

Resolving CFO Ambiguity via IFDMA-Inspired Signatures for High-Mobility OFDM Communications

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Abstract—This paper addresses carrier frequency offset (CFO) ambiguity resolution in high-mobility orthogonal frequency division multiplexing (OFDM) systems operating at extremely low signal-to-noise-ratio (SNR) environments. Although fifth-generation New Radio (5G NR) employs paired tracking reference signals (TRS) for low-complexity CFO estimation, the limited temporal separation between the signals leads to ambiguity when the CFO exceeds the unambiguous capture range. By exploiting the structural equivalence between comb-type TRS and interleaved frequency-division multiple access (IFDMA) waveforms, we derive an ambiguity-free signature that distinguishes among ambiguous CFO candidates. Simulations in 5G non-terrestrial networks (NTN) scenarios demonstrate that the proposed IFDMA-inspired CFO signature (ICS) algorithm significantly outperforms the baseline methods, especially under very low SNR conditions.

Index Terms—OFDM, carrier frequency offset, IFDMA, high mobility, tracking reference signals

I. INTRODUCTION

Enabling reliable communications in ultra-high-mobility scenarios is a key challenge for fifth-generation (5G) and beyond wireless networks, such as non-terrestrial networks (NTN), vehicle-to-vehicle (V2V) communications, and high-speed railway systems. Orthogonal frequency division multiplexing (OFDM) is widely adopted because of its near-optimal performance in frequency-selective, time-invariant channels; however, it is inherently sensitive to carrier frequency offset (CFO). CFO causes inter-carrier interference (ICI) and undesired constellation rotation, significantly degrading the demodulation performance [1]. Therefore, the CFO must be accurately estimated, tracked, and compensated. To mitigate this, 5G new radio (NR) utilizes paired tracking reference signals (TRS) in the downlink [2]. By measuring the phase rotation between paired TRS symbols, the CFO can be efficiently estimated with a low computational complexity [3]. However, the CFO capture range is limited by the time interval between the reference symbol pairs. Consequently, under extreme Doppler shifts or substantial local-oscillator drift, the true CFO may exceed this range, resulting in ambiguous estimates. This paper addresses this limitation to enable reliable synchronization in next-generation high-mobility networks.

Several methods have been proposed to enable unambiguous CFO estimation in high-mobility scenarios. The method in [4] adapts the temporal density of the reference symbols according to the user's speed, at the cost of increased pilot overhead. The method in [5] exploits the Chinese remainder theorem (CRT) to achieve non-ambiguous CFO estimation under high

mobility. However, in 5G NR, the unknown data subcarriers for other users are frequency interleaved with the known reference subcarriers within a single OFDM symbol. This makes the target user not able to re-construct the full time-domain waveform of the corresponding OFDM symbol and hence not able to apply the CRT method. Other schemes, such as the cyclic-prefix (CP)-based method in [6], use the cross-correlation between the CP and the corresponding data segment. This approach is not suitable for multi-cell reception, because CFO contributions from different cells may cancel or reinforce each other, leading to erroneous estimates. Blind CFO estimation combined with data demodulation has also been investigated in [7], [8], but the iterative processing incurs a high computational complexity and latency. The method in [9] resolves the ambiguity by dividing a single time-domain OFDM symbol into two halves and calculating the phase difference between them. However, this method is severely affected by multi-access interference (MAI) caused by the leakage from unknown data symbols transmitted within the same OFDM symbol. Another approach in [10] uses a leakage ratio function (LRF) and transmits reference symbols with fixed but opposite frequency biases to avoid channel estimation at the receiver. However, this method discards phase information and therefore remains suboptimal under very low signal-to-noise-ratio (SNR) conditions.

In our recent work in [11], we proposed a mathematical framework that enables joint MAI separation and CFO estimation using a single time-domain OFDM symbol. In this work, we leverage this framework to address ambiguity resolution in multi-symbol scenarios. Specifically, we exploit the time-domain waveform separation capability to obtain an unambiguous coarse CFO estimate from each individual symbol. Although this estimate has limited intrinsic precision, it provides sufficient information to disambiguate multiple CFO candidates derived from the phase-based estimator. Simulation results for 5G NTN scenarios show that the proposed IFDMA-inspired CFO signature (ICS) method consistently outperforms existing techniques and maintains reliable performance, especially at very low SNRs.

Notation: Upper-case bold-faced letters denote matrices, and lower-case bold-faced letters denote vectors. The transpose, conjugate, and Hermitian transpose are denoted by $\{\cdot\}^T$, $\{\cdot\}^*$, and $\{\cdot\}^H$, respectively. The operator $\text{diag}(\mathbf{x})$ denotes a diagonal matrix constructed from the elements of $\mathbf{x}$, and $\|\mathbf{x}\|$ denotes the ℓ_2 -norm of $\mathbf{x}$. The argument of a complex number is denoted by $\arg\{\cdot\}$, the index of the maximum-magnitude

element by $\arg \max\{\cdot\}$, and the absolute value by $|\cdot|$.

