A Scalable 26 GHz RoF Relay System using Optoelectronic Extender

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***Abstract*— This paper presents data transmission over a 26 GHz millimeter-wave (mmW) radio signal and its coverage extension in an indoor environment using the radio-over-fiber (RoF) technology. The proposed system consists of two RoF seamless wireless links to emulate a mobile fronthaul using a transparent RoF relay link to overcome higher attenuation of the mmW signal. The system is experimentally evaluated for up to 64-quadrature amplitude modulation (QAM), showing the possibility of signal transmission over up to 20 km of optical fiber in the first section transmission scheme without the usage of an optical amplifier. For the system with 20 km and 30 m long RoF links as well as 4 m and 1 m long relays with no optical amplification, the minimal experimentally measured error vector magnitude is as low as 5 % for 64-QAM. Further, a self-developed integrable optoelectronic extender is used for the relay RoF system to simplify the antenna site and keep its footprint small. Moreover, the proposed setup is extended using an optical amplifier toward a scalable scheme with up to 75 km of optical fiber and 5 m long free space optical link.**

***Index Terms*— Microwave photonics, optical fiber, FSO, millimeter wave.**

I. Introduction

THE usage of microwave photonics has become a powerful tool for meeting the ever-increasing demands on flexibility, reliability, and transmission capacity of especially wireless networks [1]. In such scenarios, radio-over-fiber (RoF) systems, which combine an optical fiber infrastructure and radio frequency (RF) technologies, can provide a scalable solution towards millimeter-wave (mmW) signals transmission, which is vital for enhancing mobile broadband in the case of 5th generation (5G) networks. One of the key aspects of the RoF technology is its capability to realize a seamless analog RF signal transmission without the need for signal processing following optical-to-electrical (OE) conversion and prior to transmission via an antenna. This feature enables a high number of electrical-to-optical (EO) and OE conversions, which can be used to provide additional wireless connectivity. Moreover, the RoF technology can be supplemented with a free space optics (FSO) link where the use of fiber cables is not possible or expensive [2]. In this case, a radio over FSO (RoFSO) system can be realized to provide a flexible mobile fronthaul transmission from a central office (CO) to base stations (BSs). On the other hand, RoF systems can also be utilized for transparently relaying radio signals from outdoor to indoors to avoid penetration losses, especially for radio signals in the high frequency bands. The concept of a cascade of a RoF/RoFSO mobile fronthaul, mmW radio access network (RAN), and indoor RoF relay system for the mmW indoor coverage in a mobile network is illustrated in Fig. 1. The relay RoF system in the mmW or the THz frequency band can overcome natural or artificial obstacles by employing a high directional antenna session without data demodulation. The relay system is especially relevant for the indoor coverage due to high penetration losses of mmW signals. For example, a typical wall can introduce an attenuation of ~ 0.05, 0.8, and 16 dB at 2.4, 3.5, and 26 GHz, respectively [3]. In [4], a fiber-wireless-fiber signal relay at 81.4 GHz was realized between two single mode fibers (SMFs). It was shown that, the transmission distance can be increased to over 15 m when using an active wireless transmitter with an amplifier. In [5], a low-latency fiber wireless bridge for a fronthaul network was proposed, where a 3 m long RF wireless link at 92.5 GHz was

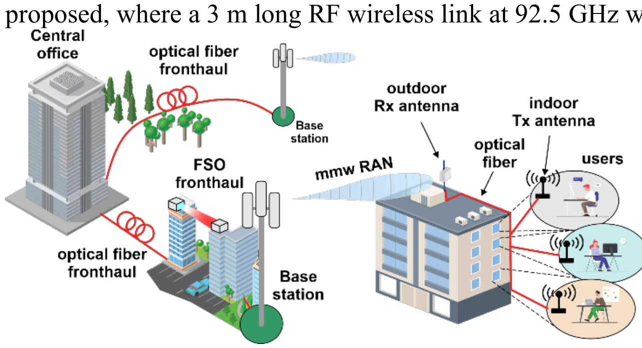

Fig. 1. The proposed end-to-end mmW signal transmission for indoor networks using RoF and RoFSO systems.

