Demonstration of PDM-2048QAM W-Band Signal Delivery over 4.6 km Wireless transmission Employing One bit DSM

Wen Zhou[1], Xiongwei Yang[1], Weiping Li[1], Feng Wang[1], Bowen Zhu[1], Huajiong Lin[2], Junting Shi[1], Tangyao Xie[3], Kaihui Wang[1], Li Zhao[1], Jianguo Yu[3], Feng Zhao[4], and Jianjun Yu [1] *

*[1] Fudan University, Shanghai, 200433, China * jianjun@fudan.edu.cn*
[2] Huawei Technologies Co., Ltd, Chengdu, China
[3] Beijing University of Posts and Telecommunications, Beijing, 100876, China
[4] School of Electronic Engineering, Xi'an University of Posts and Telecommunications, Xi'an, 710121, China

Abstract: In a photonics-aided mm-wave communication system, we successfully achieved W-band long-distance transmission of PDM-1024QAM/2048QAM signals over 4.6 km by using a PTFE lenses and Delta-Sigma Modulator (DSM).

1. Introduction

With the emergence of new applications such as virtual reality (VR), digital twin, and short video, etc., new requirements are put forward on the capacity, speed and latency of current wireless communication networks [1]. The millimeter wave (MMW) band is considered as one of the solutions of current spectrum resource scarcity, which has a huge bandwidth and enables high-speed wireless communication [2-3]. Therefore, many researches have been carried out on MMW communication. Among them, one of the research hotspots is photonic-aided MMW communication. Photonics-aided technology effectively resists the bandwidth limitation and electromagnetic interference of electronic equipment, so it can realize the generation of high-speed MMW signals [4-7]. Due to the high capacity and high data rate requirements, large numbers of fiber are needed that resulting in increased cost for operators to deploy the front-haul links. Spectral efficient technologies, ROF technique and mm-wave frequency band [8-11] are therefore attracting attention to provide both high bandwidth and cost-effective front-haul solutions, especially in applications such as wireless data transmission between base station and antennas, emergency communication and remote base station. However, the current front-haul network usually adopts high-order QAM format, which makes it difficult to be compatible with ROF communication technology. Higher-order QAM implies higher SNR requirements and smaller nonlinear tolerance, also the nonlinear effects of optoelectronic and electro-optical conversion in photonics-aided systems make higher-order modulation formats difficult to be directly transmitted in the system.

In this paper, we experimentally demonstrate the transmission of 1G baud W-Band PDM-1024QAM/2048QAM signal over a 4.6-km wireless distance in a photonics-aided system. Based on software DSP, we successfully use a 1-bit Delta-sigma Modulator (DSM) in the digital domain to encode a high-order QAM signal into a QPSK signal, effectively solving the nonlinear impairment problem of high-order QAM [12-14]. At the same time, thanks to the high gain polytetrafluoroethylene (PTFE) lenses, the long-distance transmission of 1024QAM/2048-QAM over 4.6km in the W-band has been successfully achieved. To the best of our knowledge, it is the first time that DSM technology has been combined with photonics-aided technology to achieve long-distance wireless transmission of high-order QAM signals.

2. Experimental setup

Fig. 1 shows the experimental setup of photonics-aided long-distance W-band polarization multiplexing wireless delivery over 4.6 km. The transmit-side (Tx-side) is located at Guanghua Building with a height of 142 m on Handan campus, and the receiver-side (Rx-side) is located at Wuli Building with a height of 24 m on Jiangwan campus. Figs. 1(a)-(c) give the photos of the transmission link, transmitter and receiver, respectively. As shown in Fig. 1(d), the base band high-order modulated DSM digital signal at the transmitter is firstly offline created via PRBS sequence generation and *m*-QAM mapping. Next, high-order *m*-QAM signal is up-sampled and filtered via a RC filter. In Particular, the1-bit DSM quantization is employed for *I* and *Q* branch, respectively. Finally, *I* and *Q* components after the resampling step are fed into DAC and amplified via two parallel electrical amplifiers (EAs), respectively. The boosted real and imaginary signals are used to drive *I*/*Q* modulator with a 3dB bandwidth of 30 GHz. The external cavity laser 1(ECL1) operated as a signal light source is modulated *I*/*Q* modulator and boosted by a polarization-maintaining Erbium-doped fiber amplifier (PM- EDFA) to compensate for the insertion loss of the modulator, and ECL2 used as local oscillator (LO) has a frequency space of 87.5 GHz with ECL1. Both ECLs are tunable lasers with a line-width of 100 KHz and coupled together by a polarization maintaining optical coupler (PM-OC). After transmission over 10 km SMF-28 transmission, the attenuator (ATT) is used to adjust the optical power into the photodiode (PD). It is worth noting that the part of the experimental setup before 10 km SMF-28 is placed indoors. The output signal after the ATT is splitted into two paths by an optical coupler (OC). In order to remove the correlation of Horizontal/vertical (*H*/*V*) polarization directions, an additional 100 m fiber transmission used an optical delay line (ODL) is applied on the upper path, and the delayed optical signal is optical heterodyne beated by PD1 to generate 87.5 GHz W-band signal in *H*-polarization. The generated *H*-polarization W-band signal is subsequently amplified by the cascaded low-noise amplifier (LNA1) with a gain of 30 dB and power amplifier (PA1) with a saturated output power of 18 dBm. Differently from the upper branch, the other separated light beam on the lower branch is directly through PD2 to realize *V*-polarization W-band signal generation, and then boosted via LNA2 and PA2 identical to LNA1 and PA1. And then *H*- and *V*-polarization W-band signals are multiplexed by an *H*/*V* polarization multiplexer and fed into a W-band conical antenna (CA1) with a 25 dBi gain. The transmitted power is measured as 16 dBm. Especially, we adopt a pair of our designed PTFE lenses (i.e., Lens1 and Lens2) to focus the collimated W-band beam, and the distance between the transmitter and receiver is improved to 4.6 km. Here, the gain of Lens1 is about 9 dBi, and the gain of Lens2 is about 31 dBi, so the total gain of lens is 40 dBi. We also measure the received power after 4.6 km wireless transmission is -41.96 dBm.