II. PROBLEM FORMULATION

This section outlines the system model for OFDM pilot-based CFO estimation and formalizes the CFO ambiguity problem arising from the inherent 2π phase wrapping of phase measurements.

A. System Model

We consider a conventional OFDM communication system in which a transmitter sends a frame of OFDM symbols over a wireless channel to a receiver. As illustrated in Fig. 1, two OFDM reference symbols are embedded in the transmitted frame for CFO tracking. The indices of these reference symbols are denoted by m_1 and m_2 . In each reference OFDM symbol, N_p reference subcarriers are inserted among the data subcarriers in a comb-type arrangement. The sequences transmitted on the reference subcarriers are assumed to be known at the receiver. Without loss of generality, we assume that the integer CFO component has already been estimated and compensated for through raster-scan processing using synchronization signals. Consequently, only the fractional CFO remains to be estimated, with an uncertainty of up to half of the subcarrier spacing (SCS).

At the receiver, the cyclic prefix (CP) is removed from each of the two reference symbols, and the resulting signals are transformed into the frequency domain using a discrete Fourier transform (DFT). The reference subcarriers are then extracted and descrambled using the known sequences. The resulting signals can be expressed as [10]:

$$y_{m,k} = L(\Delta f) \lambda_k e^{j2\pi m \Delta f} + I_{m,k}(\Delta f) + z_{m,k}, \quad (1)$$

where $m \in \{m_1, m_2\}$ denotes the reference OFDM symbol index, and $k \in \{0, N/N_p, 2N/N_p, \dots, N_p - 1\}$ represents the index of the reference subcarriers. Here, Δf is the CFO normalized by the SCS, $\Delta f = f_{\text{CFO}}/f_{\text{SCS}}$ and N denotes the DFT size. The term $L(\Delta f)$ denotes the CFO-induced leakage ratio [10], $I_{m,k}$ represents the ICI at the k -th subcarrier, and $z_{m,k}$ denotes the additive white Gaussian noise (AWGN). The term λ_k represents the channel frequency response at subcarrier k , $\lambda_k = \sum_{l=0}^{L-1} \alpha_l e^{-j2\pi k f_{\text{SCS}} \tau_l}$, where L denotes the total number of multipath components. Moreover, α_l and τ_l are the complex path gain and the propagation delay associated with the l -th channel path, respectively.

B. Phase-Wrapping Induced Ambiguity in CFO Estimation

A commonly adopted low-complexity approach for CFO estimation is to evaluate the phase rotation between the reference symbols indexed by m_1 and m_2 [12]. To mitigate the effects of noise and ICI, a practical strategy is to transform the descrambled reference signals defined in (1) into the delay domain by applying an N_p -point inverse discrete Fourier transform (IDFT). Subsequently, the dominant delay tap is selected for further processing. The resulting delay-domain signals after the IDFT can be expressed as

$$r_{m,n} = L(\Delta f) e^{j2\pi m \Delta f} \sum_{l=0}^{L-1} \alpha_l \delta(n - n_l) + z'_{m,n}, \quad (2)$$

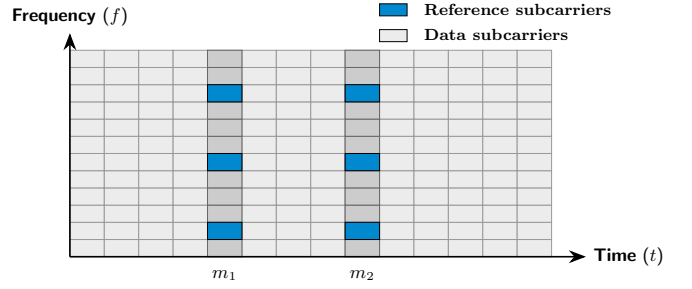


Fig. 1: OFDM frame containing two reference symbols

where n represents the delay-domain sample index, and n_l corresponds to the discrete delay associated with the l -th path. The term $z'_{m,n}$ denotes the effective noise component in the delay domain and includes contributions from both ICI and AWGN in the frequency domain.

The dominant delay-domain component for the m -th reference symbol is obtained by selecting the tap with the largest magnitude. Let

$$n_m^* = \arg \max_{n \in \{1, \dots, N_p\}} |r_{m,n}|, \quad (3)$$

and define the corresponding complex peak value as

$$p_m = r_{m,n_m^*} \approx L(\Delta f) \alpha_{\max} e^{j2\pi m \Delta f}, \quad (4)$$

where $\alpha_{\max}$ denotes the strongest delay-domain channel coefficient. In other words, p_m represents the dominant complex tap after the IDFT operation.

