IEEE 802.15.3d-Compliant Waveforms for Terahertz Wireless Communications

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Abstract—The terahertz electromagnetic band has been foreseen as a promising candidate to accommodate the ever-increasing wireless data traffic. To this end, the development of novel transceiver architectures and signal processing solutions is crucial to handling massive data volume transmitted over terahertz wireless communications networks. In this paper, we propose a waveform that shows full compliance with the spectral emission mask imposed by the IEEE Standard for terahertz communications. The designed waveform exploits 99.3% of the total in-band energy admissible by this mask and provides an extra degree of freedom for out-of-band interference management. A proof-of-concept experiment is conducted using a 300 GHz photonics-based terahertz communications link to demonstrate the generation and wireless transmission of the proposed waveform. Experimentally validated bit error rates show that the proposed waveform outperforms the widely adopted raised-cosine waveform and the better-than-Nyquist waveform even when the Nyquist criterion for inter-symbol interference-free signaling is not satisfied. Moreover, an error-free transmission at 1.44 Gbit/s is achieved without employing complicated digital signal processing at the receiver side.

Index Terms—IEEE 802.15.3d-2017 Standard, pulse shaping, spectral radiation efficiency (SRE), terahertz communications, terahertz photonics, waveform design.

I. INTRODUCTION

CONTINUOUSLY increasing demands for short-range high-speed wireless communications have stimulated intensive research interests in innovative solutions towards spectrally efficient communications technologies amid the radio spectrum, which is fully allocated up to 100 GHz. As an unoccupied part in the electromagnetic spectrum, the terahertz band from 100 GHz to 10 THz has emerged as a promising solution to meet these demands [1]. To accommodate multi-user access to this band, the maximum effective isotropic radiated powers (EIRPs) of practical wireless transmitters and their usable bandwidths are regulated by the local regulatory authorities through the globally-adopted wireless communications standards. To meet the spectral emission requirements of these standards, the over-the-air (OTA) signals’ spectra are reshaped at the transmitter side before being wirelessly distributed over free-space channels [2], [3]–[9].

In the field of terahertz communications, the first worldwide standard, officially called the IEEE 802.15.3d Standard [10], was released in 2018 to support the operation of high-speed Ethernet wireless links up to 100 Gbit/s. In this standard, a 69 GHz bandwidth is dedicated to terahertz communications in the frequency range from 252 GHz to 321 GHz, commonly called the IEEE terahertz band. It is important to highlight that, although the IEEE 802.15.3d Standard does not specify a pulse shaping filter, filtering is implied in the spectral emission masks specified by this standard. Despite the broad bandwidth allocated by the IEEE 802.15.3d Standard to terahertz communications, the power levels offered by currently available terahertz wireless transmitters are relatively limited [11], [12]. The power is further reduced at the receiver side due to the high free-space path loss at terahertz frequencies. Hence, the prudent utilization of the emission masks admissible by the IEEE 802.15.3d Standard raises a key challenge in the development of future terahertz communications systems. Despite its importance, this challenge remains under-investigated.

In most of the earlier demonstrations, the terahertz spectrum has been explored freely without imposing any constraints on the EIRPs, the central frequencies and the bandwidths of the generated terahertz signals [13]–[17]. Only a limited number of these demonstrations have partially considered the physical (PHY) layer specifications defined by the IEEE 802.15.3d Standard [10], including the pulse shaping required to comply with this standard. For instance, in [12], [18], the first successful transmission of an IEEE 802.15.3d terahertz signal in the 300 GHz band was reported. A raised cosine (RC) filter, with a roll-off factor of 0.35, was employed to reshape the spectrum of a quadrature amplitude modulated (QAM) signal in the baseband before being up-converted and transmitted over the IEEE band at data rates of 56, 80 and 100 Gbit/s. In [19], an all-electronic transmitter was implemented to demonstrate the generation of a 27 GHz bandwidth signal at 300 GHz. The generated terahertz signal spanned 12.5 single-user channels of 2.16 GHz bandwidth.
each, which violates the frequency allocation plan defined by the IEEE 802.15.3d Standard for multi-user operation schemes [10]. Moreover, the design criteria of the generated signal spectrum were not reported. In [20], a dual-channel generation and transmission of 2.16 GHz bandwidth terahertz signals in the 300 GHz band was reported. An RC pulse shaping filter, with a roll-off factor of 0.35, was employed to reshape the signals spectra in the baseband. The conformity of the generated spectra to the emission mask defined in [10] was not investigated either. Obviously, a common shortcoming in the aforementioned demonstrations is the lack of compliance to this IEEE Standard. As a preliminary investigation, in [21] we proposed the first IEEE 802.15.3d Standard-compliant waveform.

