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Research Article

Phase Noise Aware Orthogonal Time Frequency Space Modulation for sub-THz and High-Mobility Wireless Systems

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Abstract

The continuous evolution of wireless communication systems toward sixth-generation paradigms has intensified the exploration of new waveforms capable of supporting extreme data rates, ultra-reliable links, and high mobility in challenging propagation environments. Among the most critical operating regimes under consideration are millimeter-wave and sub-terahertz frequency bands, where hardware imperfections, propagation losses, and time-varying channels pose fundamental obstacles to reliable transmission. Orthogonal Time Frequency Space modulation has emerged as a promising alternative to conventional orthogonal frequency division multiplexing due to its inherent robustness in doubly dispersive channels and its ability to exploit the delay-Doppler domain representation of wireless channels. At the same time, phase noise originating from local oscillators becomes increasingly detrimental at high carrier frequencies, manifesting as inter-carrier interference, common phase error, and loss of orthogonality. This article presents an extensive theoretical investigation into phase noise effects on OTFS-based communication systems operating in sub-THz and high-mobility scenarios. Drawing strictly on established literature, the study synthesizes propagation modeling, waveform design, channel estimation, synchronization, and phase noise compensation strategies into a unified analytical narrative. Emphasis is placed on understanding how OTFS fundamentally reshapes the impact of phase noise compared to OFDM, particularly in sparse delay-Doppler channels and under fractional Doppler conditions. The methodology integrates descriptive modeling of oscillator impairments, pilot-aided synchronization techniques, coherence bandwidth exploitation, and non-iterative compensation approaches adapted from OFDM to OTFS frameworks. Results are discussed qualitatively in terms of robustness trends, interference mitigation capabilities, and system-level performance implications without reliance on mathematical formalism. The discussion further explores theoretical limitations, trade-offs between complexity and robustness, and the relevance of emerging machine learning-based transceiver designs. The article concludes by positioning phase noise aware OTFS as a foundational waveform concept for future sub-THz mobile systems while identifying open research challenges in practical implementation and standardization.

Keywords: Orthogonal Time Frequency Space modulation, phase noise, sub-THz communications, high mobility channels, delay-Doppler domain, waveform design

INTRODUCTION

The historical development of wireless communication systems has been characterized by a continuous tension between spectral efficiency, robustness, and implementation complexity. From early single-carrier systems to multicarrier techniques, each demands. Orthogonal frequency division multiplexing became the cornerstone of fourth- and fifth-generation cellular systems due to its efficient handling of frequency-selective channels and compatibility with fast Fourier transform-based implementations, as comprehensively discussed in classical mobile broadband literature (Ergen, 2009). However, as wireless systems extend toward extreme mobility, ultra-low latency, and operation at millimeter-wave and sub-terahertz frequencies, the fundamental assumptions underpinning OFDM begin to erode.

High carrier frequencies introduce severe sensitivity to oscillator imperfections, particularly phase noise, which disrupts the orthogonality among subcarriers and leads to substantial performance degradation (Casas et al., 2002; Leshem and Yemini, 2017). At the same time, high mobility induces rapid channel variations that violate the quasi-static channel assumption within an OFDM symbol, resulting in Doppler-induced inter-carrier interference. These effects are exacerbated in emerging scenarios such as vehicular communications, high-speed rail, and drone-based networks, as well as indoor and urban microcell deployments at sub-THz frequencies (Xing and Rappaport, 2021; Pometcu and D'Errico, 2020).

Orthogonal Time Frequency Space modulation has been proposed as a fundamentally different waveform paradigm that addresses these challenges by mapping information symbols into the delay-Doppler domain rather than the time-frequency domain (Hadani and Monk Cohere, 2018). By aligning modulation with the physical characteristics of wireless channels, OTFS transforms time-varying multipath effects into a nearly time-invariant representation, enabling improved diversity and robustness in high-mobility conditions. Comparative studies between OTFS and OFDM have demonstrated superior performance of OTFS in line-of-sight mobility channels at both sub-6 GHz and millimeter-wave frequencies (Wiffen et al., 2018).

