Terahertz Band Communication System with 1-bit ADC, Oversampling and Phase Compensation

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Abstract

This paper addresses the challenges of power consumption and phase distortion in Terahertz (THz) communication systems. Exploring 1-bit resolution Analog to Digital Converters (ADCs) for reduced power consumption, the study introduces a comprehensive strategy involving oversampling and Faster-than-Nyquist (FTN) signaling. Various conventional and Deep Learning (DL)-based transceivers are reviewed, leading to a proposed DL-based transceiver that demonstrates improved Bit-Error-Rate (BER) performance. A problem formulation is presented, offering a unified design and assessment platform. Numerical results highlight the effectiveness of the DL transceiver in enhancing BER performance, showcasing its potential for THz communication optimization. Additionally, a DL block for phase compensation proves effective in mitigating hybrid distortions, showcasing the robustness of the proposed end-to-end structure. In conclusion, this work contributes insights into THz communication challenges and presents innovative solutions for further advancements in the field.

I. Introduction

To address the escalating demand for heightened data rates in emerging communication systems, there has been a notable focus on Terahertz (THz) band systems. However, the persistent challenge of power consumption necessitates an enhancement in the power efficiency of prevailing Analog to Digital Converters (ADCs). In response, the exploration of 1-bit resolution ADCs has arisen, leveraging time resolution to achieve reduced power consumption in comparison to amplitude resolution. Nevertheless, this advantage is tempered by performance degradation concerning spectral efficiency (SE) and error rates.

To navigate these trade-offs, a comprehensive strategy has been proffered, entailing oversampling at the receiver and the incorporation of Faster-than-Nyquist (FTN) signaling at the transmitter. The distinctive characteristics of THz systems further amplify the inherent challenges. As the carrier frequency ascends, THz signals confront heightened pass-loss. Additionally, imperfections in radio frequency (RF) devices, such as power amplifier (PA) nonlinearity and local oscillator (LO) phase noise, become more pronounced, producing hybrid distortions in the received signal.

Various conventional and (Deep Learning) DL-based transceivers have been proposed with the objective of optimizing either bit-error-rate (BER) or information rate performance and/or addressing phase distortion of THz [2-6]. In this paper, a problem formulation is provided to create a common design and assessment platform. Furthermore, a DL-based transceiver is proposed to address the power efficiency as well as the phase distortion challenges. Numerical results show BER performance improvement of proposed design when compared to previous attempts.

II. System Model and Problem Formulation

Fig. 1 presents a comprehensive system model that includes existing implementations performing 1-bit ADC and oversampling at the receiver and FTN signaling at the transmitter [2-6]. Let $\mathbf{b} \in \mathbb{B}^{s}$ denote information bits to be transmitted, which is then channel coded with rate $r = s/\mathrm{k}$ and output $\mathbf{c} \in \mathbb{B}^{k}$. Then, $\mathbf{c}$ is modulated with an order of M (bits/symbol) to produce complex modulated symbol $\mathbf{d} \in \mathbb{C}^{k/\log_2 M}$. The transmitted signal has to encode its information in the distance between zero crossings, for detection after quantization. This is expressed as symbol-to-sequence mapping with rate of $\Delta \in (0,1]$, influencing transmission rates. The mapping can be expressed as $\mathbb{C}^{k/\log_2 M} \rightarrow \mathbb{R}^{N}$. Finally, the FTN block transmits M_{Tx} symbols per Nyquist interval T_N by utilizing a pulse shaping filter like Root-Raised Cosine pulse. Consequently, the achieved transmission rate for the transmitter, is given as $r \cdot \Delta \cdot \log_2 M \cdot M_{Tx}(\text{bits}/T_N)$. On receiver side, the oversampling factor M_{Rx} determines the *achievable* rate of the scheme as given by Shamai's limit $2 \cdot \log_2(M_{Rx}+1)\text{bits}/T_N$ in [1]. This gives upper bound to the *achieved* transmission rate, and the following constraint:

$$r \cdot \Delta \cdot \log_2 M \cdot M_{Tx}(\text{bits}/T_N) \leq 2\log_2(M_{Rx}+1) \quad (1)$$

Therefore, the main objective of [2-6] has been to design a system that can approach Shamai's limit for a given M_{Rx} by developing detailed transceiver structure and optimizing the values of M_{Tx}, r, M and Δ while maintaining performance in challenging

