Simple Multi-RAT RoF System with 2×2 MIMO Wireless Transmission

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Abstract—A simple multi-radio access technology (multi-RAT) capable radio over fiber (RoF) system with 2×2 multiple-input multiple-output (MIMO) wireless transmission is proposed and experimentally demonstrated. The transmission of sub-6 GHz and 60 GHz millimeter-wave (MMW) services is enabled by a dual-drive Mach-Zehnder modulator (DDMZM) and an optical interleaver. In the central office (CO), sub-6 GHz and 30 GHz signals are applied to the dual branches of the DDMZM which is biased at the quadrature point. After transmission over single-mode fiber (SMF), the two services are separated by an optical interleaver. One output port of the interleaver is used for delivering the sub-6 GHz signal while the other one is used for the generation and transmission of the 60 GHz MMW signal. Furthermore, we also demonstrate the MIMO technology can be used in the proposed architecture to improve the capacity. A proof-of-concept experiment is performed to verify the feasibility of the proposed scheme. In the experiment, a 1.3 Gb/s orthogonal frequency division multiplexing (OFDM) signal at 55 GHz is transmitted over 25 km of SMF and 1 m 2×2 MIMO wireless distance while a 675 Mb/s OFDM signal at 0.375 GHz is delivered over 25 km of SMF at the same time.

***Index Terms*—Radio over fiber, Optical communications.**

I. INTRODUCTION

Current wireless communications such as Wi-Fi and LTE mainly rely on sub-6 GHz frequency bands due to their mobility and in-building converge. However, since the wireless data traffic driven by video stream, mobile internet and cloud service on smartphones and tablets has been increasing continuously, the communication industry is moving to its fifth generation (5G) that will use millimeter wave (MMW) frequency bands to offer unprecedented spectrum and broadband services [1]. For example, 60 GHz MMW can provide 7 GHz license-free band, leading to multi-Gbps wireless services. As a result, the next generation communication network will be a heterogeneous network which supports multi-radio access technologies (multi-RATs) for different data rate requirement and coverage [2]. Radio over fiber (RoF) is an attractive technology for such heterogeneous access networks. In the RoF architecture, the multiple wireless signals are generated in the central office (CO) and directly transmitted to remote access units (RAUs) with no differentiation in protocols or interfaces, and thus greatly reduce the cell site complexity and cost [3]. Previously, many heterogeneous RoF systems supporting sub-6 GHz and MMW services have been proposed [4-10]. The transmission of microwave and MMW services is achieved based on a wideband electro-absorption modulator (EAM) in [4]. The drawback of the scheme is that large bandwidth photonic and electronic devices should be used, such as the EAM, the electronic combiner, the local oscillator (LO) and the electronic filter. In [5], M. Zhu proposes a multi-RAT RoF architecture based on subcarrier multiplexing and dual-wavelength heterodyne beating techniques. To generate a stable MMW signal, the polarization of the dual-wavelength lightwave should be aligned. However, the two wavelengths are placed in CO and RAU separately, so the alignment of the polarization is hard to be achieved in practical scenarios [5]. In [6-8], multi-RAT RoF links are proposed based on polarization-division multiplexing (PDM). In these architectures, the sub-6 GHz and MMW signals are polarization multiplexed by employing the birefringence of lithium-niobite modulators in the CO. By adjusting the polarization controller (PC) in the RAU, different modulation schemes can be flexibly implemented, i.e. double sideband (DSB) for sub-6 GHz services and optical carrier suppression (OCS) for MMW services. Nevertheless, since the polarization state in the optical fiber is not stable, the PC in the RAU should be adjusted adaptively, which is also not easy to be implemented. Another RoF architecture which supports multi-RAT is proposed in [9]. The sub-6 GHz and MMW signals are modulated to different modulators in the CO and separated by an optical interleaver. However, different services are modulated to different modulators and multiplexed afterwards, which makes the system complex and expensive. Recently, a field trial of a multi-RAT mobile network is reported [10]. A key technology to achieve multi-RAT is the optical up-conversion in the RAU which can decrease the bandwidth requirement of the transmission system.

