

A Bidirectional Multi-Band 60-GHz Wireless-over-Fiber Transmission System with Compacted Base Station and Mobile Terminal Using a Robust mm-Wave LO Free Technique

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Abstract: For the first time, bidirectional multi-band multi-gigabit wireless-over-fiber transmission at 60-GHz mm-wave band has been accomplished with centrally supplied LO service.

It does not require mm-wave LO devices in each base stations and mobile terminals.

OCIS codes: (060.2330) Fiber optics communications; (060.5625) Radio frequency photonics

1. Introduction

Millimeter-wave (mm-wave) band wireless-over-fiber (WoF) technology has received tremendous attention lately for its capability to transmit multi-gigabit wireless data over well-known, license-free transmission bandwidth of ~7 GHz near 60 GHz [1]. However, the cell coverage area of each base station (BS) shrinks dramatically when the carrier frequency goes up to 60 GHz. As a consequence, the BS density (per unit area) rises by orders of magnitude and unavoidably it will incur higher system complexity and cost. It is critical to design an efficient architecture for WoF system elements (especially, the BS) to attain low maintenance and operation cost. Recently, several WoF schemes with remote up-conversion techniques have been developed for system design and integration [1-3]. Owing to the development of cost-effective all-optical photonic technologies, a new concept known as “mm-wave local-oscillator-free (LOF)” has been proposed and experimentally demonstrated to avoid using expensive mm-wave LO devices in the BSs. The mm-wave LOF could be realized either by employing optical four-wave-mixing (FWM) techniques or optical heterodyning detection mechanisms. Nevertheless, in most of the published works, mm-wave WoF system, mobile terminals (MT) have not yet been fully considered in their designs of a practical, bidirectional WoF infrastructure, of which the MT is an essential part of the end-to-end system besides the central station (CS) and BS. Meanwhile, the mm-wave LOF technique can currently only be applied in downlink WoF transmission, while uplink transmissions (from MT to BS and then to CS) with the mm-wave LOF technique is still regarded as a key challenge in designing bidirectional WoF systems.

To remedy WoF system performance issues, we have proposed a full-duplex bidirectional multi-gigabit vector data WoF transmission system with a more robust technique of mm-wave LOF as reported in [4]. In this paper, we have theoretically analyzed and experimentally demonstrated a system architecture to support multi-band services for both downlink and uplink transmissions with no mm-wave LO devices required in both BS and MT. Wired and wireless link performance of multi-band services, each operates at data rate of 1 Gb/s carried by intermediate frequency (IF) sub-carrier (SC) of 4 GHz and 6 GHz for downlink and 800 Mb/s data at 4/5/6/7 GHz IF SC for uplink services have been evaluated after transmission over 25 km single-mode fiber and 4 feet air distance.

2. Principle of Operation

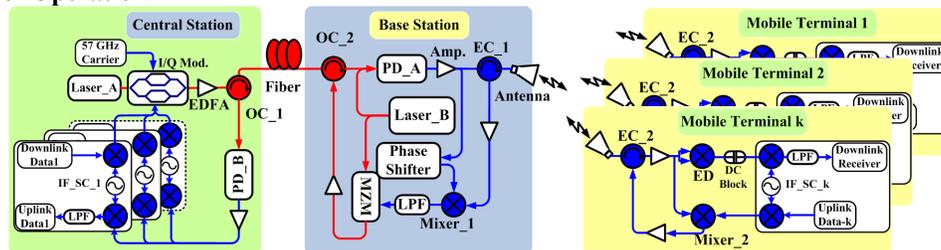


Fig. 1. Conceptual diagram of the proposed bidirectional multi-service 60 GHz WoF CS-BS-MT transmission system employing mm-wave LO-free techniques.

The proposed bidirectional WoF transmission system employing a robust mm-wave LOF technique is illustrated in Fig. 1. At the CS, multi-services are denoted by Downlink Data1, 2...n, each carried on an individual IF SC (IF_SC_n). The multi-band data services are combined and modulated simultaneously in an IQ modulator (IQM) via one of its two RF ports. The IF-modulated continuous wave (CW) lightwave is delivered from the CS to a remote BS over optical fiber. In the mean time, another independent single-wavelength laser source in the BS with the

wavelength centered 0.456 nm (i.e., 57 GHz) away from the Laser_A in CS is employed to introduce wavelength beating in a photo detector (PD), up-converting the IF data to a mm-wave band over 57 GHz. The multi-band mm-wave signals are then broadcasted wirelessly to MTs from the BS. In the MT's transceiver, for downlink, self-heterodyning detection technique is implemented to down-convert the received mm-wave signal and retrieve the IF multi-band signals by using an electrical envelope detector (ED). In the second section of the two down-converting stages, the data on each service could be demodulated and recovered at its baseband by multiplying the IF group signals with the corresponding IF SC of interests.

