Mitigating the Timing-Jitter in Terahertz Communications via Nyquist Pulse Shaping

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Abstract: We propose and experimentally demonstrate a Nyquist pulse that can improve the error rate of a 311 GHz photonic-terahertz communications system by more than an order of magnitude at a normalized timing-jitter of 22.5% and 1.44 Gbit/s bit rate.

1. Introduction

Terahertz technology is a key enabler for 6G communications as it makes it possible to access ample spectral resources in the terahertz band, namely, from 100 GHz to 10 THz. However, the generation of terahertz signals is usually accompanied by phase noise, which becomes noticeable as random timing-jitter in their corresponding baseband signals at the receiver (Rx) side. In terahertz communications, the measured time-jittering can be as high as 25 ps at 12 Gbit/s, which corresponds to about 30% of the symbol duration [1]. This timing-jitter gives rise to imperfect synchronization between the transmitter (Tx) and the receiver, which severely deteriorates the bit error rate (BER) performance [2]. To put into perspective, at a signal-to-noise ratio (SNR) of 15 dB, the BER of a binary phase shift keying (BPSK)-modulated raised-cosine (RC) pulse is in the order of 10^{-16} in the absence of timing-offset. This BER rises to about 10^{-4} when the BPSK signal experiences a timing offset of about 20% of the symbol duration. Although the RC pulse is widely adopted in terahertz communications due to its spectral efficiency, the severity of time-jittering on the BER performance of this pulse has not been investigated. This is because, in most of the previous demonstrations of terahertz communications, it has been a common practice to incorporate the timing-jitter compensation into the digital signal processing (DSP) at the receiver side, which is often implemented offline. However, in real-time, mitigating the time-jittering can be a challenging DSP task, especially for receivers with limited computational resources and high baud rates. To reduce the severity of this problem, Nyquist pulses other than the RC pulse have been proposed, such as the better-than RC (BTRC) pulse [3]. These pulses have rapidly decaying profiles so that the power contained in their time-domain sidelobes is reduced. This way, the inter-symbol interference arising from the interaction between adjacent pulses decreases and consequently, the BER can be improved. Here, we experimentally investigate the BER performance of the RC and BTRC pulses in the presence of time-jittering using a 311 GHz photonic-terahertz communications system. Experimental results show that, unlike optical communications, in terahertz communications, the RC and BTRC pulses are almost equivalent in terms of the BER performance. More importantly, we also propose and experimentally demonstrate a Nyquist pulse that can outperform both pulse shapes in terms of the BER by an order of magnitude at a normalized timing-jitter of 22.5% and a bit rate of 1.44 Gbit/s.

2. Proposed Nyquist Pulse

The proposed pulse is defined mathematically as follows [4]:

$$p(t) = \frac{\gamma T_s}{\gamma\alpha^- + T_s}\left\{\frac{\alpha^- \operatorname{sinc}\left(\frac{\alpha^- t}{T_s}\right)}{T_s} + \frac{\cos\left(\frac{\pi\alpha^- t}{T_s}\right) - \left(\frac{\pi t}{\gamma}\right)\sin\left(\frac{\pi\alpha^- t}{T_s}\right)}{\gamma + \left(\frac{\pi^2 t^2}{\gamma}\right)}\right\}\operatorname{sinc}\left(\frac{t}{T_s}\right), \tag{1}$$

where $\alpha^- = 1-\alpha$, $\gamma = \zeta T_s$, T_s is the symbol duration and α is the roll-off factor of the conventional RC and BTRC pulses [3]. The parameters α and ζ are dimensionless and can be used to flexibly control the temporal and spectral characteristics of their relevant pulses, i.e., the decay rate in the time-domain and the stop-band attenuation in the frequency-domain. The derivation of (1) is detailed in [4] and [5]. We set α to 0.35 for the RC and BTRC waveforms as this value is commonly used in terahertz communications [6]. However, for the proposed waveform, the analysis presented in our previous work [4] shows that, for the proposed pulse shape, the effective signal-to-noise ratio (SNR) per symbol is almost independent of α in the range $0 \leq \alpha \leq 0.5$. Therefore, here, we set α to zero to simplify the analysis without significantly affecting the results. Additionally, reducing ζ below 10.47 unit-less does not improve the effective SNR per symbol.