In this paper, we propose and experimentally demonstrate a simple multi-RAT RoF system supporting sub-6 GHz and MMW services with MIMO transmission. In the CO, the sub-6 GHz signal and the MMW signal at 30 GHz are applied to the dual branches of a dual-drive Mach-Zehnder modulator (DDMZM), respectively. Then the modulated signal is

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transmitted to the RAU over a spool of single-mode fiber (SMF). In the remote note, an optical interleaver with two output ports is used to separate the optical carrier modulated by the sub-6 GHz signal and the optical sidebands. As a result, an optical DSB signal is generated in one output port of the interleaver while an OCS signal is generated in the other output port. The DSB signal is used to deliver the sub-6 GHz signal while the OCS signal is used to generate the 60 GHz MMW signal which also doubles the frequency applied to the DDMZM. Therefore, low-speed and low-cost photonic and electronic devices can be utilized in the proposed RoF system to generate and transmit the MMW signal compared to the scheme proposed in [4]. Moreover, compared to the scheme proposed in [9], our scheme uses only one modulator to convey the sub-6 GHz and 60 GHz MMW services, resulting in a more compact and cost-efficient CO configuration. The centralization in the CO provides resource sharing and synchronization of clock and carrier frequency, which shows advantages in some scenarios such as coordinated multipoint transmissions in contrast with the scheme proposed in [10] where the MMW generation is distributed in RAUs. The proposed scheme also avoids adaptive polarization control in the RAU compared to the schemes proposed in [5-8]. It is worth noting that the previous multi-RAT RoF systems [4-9] only demonstrate single input single output (SISO) wireless transmission while 2×2 MIMO transmission is demonstrated in [10] based on wavelength division multiplexing (WDM). Since the proposed heterogeneous RoF system is based on the DDMZM and the interleaver rather than PDM [6-8], the PDM can be used in the proposed RoF system to provide 2×2 MIMO transmission.

A proof-of-concept experiment is performed to verify the feasibility. To study the crosstalk between the sub-6 GHz and MMW services, the intermediate-frequencies (IFs) and the bandwidths of the two services are set to be identical, i.e. 0.375 GHz and 203.125 MHz. In the experiment, a 1.3 Gb/s 16-QAM OFDM signal at 55 GHz is transmitted over 25 km of single-mode fiber (SMF) and 1 m 2×2 MIMO wireless channel. At the same time, a 635 Mb/s OFDM signal at 0.375 GHz is delivered over 25 km of SMF as the sub-6 GHz wireless service.

II. OPERATION PRINCIPLE

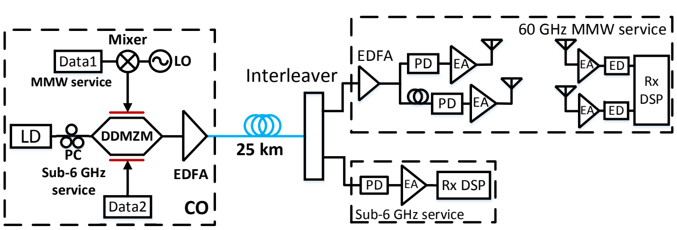

Fig. 1. Schematic diagram of experimental setup.

The schematic diagram of the proposed RoF system is shown in Fig. 1. The CO consists of a laser diode (LD) and a DDMZM. The DDMZM can be viewed as parallel phase modulators whose relative phase relationship can be tuned by the bias voltage. Data1 and Data2 which represent MMW and sub-6 GHz services are IF OFDM signals. Data1 is up-converted to the 30 GHz band by an electronic mixer, and then the up-converted signal is applied to one branch of the DDMZM. Mathematically, the up-converted signal can be expressed as $v_1(t) = [r+S_1(t)(1\text{-}r)]V_1\cos\omega_1 t$ [14], where r is the leakage ratio from the RF port to the LO port of the mixer, V_1 is the amplitude of the LO, ω_1 is the angular frequency of the LO, and $S_1(t)$ is the waveform of Data1. On the other hand, Data2 is applied to the other branch of the DDMZM, which can be expressed as $v_2(t)=V_2S_2(t)$, where V_2 is the amplitude of the sub-6 GHz signal, and $S_2(t)$ is the waveform of Data2. Since the MMW and sub-6 GHz signals are applied to the DDMZM, respectively, the normalized signal after the DDMZM can be expressed as

$$E_D(t) = \left(e^{j\pi v_1(t)/V_\pi} + e^{j\pi v_2(t)/V_\pi} e^{j\theta_B}\right) e^{j\omega_c t} \approx \begin{bmatrix} J_0\left(\alpha(t)\right) + jJ_1\left(\alpha(t)\right) e^{j\omega_1 t} + jJ_1\left(\alpha(t)\right) e^{-j\omega_1 t} \\ + e^{j\beta S_2(t)} e^{j\theta_B} \end{bmatrix} e^{j\omega_c t}, \tag{1}$$