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placed between two 10 km long SMFs for transmission of up to 64-quadrature amplitude modulation (QAM) fulfilling the required performance requirements by using of a high-linear detector. A 1.25 Gb/s multichannel digital radio distribution system with 64-QAM long term evolution (LTE) services over an aggregated 50 km of SMF and a 1 m long wireless mmW bridge at 42.4 GHz was investigated with RF dynamic ranges of 35 dB [6]. However, to date, an end-to-end mmW radio signal transmission over a cascaded system consisting of a mobile fronthaul, outdoor radio access and indoor network using transparent RoF systems has not been reported yet. In this paper, to the best of authors' knowledge, we demonstrate for the first time an end-to-end transmission of a 26 GHz signal from a CO to an indoor end user using RoF/RoFSO systems. For the use of RoF mobile fronthaul, a simple optical double sideband signal transmission was transmitted over a 20-km SMF without using an optical amplification. For the case of RoFSO mobile fronthaul, an optical single sideband (SSB) signal was transmitted and an EDFA was utilized to extend the fiber reach for the fronthaul network.

II. Experimental Setup

A. Fiber mobile fronthaul

The experimental setup for the proposed scheme is depicted in Fig. 2. The 26 GHz mmW signal was generated using a vector signal generator (VSG, R&S SMW200A), which produced the baseband (BB) by in-phase and quadrature (IQ) components. The used IQ signals are predefined LTE test models TM 3.1, 3.2, and 3.3 [7] using 4-, 16-, and 64-QAM modulation schemes with 20 MHz bandwidth. The BB data are up-converted with a 26 GHz sinusoidal signal from a signal generator (SG, R&S SMF100A) using an IQ mixer. The up-converted mmW signal is amplified using a power amplifier 1 (PA-1) prior to being applied to a first Mach-Zehnder modulator (MZM-1, Fujitsu FTM7938EZ/201), which results in a double sideband (DSB) transmission scheme. A continuous wave optical signal from a laser source (Laser-1, CoBrite DX4) with an output power of 16 dBm at a wavelength of 1550 nm is applied to MZM-1, which is biased in its linear point.

Next, the output of MZM-1 is launched into the 20 km long SMF-1 section. The optical signal is directly converted back to the mmW domain by a high-speed photodetector (PD-1, Optilab PD40) prior to amplification using a cascade of amplifiers (PA-2 and PA-3). The amplified mmW signal is transmitted over a wireless channel using a 4 m long RF wireless link at 26 GHz, i.e., RF-1 while employing a pair of double ridged horn antennas (ANT, RFspin DRH40).

At the receiving side, the mmW signal is further amplified (PA-4) to compensate for the transmission loss of 44.8 dB prior to being applied to MZM-2 (Fujitsu, FTM7937EZ/202) for modulation of an optical carrier from a laser source (Laser-2, Optilab DFB-1550H-PM-40). Following transmission over a 30 m SMF-2 section represents a part of the fronthaul access network for indoor coverage. A variable optical attenuator (VOA) is used to control the received optical power level at PD-2 (Optilab, PD-40). After OE conversion, the regenerated