To further address this issue, here we provide an analytical framework for the design and performance assessment of terahertz waveforms developed for IEEE 802.15.3d terahertz communications. Then, we investigate two widely-used waveforms, namely the RC and the better-than-Nyquist (BTN) waveforms, using the developed analytical framework. Importantly, we propose an alternative waveform for terahertz communications under the most stringent spectral constraints defined by the IEEE 802.16.3d Standard. The transmission performance of the three considered waveforms is experimentally investigated using a photonics-based terahertz communication system, with the bit error rate (BER) as a performance metric. It should be highlighted that, using photonics-based terahertz systems for experimental demonstrations emphasizes the possibility of seamless integration of radio-over-fiber passive-optical-networks (RoF-PONs) to terahertz wireless links as well as the applicability of microwave-photonic (MWP) signal processing techniques, at least conceptually, to terahertz communications [13].

The rest of this paper is organized as follows. Section II overviews the IEEE 802.15.3d Standard and introduces a relevant analytical framework for the terahertz waveform design. In Section III, two of the most commonly used pulse shapes in digital communications are analyzed and the proposed waveform is presented. Section IV presents the experimental investigation of the transmission performance of the three considered waveforms using a terahertz photonic system. The paper is concluded in Section V.

II. PROBLEM FORMULATION AND DESIGN GUIDELINES

Since the IEEE 802.15.3d Standard-compliant terahertz waveforms are subject to a set of spectral constraints, designing the targeted waveform in the frequency domain followed by frequency-to-time conversion is a straightforward approach. However, reshaping the spectra of narrow band signals in the terahertz band is not practical when using the currently available all-electronic digital platforms. Therefore, to relax the computational efforts required, we map the IEEE spectral emission mask from the passband to the baseband [22]. Then, the baseband spectrum is reshaped and up-converted to the passband to produce the spectrally compliant terahertz OTA signal. This approach facilitates the efficient utilization of the all-electronic-based processing platform.

Since the IEEE 802.15.3d Standard relies on multi-rate adaptive coding and modulation (ACM) schemes, the proposed design approach can be considered highly adaptive as it allows for a modular transmitter design and implementation using all-electronic software-defined radio (SDR) platforms based on field-programmable gate arrays (FPGAs), regardless of the terahertz carrier frequency and/or the generation technique. These platforms are generic as they have the capacity to implement sophisticated communications processing in the baseband, including the pulse shaping and the ACM [23]. The implementable modulation schemes can be simple on-off keying (OOK) and binary phase shift keying (BPSK), or higher-order vector modulation formats such as the \( \pi/2 \)-quadrature phase shift keying (\( \pi/2 \)-QPSK), 16-quadrature amplitude modulation (16-QAM) and 64-QAM. Moreover, the transmission bit rates supported by all-electronic SDR-driven optical systems can exceed 100 Gbit/s [24]. It is noteworthy that all of the aforementioned modulation formats and data rates are compatible with the technical requirements defined in the IEEE 802.15.3d Standard [10].

A. The IEEE 802.15.3d Standard Spectral Emission Mask

The IEEE 802.15.3d Standard defines eight different channelization schemes within the range form 252 GHz to 321 GHz. Each channelization scheme comprises multiple parallel channels with bandwidths ranging from 2.16 GHz to 69.1 GHz. To limit the mutual inter-band interference (IBI) among the OTA terahertz signals transmitted in adjacent channels, a spectral emission mask is imposed to the EIRP of each signal. The spectral emission mask of the \( i \)th channelization scheme, denoted by \( M_i(f) \), can be modeled by a piecewise linear function when expressed in the dBr unit. This spectral mask is defined by a unique set of four knee frequencies, denoted by \( f_{i,k} \), and the corresponding power spectral density (PSD) upper-bounds at these frequencies. Here, \( i \in \{1,2,...,8\} \) denotes the channelization scheme number and \( k \in \{0,1,2,3,4\} \) is the knee frequency index. This can be formulated mathematically as follows:

\[
M_i(f) \text{ (dBr)} = \begin{cases} 
\left( \frac{M_{i,k} - M_{i,k-1}}{f_{i,k} - f_{i,k-1}} \right) f - \left( \frac{M_{i,k+1} - M_{i,k}}{f_{i,k+1} - f_{i,k}} \right) f_{i,k} + M_{i,k} \\
\quad : f_{i,k-1} \leq f < f_{i,k}
\end{cases} 
\]

\[
\leq -30 : f \geq f_{i,4}.
\]

Tables I and II list the numerical values of the knee frequencies and the corresponding PSD limits for the eight channelization schemes specified by the IEEE 802.15.3d Standard. It should be pointed out that the standard does not specify the absolute EIRP level as it is dependent on the respective local regulating authorities.

