Real-Time Photonics-Aided MMW Mobile Communication Based on Integrated 256-Element Phased Array Antenna

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Abstract—**We propose and realize the bi-directional self-steering beamforming of 256-element phased array antennas base on automatic beam tracking technique, the real-time photonics-aided 28 GHz MMW mobile communication over 1.5 m wireless distance within ±25° range is achieved.**

Keywords-5G, MMW, phased array, real-time, wireless communication, beamforming and beam steering

I. INTRODUCTION

The spectrum resources of traditional wireless communication are increasingly exhausted, thus it is imminent to explore and develop new spectrum resources such as millimeter-wave (MMW). MMW band such as 28 GHz can achieve enhanced mobile broadband with super Gb/s throughput and sub-millisecond latency, which is suitable for serving new applications such as virtual reality, digital twin and metaverse that are currently booming [1]. However, compared with sub-6GHz band, the MMW frequency presents a higher path loss, leading to the existing MMW systems are mainly limited to fixed wireless access scenario within the line-of-sight range [2]. Fortunately, the following two approaches can significantly expand the coverage and application scenarios of MMW. One is the photonics-aided MMW communication, which can generate MMW signal with low-cost by heterodyne beating of two light waves, and supports indoor and outdoor distributed coverage via optical fiber media to overcome the high wall-penetrating loss [3-6]. The other is MMW large-scale integrated phased array antenna (PAA), which can not only achieve high point-to-point directional gain but also support terminal mobile

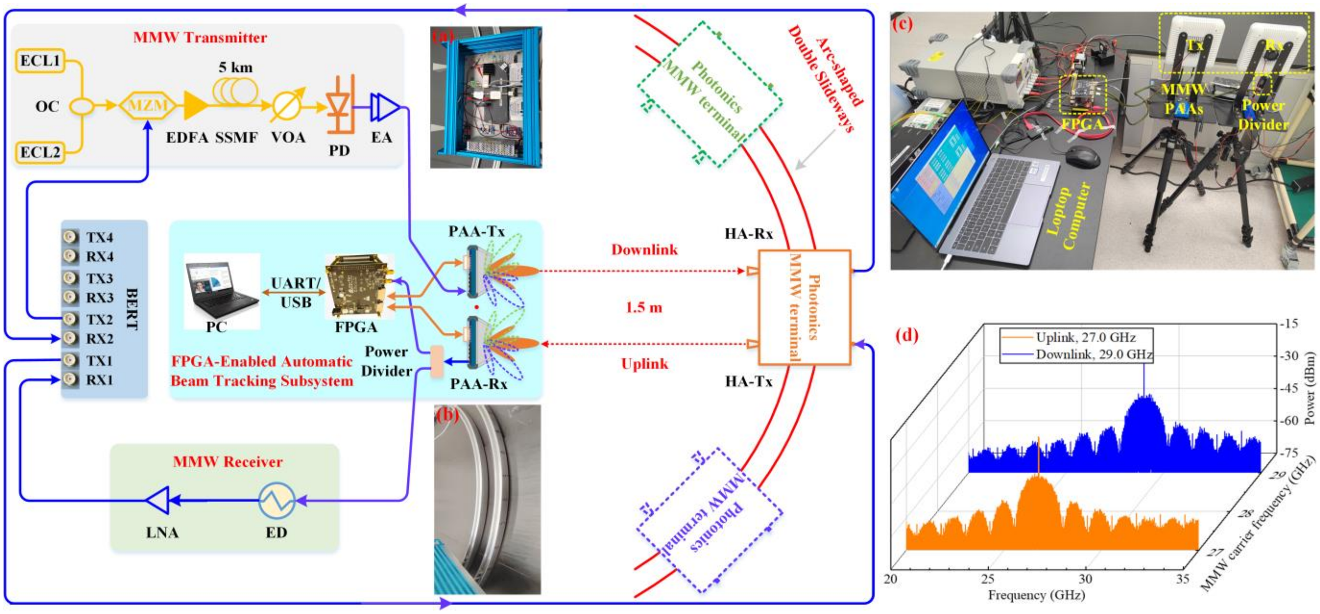

Figure 1. Experimental setup of real-time photonics-aided MMW bi-directional communication in mobile scenario. (a) The packaged chassis of photonics MMW terminal, (b) arc-shaped double slideways, (c) setup of FPGA-enabled automatic beam tracking subsystem, (d) MMW signal spectra of uplink and downlink.

communication through beamforming and beam steering capabilities.

Some recent studies have demonstrated the photonics-aided MMW communication system based on the PAA [7-10]. Nevertheless, some drawbacks also remains. Firstly, part of the work only enable a few fixed directions, which still cannot support mobile communication. Secondly, most of the work just involve uni-directional or offline MMW transmission, and do not support bi-directional real-time communication. Finally, all systems are demonstrated based on the small-scale PAA (no more than 4 channels), whereas it is inconsistent with the trend of adopting large-scale PAA in future beyond 5G (B5G) networks.

