RFO Estimation for in CP-OFDM Based Private 5G NR Sidelink System

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***Abstract*—This letter presents an enhanced approach for estimating the residual frequency offset (RFO) in wireless communication systems employing cyclic prefix orthogonal frequency division multiplexing (CP-OFDM), such as those used in private 5G NR sidelink system. The proposed scheme leverages the sidelink primary synchronization signal (S-PSS), which is embedded within the sidelink synchronization signal block (S-SSB) structure of the 5G NR sidelink system, to effectively estimate synchronization errors. This technique is particularly suited for device-to-device (D2D) communication scenarios in private 5G NR sidelink systems, where reliable synchronization is critical. Compared to the conventional method, the proposed RFO estimation technique shows improved accuracy. The performance of the proposed method is evaluated and compared with conventional schemes through computer simulations.**

Keywords—CP-OFDM, Synchronization, Frequency offset,

I. INTRODUCTION

The development of the 5G New Radio (NR) communication system builds upon the foundational technologies established in 4G Long Term Evolution (LTE). A distinguishing feature of 5G NR is its ability to support multiple numerologies, allowing for flexible frame structures to meet diverse service requirements. These numerologies and the corresponding physical layer parameters are primarily defined by the subcarrier spacing [1]-[3]. 5G NR adopts cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) as its waveform. CP-OFDM is particularly effective for high-speed data transmission over frequency-selective fading channels, as it divides the broadband channel into multiple narrowband subchannels that are orthogonal to one another. This division enables each subcarrier to experience flat fading, simplifying equalization and improving reliability in challenging propagation environments. Despite its advantages, CP-OFDM systems are inherently sensitive to synchronization errors, which can significantly impair system performance. These synchronization issues give rise to inter-symbol interference (ISI) and inter-carrier interference (ICI), both of which degrade signal integrity. Consequently, numerous techniques have been proposed to estimate and mitigate these synchronization errors [4]. Synchronization errors in CP-OFDM systems are generally categorized into symbol timing offset (STO) and carrier frequency offset (CFO). CFO can be further broken down into components such as fractional frequency offset (FFO), integer frequency offset (IFO), residual frequency offset (RFO), and sampling frequency offset (SFO) [5]-[10]. Typically, STO and FFO are addressed during the pre-FFT processing stage, while IFO, RFO, and SFO are corrected in the post-FFT stage. In mobile systems like 4G LTE and 5G NR, the physical cell identity (PCI) estimation is also incorporated in the post-FFT phase [1]. Even after FFO compensation, RFO can persist and continues to introduce phase rotation in the received signal. This phase distortion can severely hinder accurate demodulation, especially in scenarios involving high mobility. Therefore, tracking and compensating RFO becomes critical in CP-OFDM systems. In use cases such as vehicle-to-everything (V2X), device-to-device (D2D) communications, where both transmitter and receiver are mobile, synchronization becomes even more crucial. In particular, direct communication scenarios such as D2D applications require highly accurate synchronization due to the lack of centralized coordination. In private 5G NR sidelink environments, where autonomous nodes such as robots or vehicles exchange information without base station intervention, robust residual frequency offset (RFO) estimation becomes even more critical for maintaining reliable connectivity. This letter proposes an enhanced RFO estimation technique tailored for the mobile communication based wireless communication system. By leveraging the unique characteristics of the synchronization signals, particularly the sidelink primary synchronization signal (S-PSS), the method estimates RFO using a correlation-based approach, aiming to improve synchronization robustness in dynamic environments.

The remainder of this letter is organized as follows. Section II describes the system model for the 5G NR sidelink configuration based on the CP-OFDM waveform. In Section III, an enhanced RFO estimation method utilizing the S-PSS sequence is introduced. Section IV provides simulation result that demonstrate the effectiveness of the proposed approach. Finally, Section V concludes the letter.

II. SYSTEM MODEL

This letter focuses on the estimation of the RFO in the private 5G NR sidelink system, it is assumed that coarse synchronization has already been successfully performed. Under this assumption, the received signal at the l-th symbol in the private 5G NR sidelink system can be expressed as follows

$$Z_l(k) = C_l(k)T_l(k)e^{j2\pi\varphi(lN_u+N_g)/N} + I_l(k) + W_l(k) \quad (1)$$

where $\varphi = \delta_r + k\delta_s$, δ_r means RFO, δ_s means SFO, $C_l(k)$ means frequency response of wireless channel, $T_l(k)$ is the transmitted CP-OFDM symbol, $I_l(k)$ is the ICI, $N_u = N + N_g$, N is FFT size, N_g is cyclic prefix, and $W_l(k)$ is the complex additive white Gaussian noise (AWGN). In this letter, the impact of SFO is considered negligible during the synchronization error tracking process. This assumption is based on the relationship between SFO and RFO, which is given by $\delta_s = \delta_r \times (\Delta f / f_c)$, where Δf denotes the subcarrier spacing and f_c is the center frequency. For example, in a private 5G NR system with a center frequency of 4.75 GHz and a subcarrier spacing of 30 KHz, the resulting SFO becomes significantly small even under non-negligible RFO conditions.