where ω_c is the angular frequency of the lightwave, θ_B is the bias angle of the DDMZM, $\alpha(t) = \pi V_1[r+S_1(t)(1\text{-}r)]/V_\pi = \alpha_0[r+S_1(t)(1\text{-}r)]$ and $\beta = \pi V_2/V_\pi$. If small-signal modulation is assumed, then $J_0(\alpha(t)) \approx 1$ and $J_1(\alpha(t)) \approx \alpha(t)/2$. The optical signal after the DDMZM can be simplified to

$$E_D(t) \approx \begin{bmatrix} 1 + j\alpha(t)e^{j\omega_1 t}/2 + j\alpha(t)e^{-j\omega_1 t}/2 \\ + e^{j\beta S_2(t)} e^{j\theta_B} \end{bmatrix} e^{j\omega_c t}. \tag{2}$$

From (2) we can see the optical carrier is modulated by Data2 while the optical sidebands are modulated by Data1. If this signal is directed to an optical interleaver and the wavelength of the optical carrier is aligned to the interleaver, then the optical carrier and optical sidebands will be separated. The two sidebands which form an OCS signal for the 60 GHz service is expressed as

$$E_{MMW}(t) = \left[j\alpha(t)e^{j\omega_1 t}/2 + j\alpha(t)e^{-j\omega_1 t}/2 \right] e^{j\omega_c t}. \tag{3}$$

The optical carrier which delivers the sub-6 GHz signal is given by

$$E_{RF}(t) = \left[1 + e^{j\beta S_2(t)} e^{j\theta_B} \right] e^{j\omega_c t}. \tag{4}$$

The OCS signal is sent to a photodetector (PD) for optical-to-electronic conversion, and the generated MMW signal can be expressed as [14]

$$\begin{aligned} I_{MMW}(t) &\propto E_{MMW}E^*_{MMW} \\ &= \alpha_0^2\left[r^2 + 2r(1-r)S_1(t) + S_1^2(t)(1-r)^2\right]\left(1+\cos 2\omega_1 t\right)/2, \end{aligned} \tag{5}$$

where $S_1(t)$ is the desired signal, and $S_1^2(t)$ is the signal-signal beating interference (SSBI) which can be mitigated by applying an iterative SSBI mitigation algorithm in the receiver [15]. On the other hand, the optical carrier modulated by the sub-6 GHz signal is sent to another PD, and the generated RF signal can be expressed as

$$I_{RF}(t) \propto E_{RF}E^*_{RF} = 2 + 2\cos\left[\beta S_2(t) + \theta_B\right]. \tag{6}$$

The joint process of the DDMZM and the interleaver for delivering the sub-6 GHz and 60 GHz MMW signals is shown in Fig. 2. The horizontal plane in Fig. 2 represents the optical signal generated by the lower phase modulator in the DDMZM while the vertical plane represents the upper phase modulator. The angle of the two planes represents the bias angle of the DDMZM. As can be seen from Fig. 2, the sub-6 GHz signal is generated by the beating of the optical carrier from the upper phase modulator and the sidebands from the lower phase modulator. By tuning the bias angle of the DDMZM, the phase relationship of the optical carrier and sidebands can be adjusted. When the DDMZM is biased at the quadrature point, i.e. $\theta_B = \pm\pi/2$ according to (6), the sub-6 GHz signal is maximized.

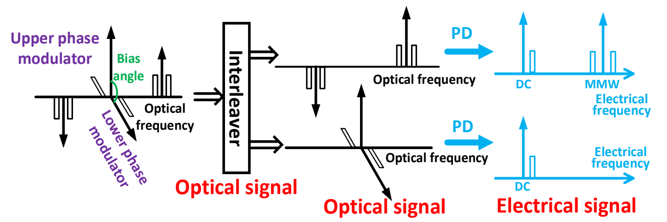

Fig.2. Schematic diagram of the separation and generation of MMW and sub-6 GHz signals.

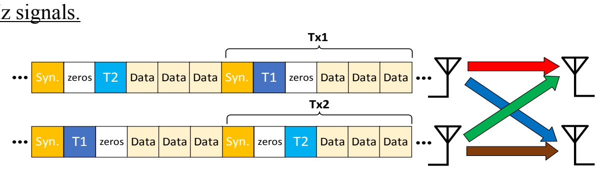

Fig.3. Frame structure for emulation of 2×2 MIMO.