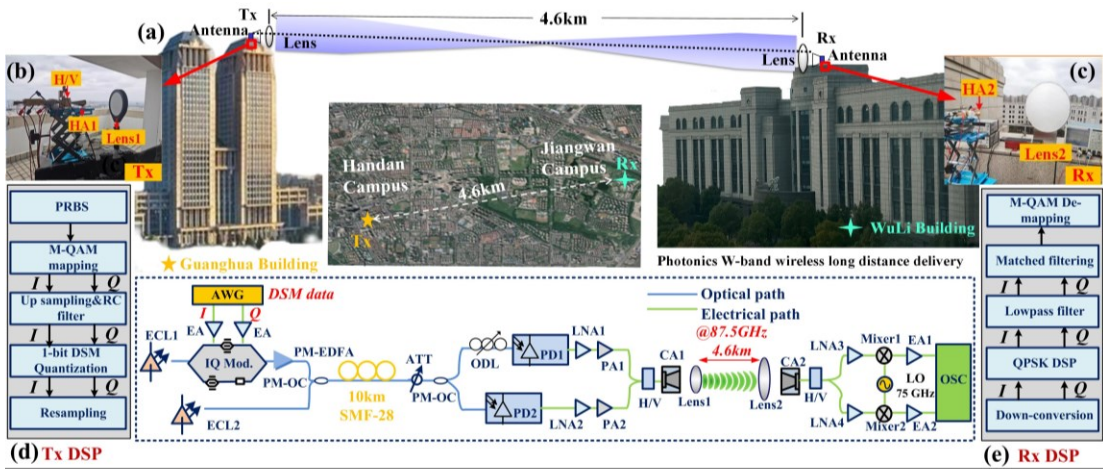

Fig. 1. Experimental setup of PDM-2048QAM W-band wireless delivery over 4.6 km employing one bit DSM. Photos of (a) transmission link; (b) transmitter; (c) receiver. (d) Tx DSP; (e) Rx DSP.

For W-band 4.6 km wireless transmission, according to the power budget of wireless transmission link over free space, the received power can be defined as $P_R = P_T + G_T + G_R + G_{lens} - 20\log(4\pi d/\lambda) - L_m$, where the atmospheric loss L_m is 2.3 dB for 4.6 km wireless at 87.5 GHz, and $20\log(4\pi d/\lambda)$ is calculated as 144.63 dB. Therefore, the received power is calculated as -40.93 dBm (16+2×25+40-144.63-2.3=-40.93 dBm), which has a difference of 1.03 dB from the measured value. It may be caused by the device connection loss.

At receiver, the received signal by the other Lens2 and CA2 is firstly separated into *H*- and *V*-polarization respectively by the *H*/*V* polarization de-multiplexer. Each polarization W-band signal is then amplified a LNA (LNA3 or LNA4) with a gain of 30 dB and down converted into intermediate frequency (IF) signal at 12.5 GHz (87.5-75=12.5GHz) by a 75 GHz RF source and a sub harmonic mixer (Mixer1 or Mixer2). We use a pair of EAs (EA1or EA2) with a gain of 26 dB to amplify each IF signal in *H*- and *V*-polarization, respectively. Finally, the amplified IF signal after EA is captured by 50 GSa/s OSC (Tektronix0, DSA73304D). The captured IF signal spectrum is shown in Fig. 2. As shown in Fig. 1(e), the offline DSP at Rx is followed by down conversion, QPSK traditional DSP steps including 33-tap constant modulus algorithm (CMA) equalization, frequency offset estimation, principal component-based phase estimation (PCPE) and 131-tap Decision-Directed Least mean square (DDLMS), low pass filtering, match filtering and m-QAM de-mapping. Thanks to DSM, only traditional DSP processing with a low complexity is required.