Recently, we presented and demonstrated the real-time HD video transmission demo based on the Ka-band large-scale MMW PAA in 2022 OFC Demo Zone [11]. In this paper, we further explore the performance of proposed bi-directional real-time MMW mobile communication system in detail. Based on the self-developed FPGA, the automatic beam tracking control for integrated 256-element PAAs is realized. Through the proposed bi-directional self-steering photonics-aided MMW communication links, we also successfully demonstrate 1.25 Gbps real-time MMW mobile communication within ±25°angle range at 26.5 ~ 29.5 GHz band over 5 km optical fiber and 1.5 m wireless transmission.

II. System Setup

The experimental setup of real-time photonics-aided MMW bi-directional communication is shown in Fig. 1. The system consists of six parts, including bit error rate tester (BERT), MMW transmitter, MMW receiver, photonics MMW terminal and FPGA-enabled automatic beam tracking subsystem, as well as the bi-directional wireless links. The BERT (E410A) supports four channels simultaneous transmission and reception of NRZ signal with the maximum rate of 10 Gbps per channel. In our experiment, two channels (CH1 and CH2) are used for uplink and downlink real-time BER test, respectively.

At the MMW transmitter, the photonics-aided technique is utilized to generate the desired MMW signal. The light waves from two external cavity lasers (ECL) are coupled via an optical coupler (OC), and then are fed into one single-arm Mach–Zehnder modulator (MZM) to achieve electro-optic conversion of the NRZ signal produced by BERT. After amplified by an erbium-doped fiber amplifier (EDFA) and transmission over 5 km standard single-mode fiber (SSMF), the obtained optical signal is input into a photodetector (PD) (3 dB bandwidth of 40 GHz) to generate MMW signal. A variable optical attenuator (VOA) is used to control the optical power incident to the PD. Afterwards, the generated MMW signal is amplified by the two-stage electrical amplifier (EA) and then fed to the corresponding MMW antenna for transmitting.

A pair of integrated 256-element CMOS PAAs operating at 26.5 ~ 29.5 GHz and a pair of horn antennas (HAs) working at 26.5 ~ 40 GHz cooperate to establish the bi-directional MMW links. The wireless distance is set to 1.5 m, which mainly limited by the experiment platform and available cabling.

At the MMW receiver, an envelope detector (ED) with cut-off frequency up to 67 GHz and 3 dB bandwidth over 500 MHz downconverts the received MMW signal to baseband. The obtained baseband NRZ signal is first amplified by a low-noise amplifier (LNA) with 30 dB gain, and then is fed back to the corresponding channel of BERT for BER calculation.

To facilitate system demonstration for mobile communication, we package the MMW transceiver and two HAs into a portable 3U chassis, which termed as photonics MMW terminal (shown in Fig. 1 (a)). Inside the chassis, the transceiver contains the aforementioned MMW transmitter and receiver, except that there is no EDFA and 5 km SSMF any more at the transmitter side. In addition, the arc-shaped double slideways help ensure the alignment of HAs and PAAs during the movement of the chassis, as shown in Fig. 1 (b). On the other hand, as shown in Fig. 1 (c), an automatic beam tracking subsystem is also proposed and successfully implemented, in order to achieve bi-directional self-steering beamforming for two 256-element MMW PAAs. One laptop computer, one self-developed FPGA board, one 40 GHz MMW power divider as well as two PAAs constitute this subsystem. The power divider divides the MMW signal received from PAA-Rx into two parts, one of which is input to the FPGA board for power monitoring. This power value is viewed as a feedback signal to determine whether it is necessary to scan the beam of PAA-Rx. If scanned, the finally obtained beam direction is also update synchronously to the PAA-TX, so that the beams of the two PAAs can both accurately point to the corresponding HAs of terminal in the mobile scenario. The detailed beam tracking algorithm can refer to [11].

In our experiment, to avoid the mutual crosstalk, the generated MMW frequencies for uplink and downlink are set to about 27 GHz and 29 GHz, respectively. The MMW signal spectra of uplink and downlink are shown in Fig. 1 (d).

III. Results and Discussion

The homemade integrated 256-element MMW PAA, designed by Purple Mountain Laboratories and Chengdu Team Retone Technology Co., Ltd., suports linear polarization. Its maximum beam sweep angles in E-plane and H-plane can reach up to ±25° and ±50°, respectively. The measured beam patterns at 28 GHz are shown in Fig. 2. For ease of operation and testing, we will focus on the results of E-plane in the following.

After optimizing system parameters, we firstly study the real-time BER performance of NRZ signal at different transmission rates. It can be seen from Fig. 3 (a), BER at 1.25 Gbps rate is approximate to error-free with the received optical power (ROP) of -7 dBm, whereas all of the other higher rates exist error floor. For the transmission rates of 2.125 and 2.488 Gbps, the BER floors mainly come from the bandwidth limitation of ED. With respect to 3.125 Gbps case, besides the ED, the bandwidth of PAA also limits its performance. Secondly, based on 1.25 Gbps NRZ signal, the BER versus ROP for bidirectional links is shown in Fig. 3 (b). Noting that both uplink and downlink transmit 1.5 m wireless distance, meanwhile the downlink has also gone through 5 km SSMF transmission, whereas the uplink does not. Mainly benefited from the higher gain of PAA transmission than reception, the downlink performance is slightly better than that of uplink.

