Long-Distance Wireless mm-Wave Signal Delivery at W-Band

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Abstract—W-band (75–110 GHz) is a potential radio frequency band to provide long-distance wireless links for mobile data transmission. We proposed a high-speed long-distance wireless transmission link at W-band based on some enabling technologies and advanced devices, such as antenna polarization multiplexing combined with multiple-input multiple-output, high-gain/high-power W-band electrical amplifiers, high-gain small-beamwidth Cassegrain antennas, and wideband optical/electrical components. We experimentally demonstrated that our proposed wireless transmission link can realize up to 1.7-km wireless delivery of 20-Gb/s@85.5-GHz millimeter-wave signal with a bit-error rate less than $3.8 \times 10^{-3}$.

Index Terms—Antenna polarization multiplexing, Cassegrain antenna (CA), long-distance wireless delivery, W-band.

I. INTRODUCTION

NOT only high-speed but also long-distance wireless transmission links are required in order to meet the demand of mobile backhauling between wireless macro stations as well as emergency services when large-capacity long-distance optical cables are cut during natural disasters such as earthquake and tsunami [1]. Recently, the W-band (75–110 GHz), with inherent wider bandwidth available at higher frequencies, has attracted increasing interest as a candidate radio-frequency (RF) band to provide multi-gigabit wireless links for mobile data transmission [1]–[24]. Moreover, the W-band has relatively small atmospheric loss (as shown in Fig. 1) [25] and good directionality, and is thus a potential RF band to offer long-distance wireless links for mobile data transmission as well [26]–[30]. Although electrical millimeter-wave (mm-wave) generation techniques typically have a relatively simple architecture [31]–[35], mm-wave generation based on photonic techniques, particularly for the high frequency W-band mm-wave, can effectively overcome the bandwidth limitation of commercially available electrical components and meanwhile promote the seamless integration of wireless and fiber-optic networks [36]–[41]. Experimentally demonstrated 100-Gb/s and 400-Gb/s wireless signal delivery at W-band were reported adopting photonic mm-wave generation, but the wireless transmission distance is no more than 2 m [7]–[12]. Up to 15-m wireless signal delivery at W-band enabled by photonic mm-wave generation was also reported at the cost of a relatively low bit rate of 50 Gb/s [8]. It is evident that, however, even tens of meters of wireless transmission distance cannot effectively meet the demand of the aforementioned mobile backhauling and emergency communications.

In this paper, we proposed a high-speed long-distance wireless transmission link at W-band based on some enabling technologies and advanced devices, such as antenna polarization multiplexing, high-gain Cassegrain antennas (CAs) and wideband optical/electrical components. We experimentally demonstrated our proposed wireless transmission link can realize up to 1.7-km wireless delivery of 20-Gb/s polarization-division-multiplexing quadrature phase keying (PDM-QPSK) signal at 85.5 GHz with a bit-error rate (BER) less than $3.8 \times 10^{-3}$ [26].

The remainder of this paper is organized as follows. Section II introduces the key devices for long-distance wireless mm-wave delivery at W-band, including large-gain/high-power W-band electrical amplifier (EA), large-gain small-beamwidth CA as well as photo detector (PD) with good frequency response at W-band. Section III shows the principle of the antenna polarization multiplexing technique for long-distance wireless mm-wave delivery at W-band. Section VI reviews our field trial demonstration of up to 1.7-km wireless delivery of 20-Gb/s@85.5-GHz PDM-QPSK signal. Section V concludes our work.
II. KEY DEVICES FOR LONG-DISTANCE WIRELESS MM-WAVE DELIVERY AT W-BAND

A. LARGE-GAIN/HIGH-POWER W-BAND ELECTRICAL AMPLIFIER

The commercially available W-band EAs can have a large gain or a high output power [42]–[45], which will effectively extend wireless transmission distance when added into the wireless transmitter/receiver end.

Fig. 2 gives the gain performance of two large-gain W-band LNAs which are used in our experiment. We can see that, in the whole W-band, one LNA has about 25-dB gain while the other has about 35-dB gain. Fig. 3 shows the output power performance of a high-power W-band power amplifier (PA) which is also used in our experiment. We can see that the output power is over 20 dBm at 77–100 GHz band.

worth noting that the two W-band LNAs and the W-band PA are all specially ordered. In addition, we can see from Figs. 2 and 3 that the performance curves of the W-band EAs are not flat, but the advanced digital-signal-processing (DSP) employed in our experiment can compensate for it and good performance can be realized.

