Spectrally Efficient Dual Signal Transmission in Direct-Detection THz Communication System

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***Abstract*—We proposed a spectrally efficient dual signal transmission scheme for direct-detection THz communication system. The simultaneous transmission of two independent 10-GBd QPSK single-sideband signals with an overlapped spectrum at 300 GHz band is demonstrated experimentally.**

***Keywords*—dual signal transmission, THz communication, single-sideband modulation, direct detection**

I. Introduction

As is well known, the new sixth generation (6G) communication networks should support a large number of user connections and multifarious data services, which puts forward an urgent need for the high-bandwidth and large-capacity communications. The THz wireless communication, which can provide extremely rich spectrum resources, is expected to play an important role in the 6G networks. It has an extensive application prospect in the future inter-satellite communication and space-earth integrated communication, as well as the wireless backhaul for optical fiber replacement. Figure 1 shows the concept diagram of THz wireless backhaul, in which the aggregated data from multi-user and multi-service can be transmitted via a large-capacity THz wireless link. This is quite suitable for the regions/scenarios where the optical fiber access is difficult or costly. On the other hand, to reduce the deployment cost and power consumption of THz wireless communication, the direct detection solution is more competitive than the coherent detection scheme [1]. In a direct-detection THz communication system with the fixed bandwidth, how to achieve the efficient and cost-effective transmission of different signals from multiple users and multiple services is a key problem worth studying [2].

Other than adopting commonly used wavelength division multiplexing technique, many previous works have strived to achieve the simultaneous transmission of two or more signals on a single optical/wireless carrier in the hybrid fiber and wireless links. Two independent wireless signals are successfully transmitted and demodulated with overlapped double-sideband spectra via the single-polarization [3] or dual-polarization [4] microwave photonic links, which significantly improve the spectral efficiency (SE) of traditional double-sideband (DSB) transmission scheme. Additionally, an enhanced SE can also be achieved through twin single-sideband (SSB) technique for dual signal transmission with non-overlapped spectra [5]. However, the above schemes are mainly demonstrated through the optical or wireless coherent receiver, which is not applicable to the direct detection THz system.

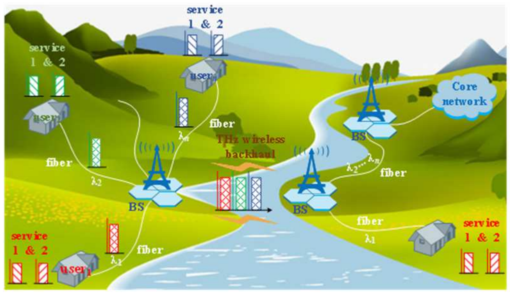

Fig. 1. Concept diagram of multi-user and multi-service THz wireless backhaul.

In this paper, we proposed a spectrally efficient dual signal transmission scheme for direct detection THz communication system enabled by photonics. Two independent wireless signals based on SSB modulation, can be simultaneously transmitted over a single optical and THz carrier with an overlapped spectrum, and successfully recovered in the DSP after simple envelope detection. The feasibility of proposed overlapping SSB scheme is verified in a direct-detection THz communication system. Two independent overlapping 10-GBd quadrature phase-shift keying (QPSK) SSB signals are successfully transmitted over 20-km standard single-mode fiber (SSMF) and 3-m wireless at 300 GHz band. Only one zero-bias diode (ZBD) THz receiver is used in our experiment to detect and recover the above overlapping dual SSB signals. Utilizing this scheme, the transmission SE of dual signals is nearly twice as much as that of the previous twin SSB [5] and four times that of traditional the DSB scheme.

II. Experimental Setup

Figure 2 shows the experimental setup of the proposed overlapping SSB scheme for dual signal transmission in the 300-GHz direct-detection THz communication system.