III. Proposed Scheme

The S-PSS sequences are transmitted by placing them in the first and second OFDM symbols of the sidelink synchronization signal block (S-SSB). Assuming that the S-PSS sequences of length 127, which are known to both the transmitter and the receiver, are denoted as $S_{p1}(k)$, and $S_{p2}(k)$. In the receiver, received S-PSS sequences corresponds to the l-th and $l+1$-th CP-OFDM symbol and the differential correlation function (DCF) between adjacent subcarriers of the received S-PSS sequences can be expressed as follows

$$D_i(k) = Z^*_{l+i}(k-1)Z_{l+i}(k), \quad i = 0,1 \quad (2)$$

and

$$P_i(k) = S^*_{p_i}(k-1)S_{p_i}(k), \quad i = 0,1 \quad (3)$$

where $(\cdot)^*$ denotes the complex conjugate operation. This detection scheme yields reliable estimation performance under the assumption that $C_l(k) \approx C_l(k-1)$. To achieve more accurate RFO estimation, the expressions second correlation function can be formulated as follows

$$\hat{\delta}_r = \frac{N}{4\pi(N+N_g)} \arg\left\{\sum_{k=0}^{K-1} \bar{D}^*(k)\bar{P}(k)\right\} \quad (4)$$

where $\arg\{x\}$ means argument of complex number x , K is length of S-PSS, $\bar{D}(k) = D_1^*(k)D_2(k)$, $\bar{P}(k) = P_1^*(k)P_2(k)$. The proposed scheme enables accurate estimation of RFO in D2D communication systems operating within a private 5G network environment.

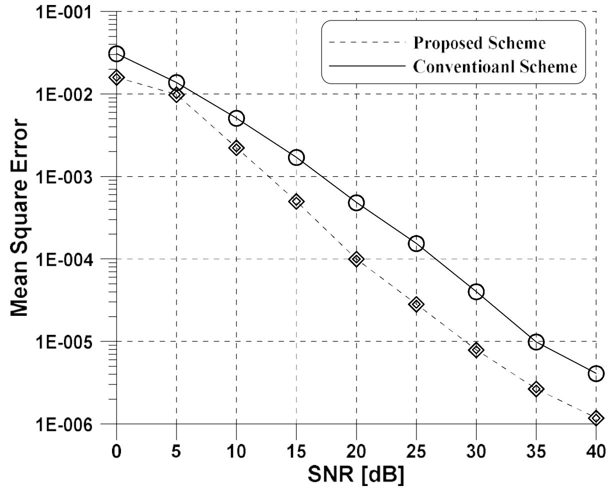

Fig.1. MSE performance of the proposed RFO estimation scheme with respect to SNR

IV. Simulation Result

The effectiveness of the proposed RFO estimation scheme is evaluated through computer simulations. The simulation scenario is based on a private 5G NR sidelink system utilizing the CP-OFDM waveform. As system parameters for the simulation, an FFT size of 2048, a CP length of 144, and QPSK modulation are considered. The center frequency is set to 4.75 GHz, with a subcarrier spacing of 30 KHz. A Rayleigh fading channel model is applied to emulate frequency-selective conditions. Fig. 1 demonstrates that the proposed scheme exhibits strong robustness under frequency selective fading channel. The simulation results further indicate that the proposed estimation method can be effectively applied to private 5G NR sidelink systems under various delay spread conditions.

V. Conclusion

In this letter, an enhanced RFO estimation scheme was proposed for CP-OFDM based private 5G NR sidelink systems. The proposed scheme leverages known S-PSS sequences embedded within the S-SSB structure to enable accurate RFO estimation via a correlation based approach. This approach is particularly effective in D2D communication scenarios, where centralized coordination is absent and robust synchronization is essential. Simulation result shows that the proposed scheme outperforms the conventional scheme, especially under frequency selective fading channel. This result confirms the robustness and practical applicability of the proposed scheme in private 5G network environments, such as those involving autonomous robots or industrial devices.

Acknowledgment

This work was supported by the 2023 Korea Industrial Complex Corporation Industrial Cluster Competitiveness Reinforcement Project R&D Support Project (Project No. VCKB2301, To realize carbon neutrality and strengthen the value chain of affiliated organizations Establishment of 5G network-based quality tracking system).

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