B. LARGE-GAIN SMALL-BEAMWIDTH CASSEGRAIN ANTENNA

Compared to the typical horn antenna (HA), CA has a large gain and a small half-power beamwidth at the cost of a large size and a heavy weight [26]–[30]. Table I gives the comparison of several key parameters of a typical HA and a typical CA. Fig. 4 gives the photos of a typical CA and a typical HA, respectively.

TABLE I
THE COMPARISON OF KEY PARAMETERS OF HA AND CA

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Horn Antenna (HA)</th>
<th>Cassegrain Antenna (CA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Range</td>
<td>75–110 GHz</td>
<td>75–110 GHz</td>
</tr>
<tr>
<td>Gain (dBi)</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>12°</td>
<td>0.8°</td>
</tr>
<tr>
<td>Polarization</td>
<td>H- or V-polarization</td>
<td>H- or V-polarization</td>
</tr>
<tr>
<td>XPD (dB)</td>
<td>&gt; 33</td>
<td>&gt; 35</td>
</tr>
<tr>
<td>Diameter (cm)</td>
<td>~1.8</td>
<td>30.5</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>~0.1</td>
<td>8.8</td>
</tr>
</tbody>
</table>

Fig. 4. Photos of CA: (a) front and (b) back. (c) Photo of HA.

\[ L = \frac{2D^2}{\lambda} \] (1)

Where D is the CA diameter and \( \lambda \) is the mm-wave operating wavelength. We measured beam power intensity distribution of the CA, and the measured average 3-dB beamwidth is about 0.7 m, from which we can derive that the half-power beamwidth of the CA is about 0.8° (2 tan\(^{-1}(0.7/2/50)\) ≈ 0.802°).
Assume that the two CW lightwaves used for heterodyne beating in Fig. 5 can be respectively expressed

\[ E_1(t) = a_1 \cos[2\pi f_1 t + \varphi(t)] \]  
\[ E_2(t) = a_2 \cos[2\pi f_2 (t - \tau) + \varphi(t - \tau)] \]

Where \( a_1 \) and \( a_2 \) denote the amplitude, \( f_1 \) and \( f_2 \) denote the carrier frequency, \( \varphi(t) \) and \( \varphi(t - \tau) \) denote the random phase noise due to the laser linewidth, and \( \tau \) denotes the time delay between the two CW lightwaves. Due to the time delay \( \tau \), \( \varphi(t) \) and \( \varphi(t - \tau) \) have the similar form but are staggered in time. The phase noise of the generated mm-wave after heterodyne beating entirely depend on the correlation between \( \varphi(t) \) and \( \varphi(t - \tau) \). Since the two CW lightwaves are generated from two identical free-running lasers, \( \varphi(t) \) and \( \varphi(t - \tau) \) are entirely irrelevant and can be considered to be two independent random functions. Thus, the phase noise of the generated mm-wave is equal to the sum of that of the two CW lightwaves, that is, twice of the laser phase noise. In addition, the time derivative of \( \varphi(t) \) can be approximated a Gaussian distribution, the average and root-mean-square values of which are equal to zero and the laser linewidth, respectively [46]. As a result, the doubled phase noise of the generated mm-wave also means its doubled linewidth compared to the laser linewidth. However, the phase noise of the generated mm-wave can be offset by advanced DSP at the receiver in our experiment and thus will not affect our system performance.