B. Spectral Compliance Metric

Several metrics have been introduced to quantify the compliance of a given signal spectrum with a pre-specified spectral emission mask [25], [26]. In [27], a frequency-dependent
The concept of maximizing the spectral radiation efficiency (SRE) of an emitted OTA signal, whilst complying with the constraints of a spectral emission mask, has been well-known in the context of UWB communications [27]. In this work, we apply this concept to the design of IEEE 802.15.3d-compliant signals. Assume that $|\tilde{\Psi}_n(jf)|^2$ is defined over the bandwidth of an IEEE 802.15.3d channel. The SRE of this envelope signal is defined as the ratio of the power contained within its spectrum to the total PSD admissible by the spectral emission mask. This definition is expressed mathematically as follows:

$$
\eta = \frac{\int |\tilde{\Psi}_n(jf)|^2 df}{\int BF M_i(f) df},
$$

where $\eta$ is the SRE of the baseband envelope of the terahertz signal.

### Problem Formulation

A number of benefits can be achieved by maximizing the SRE of terahertz signals at the receiver front-end, including the improvement of the signal-to-noise plus interference ratio (SNIR) and extending the wireless communications reach. An implicit challenge arises when considering (3) and (4) jointly, where the PSD of an optimal terahertz waveform should be carefully shaped to achieve the maximum SRE, and at the same time, be subject to the EIRP constraints imposed by the IEEE 802.15.3d spectral regulation mask. This design trade-off leads to the definition of the following non-convex multi-objective optimization problem:

**Problem Statement.** An optimal terahertz signal that fully complies with the spectral emission mask of the IEEE 802.15.3d Standard can be obtained by designing its baseband envelop waveform $\psi(t)$, defined by a complete parameter set of $\Xi$, such that the following two independent optimization problems are jointly satisfied:

$$
\max_{\Xi} \left( \int \frac{|\tilde{\Psi}_n(jf, \Xi)|^2 df}{BF M_i(f)} \right),
$$

such that

$$
\max \left\{ |\tilde{\Psi}_n(jf, \Xi)|^2 \right\} \leq M(f) \forall f \text{ or } \rho_{\tilde{\Psi}} = 1.
$$

The solution of the multi-objective optimization problem defined in (5) and (6) jointly yields a desired optimal terahertz waveform.

### III. Terahertz Waveforms for The IEEE 802.15.3d Standard

#### A. Conventional Signaling Waveforms

The RC pulse shape has been widely adopted for signaling over the physical layers of various wireless and optical communications systems. However, in non-terahertz wireless communications, several reports have demonstrated pulse shape

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**Table I**

Knee Frequencies of the Spectral Emission Masks of the IEEE 802.15.3d Standard [10]. Frequencies are in GHz.

| ID | $f_{i,1}$ | $f_{i,2}$ | $f_{i,3}$ | $f_{i,4}$ |
|----|-----------|-----------|-----------|-----------|
| 1  | 7.16      | 0.99      | 1.1       | 1.6       |
| 2  | 4.32      | 2.02      | 2.18      | 2.68      |
| 3  | 8.64      | 4.18      | 4.34      | 4.84      |
| 4  | 12.96     | 6.34      | 6.50      | 7.00      |
| 5  | 17.28     | 8.50      | 8.66      | 9.16      |
| 6  | 25.92     | 12.82     | 12.98     | 13.48     |
| 7  | 51.84     | 25.78     | 25.94     | 26.44     |
| 8  | 69.12     | 34.42     | 34.58     | 35.08     |

**Table II**

PSD Limits of the Spectral Emission Masks of the IEEE 802.15.3d Standard [10]. $M_{i,k}$ is in dBr unit.

| ID | $M_{i,0}$ | $M_{i,1}$ | $M_{i,2}$ | $M_{i,3}$ | $M_{i,4}$ |
|----|-----------|-----------|-----------|-----------|-----------|
| 0  | 0         | -20       | -25       | -30       |           |