Time division duplexing (TDD) operation mode has been considered to transmit uplink services at a different time slot other than the downlink transmission. Data for downlink services will be switched off in the CS when a 57 GHz pure sinusoidal signal is modulated onto the same laser in the CS and transmitted over the same fiber and wireless link to remote BS and MT ends to function as an mm-wave LO signal for uplink transmission. The remotely recovered 57 GHz mm-wave LO signal is partially reserved in BS and partially wirelessly delivered to MT to carry out the wireless transmission and up-/down-conversion functions for the uplink services from the remote MT. Thus, in our proposed scheme, no mm-wave LO devices are required in both BS and MT for both up- and down-link transmissions.

3. Analysis of Multi-band Modulation in the IQM

According to the modulation scheme in CS as shown in the Fig. 1, the generated multi-band signals after the IQM, each carrier on an IF SC could be expressed as:

$$E_{out}(t) = \left(\frac{1}{2} \cos \left\{ \frac{\beta_1}{2} \sin(\omega_{RF} \cdot t) + \frac{B_1}{2} \right\} + \frac{1}{2} \cos \left\{ \sum_{i=1}^{i \leq n} \frac{\beta_{2i}}{2} \sin(\omega_{IF_i} \cdot t) \times Data_i(t) + \frac{B_2}{2} \right\} \right) \cdot e^{j\beta_3} \cdot E_{in}(t) \quad (1)$$

where $E_{in}(t)$ is the electric field of the input CW lightwave to the IQM; $B_{1,2,3}$ represent the DC biases on the IQM, respectively; β_1 is the modulation depth (MD) of the radio frequency (RF) signal with an angular frequency of ω_{RF} for uplink; β_{2i} are the MDs determined by the amplitude-to- V_π ratio of each data, carried on an IF SC of ω_{IF_i} , n is the number of the services. Under the assumption of small signal model (SSM), the output signal, $E_{out}(t)$ is given by:

$$E_{out}(t) \cong -2 \sin \left(\frac{B_2}{2} \right) \cdot \sum_{k=1}^{k \leq n} \left[\prod_{i=1}^{i \leq n, i \neq k} J_0 \left(\frac{\beta_{2i}}{2} \cdot Data_i(t) \right) \right] \cdot J_1 \left(\frac{\beta_{2k}}{2} \cdot Data_k(t) \right) \cdot \sin(\omega_{IF_k} \cdot t) \cdot E_{in}(t) \quad (2)$$

where $J_n(x)$ denotes the Bessel function of the 1st kind of n^{th} order. As we can see in Eq. (2), distinguished from the single-band case, each service of $Data_k$ carried at IF SC of $\sin(\omega_{IF_k} \cdot t)$ is intensity impacted by the data at the other IF SCs. The affecting factors consist of the amplitude (corresponding to β_{2i}), DC component and SNR of each service data (contained in $Data_i$, where $i \neq k$). The impact degree of the interference is determined by the product of $J_0(\beta_{2i}/2 \cdot Data_i)$ for $i \neq k$. Since $J'_0(x) \ll J'_1(x)$ holds under SSM, the instinctive interference could be theoretically analyzed and is pre-determinable.

4. Experimental Results and Discussion

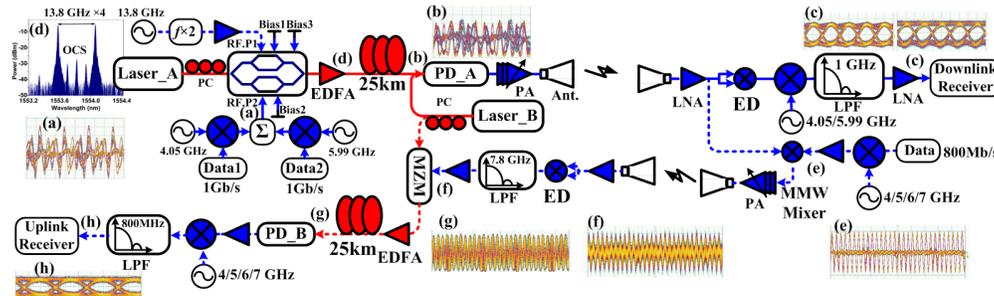


Fig. 2. Experimental setup of the proposed scheme with test results shown in the insets from (a) to (h).

A proof of concept experiment for both downlink and uplink services are carried out with the experimental setup depicted in Fig. 2. For downlink data services, two IF-band SC (one at 4.05 GHz and the other at 5.99 GHz) are used to mix $Data1$ and $Data2$ to IF-band in the first of the two up-conversion stages. $Data1$ and $Data2$ are both set at a data rate of 1 Gb/s with a $2^{31}-1$ sequence length. The electrically combined IF signal group is launched to an RF port (RF P2 as shown in the Fig. 1) of an IQM, and the corresponding DC bias (Bias 2) is tuned at quadrature point. The eye diagrams of the signal after the electrical coupler at position (a) and at the end of 25 km fiber transmission at position (b) are shown in the insets (a) and (b), respectively. By optical beating between the optical sources of Laser_B at 1554.276 nm and the Laser_A at 1553.82 nm, the group signals are up-converted to over 57 GHz mm-