3. Experiment and Results

We experimentally demonstrate the transmission performance of the three considered pulse shapes using the setup shown in Fig. 1, which is similar to that used in [5]. As shown in this figure, at the Tx side, a 64 GSample/s arbitrary waveform generator (AWG) generates a BPSK-modulated baseband signal at a data rate of 1.44 Gbit/s and a peak voltage of $V_p = 300$ mV. Two optical carriers at 193.5000 THz and 193.8100 THz are emitted by the dual-channel continuous wave tunable laser source (CW-TLS) and combined by a 50:50 optical coupler (OC). The Mach-Zehnder modulator (MZM) modulates the generated baseband signal onto the optical carriers. After that, the modulated optical signal is amplified before being forwarded to the uni-travelling carrier photo-diode (UTC-PD) for photo-mixing. The terahertz carrier frequency is 311.00 GHz. The SNR at the Rx side is controlled by changing the UTC-PD photo-current at the Tx side. At the Rx side, the baseband envelope of the received terahertz signal is detected via the SBD and the free space path loss is compensated by a 30 dB low-noise amplifier (LNA). The amplified signal is then sampled by a 80 GSample/s real-time oscilloscope (RTO), which records the sampled signal for offline DSP as illustrated in Fig. 1. The recorded signal is down-sampled from 80 GSample/s to 64 GSample/s to match the AWG sampling rate, and a 44-taps moving average (MA) filter is applied to the down-sampled signal for denoising.

The robustness of the three considered pulse shapes to the time-jittering is investigated as follows. First, the Tx-Rx synchronization is recovered by estimating the optimum delay that maximizes the cross-correlation of the transmitted and received sequences. Second, a pre-determined timing-offset of δt is introduced to the synchronized signal before matched filtering and BER evaluation. Figure 2(a) plots the BER versus the normalized timing-offset for the three considered pulse shapes at an emitted terahertz power of $P_{\text{THz}} = -13.3$ dBm. The eye diagrams in the same figure are plotted for the three pulses at $\delta t = 0.05T_s$. As shown in this figure, at $\delta t = 0.35T_s$, the BER performance of the proposed pulse is improved by about an order of magnitude compared to the RC and the BTRC pulses. Additionally, whilst the RC and the BTRC pulses show a minimum BER of 3.2×10^{-3} over the range $0 \leq \delta t < 0.225T_s$, the proposed Nyquist pulse shows error-free transmission over the same range. Also, the eye diagrams in Fig. 2(a) are in line with the BER performance of the corresponding pulses. In these diagrams, the proposed pulse shows wider eye opening compared with the RC and BTRC pulses, which exhibit similar eye widths.

The survivability of the proposed Nyquist pulse, compared with the RC and BTRC pulses, in the presence of

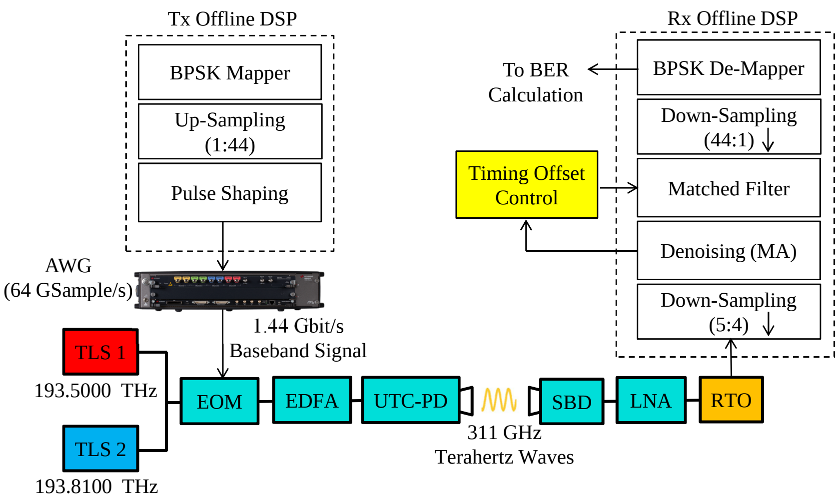

Fig. 1. Block diagram of the experimental setup including the receiver processing. TLS: tunable laser source. Tx: transmitter. BPSK: binary phase shift keying. AWG: arbitrary waveform generator. EOM: electro-optic modulator. EDFA: erbium doped fiber amplifier. UTC-PD: uni-traveling carrier photo-diode. SBD: Schottky-barrier diode. RTO: real-time oscilloscope. LNA: low-noise amplifier. MA: moving average. Rx: receiver. DSP: digital signal processing. The maximum sampling rate of the AWG is 65 GSample/s.