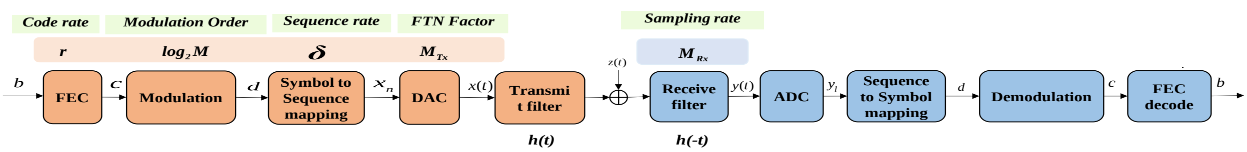

Fig.1 Comprehensive system model for 1bit quantization and oversampling communication schemes

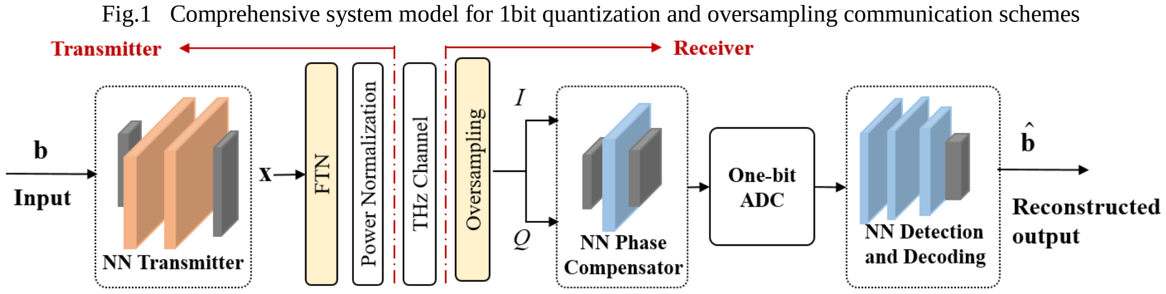

Fig. 2. A system model for the proposed auto encoder-based transceiver with 1-bit quantization and oversampling

channel conditions. To formulate the problem, we use SNR γ with its threshold $\gamma^{(th)}$ that satisfies target error rate, to constraint the SE maximization. The error rate should reflect that is influenced by quantization and ISI, in addition to channel effects. We assume a line-of-sight THz transmission which experiences path loss represented by α , PA nonlinearity $\boldsymbol{\varphi}$ and phase noise at receiver θ that adheres to a block-based random walk model, undergoing a change with each transmission block such that overall distortion is represented by $\mathbf{D}=\begin{bmatrix}\cos\theta & -\sin\theta \\ \sin\theta & \cos\theta\end{bmatrix}$. This model is commonly employed to characterize robust phase noise, reflecting variations in phase noise per transmission block, a phenomenon prevalent in ultra-high-rate THz communication. Therefore the received signal looks like $y(t)=\mathbf{D}\ \mathbf{H}\boldsymbol{\varphi}x(t)+z(t)$ where $x(t)$ is the complex baseband transmitted signal, $z(t)$ is Additive White Gaussian Noise (AWGN) with noise power σ^2 and $\mathbf{H}=\alpha e^{js}\mathbf{I}$ is the channel response with phase shift s . Furthermore, practical hardware limits of 1-bit ADC should be considered by setting $M_{Rx}{}^{(th)}$ and $M_{Tx}{}^{(th)}$ as design constraints. Consequently, the following problem formulation comprehensively summarizes the practical design objectives of 1-bit ADC given in [2-6]:

$$\begin{aligned}(r^*,\Delta^*,M^*,M_{Tx}^*) &= \underset{(r,\Delta,M,M_{Tx})}{\arg\max}\left(r\cdot\Delta\cdot\log_2 M\cdot M_{Tx}\right)(\text{bits}/T_N)\\ \text{s.t. }\ & 2\log_2(M_{Rx}+1)\geq r\cdot\Delta\cdot\log_2 M\cdot M_{Tx}\\ & M_{Tx}\leq M_{Tx}^{(th)},\ M_{Rx}\leq M_{Rx}^{(th)},\\ & \gamma(r,\Delta,M,M_{Tx},M_{Rx},\mathbf{D},\boldsymbol{\varphi},\mathbf{H})<\gamma^{(th)}\end{aligned} \quad (2).$$

