Zehnder interferometer (MZI). The downlink data that modulates the intensity of this frequency-swept optical signal is composed of a subcarrier $f_{\mathrm{sc-DL}}$, which conveys the wireless signal to be radiated, and a single subcarrier $f_{\mathrm{sc-pilot}}$, which is employed for the remote LO generation. The subcarriers $f_{\mathrm{sc-DL}}$ and $f_{\mathrm{sc-pilot}}$ must be lower than $f_{\mathrm{sw}}/2$, in order not to exceed the maximum RF bandwidth capacity allowed by the OFM technique [11]. The resulting optical signal is then launched into the optical fiber link and recovered at the AS by a photodetector.

At the output of the photodetector, radio frequency components at every harmonic of the sweep frequency f_{sw} are obtained, with relative amplitudes depending on f_{sw}, the frequency modulation index, and the free-spectral range (FSR) of the MZI. Along with the harmonics, the subcarriers $f_{\mathrm{sc-DL}}$ and $f_{\mathrm{sc-pilot}}$ introduced at the CS are up-converted
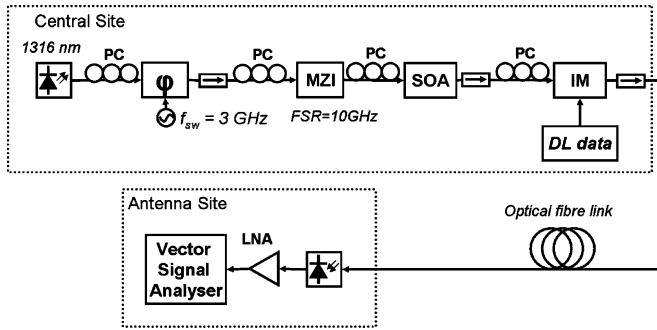
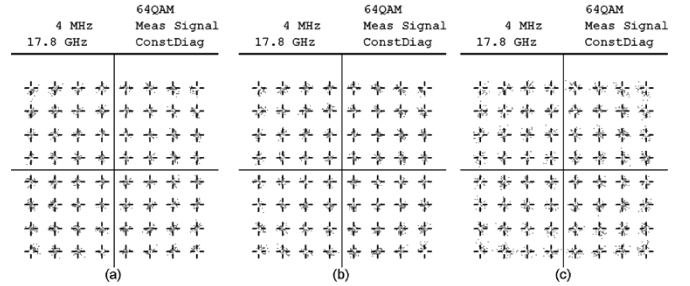Fig. 2.   Experimental setup for the downlink RoF link employing OFM.

Fig. 3.   IQ-constellation diagrams of the 64-QAM 4-Msymb/s signal recovered at 17.8 GHz after transmission over (a) 4.4 km of MMF, (b) 12.5 km of SMF, and (c) 25 km of SMF.

to $f_{RF} = n \cdot f_{sw} \pm f_{sc-DL}$ and $f_{LO} = n \cdot f_{sw} \pm f_{sc-pilot}$, respectively ($n$ indicates the nth harmonic). For the downlink RF transmission, the desired f_{RF} signal can be selected with adequate bandpass filtering and conveyed to the antenna. Similarly, the desired f_{LO} is selected with another bandpass filter and employed as a LO at the AS. The selected f_{LO} is then mixed with the RF signal coming from the uplink RF transmission. The resulting uplink IF signal (at f_{sc-UL}) is employed to directly modulate the intensity of the uplink light source λ_{UL}, and sent back to the CS through the optical fiber link, where it is recovered by direct detection. The uplink RF signal can then be further processed by the RF receiver located at the CS, working at low frequency.

The main advantage of this scheme is its inherent simplicity. For example, let us assume that the downlink light source λ_{DL} is swept by $f_{sw} = 3$ GHz, and its intensity is modulated by a wireless signal put onto a low frequency, e.g., $f_{sc-DL} = 200$ MHz, and a single subcarrier $f_{sc-pilot} = 300$ MHz, at the CS. Then, selecting, e.g., the lower sideband of the sixth harmonic at the AS, we obtain the wireless signal at $f_{RF} = 17.8$ GHz and the LO at $f_{LO} = 17.7$ GHz directly at the photodetector output. The LO is then mixed with the uplink RF signal, yielding an uplink IF signal at $f_{sc-UL} = 100$ MHz, which is sent to the CS by direct intensity modulation-direct detection (IM-DD). The introduction of an $f_{sc-pilot}$ allows more flexibility to select the desired LO at the AS. However, the generated f_{sw} harmonics can also be used as a LO, simplifying even further the implementation. Selecting the sixth harmonic yields a $f_{LO} = 18$ GHz and a $f_{sc-UL} = 200$ MHz.