Despite these advantages, OTFS is not immune to hardware impairments. Phase noise remains a critical limiting factor, especially at sub-THz frequencies where oscillator quality is constrained by power consumption and integration challenges. Recent investigations have begun to explore the interaction between phase noise and OTFS waveforms, highlighting unique impairment patterns distinct from those observed in OFDM systems (Bello et al., 2022). However, a comprehensive theoretical synthesis that integrates phase noise modeling, compensation techniques, channel estimation, and propagation characteristics within an OTFS framework remains underdeveloped.

The present article addresses this gap by providing an exhaustive, publication-ready analysis of phase noise aware OTFS systems based strictly on existing scholarly references. The objective is not to introduce new mathematical formulations but to deeply elaborate the theoretical implications, system-level interactions, and design trade-offs that emerge when OTFS is deployed in sub-THz and high-mobility environments. By drawing connections across disparate research strands, including OFDM phase noise compensation, delay-Doppler channel estimation, and sub-THz propagation modeling, this work aims to establish a coherent conceptual foundation for future research and development.

METHODOLOGY

The methodological approach adopted in this article is rooted in analytical synthesis rather than experimental or simulation-based validation. Given the constraint of avoiding mathematical expressions, the methodology focuses on descriptive modeling and conceptual integration of established techniques. The analysis begins with a detailed characterization of phase noise as a stochastic process arising from imperfections in local oscillators. Classical studies have shown that phase noise manifests as a combination of slowly varying common phase error and rapidly fluctuating components that spread energy across subcarriers in multicarrier systems (Casas et al., 2002; Bhatti and Moeneclaey, 2007).

In OFDM systems, extensive research has been devoted to pilot-aided synchronization and compensation methods, including approximate discrete cosine transform-based phase noise models and non-iterative inter-carrier interference mitigation techniques (Bhatti and Moeneclaey, 2007; Rabiei et al., 2010). These methods exploit the structure of OFDM symbols and the statistical properties of phase noise to estimate and correct impairments with manageable complexity. More recent approaches leverage coherence bandwidth concepts to enhance compensation performance in frequency-selective channels (Chung et al., 2022).

The methodology extends these conceptual tools to OTFS by examining how the delay-Doppler domain representation alters the manifestation of phase noise. In OTFS, information symbols experience a two-dimensional convolution with the channel response, resulting in structured interference patterns that differ fundamentally from OFDM. Phase noise in this context does not simply destroy subcarrier orthogonality but induces coupling across delay-Doppler bins, as highlighted in sub-THz OTFS waveform studies (Bello et al., 2022).

Channel estimation and equalization form another critical methodological pillar. Techniques developed for fifth-generation systems, including filter bank multicarrier and asynchronous fragmented spectrum scenarios, provide valuable insights into pilot design and estimation strategies under non-ideal conditions (Doré et al., 2014). These concepts are adapted to OTFS, particularly in scenarios involving fractional Doppler shifts where conventional grid-aligned assumptions break down (Hashimoto et al., 2021). The descriptive methodology emphasizes how pilot placement and channel sparsity can be exploited to mitigate both channel uncertainty and phase noise effects.

Propagation modeling at sub-THz frequencies is incorporated to contextualize waveform and impairment interactions within realistic environments. Indoor channel models and urban microcell measurements reveal distinct path loss characteristics, multipath sparsity, and temporal stability that influence the effectiveness of OTFS and phase noise compensation strategies (Pometcu and D'Errico, 2020; Xing and Rappaport, 2021). By integrating these models conceptually, the methodology accounts for environmental factors that shape system performance.

Finally, the methodology acknowledges emerging machine learning-based transceiver designs that incorporate neural networks for channel training and impairment compensation (Naikoti and Chockalingam, 2021). While not the primary focus, these approaches are discussed as complementary strategies that align with the delay-Doppler representation of OTFS and may offer robustness against complex impairment interactions.

RESULTS

The results of this analytical investigation are presented in descriptive form, focusing on qualitative trends and comparative insights rather than numerical metrics. One of the central findings is that OTFS fundamentally reshapes the impact of phase noise compared to OFDM. In OFDM, phase noise leads to a well-understood combination of common phase rotation and inter-carrier interference that grows with subcarrier spacing and oscillator instability (Leshem and Yemini, 2017). In contrast, OTFS distributes the effects of phase noise across the delay-Doppler domain, resulting in interference patterns that are more structured and, in some cases, more amenable to mitigation.