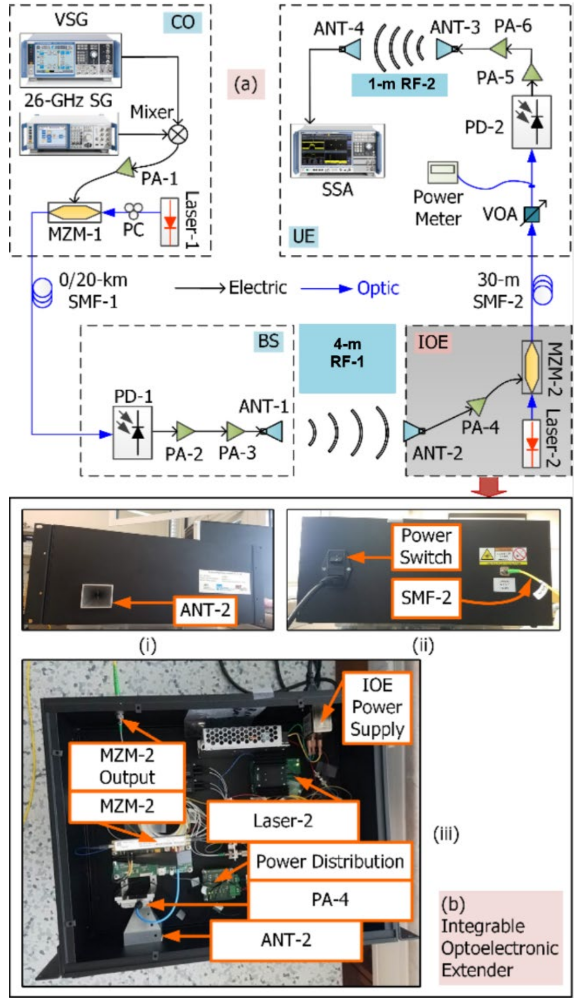

Fig. 2. (a) Experimental setup for mmW signal transmission over a cascaded RoF mobile fronthaul, mmW RAN, and RoF relay system; (b) compact prototype of the mmW IOE.

mmW signal is amplified using a cascade of two amplifiers (PA-5 and PA-6) for transmission over a 1 m long wireless channel, i.e., RF-2 using the same type of antennas as in RF-1. A signal and spectral analyzer (SSA, R&S FSW) is used to evaluate the received mmW signal. It is worth mentioning that, in the second RoF link, we have used a self-developed integrable optoelectronic extender (IOE) that combines all necessary components, as shown in Fig. 2(b).

B. Combined fiber & FSO mobile fronthaul

The extension of the proposed setup was realized with the main emphasis on the first optical section because a considerably longer SMF-1 link can be expected compared to SMF-2, which only serves for indoor coverage. To increase the distance of the SMF-1 link, we generated and transmitted an optical SSB signal. Further, we inserted an FSO link to the SMF-1 to emulate the usage of the RoFSO system for mobile fronthaul transmission from the CO to the BS. We updated the first optical section of the scheme from Fig. 2, as shown in Fig. 3(a). The output signal from CO is launched to the optical channel by the dense wavelength division multiplexing (DWDM) multiplexer with a 0.8 nm grid (100 GHz). Simultaneously, the

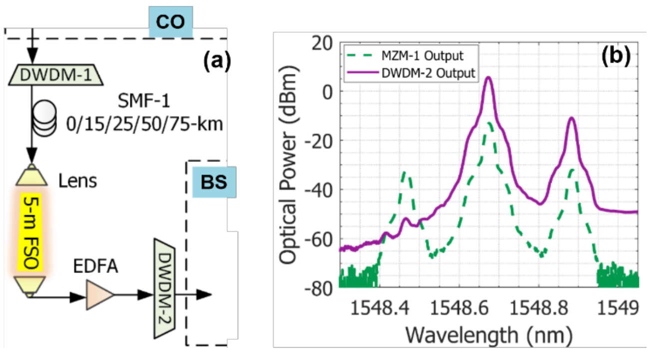

Fig. 3. (a) The experimental setup using the RoFSO system in the mobile fronthaul; (b) optical spectra before and after the DWDM-1.

wavelength of the Laser-1 is tuned to the wavelength of 1548.67 nm, while the center wavelength in the corresponding channel is 1548.51 nm. Thus, the intensity modulated optical carrier, operating in the DSB regime with side bands ±26 GHz, is turned into the SSB transmission due to the filtering of one sideband out by the DWDM; see corresponding optical spectra in Fig. 3(b).

