CPRI-equivalent Data Rate of 3.12 Tbps 16384QAM DSM 300GHz Terahertz Wave Signals over Hollow-core Fiber

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Abstract: We experimentally demonstrate ultra-large-capacity hybrid fiber and THz-Wave wireless fronthaul over 2-km hollow-core fiber and 2-m wireless distance based on 80 channel WDM and DSM, achieving CPRI-equivalent data rate of 3.12 Tbit/s.

1. Introduction

With the increase in the number of mobile Internet terminals, network data traffic has exploded, and the common public radio interface (CPRI) with low spectral efficiency in mobile fronthaul (MFH) has become a bottleneck for further improvement of transmission capacity [1,2]. In additional, in the CPRI-based MFH link, the antenna unit in the MFH link requires devices such as DACs to restore analog signals, which is extremely detrimental to 5G communications that require the deployment of a large number of micro base stations [3]. In order to achieve high-fidelity transmission while taking into account the simplicity of the system architecture, researchers have turned their attention to Delta-Sigma Modulation (DSM) technology. In the DSM-based MFH architecture, the antenna unit can utilize filters for analog signal recovery without the need for additional DAC devices, which greatly simplifies the system architecture of the MFH [4,5]. In addition, the terahertz (THz) frequency band has received widespread attention from researchers due to its huge bandwidth resources and license-free characteristics [6]. Under the Radio-over-Fiber (RoF) architecture, combining photonics-aided THz communication with fronthaul links can achieve high-speed wireless fronthaul networks, which is of great significance for areas where fiber optic links are difficult to deploy directly [7,8]. However, the signal transmitted over the MFH link is usually the OOK signal after quantization and encoding of the analog waveform. In order to generate high-quality THz-wave OOK signals, a reliable scheme is to use two beams of modulated light carrying the same modulation information with a frequency interval of THz band for heterodyning. However, when two light waves with a frequency interval of THz are transmitted over fiber link, the wavelength walk-off effect caused by dispersion will cause a time shift in the encoding codes on the two light waves, resulting in severe inter-symbol interference [9].

In this paper, we successfully solve the wavelength walk-off problem with the help of low-dispersion hollow-core fiber (HCF) and experimentally demonstrate ultra-large-capacity hybrid fiber and THz-wave wireless fronthaul based on WDM and DSM, which can support mobile fronthaul of up to 38-channel base stations at the same time. To the best of our knowledge, this is the first demonstration of ultra-large-capacity hybrid fiber and terahertz wave wireless fronthaul experiments.

2. Experimental setup

Fig. 1 depicts the principle and experimental setup of an ultra-large-capacity hybrid fiber and THz-Wave wireless fronthaul system. We combine 80 ECLs with a linewidth less than 100 kHz (1530 to 1563 nm) and a tunable wavelength covering the entire C-band using two polarization-maintaining array waveguide gratings (PM-AWG) to form an 80-channel WDM with a frequency interval of 50 GHz, where half are odd channels and the other half are even channels. In the Tx off-line DSP, PRBS is used for QAM mapping and then OFDM modulation. The IFFT size is 1024, the effective subcarrier is 900. It should be noted that the frequency-domain Hermite conjugation method is adopted to obtain the real-valued signal in the time domain. After up-sampling, the OFDM signal is sent to the 1-bit quantization DSM modulator for quantization. Afterwards, the generated OOK-DSM signal is imported into the 64-GSa/s AWG to generate baseband electrical signals. We deploy the EA to amplify the output of two separate electrical signals and drive two 35 GHz IM modulators in odd and even channels respectively. After adjusting the DC-bias points of the IMs, a baseband optical signal is generated at each optical carrier frequency fc_i (i=1, 2, …,80). Subsequently, a PM-OC is utilized to combine the optical signals in the odd and even channels. After PM-EDFA adjusted the power, we conducted SMF-28 and HCF transmissions, respectively.

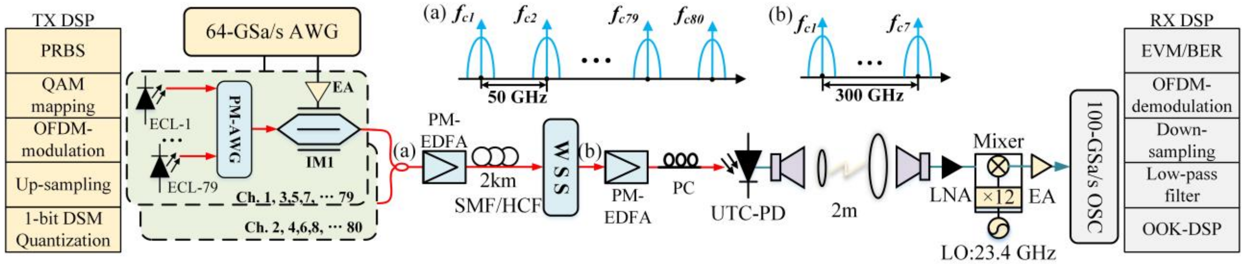

Fig. 1. Experimental setup of ultra-large capacity hybrid fiber and THz-Wave wireless fronthaul based on WDM and Delta-Sigma Modulation; (a) the schematic diagram of IM output; (b) the schematic diagram of WSS output.