III. ANTENNA POLARIZATION MULTIPLEXING TECHNIQUE FOR LONG-DISTANCE WIRELESS MM-WAVE DELIVERY AT W-BAND

As mentioned in Table I, the CA has two orthogonal antenna polarization states, that is, horizontal-polarization (H-polarization) state and vertical-polarization (V-polarization) state. Fig. 7 shows the schematic diagram of the CA-based 2 × 2 MIMO wireless links based on one single antenna polarization and antenna polarization multiplexing, respectively [11]. For the CA-based 2 × 2 MIMO wireless link as shown in Fig. 7(a), two pairs of CAs are all at the same antenna polarization (H- or V-polarization). For the CA-based 2 × 2 MIMO wireless link as shown in Fig. 7(b), one pair of CAs is vertically polarized while the other pair is horizontally polarized. Here, take an optical polarization-division-multiplexing (PDM) signal after fiber transmission as an example. The optical PDM signal after fiber transmission is first up-converted to a wireless PDM signal at mm-wave frequency band by an optical polarization-diversity heterodyne up-converter, the structure of which will be intro-
duced in section IV. Then, the X- and Y-polarization components of the wireless PDM signal are independently broadcasted by two transmitter CAs into the air, and simultaneously received by two receiver CAs. It is worth noting that, at the input port of the optical heterodyne converter in Fig. 7, the polarization state of the optical PDM signal is arbitrary due to fiber transmission. Thus, the X- or Y-polarization component at the output port of the optical heterodyne converter contains a mix of the data which is simultaneously encoded on the X- and Y-polarization at the transmitter, and each transmitter CA actually transmits a dual-polarization signal. Here, we define one output port of the optical heterodyne up-converter as X-polarization component and the other as Y-polarization for simplification.

The received wireless power from one transmitter CA should be equal to that from the other transmitter CA, and otherwise the transmitted data cannot be effectively recovered from the received wireless signal at the wireless receiver. It is because the unequal wireless power from two transmitter CAs will cause the amplitude imbalance of the X- and Y-polarization components of the received wireless signal. When the amplitude imbalance is severe, the receiver-based DSP procedure will become ineffective and the system performance will be degraded [47]. In order to receive the same wireless power from two transmitter CAs, the position and direction of each receiver CA should be properly adjusted. For the $2 \times 2$ MIMO wireless link shown in Fig. 7(a), each receiver CA can simultaneously receive the wireless power from two transmitter CAs and wireless crosstalk may occur [19]. Moreover, the wireless crosstalk can become more severe with the increase of wireless transmission distance, which makes the proper adjustment of two receiver CAs difficult for long-distance wireless transmission. As mentioned in Table I, the cross polarization discrimination (XPD) can be over 35 dB between H- and V-polarization CAs. It means that, for the $2 \times 2$ MIMO wireless link shown in Fig. 7(b), the wireless crosstalk can be ignored and the receiver CA at one antenna polarization can only detect the wireless signal from the transmitter CA at the same antenna polarization. Thus, the CA adjustment for the $2 \times 2$ MIMO wireless link shown in Fig. 7(b) is much easier compared to the $2 \times 2$ MIMO wireless link shown in Fig. 7(a).

For the PDM signal, the fiber transmission and the $2 \times 2$ MIMO wireless delivery can be both considered based on a $2 \times 2$ MIMO model and denoted by a $2 \times 2$ Jones matrix. The multiplication of two $2 \times 2$ Jones matrices is still a $2 \times 2$ matrix. Thus, the classic constant-modulus algorithm (CMA) equalization can be used at the wireless receiver to simultaneously implement PDM signal polarization de-multiplexing and wireless crosstalk suppression [9]. When two pairs of CAs have a high directionality in the $2 \times 2$ MIMO link, X- and Y-polarization transmission links are parallel and each receiver CA can only get the wireless power from corresponding transmitter CA. Thus, no wireless crosstalk can occur and similar CMA taps are required whether the $2 \times 2$ MIMO wireless link is based on one single antenna polarization or antenna polarization multiplexing. However, when X- and Y-polarization transmission links are cross in the $2 \times 2$ MIMO link, each receiver CA can get the wireless power from two transmitter CAs if one single antenna polarization is adopted. Thus, wireless crosstalk occurs and longer-tap CMA equalization is required [19]. Particularly, when X- and Y-polarization transmission links also have different wireless transmission distance, a large equivalent differential group delay (DGD) effect will be caused and more additional taps are required [19]. However, if antenna polarization multiplexing is adopted, the pair of H-polarization CAs is well isolated from the pair of V-polarization CAs. Thus, not only wireless crosstalk can be effectively avoided, but also equivalent DGD effect can be effectively mitigated. Thus, in the cross-over case, the adoption of antenna polarization multiplexing can reduce the required CMA tap number and the calculation time.