The SSB transmission scheme is immune to CD-induced fading [1], and thus almost any length of the SMF can be used. It should be noted that SMF-2 link, operating in DSB regime at ±26 GHz, perfectly withstands the CD fading for the considered indoor range, which is expected within 100 m. Furthermore, a 5 m long FSO channel, realized by a pair of doublet collimators (Thorlabs, F810APC-1550), is implemented to provide better flexibility. An EDFA (Keopsys CEFA-C-HG-SM-50-B130-FA-FA) is employed to compensate for additional losses of longer fiber section and 6 dB insertion loss (IL) of the FSO channel. After the EDFA, the signal is demultiplexed in DWDM-2 demultiplexer. It is worth mentioning that a number of DWDM channels can be exploited, which significantly extends the capacity of the first stage of the setup.

III. Experimental Results and Discussion

A. Results from fiber mobile fronthaul

First, we characterized the optical back-to-back (OB2B) system, corresponding to the system shown in Fig. 2(a) without the 20 km SMF in section 1, for 4-,16-, and 64-QAM in terms of EVM as a function of IQ voltage from the VSG and RF oscillator power from the SG as depicted in Figs. 4(a) and (b), respectively. For optimum performance, we changed the VSG IQ voltage for all three signals from 100 mV to 1.7 V and carried out the same optimization for the SG mmW signal serving as a local oscillator. Based on this, we have adopted for the OB2B link 900 mV, corresponding to the power of 12.1 dBm, and 8 dBm for VSG and SG, respectively, while the lowest achieved EVM values are 7, 5, and 4 for 4-, 16- and 64-QAM, respectively. The captured RF spectrum in Fig. 4(c) with an SNR of 29 dB for the OB2B link. The performance degradation when the voltages are below the optimum value is caused by the insufficient SNR, whereas the performance in the voltage region beyond the optimum values was degraded by the

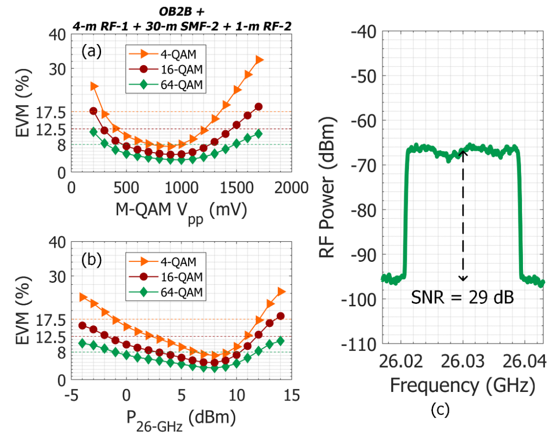

Fig. 4. OB2B SMF1 optimization: (a) EVM vs. BB voltage from VSG, (b) EVM vs. RF oscillator power from SG, and (c) the measured electrical spectrum.

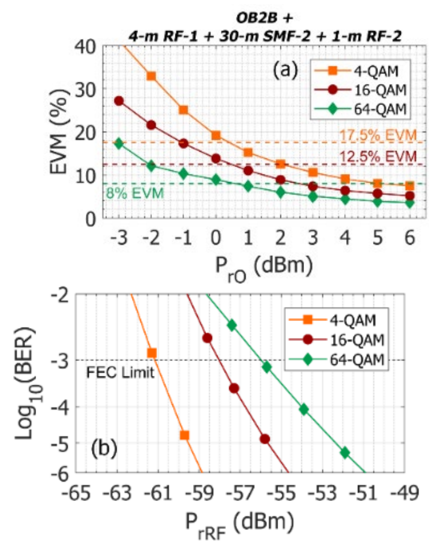

Fig. 5. The OB2B performance for 4-, 16-, and 64-QAM: (a) EVM vs. P_{rO}, and (b) Log_{10}(BER) vs. P_{rRF}.