Binary compliance metric, denoted by $B_\psi(f) \in \{0, 1\}$, has been proposed to quantify the compliance of ultra-wideband (UWB) signals’ spectra with the FCC spectral emission mask. Likewise, this metric can be employed in the context of IEEE 802.15.3d Standard-compliant terahertz communications. For an arbitrary terahertz signal envelope $\psi(t)$ with a normalized PSD of $|\tilde{\Psi}_n(jf)|^2$, $B_\psi(f) = 1$ if $|\tilde{\Psi}_n(jf)|^2$ does not exceed $M_i(f)$ at $f$, and $B_\psi(f) = 0$ if these spectral constraints are exceeded. This point-wise definition can be reformulated mathematically as follows:

$$
B_\psi(f) = \frac{1}{2} (U(\zeta) - U(-\zeta) + 1),
$$

where $\zeta(f) = 10 \log \left( \frac{M_i(f)}{|\tilde{\Psi}_n(jf)|^2} \right)$, and $U(\zeta)$ is the Heaviside unit step function, defined as $U(\zeta) = 1$ if $\zeta \geq 0$ and $U(\zeta) = 0$ if $\zeta < 0$. It should be pointed out that, in contrast to the definition provided in [27], $\zeta(f)$ is defined in the dBr unit, rather than in the linear unit, to capture spectral details at low PSD levels such as the additive white Gaussian noise (AWGN) floor level. Hence, this modified metric can precisely identify the frequencies at which the signal PSD should be particularly considered. Meanwhile, it is also reasonable to define a figure-of-merit (FoM) that quantifies the overall compliance of the signal PSD over an arbitrary bandwidth of interest. We define the average compliance coefficient (CC), denoted by $\rho_\psi$, as:

$$
\rho_\psi = \frac{1}{2\Delta f} \int_{f_0-\Delta f}^{f_0+\Delta f} B_\psi(f) df,
$$

where $0 \leq \rho_\psi \leq 1$, $f_0$ is the central terahertz carrier frequency of interest, and $2\Delta f$ is the bandwidth over which the CC of $|\tilde{\Psi}_n(jf)|^2$ is calculated. Although the IEEE 802.15.3d Standard [10] limits the operation of a terahertz signal to the passband bandwidths listed in Table I, the value of $\Delta f$ in (3) can be arbitrarily large ($\Delta f \gg BW$) to capture the aggregate contributions of the spurious out-of-band (OOB) emissions and the spectral regrowth effects in the overall compliance analysis.
designs that can outperform, or at least be comparable with, the RC pulse. In [28] it has been proven that, compared with the RC waveform, employing the BTN waveform in the generalized frequency division multiplexing (GFDM) systems can potentially improve the symbol error rate (SER) performance. In [29], the transmission performance of the BTN waveform has been experimentally tested using a visible light communication system operating under AWGN channel conditions. It was found that the BTN pulse shape offers superior bit-error rate (BER) performance and lower computational complexity compared with the RC pulse shape.

In this work, we adopt the RC and the BTN waveforms as comparison benchmarks. The spectrum of an RC waveform is given by [30]

\[ S_{RC}(f) = \begin{cases} 
1, & 0 \leq |f| < B(1-\alpha) \\
\frac{1}{2} \left\{1 + \cos \left(\frac{\pi}{2B} (|f| - B(1-\alpha))\right)\right\}, & B(1-\alpha) \leq |f| \\
0, & B(1+\alpha) \leq |f|,
\end{cases} \]

(7)

where \( T_s \) is the symbol duration, \( R_s \) is the symbol rate, \( \alpha \) is the roll-off factor and \( B = 1/(2T_s) \) is the minimum transmission bandwidth. The corresponding RC time-domain waveform is given by [30]

\[ s_{RC}(t) = \text{sinc} \left(\frac{t}{T_s}\right) \cos \left(\frac{2\pi\alpha t}{T_s}\right) \frac{1}{1-4\alpha^2 t^2/T_s^2}. \]

(8)

The spectrum of the BTN pulse shape is defined as follows [30]:

\[ S_{BTN}(f) = \begin{cases} 
1, & 0 \leq |f| < B(1-\alpha) \\
\exp \left\{ \frac{\ln 2}{\alpha B} |f| \right\}, & B(1-\alpha) \leq |f| < B \\
1 - \exp \left\{ \frac{\ln 2}{\alpha B} |B(1+\alpha) - f| \right\}, & B \leq |f| < B(1+\alpha) \\
0, & B(1+\alpha) \leq |f|.
\end{cases} \]

(9)

The corresponding time-domain BTN waveform is given by [30]

\[ s_{BTN}(t) = 2B \text{sinc}(2B t) \times \frac{4\beta \pi t \sin(2\pi B\alpha t) + 2\beta^2 \cos(2\pi B\alpha t) - \beta^2}{4\pi^2 t^2 + \beta^2}, \]

(10)

where \( \beta = (\ln 2/\alpha B) \). To satisfy the IEEE 802.15.3d Standard, the value of \( T_s \) in (7)-(10) is selected according to the discrete set of the symbol rates defined in [10]. Therefore, \( \alpha \) is the only parameter that can be tuned to control the PSDs of the RC and the BTN waveforms. It should be pointed out that, practically, the RC and the BTN pulse shaping are divided between the transmitter and the receiver sides. Each stage employs the square root of (7) and (9).