Here, the non-explicit representation of the SNR hinders us from solving the optimization. This work proposes an autoencoder (AE)-based transceiver has been proposed as seen in Fig 2 which is expected to perform the tasks of the comprehensive system model in Fig 1. While training to encode the input vector, the AE learns ideal modulation, channel coding and symbol to sequence mapping such that we can represent the optimized block with one *bit-to-one-bit-sequence* mapping rate $\kappa=r\cdot\Delta\cdot\log_2 M$. Hence:

$$\begin{aligned}(\kappa^*,M_{Tx}^*) &= \underset{(\kappa,M_{Tx})}{\arg\max}\left(\kappa M_{Tx}\right)(\text{bits}/T_N)\\ \text{s.t. }\ & 2\log_2(M_{Rx}+1)\geq\kappa\cdot M_{Tx}\\ & M_{Tx}\leq M_{Tx}^{(th)},\ M_{Rx}\leq M_{Rx}^{(th)},\\ & \gamma(\kappa,M_{Tx},M_{Rx},\sigma^2,\mathbf{D},\boldsymbol{\varphi},\mathbf{H})<\gamma^{(th)}\end{aligned} \quad (3).$$

By our simple AE design, we can easily heuristically optimize the 1-bit quantization system model to various performance parameters. Furthermore, the end-to-end (E2E) system can be trained to be robust against the hybrid distortions associated with THz channel. Particularly since the prevailing cause of demodulation performance loss for this range of transmission is the phase offset, which cannot be adjusted once the signal has been quantized [4]. Therefore, as shown in Fig 2, a DL block for phase compensation is utilized before the quantization in order to estimate and correct the encountered hybrid distortions.

III. Numerical Results

Numerical results are obtained using Monte-Carlo simulation of the trained autoencoder with test dataset over single path THz channel. The BER performance of the proposed end-to-end AE structure with 1-bit quantization is evaluated at SE equivalent to QPSK an 16QAM modulation with $M_{Tx}=M_{Rx}=10$. The work in [4] which suggested a DL-THz receiver used for QPSK level demodulation along with an algorithmic phase estimator and corrector is the most recent work to tackle phase distortions in THz with a single bit receiver. The hybrid distortions parameters used in [4] are implemented for fair comparison with the work. The result in Fig. 3 shows that for QPSK, the proposed E2E transceiver outperforms the scheme in [4] by up to 8 dB by utilizing the

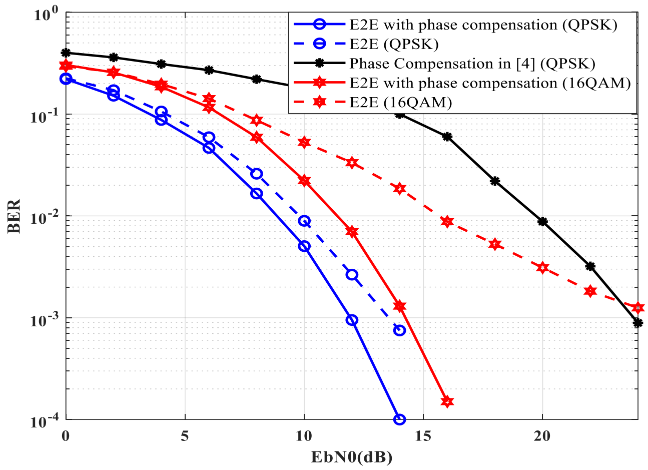

Fig. 3 BER performance of Proposed AE Transceiver for $M_{Tx}=M_{Rx}=10$

encoding and decoding robustness of the AE along with the phase compensator block. Without the phase compensation block, the E2E scheme is robust against the quantized and distorted THz channel and still outperforms 6 dB. As shown in Fig 3, our work also extends the SE of transmitted block to what would be equivalent to 16 QAM and corresponding harder demodulation is shown to rely more on the phase compensator.

IV. Conclusion and Future Works

In conclusion, this paper addresses power consumption and phase distortion challenges in Terahertz (THz) communication. Exploration of 1-bit resolution ADCs, combined with oversampling and Faster-than-Nyquist (FTN) signaling, establishes a foundation for improved power efficiency with trade-offs in performance. The proposed Deep Learning (DL) transceiver, trained for modulation and channel coding, demonstrates enhanced Bit-Error-Rate (BER) performance, offering a promising solution. The integration of an autoencoder-based transceiver and a DL block for phase compensation contributes versatility and robustness to the system. Numerical results affirm the effectiveness of the DL transceiver in enhancing BER performance, showcasing its potential for THz communication optimization. The proposed end-to-end structure outperforms existing schemes, demonstrating resilience against quantized and distorted THz channels.

Acknowledgement

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