distortion, mainly at the PA1 and MZM1. Thus, the optimum values should be transmitted to maximize the performance to avoid distortions regardless of the fiber lengths of SMF1. Following optimization, we measured the EVM as a function of received optical power P_{rO}, which is related to the RF transmit power and needed to estimate the link margin and link distance, for OB2B with 4 m RF-1, 30 m SMF-2, and 1 m RF-2 as illustrated in Fig. 5(a). As can be seen, the EVM values drop with the increasing P_{rO} and almost converge at $P_{rO} > 5$ dBm. The lowest EVM values of 5, 8, and 11.5 % are observed for 64-, 16, and 4-QAM, respectively at P_{rO} of 6 dBm, which are well below EVM limits. The EVM limits are fulfilled for up to 0.5 dBm of P_{rO} for all modulations, which means the system IL margin for OB2B is independent of the modulation type. Fig. 5(b) depicts the bit error rate (BER), which is determined from each EVM value, against the received electrical RF power P_{rRF}. The conversion between EVM and BER can be found e.g., in [8]. At the forward error correction (FEC) BER limit, i.e., $\log_{10}$(BER) of 10^{-3}, the power penalties are 1.5 and 2.6 dB for 16- and 64- QAM compared with 4-QAM.

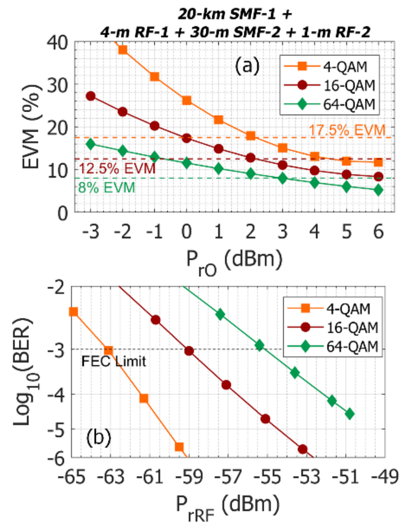

Fig. 6. The full system performance for 4-, 16-, and 64-QAM: (a) EVM vs. P_{rO}, and (b) Log_{10}(BER) vs. P_{rRF}.

Next, we evaluated the EVM and the BER performance of the full system including 20 km SMF-1 for the primary access network, 30 m SMF-2 as well as 4 and 1 m long mmW relay nodes. Similar to the OB2B link, we first evaluated the optimal voltage and the transmit power from VSG and SG. In the IQ and RF signals, the optimal voltage and power values were 1 V, corresponding to 13, and 12 dBm, respectively, whereas the receiving SNR was 25 dB, which is 4 dB lower than OB2B. The 20 km of SMF increased the transmitted powers owing to the chromatic dispersion effect. The overall system performance is shown in Fig.6 depicting the EVM and the BER performance as a function of P_{rO} and P_{rRF}, respectively for 4-, 16-, and 64-QAM. The EVM plots show the same trend as in Fig. 5(a) with minimum values observed at P_{rO} > 5 dBm, so to keep the EVM values below a particular EVM limit, P_{rO} is at least 1.5 and 2.5 dB higher for 4- and 16-QAM, and 64-QAM, respectively, compared with the OB2B. The minimum P_{rRF} to meet the FEC BER limit are -63, -59, and -55 dBm for 4-, 16-, and 64-QAM, respectively.

B. Results from combined fiber & FSO mobile fronthaul

Further, an extended experimental setup was employed towards a scalable versatile solution, as shown in the scheme in Fig. 3. According to the DSB results, Fig. 7(a) depicts the dependence of the EVM for 64-QAM signal with a 20 MHz bandwidth at 26 GHz on P_{rO} for various SMF lengths and EDFA. It can be seen that up to 75 km is applicable while a wide range, i.e., for P_{rO} between 2 and 6 dBm, maintains the EVM below 8 %. In addition, there is only approx. 1 dB penalty between using 15 and 75 km of SMF in the first stage.