Studies on OTFS waveforms in sub-THz regimes indicate that while phase noise remains a significant impairment, its interaction with sparse delay-Doppler channels can preserve a degree of symbol separability that is lost in OFDM under similar conditions (Bello et al., 2022). This suggests that OTFS may tolerate higher levels of oscillator phase noise without catastrophic performance degradation, particularly in scenarios dominated by a limited number of propagation paths.

Another key result pertains to channel estimation and synchronization. Pilot-aided techniques originally developed for OFDM demonstrate partial effectiveness when conceptually adapted to OTFS, especially when pilots are placed to exploit delay-Doppler sparsity (Hashimoto et al., 2021). The use of coherence bandwidth concepts further enhances robustness by leveraging frequency correlation properties to smooth phase noise estimates across dimensions (Chung et al., 2022).

Propagation environment analysis reveals that sub-THz channels often exhibit reduced multipath richness compared to lower frequencies, which aligns well with OTFS assumptions and mitigates the compounded effects of phase noise and Doppler spread (Pometcu and D'Errico, 2020; Xing and Rappaport, 2021). In high-mobility line-of-sight scenarios, OTFS consistently demonstrates improved resilience relative to OFDM, corroborating comparative studies conducted at both millimeter-wave and sub-6 GHz bands (Wiffen et al., 2018).

The descriptive results also indicate that non-iterative phase noise mitigation techniques, while originally designed for OFDM, provide valuable conceptual guidance for low-complexity OTFS implementations (Rabiei et al., 2010). When combined with delay-Doppler domain processing, such approaches may offer practical pathways to phase noise aware receiver designs.

DISCUSSION

The findings discussed above carry significant theoretical and practical implications for the design of future wireless systems. The delay-Doppler perspective introduced by OTFS represents a paradigm shift that challenges long-standing assumptions about waveform design and impairment mitigation. By aligning modulation with the inherent structure of wireless channels, OTFS alters the balance between channel-induced and hardware-induced distortions.

One of the most important implications is the redefinition of phase noise tolerance. While phase noise cannot be eliminated, its impact can be reshaped through waveform design. OTFS demonstrates that robustness does not necessarily require reducing oscillator imperfections but can instead be achieved by transforming how impairments manifest at the symbol level (Bello et al., 2022). This insight is particularly valuable for sub-THz systems, where achieving low phase noise through hardware alone may be economically or technologically infeasible.

Nevertheless, the discussion must also acknowledge limitations. OTFS introduces increased receiver complexity due to two-dimensional signal processing and the need for accurate channel knowledge in the delay-Doppler domain. Phase noise compensation in OTFS is less mature than in OFDM, and many existing techniques require substantial adaptation. Moreover, the benefits of OTFS are most pronounced in channels with sufficient Doppler spread or sparsity; in quasi-static or richly scattered environments, the advantages may diminish.

Future research directions include the integration of machine learning techniques for joint channel estimation and phase noise compensation, as suggested by recent DNN-based transceiver designs (Naikoti and Chockalingam, 2021). Such approaches may overcome analytical modeling limitations and adapt dynamically to complex impairment interactions. Additionally, further exploration of coding and detection strategies under correlated fading conditions may enhance OTFS performance in realistic deployment scenarios (Bouras et al., 1993).

CONCLUSION

This article has presented an extensive, theoretically grounded examination of phase noise aware Orthogonal Time Frequency Space modulation for sub-THz and high-mobility wireless systems. By synthesizing insights from waveform design, phase noise modeling, channel estimation, and propagation studies, the analysis demonstrates that OTFS offers a fundamentally different and potentially more robust approach to dealing with oscillator impairments and time-varying channels than conventional OFDM.

While challenges remain in terms of complexity and practical implementation, the conceptual advantages of OTFS, particularly its alignment with the delay-Doppler structure of wireless channels, position it as a strong candidate for future-generation communication systems. Phase noise, once considered a prohibitive limitation at high frequencies, may become a manageable impairment through thoughtful waveform and receiver design. As research continues to evolve, phase noise aware OTFS is likely to play a central role in enabling reliable, high-capacity wireless communication in the sub-THz era.

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