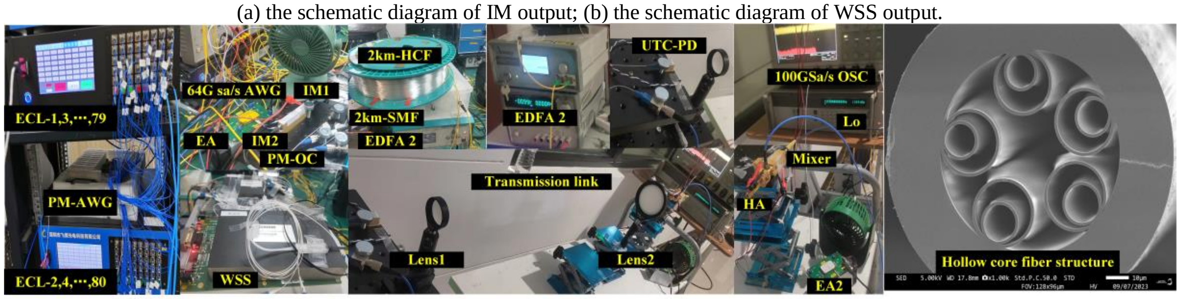

Fig. 2. Photos of experimental setup.

To generate THz signals, a wavelength selective switch (WSS) is used to select the modulated optical of each test WDM channel and the modulated optical spaced 300 GHz apart, such as ch. 1 and ch. 7. Repeat this process across the band until all 74 channels have been measured. Afterwards, another EDFA is utilized to adjust the input power into the UTC-PD, and the polarization controller (PC) is used to control the polarization state of the input optical signal into the UTC-PD, which can maximize the strength of the generated THz signal. The generated THz-wave signal is collimated by the lens and then launched into free space for 2 m wireless transmission. At the receiver, the received THz signal is first amplified by an LNA and then analog down-converted through a ×12 mixer. The received IF signal frequency is 300-23.4×12=19.2 GHz. The IF signal is amplified by EA and then captured by a 100-GSa/s OSC with 33-GHz bandwidth. The DSP at the receiving end includes digital down-conversion, the OOK traditional algorithm, low-pass filtering, down-sampling, and OFDM de-modulation. Among， the traditional algorithms of OOK including 31-tap FFE and a 5-tap DFE. Fig. 2 shows photos of an ultra-large-capacity fiber and THz hybrid wireless fronthaul system, including photos of an 80-channel WDM optical source, transmitter, receiver, transmission link, and structural diagram of HCF. Among them, the cladding diameter of HCF is 251.22 um, the nonlinear coefficient is 0.0047 $W^{-1}\cdot km^{-1}$, the C-band dispersion coefficient is about 5 ps/nm/km, and the actual measured transmission loss including splicing loss is 5.2 dB/km.

3. Results and discussion

We first conducted a dual-wavelength transmission experiment and tested 2 km-SMF and 2 km-HCF, respectively. Fig. 3(a) shows the power spectrum of the received signal. It can be seen that after SMF transmission, there is a spectrum null at the 8 GHz frequency, which is caused by the walk-off effect between the two wavelengths. In contrast, HCF does not suffer from similar problems. Fig. 3(b) shows the optical spectra of the 80-channel WDM signal. It can be found that after 2 km-HCF transmission, signals in the short wavelength range exhibit greater transmission loss, resulting in uneven optical spectra. Fig. 3(c) shows the optical spectra with a wavelength interval of 300 GHz after WSS filtering and EDFA amplification. In the three transmission scenarios of BTB transmission, SMF transmission, and HCF, the measured OSNRs are 32.5 dB, 31.5 dB, and 19 dB, respectively. Therefore, to ensure high-quality transmission, we utilize Pre-EDFA to perform an extra 7 dB of optical power amplification before HCF transmission, which compensates for the OSNR penalty. Fig. 3(d) shows the corresponding results. Compared with the transmission without pre-EDFA, the signal quality is significantly improved. When the optical power into UTC-PD is 14 dBm, transmission with a BER lower than 1×10^{-4} can be achieved. Fig. 3(e) shows the power of optical signals of different wavelengths after 2-km HCF transmission. It can be found that short-wavelength optical signals have higher power loss, which well explains the reason for the uneven spectra in Fig. 3(b). Fig. 3(f) shows the measurement results of 74 channels with a ROP of 14 dBm. It can be found that under the conventional FFE-DFE equalization algorithm, most wavelengths in the short wavelength region cannot achieve transmission below the 1×10^{-4} level. By cascading post-filtering (PF) with a coefficient of 0.3 and the Maximum