IV. FIELD TRIAL OF LONG-DISTANCE WIRELESS MM-WAVE DELIVERY AT W-BAND

A. Experimental Setup

We experimentally demonstrated 1.7-km wireless delivery of 20-Gb/s@85.5-GHz PDM-QPSK signal with a BER less than $3.8 \times 10^{-3}$. Fig. 8 shows the corresponding experimental setup. At the transmitter central office (CO), the CW lightwave from ECL1 at 1549.39 nm is modulated by a 4~10-Gb/s electrical binary signal using an I/Q modulator, to generate optical QPSK signal. The electrical binary signal has a pseudo-random-binary-sequence (PRBS) length of 2$^{15}$−1 and is generated from a pulse pattern generator (PPG). The I/Q modulator has a 3-dB bandwidth of 31 GHz and half-wave voltage at 1 GHz of 2.5 V. The two parallel Mach-Zehnder modulators (MZMs) in the I/Q modulator are both biased at the null point and driven at the full swing, while the phase difference between the upper and lower branches of the I/Q modulator is controlled at $\pi/2$, to implement optical QPSK modulation. The I/Q modulator is fully
driven by a dual-input dual-output EA with the output power of 4.8 $V_{pp}$. The pigtailed of the ECL and I/Q modulator are polarization maintaining fibers. Then, after passing through a polarization maintaining Erbium-doped fiber amplifier (EDFA) with over 30-dB gain, the generated optical QPSK signal is polarization multiplexed by a polarization multiplexer to generate PDM-QPSK modulated optical baseband signal. The polarization multiplexer comprises a polarization-maintaining OC to split the signal into two branches, an optical delay line (DL) in one arm to provide a 150-symbol delay, an optical attenuator in the other arm to balance the power of two branches, and a polarization beam combiner (PBC) to recombine the signals.

At the transmitter base station (BS), the received PDM-QPSK modulated optical baseband signal is up-converted into two QPSK modulated wireless mm-wave signals at W-band enabled by optical polarization-diversity heterodyne up-conversion. ECL2 at 1549.70 nm functions as optical LO and has 85.5-GHz frequency offset relative to ECL1. Both ECL1 and ECL2, with linewidth less than 100 kHz and output power of 14.5 dBm, run freely without frequency-locking. Two polarization beam splitters (PBSs) and two OCs are used to implement optical polarization diversity of the optical baseband signal and the optical LO before heterodyne beating. Fig. 9 shows the X-polarization optical spectrum (0.1-nm resolution) after optical polarization diversity. It is worth noting that the atmospheric loss factor $L_A$ is considered as an 85.5-GHz PDM-QPSK modulated wireless mm-wave signal based on spatial division multiplexing. Fig. 10 gives the map display of the 1.7-km wireless transmission link. The wireless transmitter end is located in the 32th floor of Guanghua Building in Handan Campus, while the wireless receiver end in the 12th floor of a high building near Handan Campus. The field trial demonstration was realized on a sunny day.

According to the Friis transmission equation, we estimate the received power for a given transmitter power $P_T$, transmitter/receiver antenna gain $G_T/G_R$ and wireless transmission distance $d$. The received power $P_R$ is given by

$$P_R (dB) = P_T + G_T + G_R - 20 \log \left( \frac{4 \pi d}{\lambda} \right) - L_F - L_A \times d$$

(4)

Where $\lambda$ is the transmission wavelength and $L_F$ is the loss of antenna feedline, $L_A$ is the atmospheric loss factor, and $L_A$ at W-band is 0.5 dB/km [25] on a sunny day. The term $20 \log(4 \pi d/\lambda)$ denotes the path loss. The atmospheric loss is about 0.85 dB and the path loss is about 135.65 dB for 1.7-km wireless mm-wave delivery. In our experiment, $P_T$ is 21 dBm, $G_T$ and $G_R$ are both 45 dB, and $L_F$ is 3 dB, which results in the predicted received power of -28.5 dBm for 1.7-km wireless mm-wave delivery at an 85.5-GHz center frequency. This predicted received power is close to our measured results of -31 dBm considering some additional loss such as adapter mismatching. It is worth noting that the atmospheric loss factor $L_A$ at W-band may be significantly increased in severe weather. For example, $L_A$ at W-band is about 10 dB/km on a heavy rainy day with a 25-mm/h rainfall [48]. In this scenario, the atmospheric loss will be significantly increased to about 17 dB for 1.7-km wireless mm-wave delivery. However, compared to 135.65 dB-path loss in our 1.7-km wireless delivery experiment, the 17-dB atmospheric loss on a heavy rainy day is still very small. As a result, the wireless transmission distance will be only slightly shortened on a heavy rainy day to maintain the same system performance.