3. Results and discussion

Fig. 2(a) shows the IF signal spectrum captured by the OSC. Fig. 2(b) shows the comparison of the *I*-channel waveform of the QAM signal at the transmitting end and the waveform recovered after low-pass filtering. It can be clearly seen that the waveforms are basically the same. It is noteworthy that QPSK signal errors after low-pass filtering still have a significant effect on the recovery of high-order QAM, as marked by the red circle in Fig. 2(b), so the realization of high-quality QPSK transmission is inevitable. We experimented with dual polarization transmission of 1024QAM and 2048QAM. Fig. 2(c) shows the measured BER versus the received optical power (ROP) for 1024QAM after 4.6km wireless delivery at 87.5 GHz. The BER of *H*-Pol and *V*-Pol can be below the 20% SD-FEC threshold of 2.4×10^{-2} when ROP is -1 dBm. For PDM-1024QAM signal transmission, when the ROP is -1 dBm, the BER of PDM-1024QAM is 8.5×10^{-3}. Inset (I) and Inset (II) show the constellation of *H*-Pol 1024QAM when the ROP at -3dBm and -1dBm, respectively. The isolation degree of the polarization multiplexer used in the experiment is greater than 23 dB, so the transmission performance in the *H*-Pol and *V*-Pol directions is basically the same. Fig. 2(d) shows the measured BER versus ROP for 2048QAM after wireless transmission. At the 20% SD-FEC threshold, the required ROP for 1G baud PDM-2048QAM signal transmission is -1 dBm. At -1dBm, the BER of *V*-Pol 2048QAM is less than 2.4×10^{-2}, the BER of *H*-Pol 2048QAM is less than 1.0×10^{-2}. Insets (III) and (IV) show the recovered *V*-Pol and *H*-Pol 2048QAM constellations at -1dBm, respectively.

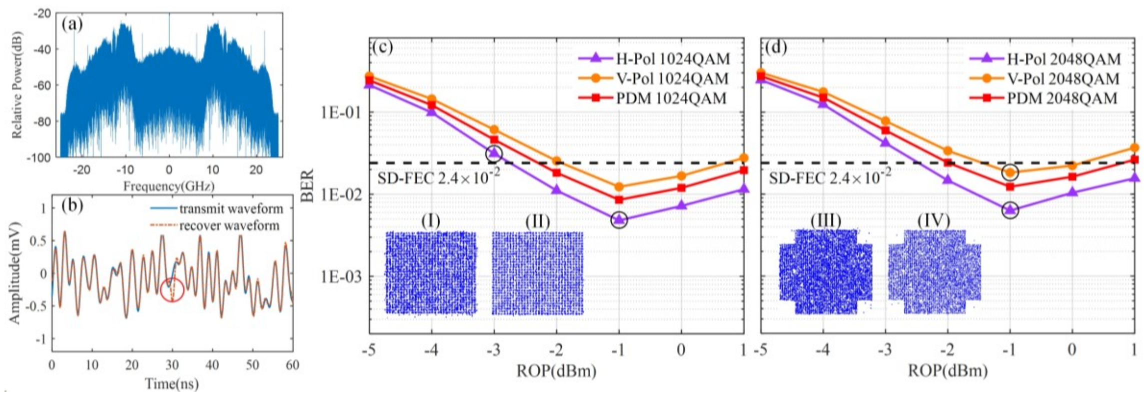

Fig. 2. (a) Captured IF signal spectrum by the DSO; (b) Transmitted/receive recovered waveform. (c) BER of the 1024QAM versus ROP. Insets (I) and (II) are constellation of *H*-Pol and *V*-Pol at 5-dBm, respectively; (d) BER of the 2048QAM versus ROP; Insets (Ⅲ) and (Ⅵ) are constellation of *H*-Pol and *V*-Pol at 5-dBm, respectively.

These results prove that our transmission is successful. For the same received power, the transmission performance of the QPSK signal after DSM quantization should be the same. However, higher-order QAM is more sensitive to errors generated by QPSK during transmission. Therefore, under the same received optical power and the same DSM quantizer, 2048QAM performs worse than 1024QAM. Considering the 20% SD-FEC overhead, the highest rate for 2048QAM signal 4.6km transmission is 1×2×11×0.8=17.6Gbit/s, 1024QAM net bit rate after 20% FEC overhead removed is 1×2×10×0.8=16Gbit/s. With the help of one pair of horizontal/vertical (*H*/*V*) polarization multiplexer/ demultiplexer, conical antennas, lenses, LNA and DSM technology, we have successfully achieved a PDM-2048QAM signal with a net bit rate of 17.6 Gbit/s W-band wireless transmission over 4.6 km.

4. Conclusions

1-GBaud (17.6 Gbit/s) W-band PDM-2048QAM signal wireless transmission over 4.6 km distance at 87.5 GHz has been experimentally demonstrated, by using antenna polarization multiplexing, DSM and photonics-aided techniques. Thanks to the quantization gain brought by 1-bit quantized DSM and the pair of special dielectric lenses, we successfully realize the long-distance transmission of high-order QAM signals in the W-band. This system is expected to be applied to the front-haul network of future 6G communications.

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5. References

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