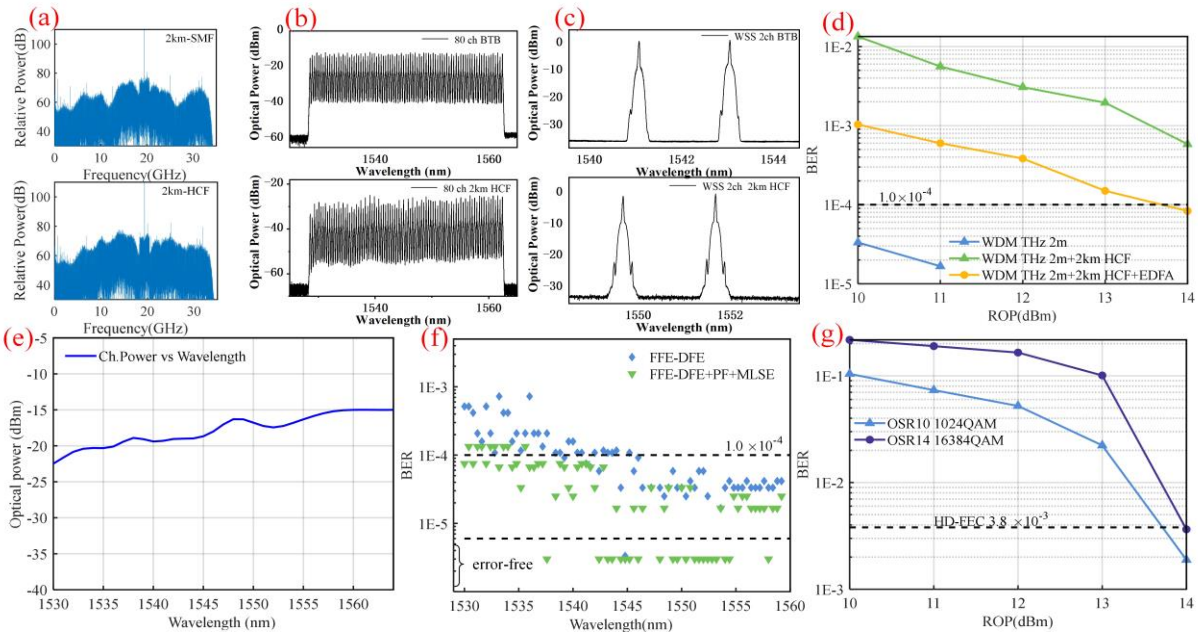

Fig. 3: (a) Received signal power spectrum; (b) WDM optical spectra; (c) WSS output optical spectra; (d) BER versus input power into UTC-PD for 24-GBaud OOK-DSM signal; (e) Measured channel power versus wavelength; (f) BER of all 74 channels 24-Gbaud OOK-DSM with ROP of 14dBm; (g):1024/16384QAM signals BER versus ROP@1548 nm.

Likelihood Sequence Estimation (MLSE) algorithm after FFE-DFE equalization, the BERs of some signals was successfully reduced to below the 1×10^{-4} level. If the power gain of the pre-EDFA can be increased, then 80 channels should be capable of achieving a BER below the level of 1×10^{-4}. During the experiment, we transmitted two DSM signals: the first was an OOK signal generated by quantizing the 1024QAM-OFDM signal under 10 times OSR, and the second was an OOK signal quantized by 16384QAM-OFDM under 14 times OSR. Fig. 3(g) shows the corresponding results, where the test wavelength is 1548 nm and the ROP is 14 dBm. The corresponding OOK can achieve error-free transmission. It can be seen that when the ROP is 14 dBm, both the corresponding 1024QAM and 16384QAM can achieve transmission that meets the HD-FEC threshold of 3.8×10^{-3}. The EVM of 1024QAM is 1.77% and the EVM of 16384QAM is 0.54%, meeting the EVM requirements of 2.5% and 0.68%, respectively. The SNR of 1024QAM is 35 dB, the SNR of 16384QAM is 45 dB, and the corresponding BERs are 1.8×10^{-3} and 3.6×10^{-3} respectively. When OSR is 10, the actual transmission bandwidth is 2.4 GHz, and the supported fronthaul rate is 2.4×450/1024×10×74=780 Gbit/s, and the CPRI-equivalent data rate is 74×2×2.4×450/1024×16×10/8=3.12 Tbit/s [10].

4. Conclusions

For the first time, we experimentally demonstrate ultra-large-capacity hybrid fiber and THz-Wave wireless fronthaul based on WDM and DSM technology. Thanks to the higher quantization SNR of DSM, the demonstration system supports mobile transmission of 1024/16384 QAM signals. In an 80-channel WDM system with 50-GHz spacing, the supported fronthaul rate reaches 780 Gbit/s, and the CPRI-equivalent data rate is 3.12 Tbit/s. The demonstrated WDM architecture can support mobile fronthaul of multiple base station units at the same time, which providing a promising solution for the future implementation of centralized/cloud RAN (C-RAN).

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