Unlike the previous heterogeneous RoF architectures based on PDM [6-8], the PDM in the proposed RoF system can be utilized for 2×2 MIMO transmission. To implement the PDM-based MIMO transmission, two DDMZMs should be used. Limited by our experimental conditions, we use one DDMZM and one signal stream to emulate 2×2 MIMO transmission in our experiment setup. The experiment setup is shown in Fig. 1. We concatenate two independent streams Tx1 and Tx2 into one stream which is generated by an arbitrary waveform generator (AWG). The AWG is set to generate the concatenated stream periodically. Then the stream is transmitted to the RAU and split into two branches by a coupler. We use a spool of fiber to delay one branch. If the lengths of the Tx1 and Tx2 frames are adjusted to align the Tx2 frame in the delayed stream to the Tx1 frame in the un-delayed stream, then the MIMO operation can be emulated. We employ two OFDM symbols for channel estimation as shown in Fig. 3. For the Tx1 frame, QPSK data are mapped on the subcarriers of the first OFDM symbols, and zeros are mapped on the subcarriers of the second symbols. On the contrary, the zeros are mapped on the first symbols, and QPSK data are mapped on the second symbol for the Tx2 frame. Using the two OFDM symbols, zero forcing (ZF) channel estimation is implemented in the MIMO receiver. Subsequently, the MIMO signal can be detected by employing the estimated MIMO channel matrix.

III. EXPERIMENT

An experiment based on the configuration shown in Fig. 1 is carried out. For simplicity, the 60 GHz MMW service is demonstrated by RoF and MIMO wireless transmission, and the sub-6 GHz service is only demonstrated by RoF transmission. In principle, the MIMO channel estimation and signal detection of the sub-6 GHz signal are similar to the 60 GHz MMW signal. In the CO, an optical carrier at 1549.862 nm generated by an LD is sent to a 40-GHz DDMZM (Fujitsu FTM7937EZ) with a half-wave voltage of 1.8 V via a PC. The optical signal after the DDMZM is boosted by an Erbium-doped fiber amplifier (EDFA) to 10 dBm. An AWG with a sampling rate of 16 GSa/s is used to generate two streams of OFDM signals with a bandwidth of 203.125 MHz at 0.375 GHz where one stream is used to emulate the MIMO transmission. The FFT size of the OFDM signals is 64 where 26 subcarriers are allocated for data transmission with 16-QAM, and 25% cyclic prefix is added to the OFDM symbol. One stream of the OFDM signals is up-converted by a 27.5 GHz LO with a power of -7 dBm via an electronic mixer. Then the up-converted signal is amplified by a 40-dB amplifier and connected to one branch of the DDMZM. Fig. 4(a) shows the spectrum of the up-converted signal which is an electrical DSB signal. The other stream of the OFDM signals at 0.375 GHz is used as the sub-6 GHz service and connected to the other branch of the DDMZM. The optical signal after the DDMZM is amplified and transmitted to the RAU over 25 km of SMF. In the RAU, a 33/66-GHz interleaver is used to separate sub-6GHz and MMW services. The optical signal at the input port of the interleaver is shown in Fig. 4(b), and the optical signals at the two output ports are shown in Figs. 4(c) and 4(d), respectively. As can be seen from Fig. 4, the optical carrier delivering the sub-6 GHz signal and the optical sidebands delivering the MMW signal are separated by the interleaver.

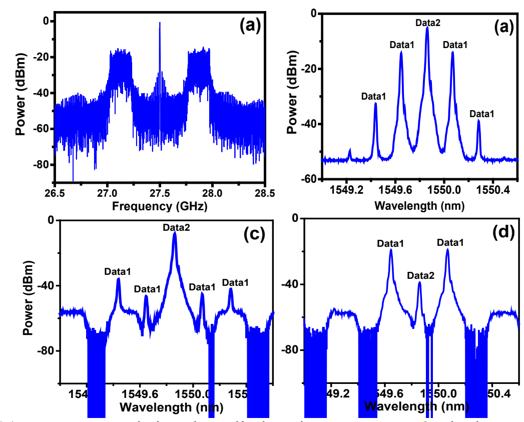

Fig. 4. (a) Up-converted signal applied to the DDMZM. Optical spectra (b) before the interleaver, (c) one output port of the interleaver for the sub-6 GHz service and (d) the other output port of the interleaver for the 60 GHz service.