**B. Proposed Waveform: Frequency and Time Domain Analysis**

Despite their unique temporal and spectral features, Lorentzian-based pulse shapes have been overlooked in the context of spectral shaping for digital communications [31]. An amplitude-scaled Lorentzian pulse can be expressed as [31]:

\[ p_L(t) = \frac{A}{1 + (\frac{t}{\beta})^2}, \]

(11)

whereas the Fourier transform of \( p_L(t) \) is given by [31]

\[ L(f, \tau) = \alpha \pi \tau \exp(-2\pi\tau |f|). \]

(12)

When expressed in the dBr unit, \( L(f, \tau) \) follows a triangular-shaped spectrum with a steady spectral roll-off [32], which can be controlled via the temporal width \( \tau \) of the Lorentzian basis pulse. This spectral feature makes it possible to use the Lorentzian pulse to match the spectral mask shape defined in (1). In particular, we propose a fully-compliant spectrum based on a linear combination of logarithmic double-sided Lorentzian spectra centered at the knee frequencies as follows:

\[
\mathcal{L}(f) \text{ (dB)} = \sum_{k=1}^{4} A_k (L_k^+(f, \tau_k) + L_k^-(f, \tau_k)) = -\sum_{k=1}^{4} (b_k |f + f_k| + |f - f_k| + 2a_k),
\]

(13)

where \( L_k^+(f, \tau_k) = 10 \log (L(f \pm f_k, \tau_k)) \), \( b_k = 10\tau_k \log(e) \) and \( a_k = 10\tau_k \log(\alpha \pi \tau_k) \). Equation (13) suggests that the area under \( M_i(f) \) can be fully occupied by four overlapping pairs of the triangular logarithmic Lorentzian spectra, corresponding to the four knee frequencies defined in (1).

To reduce the mathematical complexity associated with applying the inverse Fourier transform directly to the linear form of (13), we inspect the distribution of the emission mask PSD over frequency. The total power contained in a sub-band located between two consecutive knee frequencies is given by:

\[
P_k = \int_{-f_k}^{f_k} M_i(f) df = \frac{f_k}{\int_{-f_k}^{f_k} M_i(f) df} = \frac{f_{k+1} - f_{k-1}}{f_3 - f_1}; \quad k \in \{1, 2, 3, 4\},
\]

(14)

where \( f_0 = 0 \). Accordingly, the cumulative PSD contribution of \( M_i(f) \) at the \( k \)th knee frequency can be defined as follows:

\[
C_k = \sum_{m=1}^{k} P_m; \quad k \in \{1, 2, 3, 4\}.
\]

(15)

Figure 1 illustrates \( P_k \) and \( C_k \) versus \( k \) for the first channelization scheme specified in [10]. From this figure, it is observed that, more than 95% of the PSD under the spectral emission mask is concentrated in the frequency range of \(-f_2 \leq f \leq f_2\). This property holds for the eight IEEE 802.15.3d channelization schemes and can be utilized to simplify (13) to the following form:

\[
\mathcal{L}(f) \text{ (dB)} \approx L_1^+(f, \tau_1) + L_1^-(f, \tau_1) = 2a_1 - b_1 |f + f_1| + |f - f_1|.
\]

(16)
The corresponding PSD, measured in the units of W/Hz, is given by:
\[
|\mathcal{L}(f)|^2 = \exp(2\gamma B\pi) \exp\left(-\gamma (|f + B\pi| + |f - B\pi|)\right),
\]
where \(\gamma = \pi \tau\) and \(\bar{\tau} = 1 - \alpha\), which is defined as the complementary roll-off factor.

The time-domain waveform corresponding to (17) can be obtained by applying the inverse Fourier transform to the square root of (17), which yields:
\[
s_\mathcal{L}(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \sqrt{\mathcal{L}(f)} \exp(j\omega t) \, d\omega \\
= \exp(\gamma B\pi) \pi \exp\left(-\frac{\gamma}{T_s}\right) \\
\times \left\{ \frac{\pi}{T_s} \sin\left(\frac{\pi t}{T_s}\right) + \frac{1}{\gamma} \cos\left(\frac{\pi t}{T_s}\right) - \frac{\pi}{\gamma} \sin\left(\frac{\pi t}{T_s}\right) \right\}. 
\]

(18)

It is noted from (18) that the Nyquist sampling conditions for inter-symbol interference (ISI)-free signaling is not strictly satisfied by \(s_\mathcal{L}(t)\), i.e., \(s_\mathcal{L}(t = 0) = 1\), whereas \(s_\mathcal{L}(t = nT_s) \neq 0\) when \(n = \{\pm1, \pm2, \ldots\}\).