wave band at the output of PD_A. The wireless transmission distance is 4 feet in our experiment and it could be further enlarged only if a more robust mm-wave power amplifier is available. For the uplink transmission (in dashed lines in Fig.2), a 13.8 GHz LO signal is electrically frequency doubled up to 27.6 GHz first and then modulates the lightwave from Laser_A by double sidebands with optical carrier suppressed with its optical spectrum shown in inset (d), while the downlink data services are switched off in CS. After fiber transmission and O/E conversion in the PD_A, the 55.2 GHz mm-wave LO signal is generated and delivered to the receiver side via the same wireless transmission link. The data rate for uplink service is set at 800 Mb/s in the experiment test. Eye diagrams of the IF modulated data are monitored along the uplink transmission line as shown in the insets Fig. 2 (e-g).

In order to investigate and evaluate the interference impact from the other IF SC, a set of control experiments have been carried out with the test results shown in Fig. 3. When only 1 Gb/s Data at 4.05 GHz IF SC are transmitted in the system without Data bar at 5.99 GHz IF SC, the BER curves and eye diagram are shown in Fig. 3 (a); when the Data bar at 5.99 GHz IF SC is added, the received signal quality of Data is degraded as one can observe in the eye closure in Fig. 3 (b). Moreover, by observing the received optical power at error free transmission point at (a) and (b), an extra 0.2 dB power penalty can be noticed. Similar tests have also been carried out to evaluate the impact on the Data bar at 5.99 GHz IF SC from the Data at 4.05 GHz IF SC. We can find in Fig. 3 (c, d) that the eye diagram degradation is more severe and an extra 1 dB power penalty is introduced. With Eq. (2) in mind, the experimental results here can be comprehended, since the Data bar at 5.99 GHz IF SC is with smaller β_{2i} comparing to Data, as long as regarding the other system noises or distortions are equally introduced onto the 4.05 and 5.99 GHz channels.

Eye diagrams and BER curves for uplink transmission are shown in Fig. 4. With the frequency increase of IF SC from 4 GHz to 7 GHz, limited by the IF bandwidth restriction of the mm-wave mixer, more received optical power is required to achieve error free transmission.

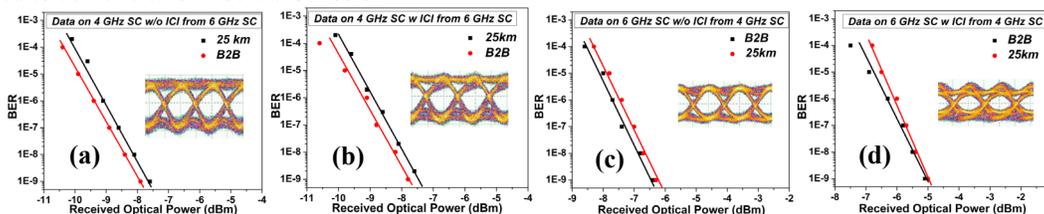


Fig. 3. BER and eye diagrams of downlink transmission over 25 km SMF and 4 feet air for 1 Gb/s data on 4.05 GHz IF SC without (a) and with (b) interference from the data on IF SC at 5.99 GHz; and for 1Gb/s data at 5.99 GHz IF SC without (c) and with (d) interference from the data on IF SC of 4.05 GHz.

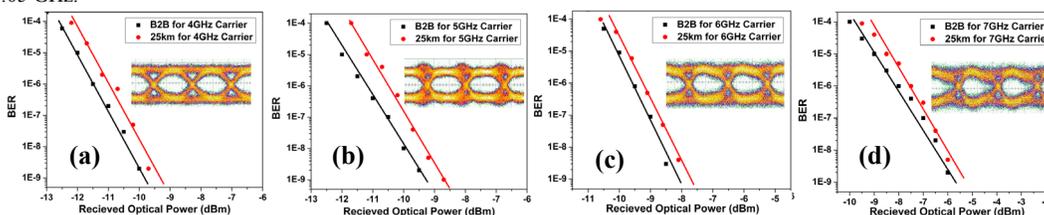


Fig. 4. BER and eye diagrams for uplink transmission over 25 km SMF and 4 feet air for 0.8 Gb/s data on (a) 4 GHz, (b) 5 GHz, (c) 6 GHz, and (d) 7 GHz IF SC.

5. Conclusion

In summary, based on a novel mm-wave LOF technique, a bidirectional 60 GHz WoF transmission system for multi-band services is proposed and experimentally demonstrated. In our scheme, expensive electrical LO devices at mm-wave frequencies in BSs and MTs can be replaced by centrally delivered low-cost LO service using microwave photonic techniques for both downlink and uplink transmission. Theoretical analysis and experimental results have been carried out to prove this proposed CS-BS-MT architecture is a promising solution for providing function-centralized, cost-effective mm-wave WoF access networks for bidirectional multi-gigabit wireless applications.

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