The optical MMW signal is amplified and split into two branches. One branch is delayed to emulate the MIMO operation, and both branches are finally sent to PDs for optical-to-electronic conversion. The two generated MMW streams are amplified and emitted by two horn antennas. After air transmission, the wireless signals are received by two receiver antennas and amplified by two amplifiers. Then the two received MMW signals are down-converted to the IF band by envelope detectors (EDs). The two IF signals are captured by an oscilloscope with a sampling rate of 10 GSa/s. Finally, an off-line DSP program including OFDM demodulation, synchronization, MIMO channel estimation and signal detection is used to demodulate the 2×2 MIMO-OFDM signals. On the other hand, the other port of the interleaver is sent to a PD with a bandwidth of 2.5 GHz. The generated electrical signal is also captured by the OSC. A conventional SISO

OFDM demodulation procedure is used to demodulate the signal. Fig. 5 shows the electrical spectra of the received MIMO signals down-converted to the IF band when the received optical power is 1 dBm. Attenuators are placed before the PDs to adjust the optical power, and the EVMs of the 55 GHz signal with and without the sub-6 GHz signal at 0.375 GHz versus received optical power are plotted in Fig. 6. We can observe the 0.375 GHz signal does not have a significant impact on the performance of the 55 GHz MMW transmission. The receiver sensitivities of the MMW link for the BER = 3.8×10^{-3} without and with the sub-6 GHz signal are -4.2 dBm and -3.3 dBm, respectively. The impairments on the signal includes the SSBI and the nonlinearity of the RoF link. By using SSBI mitigation techniques [15] and digital linearization methods [16], the transmission performance can be further improved.

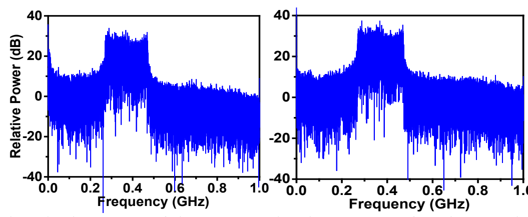

Fig. 5. Electrical spectra of the two received antennas after the envelope detectors.

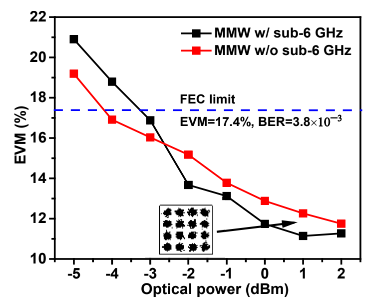

Fig. 6. EVM of the MIMO MMW signal versus optical power.

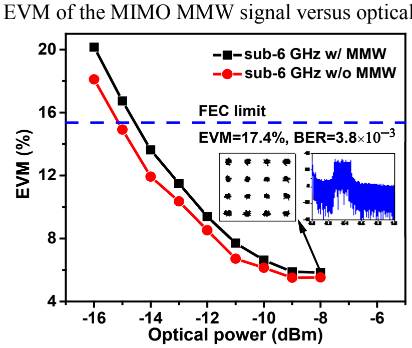

Fig. 7. EVM versus optical power.

Finally, we test the transmission performance of the signal at 0.375 GHz. The EVMs versus the optical power with and without the MMW signal are shown in Fig. 7. When the received optical power is -7 dBm, the constellation and the spectrum of the received signal are shown in the inset of Fig. 7. We can observe that the EVM of the sub-6 GHz service with the MMW service is always slightly larger than that without the MMW service. As can be seen from Fig. 4(c), a small portion of optical sidebands is leaked out into the sub-6 GHz port. According to (5) and Fig. 2, the optical sidebands generate not only an MMW signal but also an IF signal which becomes the interference to the sub-6 GHz service. However, the interference can be negligible especially when the received optical power of the sub-6 GHz service is high. The receiver sensitivities of the sub-6 GHz link for the BER = 3.8×10^{-3} without and with the MMW signal are -15.2 dBm and -14.5 dBm, respectively.

IV. CONCLUSION

In summary, a simple multi-RAT RoF system simultaneously delivering sub-6 GHz and 60 GHz MMW services was proposed. Compared to the exiting multi-RAT RoF systems, the proposed centralized architecture enabled by low bandwidth photonic and electronic devices either has a simplified CO structure or does not need adaptive polarization control in the RAU. Furthermore, the proposed RoF system can employ PDM to support MIMO wireless transmission. We experimentally demonstrated 25 km RoF transmission and 1 m 2×2 MIMO transmission at 60 GHz band and 25 km RoF transmission at sub-6 GHz band. We believe the proposed multi-RAT RoF system can be applied in the further heterogeneous radio access networks.

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