Alternatively, the ISI performance of \(s_\mathcal{L}(t)\) can be evaluated based on the relaxed Nyquist condition as follows [33]:
\[
\text{ISI (dB)} = 10 \log_2 \left| \sum_{n=-\infty}^{+\infty} s_\mathcal{L}(t - nT_s) \right|^2. 
\]

(19)

This condition considers a signaling waveform to be ISI-free as long as the instantaneous signal-to-ISI power ratio at the optimum sampling time instant is maintained above a pre-specified acceptable threshold. In Section D, the condition in (19) is employed to quantify the ISI performance of the proposed waveform after optimizing its spectrum.

**C. Comparison of the Waveform’s Spectra**

Figure 2 compares the impact of reshaping the spectra of the three considered waveforms on their compatibility to the IEEE 802.15.3d spectral requirements. Specifically, Figs. 2(a) and 2(b) show the RC and the BTN spectra at different values of \(\alpha\), whereas Fig. 2(c) plots the proposed spectrum at \(\alpha = 0\) and different values of \(\gamma\). It noteworthy that, for the RC and the BTN waveforms, the spectral flatness and the IBI are jointly controlled with only a single degree of freedom, which is \(\alpha\); whereas, according to (17), the proposed spectrum possesses two independent degrees of freedom to manage the spectral flatness and the IBI, namely, \(\alpha\) and \(\gamma\). These properties make it possible to manage the SRE and the compliance independently and more flexibly using the proposed spectrum than with the RC and BTN waveforms. Additionally, in the proposed waveform, the impact of the complementary roll-off factor, i.e., \(\bar{\tau}\), is the same as the impact of \(\alpha\) in the RC and the BTN waveforms; increasing both parameters increase the transmission bandwidth.

**D. Waveform Design Optimization**

We optimize the design of each waveform to fit the spectral emission mask defined by the IEEE 802.15.3d Standard [10] for the first channelization scheme, which has the most stringent emission mask with a steady roll-off as large as 20 dB over a transition bandwidth of only 160 MHz. Although the waveforms considered in this work are optimized to fit the first channelization spectral mask, the conducted analysis is general and also applicable to other channelization schemes. This is because the bandwidths of all channelization schemes are integer multiples of 2.16 GHz as shown in Table I.

To ensure that the designed spectrum is compliant with the first emission mask, the involved parameters are optimized for each waveform individually, based on (5) and (6). Moreover, we assume a maximum frequency of 32 GHz to define the spectra of the three spectral shapes. This maximum bandwidth is large enough compared to the baseband equivalent bandwidth of the considered channelization scheme. The SRE and CC are evaluated for the three pulse shapes over the considered parameters ranges. Then, the direct search algorithm (DSA) [27] is applied to the calculated SRE and CC to extract the optimum values of \(\alpha\) and \(\gamma\). Figure 3(a) shows the SRE and the CC versus \(\alpha\) for the RC and the BTN waveforms, whereas Fig. 3(b) shows the SRE and the CC versus \(\gamma\) for the proposed waveforms at the optimized value of \(\alpha\). From Fig. 3(a), it can be seen that...
the RC and the BTN waveforms fully comply with the IEEE 802.15.3d emission mask constraints with a roll-off factor $\alpha$ up to 0.48 and 0.6, respectively. Beyond these values, the compliance condition is violated, which is strictly prohibited for IBI considerations in multi-user channel access scenarios. The SRE is approximately independent of $\alpha$ with a constant value of 73.58% for both waveforms. As can be observed from Figs. 2(a) and 2(b), this independence is a result of substituting the unfilled parts under the emission mask at $|f| < B$ by the spectrally broadening of the PSD for $|f| > B$ and hence; maintaining a constant total power. Therefore, in this work, the roll-off factor is selected at the commonly used value of $\alpha = 0.35$ to define the optimum RC and the BTN waveforms.

For the proposed waveform, the full compliance is achieved at $\alpha = 0$ and a spectral roll-off control factor, $\gamma$, of $7.226 \times 10^{-9}$, whereas the corresponding SRE is 99.3% as can be seen from Fig. 3(b). The dips observed in the CC are due to the adopted Heaviside step function in the definition of this metric as well as the non-differentiability of the spectral emission mask at the knee frequencies. This difference between the SRE of the proposed waveform and that of the RC and the BTN waveforms implies a virtual increase of about 34% in the emitted terahertz power at no additional cost. It is noteworthy that, in [11], a 20% increase in the emitted terahertz power was achieved via the monolithic integration of two photonic transmitters. This comparison emphasizes the importance of spectral shaping in managing the available power budget.