We further verify the uplink BER performance of MMW mobile communication. First, we fix the terminal at the position of 0°, and then manually steer the beam direction of PAA-Rx through beam control software located on the laptop with the range of -10° to 10°. When automatic beam tracking is not enabled, it will obviously cause the beams between PAA and HA to misalign at this case. As shown in Fig. 3 (c), the BER remains relatively stable only within ±2° and then deteriorates sharply with the further increase of the steering angle. This result confirms that the 256-element PAA has a very narrow beam. Next, we activate the function of automatic beam tracking, and test the real-time BER performance under

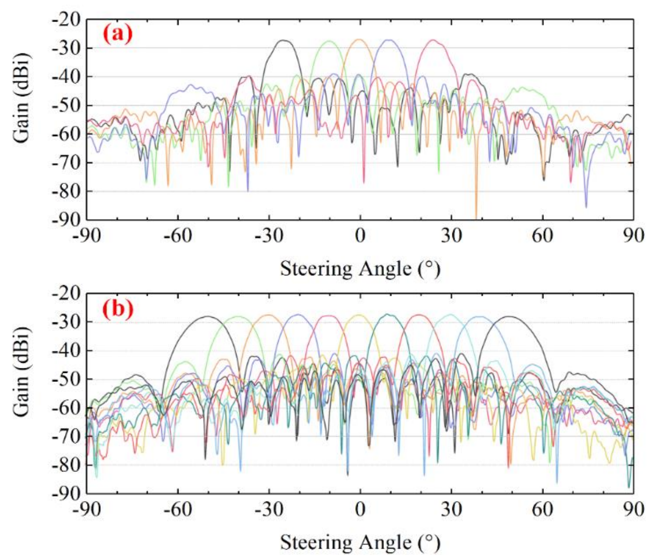

Figure 2. Measured beam patterns of the integrated 256-element MMW PAA in (a) *E*-plane and (b) *H*-plane.

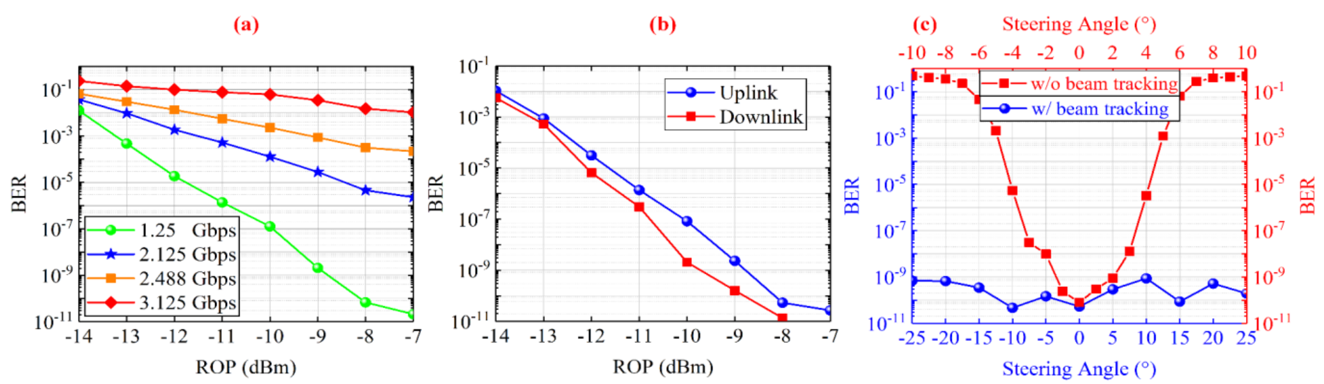

Figure 3. (a) BER performance of NRZ signal with different transmission rates. (b) BER versus ROP for bi-directional links with 1.25 Gbps NRZ, (c) BER versus steering angle for mobile communication with (w/) and without (w/o) automatic beam tracking.

the case of moving the terminal within the maximum angle range of E-plane. It can be found from Fig. 3 (c) that the BER is generally stable at the order of 1E-10 throughout -25° to +25° range. This means that we have successfully achieved the demonstration of real-time 28 GHz MMW mobile communication within the range of 50°.

IV. Conclusion

A real-time photonics-aided MMW mobile communication system based on integrated 256-element PAA has been demonstrated. The bi-directional self-steering beamforming of PAAs is achieved utilizing the proposed automatic beam tracking technique. Based on this system, we verify the real-time mobile communication within ±25° range for 1.25 Gb/s 28 GHz MMW over 1.5 m wireless transmission. Our system can combine the MMW large-scale integrated PAA with the existing broadband optical fiber access network, thus provides an efficient and economic technical solution for the upcoming B5G MMW indoor and outdoor continuous coverage.

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