As this example illustrates, the OFM RoF downlink provides directly the microwave signals for RF transmission by introducing low-frequency subcarriers at the CS, and without the need of up-conversion at the AS. Additionally, the remotely optically generated LO down-converts the uplink RF signal to an IF low enough to allow a simple IM-DD RoF uplink. In this way, bandwidth limitations in MMF transmission or chromatic dispersion in SMF transmission are much less significant than in direct high-RF signal RoF transmission.

III. Experimental Results

A. Downlink

Fig. 2 shows the experimental setup for the downlink RoF link employing OFM. A laser source frequency ($\lambda_{DL} = 1316$ nm) was swept by an optical phase modulator with a sweeping

frequency $f_{sw} = 3$ GHz (causing a frequency deviation of 18 GHz from the central wavelength), launched into an MZI with 10-GHz FSR, and boosted by a semiconductor optical amplifier (SOA). A chirp-free Mach–Zehnder intensity modulator (IM) was employed to introduce the downlink data into the link; a 64-level quadrature amplitude modulated (64-QAM) 4-MSymb/s signal at $f_{sc-DL} = 200$ MHz was used for the downlink transmission. The output of the IM was launched into an optical fiber link, and recovered by a 25-GHz IR photodetector to generate the RF harmonics of the f_{sw}. The output of the photodetector was amplified by a low noise amplifier and analyzed by a vector signal analyzer (Rhode & Schwarz FSQ-40).

At the output of the photodetector, the 64-QAM signal was obtained along with all the generated harmonics of f_{sw} at the high frequencies $f_{RF} = n \cdot f_{sw} \pm f_{sc-DL}$. On the lower sideband of the sixth harmonic, the 64-QAM signal carried by $f_{sc-DL} = 200$ MHz was recovered at $f_{RF} = 17.8$ GHz. Fig. 3 shows the IQ-constellation diagrams of the recovered 64-QAM signal at 17.8 GHz after transmission over 4.4 km of 50-μm-core MMF, 12.5 and 25 km of standard SMF. The error vector magnitude (EVM) values obtained for the 64-QAM signal at 17.8 GHz were 4.521% (signal-to-noise ratio (SNR) = 26.9 dB), 4.648% (SNR = 26.65 dB) and 5.881% (SNR = 24.61 dB), after transmission over 4.4-km MMF, 12.5-km SMF and 25-km SMF, respectively. The difference of 2 dB observed in the electrical SNR after transmission over 12.5-km SMF and 25-km SMF occurs due to the 4 dB of optical losses in the additional 12.5 km of fiber. These EVM values lie within the maximum transmitter constellation error allowed by IEEE 802.11a for 64-QAM signals at the 5-GHz band (5.62% and 7.94% for code rates 3/4 and 2/3, respectively).

B. Remote LO Generation and Uplink

A proof-of-concept experiment was set up in order to test the feasibility of an RoF uplink employing the high frequencies generated by an OFM downlink as remotely delivered LO (Fig. 4).

Similar to Fig. 2, a laser source frequency ($\lambda_{DL} = 1316$ nm) was swept by an optical phase modulator with a sweeping frequency $f_{sw} = 3$ GHz, launched into an MZI with 10-GHz FSR, and boosted by an SOA. For simplicity, instead of introducing an $f_{sc-pilot}$ for the remote generation of the LO, the generated second harmonic of f_{sw} was selected as a LO after the photodetector, yielding $f_{LO} = n \cdot f_{sw} = 6$ GHz, with a power
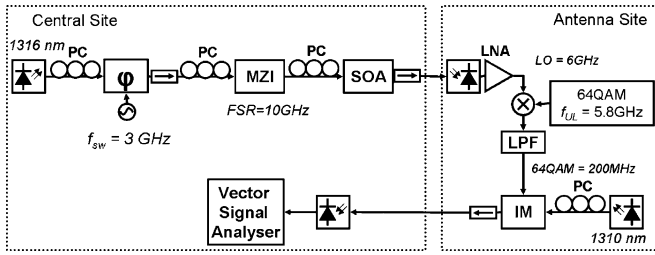
Fig. 4. Experimental setup for the remote LO generation employing OFM, remote uplink RF signal down-conversion, and uplink RoF link (proof-of-concept, back-to-back).
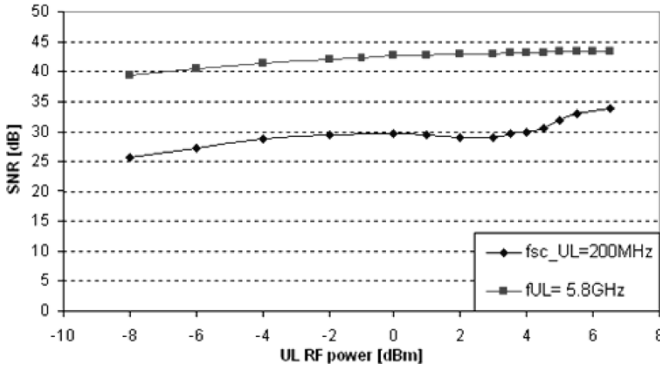