Finally, the 5 m long FSO channel in the first optical stage was deployed to make this part of the fronthaul network more flexible. To demonstrate the maximal system performance, a full configuration including 75 km of SMF and 5 m of FSO with the following EDFA in the first optical section was deployed. The RoF relay system was tested with 64-QAM; see results in Fig. 7(b). The EVM dependence on the P_{rO} has been evaluated showing great system performance for P_{rO} equal or higher than 4 dBm. In other words, there is an additional 3 dB IL margin in the final optical section. Thus, the scalability of the proposed mmW system is clearly demonstrated while expanding the use of the RoF relay system by the FSO link.

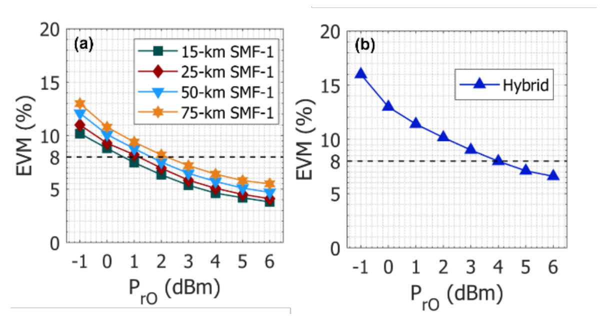

Fig. 7. The SSB system performance showing EVM for 64-QAM vs. received optical power for: (a) various SMF-1 length, and (b) for the system including 75 km of SMF-1 and FSO.

V. Conclusion

We presented experimental results of an analog relay system for indoor wireless coverage using double RoF seamless mmW links. It allows to significantly reduce the penetration loss of high-frequency mmW signals while the flexibility of the transmission system is improved. We developed experimental testbeds to evaluate the performance of a 26 GHz relay RoF system and an extension using SSB modulation has been presented. The proposed DSB relay system can operate with up to 20 km of SMFs deployed in the fronthaul without the need for optical amplification. Moreover, when the SSB scheme involves EDFA, the SMF-1 range can be extended up to 75 km with a subsequent 5 m long FSO link while EVM is kept below the 8% for 64-QAM. Finally, we showed the use of an optoelectronic extender that can be fully integrated with a low footprint making the relay solution more compact and suitable for practical deployment.

References

[1] C. Lim, Y. Tian, C. Ranaweera, T. A. Nirmalathas, E. Wong, and K. -L. Lee, "Evolution of Radio-Over-Fiber Technology," *J. Light. Technol.*, vol. 37, no. 6, pp. 1647-1656, March 2019.

[2] J. Bohata, M. Komanec, J. Spáčil, Z. Ghassemlooy, S. Zvánovec, and R. Slavík,"24–26 GHz radio-over-fiber and free-space optics for fifth-generation systems," *Opt. Lett.* 43, 1035-1038, 2018.

[3] K. Zheng, D. Wang, Y. Han, X. Zhao, and D. Wang, "Performance and Measurement Analysis of a Commercial 5G Millimeter-Wave Network," *IEEE Access*, vol. 8, pp. 163996-164011, Sept. 2020.

[4] X. Pang, A. Lebedev, J. J. Vegas Olmos, and I. T. Monroy, "Multigigabit W-Band (75–110 GHz) Bidirectional Hybrid Fiber-Wireless Systems in Access Networks," *J. Light. Technol.*, vol. 32, no. 23, pp. 4585-4592, Dec. 2014.

[5] P. T. Dat, A. Kanno, and T. Kawanishi, "Low-latency Fiber-Wireless Bridge for Flexible Fronthauling in Future Mobile Networks," European Microwave Conference (EuMC), pp. 305-308, 2015.

[6] T. Li et al., "Multi-service Digital Radio over Fibre System with Millimetre Wave Bridging," International Topical Meeting on Microwave Photonics (MWP), pp. 1-4, 2018.

[7] ETSI Technical specification 3GPP TS 36.141 version 12.6.0 Release 12: "LTE; EUTRA; Base Station conformance testing, Feb. 2015.

[8] X. Chen and J. Yao, "A High Spectral Efficiency Coherent Microwave Photonic Link Employing Both Amplitude and Phase Modulation with Digital Phase Noise Cancellation," *J. Light. Technol.* 33, 3091-3097, April 2015