Since the proposed waveform is not ISI-free, the ISI per-
formance of this waveform is evaluated using a $2^{10}$ randomly generated BPSK symbols [30], which interfere a pulse centered at $t = 0$ with no AWGN. Figure 3(c) shows the result of ISI based on (19) of the proposed waveform versus $\gamma$ at different values of $\alpha$. At the optimum values of $\alpha$ and $\gamma$, the proposed waveforms experiences a signal-to-ISI power ratio of 21.93 dB, which is high enough to ignore its impact during the matched filtering at the receiver side [33]. Figure 4 shows the three considered waveforms resulting from the optimization of their respective parameters $\alpha$ and $\gamma$.

In practice, the pulse shaping process is implemented in the digital domain using finite impulse response filter (FIRs). Here, a truncated version of the signaling waveform is generated with an adequately finite filter length, denoted by $L$, to minimize the group delay of the FIR filter. However, this truncation induces undesired side-lobe level (SLL) spectral components beyond the dedicated waveform bandwidth. For an RC waveform with a symbol span of $L = 5$ and a roll-off factor of 0.35, this SLL can be as high as 1.5 dB, which strongly violates the maximum stop-band attenuation of $-30$ dB [33]. Figures 5(a)-(c) shows the impact of hard truncation on the stop-band attenuation of the RC, BTN and the proposed waveforms, respectively. For the proposed waveform, an almost flat waveforms for a symbol span of $L$, which strongly violates the maximum stop-band attenuation roll-off factor of 0.35, this SLL can be as high as 1.5 dB, which is high enough to ignore its impact during the matched filtering at the receiver side [33]. Figure 3(c) shows the result of ISI based on (19) of the proposed waveform versus $\gamma$ at different values of $\alpha$. At the optimum values of $\alpha$ and $\gamma$, the proposed waveforms experiences a signal-to-ISI power ratio of 21.93 dB, which is high enough to ignore its impact during the matched filtering at the receiver side [33]. Figure 4 shows the three considered waveforms resulting from the optimization of their respective parameters $\alpha$ and $\gamma$.

Fig. 5. Impact of hard truncation on the stop-band attenuation of the RC, BTN and the proposed waveforms, (a) $L = 7$, (b) $L = 15$, and (c) $L = 41$. The dashed lines represent maximum OOB emission limit allowed by the IEEE 802.15.3d [10].

IV. EXPERIMENTS AND RESULTS

As a proof-of-concept, the transmission performance of the three considered waveforms is experimentally evaluated using the photonic-terahertz communications system shown in Fig. 6. This system is based on the principles of intensity modulation–direct detection (IM-DD) and photo-mixing. In the experiment, the spectrum of a $2^{20} - 1$ pseudo-random binary sequence is reshaped by each of the three considered pulse shapes to generate the baseband signals. A regular pattern of consecutive of "1"s and "0"s, running at a symbol rate of $R_s/4$, is employed as a synchronization word. This synchronization word is interleaved cyclically with the data packets. A guard time interval of 100 zero-valued symbols is inserted between consecutive data packets.

This baseband signal is generated using a 64 GSample/s arbitrary waveform generator (AWG) with a voltage of $V_p = 300$ mV and a data rate of 1.44 Gbit/s. This rate is compatible with the first channelization scheme specified in [10]. Two optical carriers at 193.5000 THz and 193.8100 THz are emitted by a dual-channel continuous wave tunable laser source (CW-TLS) and combined by a 50:50 optical coupler (OC). The linewidth of this CW-TLS is about 100 kHz. The generated baseband signal is then modulated onto the combined optical carriers by a Mach-Zhender modulator operated in the linear region of its electro-optic transfer characteristics. After optical amplification, the two optical signals are injected into a UTC-PD for photo-mixing. The terahertz carrier frequency is 311.00 GHz, which corresponds to the 32nd channel defined by the Standard. In the experiment, the photo-current is increased from 1 mA to 6 mA, with a step of 1 mA. Table III lists the UTC-PD photo-current, denoted by $I_{ph}$, and the corresponding measured terahertz output power, denoted by $P_{THz}$.

The generated terahertz signal is then propagated over a wireless channel, which comprised two identical WR-3.4 diagonal horn antennas aligned in the line-of-sight (LoS) configuration along their directions of maximum emission with an antenna separation of 15 mm. The estimated free-space propagation loss at this distance, using the Friis transmission formula, is $-25.83$ dB. Moreover, this propagation distance is within the wireless transmission range specified by the IEEE 802.15.3d Standard [10] for close-proximity terahertz wireless links [34]–[40].