Fig. 5. Down-conversion of the 64-QAM uplink RF signal at $f_{UL} = 5.8$ GHz to the IF signal at $f_{sc-UL} = 200$ MHz.
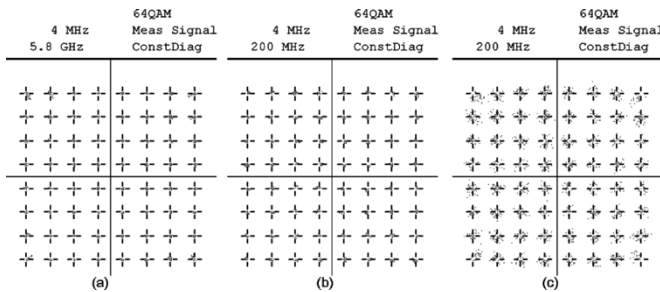

Fig. 6. IQ-constellation diagrams of the 64-QAM 4-Msymb/s signal at (a) 5.8-GHz uplink RF carrier, (b) 200 MHz down-converted at the AS, and (c) 200 MHz recovered at the CS.

level of -5 dBm. A 64-QAM 4-MSymb/s uplink RF signal at $f_{UL} = 5.8$ GHz was mixed with the selected f_{LO}. The unwanted harmonics generated by the OFM downlink were removed by the mixer bandwidth of operation. Fig. 5 shows the down-conversion of the uplink RF signal at $f_{UL} = 5.8$ GHz to the IF $f_{sc-UL} = 200$ MHz. The conversion loss observed for the 64-QAM signal was 9.5 and 13.6 dB for 6.5 and -8 dBm of uplink RF power, respectively.

After the down-conversion at the AS, the 64-QAM signal at $f_{sc-UL} = 200$ MHz was used to modulate the intensity of a second laser source ($\lambda_{UL} = 1310$ nm), and it was recovered after direct photodetection. The EVM value of the 64-QAM uplink RF signal at $f_{UL} = 5.8$ GHz was 0.68% (SNR $= 43.35$ dB). The down-converted signal to $f_{sc-UL} = 200$ MHz experienced an EVM value of 2.027% (SNR $= 33.86$ dB). The EVM value of the recovered signal after photodetection was 5.8% (SNR $= 24.63$ dB). Thus, an SNR penalty of 9.2 dB was observed in the low IF RoF uplink.

Fig. 6 shows the IQ-constellation diagrams of the 64-QAM uplink RF signal at 5.8 GHz, the down-converted signal at 200 MHz, and the recovered signal after photodetection.

IV. CONCLUSION

We have proposed a cost-effective bidirectional RoF link employing the OFM principle. It consists of an optical downlink transmission employing the OFM principle, a remote LO generation, a remote down-conversion of the RF uplink signals, and an optical uplink transmission employing direct IM-DD.

In downlink, a 64-QAM signal at 200 MHz at the CS was recovered at 17.8 GHz at the AS, after MMF and SMF transmission. In uplink, the high-frequency carrier (-5 dBm, 6 GHz) generated by OFM was employed as an LO to down-convert the uplink 64-QAM RF signal (5.8 GHz) to a low IF (200 MHz), which was transmitted back transparently to the CS.

The proposed scheme has prospects for future broad-band access employing RoF distribution antenna systems, since it enables the optical generation of high-frequency RF signals at the AS by remotely generating low IF signals at the CS, over both SMF and MMF transmission links. In addition, the remotely generated LO down-converts the uplink RF signal to an IF low enough to allow a simple IM-DD RoF uplink.

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