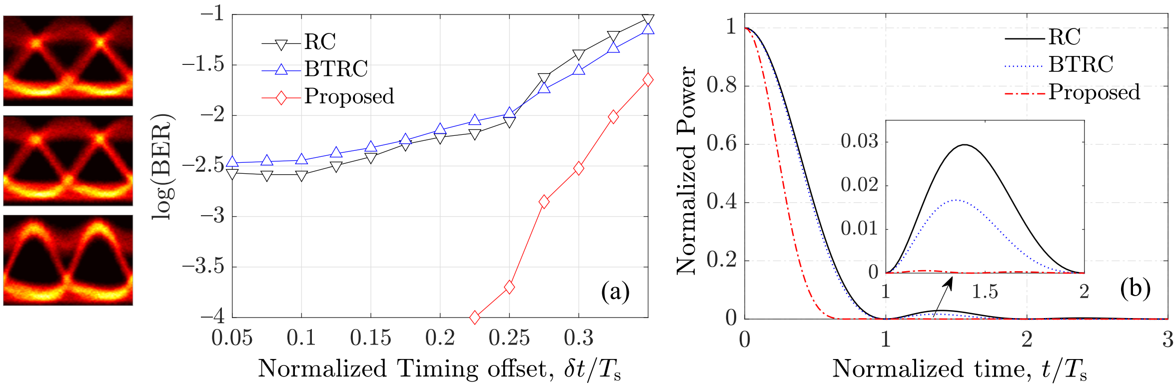

Fig. 2. (a) Bit error rate performance versus the normalized timing-offset of the received pulses at an emitted terahertz power of −13.3 dBm. The eye diagrams are plotted for the RC, BTRC, and the proposed pulses from top to bottom, respectively, at a normalized timing-offset of 0.05. (b) The power profile of the three considered pulses. The roll-off factor is fixed at $\alpha = 0.35$ for the RC and BTRC pulses, whereas, for the proposed pulse, $\alpha = 0$ and $\zeta = 10.47$.

high timing-jitter is attributed to its low time-domain sidelobe, which can be explained as follows. Figure 2(b) plots the power profile of the proposed pulse, i.e., $|p(t)|^2$, for $0 \leq t \leq 3T_s$ as well as the squared magnitude of the RC and BTRC pulses defined in [3]. As shown in this figure, for $0 \leq t \leq T_s$, the power of the proposed pulse has a more rapid decay rate, i.e., more localized, compared with the RC and BTRC pulses. Figure 2(b) also shows that, for $T_s \leq t \leq 2T_s$, the maximum sidelobe power of the proposed pulse is barely noticeable as it is lower than the corresponding levels of the RC and the BTRC pulses by 17 dBr and 15 dBr, respectively. Such low power in its sidelobes implies that the proposed pulse experiences weak interactions with the adjacent symbols, i.e., reduced ISI, and hence, can tolerate a larger timing deviation around the optimum sampling instant. Future work will investigate the application of the proposed Nyquist pulse to the orthogonal frequency division multiplexing (OFDM) scheme [7], in which the sensitivity to Tx-Rx timing synchronisation is crucial to the error performance [8].

4. Conclusion

We propose a Nyquist pulse to mitigate the timing-jitter in terahertz communications. The bit error rate performance of proposed pulse is experimentally demonstrated using a 311 GHz photonic-terahertz communications system at a data rate of 1.44 Gbit/s. Experimental results show that, compared with the conventional RC and BTRC pulses, the proposed pulse shape can improve the error rate of this system by more than an order of magnitude at a normalized timing-jitter of 22.5%. These results highlight the role of pulse shaping in improving the transmission performance of terahertz communications systems that could be vulnerable to a similar range of time-jittering. In addition, this work provides a pathway for further research on waveform design for terahertz communications in the presence of transmission impairments, including the time sampling errors at high baud rates.

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