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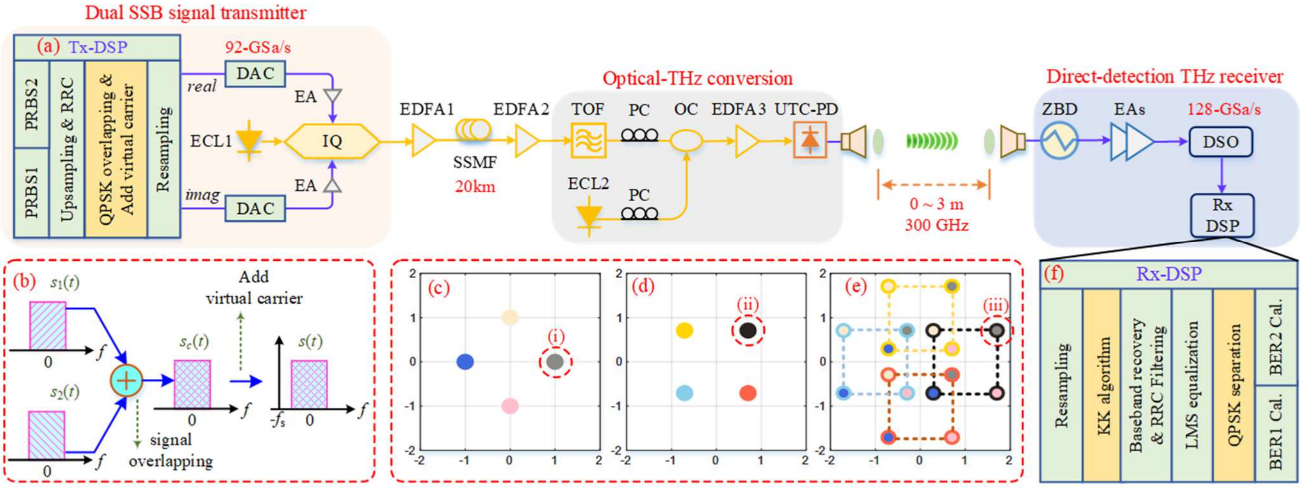

Fig. 2. Experimental setup of 300-GHz direct-detection THz communication system with overlapping SSB scheme for dual signal transmission. (a) Transmitting DSP; (b) Generation of overlapping SSB signal; (c)-(e) Constellations of original two QPSK signals and the overlapped signal; (f) Receiving DSP.

Firstly, for simplicity, the dual SSB signal generation is emulated in the transmitting DSP. Noting that our proposed scheme supports different modulation formats similar to Ref. [2], however, two QPSK signals are taken as an example for experimental verification in this paper. As shown in Fig. 2(a), two sets of independent pseudo-random binary sequences (PRBSs) with the same length of 2^{18} are mapped into the QPSK symbols with different initial phases of 0º and 45º, respectively. Assume that the two independent QPSKs are represented by $s_1(t)$ and $s_2(t)$. Subsequently, an overlapping SSB signal with virtual carrier can be obtained by the operation of $s(t) = V_C + s_1(t) + s_2(t)$. The $V_C = exp[-j2\pi f_s t]$ denotes the added virtual carrier. By changing the values of V_C and f_s, the carrier-to-signal power ratio (CSPR) and guard band (GB) of the obtained overlapping SSB signal can be adjusted, respectively. From the schematic diagram as shown in Fig. 2(b), it can be found that two independent SSB signals are combined with an overlapped spectrum, which can enable efficient transmission. At this case, for the superposition of two low-order QPSK signals as shown in Fig. 2(c) and (d), it eventually presents a high-order star sixteen quadrature amplitude modulation (16QAM) format as shown in Fig. 2(e). Each symbol in Fig. 2(e) has a one-to-one mapping relationship between the symbols in Fig. 2(c) and (d), which can be observed from the points with the corresponding colors in the outer ring and inner circle. For instance, the symbol of (iii) is the superposition of symbol (i) and symbol (ii).

Afterwards, the real and imaginary parts of digital overlapping SSB signal with virtual carrier are converted to analog signal by two 92-GSa/s digital-to-analog converters (DACs), and then are fed to an IQ modulator for electro-optic modulation. The IQ modulator is biased at minimum transmission point, hence the above overlapping SSB signal can be linearly converted from electrical domain to optical field. A free-running tunable external cavity laser (ECL1) with a central wavelength of 1549.316 nm and power of 14 dBm is used as the input laser. After transmission over a 20-km SSMF, the optical overlapping SSB signal are fed to the optical-THz conversion module.