At the receiver 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-noiser amplifier (LNA). The amplified signal is then sampled by a 80 GSample/s digital storage oscilloscope (DSO) for offline DSP using MATLAB as illustrated in Fig. 6. To match the sampling rate at the transmitter side, the recorded data is down-sampled from 80 GSample/s to 64 GSample/s using a down-sampling ratio of 2.

| $I_{ph}$ | 1   | 2   | 3   | 4   | 5   | 6   |
|---------|-----|-----|-----|-----|-----|-----|
| $P_{THz}$ | $-28.2$ | $-22.1$ | $-18.4$ | $-15.5$ | $-13.3$ | $-12.3$ |

TABLE III

THE UTC-PD PHOTO-CURRENT IN mA UNIT AND THE CORRESPONDING MEASURED OUTPUT TERAHERTZ POWER IN dBm UNIT.
The received signals’ spectra comply with the IEEE spectral mask over most of the channelization scheme bandwidth. It should be pointed out that, although the compliance requirements is achieved throughout the waveform design phase, this requirement is partially violated by the received signal spectrum. This partial violation is attributed to the spectral regrowth effects caused by the nonlinearity of the SBD-based envelope detector [43]. However, since these nonlinear effects increase with increasing the photo-current [43], the violation of the compliance condition is less severe for $I_{\text{ph}} \leq 3$ mA. Importantly, the full-compliance of the emitted terahertz signal is not affected as these nonlinear distortions occur at the receiver. Moreover, the nonlinear response of SBD-based receivers can be mitigated by employing Kramer–Kronig (KK) processing at the receiver to improve its decoding capabilities [43]–[47].

The BER performance of the RC, BTN and proposed Lorentzian-based pulse shapes are also evaluated under the OOK and BPSK modulation formats, without applying forward error correction (FEC) techniques. The results, which are plotted in Figs. 9(a) and (b), show that the lowest BER performance is achieved by the proposed waveform, regardless of the modulation format. In Fig. 9(a), the OOK-modulated RC and BTN waveforms show similar BER trends for $1 \text{ mA} \leq I_{\text{ph}} \leq 6$ mA with a minimum BER of $5.952 \times 10^{-5}$ and $1.7 \times 10^{-3}$, respectively, achieved at $I_{\text{ph}} = 5$ mA. However, increasing the photo-current $I_{\text{ph}}$ beyond 5 mA deteriorates the BER of both waveforms. This effect is attributed to the nonlinearity of the terahertz link [43], [44], which induces
harmonic and inter-modulation distortion components that grow with increasing photo-current and hence dominate the desired signal. Figure 9(b) shows that the BPSK-modulated RC and BTN waveforms also follow similar BER trends for $1 \leq I_{ph} \leq 5$ mA with a minimum BER of $1.4 \times 10^{-3}$ and $2.5 \times 10^{-3}$, respectively, both achieved at $I_{ph} = 5$ mA. An error-free transmission is observed for both waveforms when $I_{ph}$ is increased beyond 5 mA.

On the other hand, for the proposed waveform, the BER decreases monotonically with increasing the photo-current from 1 mA to 3 mA for both OOK and BPSK modulation formats. A minimum BER of about $10^{-4}$ and $10^{-3}$ is achieved by this waveform at $I_{ph} = 3$ mA with OOK and the BPSK modulations, respectively. An error-free transmission is observed when $I_{ph}$ is increased beyond 3 mA. From the aforementioned observations, it can be concluded that the transmission performance is more sensitive to the SRE rather than the ISI.

V. CONCLUSION

In this work, we establish the context of pulse shaping for terahertz communications networks that comply with the technical specifications defined in the IEEE 802.15.3d Standard. An analytical framework is formulated for the design of optimal terahertz envelope waveforms, with an aim to maximize the spectral radiation efficiency under the spectral emission constraints defined in this Standard. Importantly, a waveform design is proposed and compared to the RC and BTN waveforms via numerical analysis and experiments. The proposed waveform shows full compliance with the most stringent spectral mask defined by the IEEE 802.16.3d Standard, where the largest number of densely packed channels can be found. Additionally, this waveform utilizes more than 99% of the power spectral density admissible by this spectral mask and outperforms the conventional RC and the BTN waveforms by about 35% in terms of the radiation efficiency, leading to an improvement of, at least, one order of magnitude in the BER performance. Moreover, experimental results show that the transmission error-free limit of $10^{-12}$ defined by the IEEE 802.15.3d Standard can be achieved using the proposed waveform without employing FEC codes. Additionally, since the bandwidths of all IEEE 802.15.3d emission masks are
tager multiples of 2.16 GHz, the proposed waveform presented in this work is applicable to the design and development of standard-compliant terahertz communications systems considering the higher-order channelization schemes.

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