At the receiver BS, the received 85.5-GHz PDM-QPSK modulated wireless mm-wave signal first passes through two parallel W-band LNAs, the gain curve of which is shown in Fig. 2(a), and then in the analog domain, is down-converted to a
10.5-GHz intermediate-frequency (IF) signal by two parallel balanced mixers. Each balanced mixer has 7-dB conversion loss and is driven by a 75-GHz RF LO signal. The 75-GHz RF LO signal is generated by cascaded frequency multiplication of a 12.5-GHz RF LO signal, that is, the 12.5-GHz RF LO signal is first frequency doubled by an active frequency doubler ($\times 2$) and a narrowband EA in serial, then halved into two components by a power divider, and finally each 25-GHz component is further frequency tripled by a passive frequency tripler ($\times 3$) and a broadband EA in serial. Then, a DC $\sim$ 40 GHz EA after each balanced mixer is used to boost the X- or Y-polarization component of the 10.5-GHz IF signal before it is sent into a digital storage oscilloscope (OSC) for analog-to-digital conversion. Each DC $\sim$ 40 GHz EA has 35-dB gain and 22-dBm saturation power. The OSC has 50-GSa/s sampling rate and 20-GHz electrical bandwidth. The subsequent offline DSP includes IF down conversion, chromatic dispersion (CD) compensation, CMA equalization, carrier recovery, differential decoding and BER counting [49]. The carrier recovery includes frequency-offset estimation (FOE) based on a fast Fourier transform (FFT) method and carrier phase estimation (CPE) based on fourth-power Viterbi-Viterbi algorithm. The BER in this experiment is calculated over $10^6 \times 10^6$ bits (10 data sets, and each set contains $10^6$ bits).

B. Experimental Results

Fig. 11 shows the measured BER versus the bit rate after 1.7-km wireless PDM-QPSK signal delivery. The BER increases with the increase of bit rate, and the BER is less than $3.8 \times 10^{-3}$ when the bit rate is up to 20 Gb/s. Fig. 12 shows the measured BER versus the wireless transmission distance at different bit rates (20 Gb/s and 40 Gb/s). In the case of adopting W-band PAs, the BER for the 20-Gb/s PDM-QPSK signal is less than $3.8 \times 10^{-3}$ when the wireless transmission distance is up to 1.7 km. After removing W-band PAs, the BER for the 20-Gb/s PDM-QPSK signal reaches $3.8 \times 10^{-3}$ when the wireless transmission distance is only 650 m. Thus, we can conclude that the adoption of W-band PAs in our experiment significantly extends the wireless transmission distance. Also, in the case of removing W-band PAs, the wireless transmission distance is significantly shortened when the bit rate increases from 20 Gb/s to 40 Gb/s, and the BER for the 40-Gb/s PDM-QPSK signal reaches $3.8 \times 10^{-3}$ at a wireless transmission distance of only 170 m. It is mainly because higher-speed signal at W-band will need more input power after long-distance wireless delivery.

 Insets (a)–(c) in Fig. 12 show the measured 10.5-GHz IF signal spectrum after analog down conversion as well as the recovered X-polarization and Y-polarization constellations for the 20-Gb/s PDM-QPSK signal after 1.7-km wireless delivery, respectively. The relatively high signal-to-noise ratio (SNR) of the measured IF signal spectrum and the clearness of the recovered QPSK constellations further verify the feasibility of our proposed transmission link for long-distance wireless mm-wave signal delivery at W-band.

It is worth noting that the wireless transmission links measured in Fig. 12 are all line-of-sight (LOS). However, different from the mid-air 1.7-km wireless transmission link given in Fig. 10, the relatively short wireless transmission links below 1 km, are all built on a flat ground in Handan Campus. This is because potential interferences, such as buildings, trees, pedestrians, and so on, can be avoided and LOS can be attained on the ground when the wireless transmission links are short enough. Also note that in the measurement of both Figs. 11 and 12, the wireless transmitter power is fixed at 21 dBm.

V. CONCLUSION

We experimentally demonstrated 20-Gb/s@85.5-GHz PDM-QPSK signal delivery over a 1.7-km CA-based $2 \times 2$ MIMO wireless link based on photonic mm-wave generation and antenna polarization multiplexing. The adoption of two parallel W-band PAs at the transmitter end significantly promotes the extension of the wireless transmission distance.

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