At the optical-THz conversion module, a tunable optical filter (TOF) is first used to suppress the out-of-band amplified spontaneous emission noise resulting from the erbium-doped fiber amplifiers (EDFAs). Then the received signal light is coupled with an optical local oscillator (i.e., ECL2) which has a frequency offset of about 300 GHz relative to ECL1. Two polarization controllers (PCs) are used to adjust the polarization states of signal light and local oscillator light, respectively. After amplified by EDFA3, the coupled optical signals are fed into a uni-traveling carrier photodiode (UTC-PD), thus a 300-GHz THz overlapping SSB signal which actually contains two independent QPSK SSB signals can be generated via optical heterodyne detection. The output THz signal is then transmitted over 3-m wireless distance via a pair of horn antennas. Two PTFT lenses with a focal length of 20 cm are used to collimate the THz wave.

At the direct-detection THz receiver, the received 300-GHz THz overlapping SSB signal is directly detected via one single low-cost and power-consumption ZBD. Subsequently, the down-converted IF signal is amplified by two cascaded electrical amplifiers (EAs) with the total gain of about 33 dB, and then is sampled via a 128-GSa/s digital storage oscilloscope (DSO) for offline DSP demodulation. The detailed receiving DSP workflow is shown in Fig. 2 (f). Firstly, after resampling, the Kramers–Kronig (KK) algorithm is adopted to reconstruct the overlapping SSB vector field from the detected intensity information and simultaneously eliminate the signal-to-signal beating interference (SSBI) caused by square-law envelope detection [6]. Secondly, an overlapping baseband signal with a standard star 16QAM constellations can be obtained through the baseband recovery, root raised cosine (RRC) filtering and least mean square (LMS) equalization. Next, two independent QPSK symbols are separated from the above overlapping baseband signal, according to the one-to-one mapping relationship given as Fig. 2(c) ~ (d). Finally, the symbol de-mapping and bit error ratio (BER) calculation are conducted. At this point, the efficient transmission and successful recovery of two different wireless data has been achieved via a simple direct-detection THz link.

III. Results And Discussions

With an optimal CSPR of 9 dB, we first investigate the impact of guard band (GB) on overlapping SSB transmission under two receiving schemes with (w/) and without (w/o) KK algorithm. The results are shown in Fig. 3. Due to the existence of SSBI, the signal-to-noise ratio (SNR)

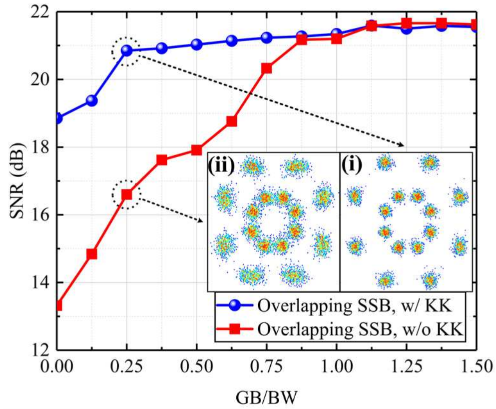

Fig. 3. Impact of GB on overlapping SSB transmission. Insets (i) and (ii) show the constellations of recovered star 16QAM with and without KK algorithm.

performance of without KK scheme improves with the increase of GB, and become stable until reaching full protection interval (i.e., GB equals to the signal bandwidth BW). Instead, after using KK algorithm, the SNR can basically maintain stable when GB is only 0.25 times of BW. This mainly benefits from effective SSBI elimination. Considering the trade-off between the transmission SE and receiving performance, the GB is set to 0.25 BW for KK receiving scheme in our following verification.

Next, the receiving sensitivity of the 300-GHz direct-detection THz system for dual signal transmission is also studied. After a hybrid optical-wireless transmission over 20-km SSMF and 1-m wireless distance, the BER versus received optical power (ROP) of UTC-PD for three different baud rate cases (2, 6, and 10 GBd) are shown in Fig. 4. To protect the UTC-PD from being damaged, the ROP is controlled to no more than 13 dBm. It can be seen that the two independent QPSK signals, which are recovered from an overlapping SSB spectrum, have similar BER performances under different transmission rates. Moreover, for the 2-GBd case, the optimal ROP is found at 12 dBm. However, the value increases with the increment of signal transmission rate. In addition, to meet the 7% overhead hard-decision forward error correction (HD-FEC) BER threshold (i.e., 3.8×10^{-3}), the required ROP for 2-GBd and 6-GBd cases are 10.5 dBm and 11.5 dBm, respectively. Accordingly, the power penalty of only 1 dB is present at the two different transmission rates. In contrast, the required ROP for the 10-GBd case to reach the 7% HD-FEC and 20% soft-decision FEC (SD-FEC) threshold (i.e., 2×10^{-2}) are above 13 dBm and 11.7 dBm, respectively.

To further evaluate the transmission performance of overlapping SSB scheme, we test the BER performance versus different wireless distances and baud rates under a fixed ROP of 13 dBm. As shown in Fig. 5 (a), with the wireless distance varying from back-to-back to 3 m, the BERs of two independent 10-GBd QPSK signals can all meet the threshold of 20% SD-FEC. Figure 5 (b) shows the photo of the 3-m THz wireless link. On the other hand, after transmission over 20-km SSMF and 1-m wireless, the maximum baud rates for dual QPSK signal transmission to meet the 7% HD-FEC and 20% SD-FEC thresholds are around 8.5 GBd (34 Gbps) and 13 GBd (52 Gbps). The main limitation factors of transmission rate are the low optical-THz conversion efficiency and the limited SNR of the direct-detection THz receiver at 300 GHz band [1]. However, the system performance may be significantly improved if available THz amplifier is used.

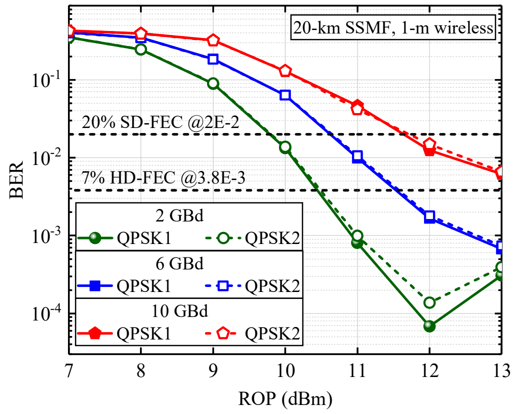

Fig. 4. Receiving sensitivity of the 300-GHz direct-detection THz system for dual signal transmission over 20-km SSMF and 1-m wireless distance.

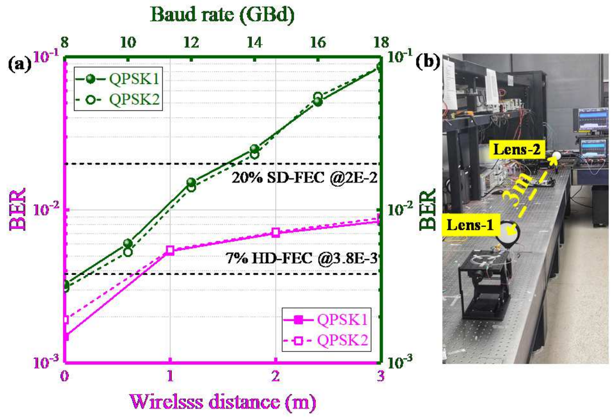

Fig. 5. (a) BER versus different wireless distances and baud rates for dual signal transmission. (b) Photograph of the 3-m THz wireless link.

IV. Conclusion

We propose and experimentally demonstrate an overlapping SSB scheme for spectrally efficient dual signal transmission in the low-cost direct-detection THz link. Two independent wireless signals can be simultaneously transmitted over an identical optical/THz carrier, and successfully recovered via a single KK-based direct-detection THz receiver. The feasibility of proposed scheme is verified by two 10-GBd QPSK signals transmitting over 20-km fiber and 3-m wireless at the 300 GHz band. It can achieve the efficient and cost-effective transmission of multi-service data in direct-detection THz link for wireless backhaul.

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