The CFO can then be obtained from the phase difference between the dominant peaks of the two reference symbols. This phase difference is computed using the product $p_{m_1}^* p_{m_2}$ as

$$\widehat{\Delta \theta} = \arg\{p_{m_1}^* p_{m_2}\} \approx 2\pi \Delta f (m_2 - m_1) - 2\pi T, \quad (5)$$

where $T \in \mathbb{Z}$ accounts for the 2π phase wrapping. The estimate is unambiguous only when the phase rotation remains within the principal range $[-\pi, \pi]$. Therefore, the corresponding unambiguous CFO capture range is $\left[-\frac{1}{2(m_2 - m_1)}, \frac{1}{2(m_2 - m_1)}\right]$. In high-mobility scenarios or under large temperature-induced oscillator drifts, the actual CFO may exceed this range. In such cases, the observed phase rotation is wrapped modulo 2π , such that multiple CFO values can produce the same measured phase. As a result, the CFO cannot be determined uniquely from $\widehat{\Delta \theta}$ alone. Using (5), and assuming that the residual CFO lies within $\pm \frac{1}{2}$ of the subcarrier spacing (SCS), the set of possible CFO candidates can be written as

$$\widehat{\Delta f}_T = \frac{\widehat{\Delta \theta} + 2\pi T}{2\pi(m_2 - m_1)}, \quad (6)$$

where T is an integer chosen such that $\widehat{\Delta f}_T \in \left[-\frac{1}{2}, \frac{1}{2}\right]$. Equivalently, the candidate set is

$$\widehat{\mathcal{F}} = \left\{ \frac{\widehat{\Delta \theta} + 2\pi T}{2\pi(m_2 - m_1)} \mid T \in \mathbb{Z}, \widehat{\Delta f}_T \in \left[-\frac{1}{2}, \frac{1}{2}\right] \right\}. \quad (7)$$

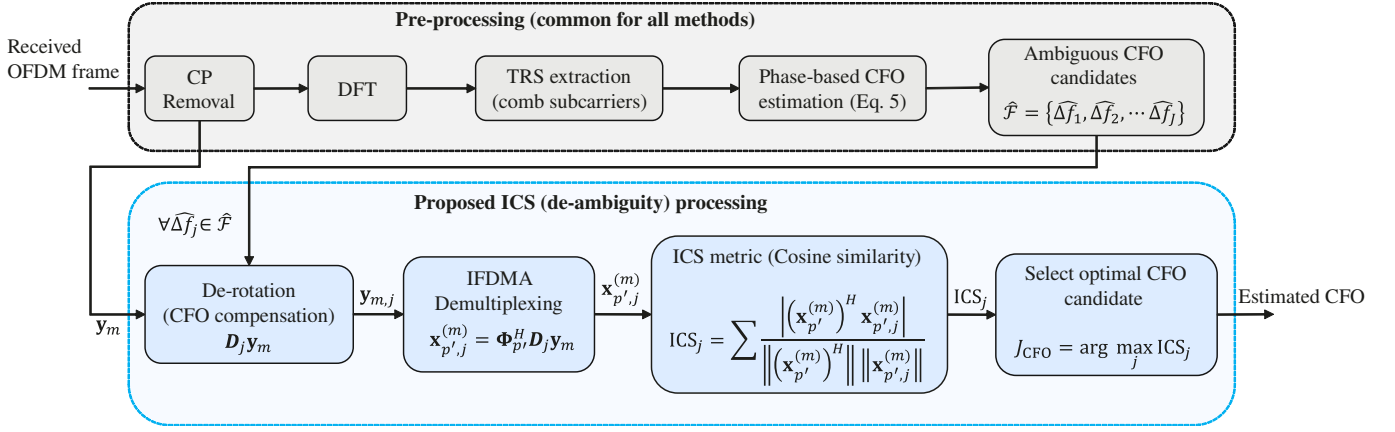


Fig. 2: Processing flow of the proposed IFDMA-inspired CFO signature (ICS) algorithm

The key challenge is to determine which candidate in $\hat{\mathcal{F}}$ corresponds to the true CFO.

C. Existing Solutions for CFO Ambiguity Resolution

Two representative approaches for resolving CFO ambiguity are presented in [9] and [10]. The first baseline method, proposed in [9], divides the time-domain reference symbol into two sub-symbols to estimate a coarse frequency offset. Although this approach expands the acquisition range, the windowing operation required for sub-symbol processing disrupts subcarrier orthogonality. This leads to a significant leakage from the unknown data payloads into the reference subcarriers, severely limiting the estimation accuracy. The second baseline method, introduced in [10], employs a LRF to identify the true CFO by measuring energy leakage into adjacent subcarriers. Although it outperforms the sub-symbol approach, the LRF-based method remains susceptible to substantial performance degradation. This vulnerability arises from the additional ICI generated by the phase rotations applied to the reference symbol; consequently, interference from adjacent data subcarriers may overwhelm the leakage signal and compromise the reliability of ambiguity resolution.

III. PROPOSED SOLUTION

To resolve CFO ambiguity, we propose a time-domain IFDMA-inspired CFO signature (ICS) technique. Fig. 2 summarizes the proposed ICS-based CFO ambiguity resolution algorithm. First, the conventional phase-based estimator generates a set of ambiguous CFO candidates. Each candidate is then compensated in the time domain and passed through an IFDMA demultiplexing stage. The resulting signal is compared with the known TRS reference using cosine similarity, which defines the ICS metric. The CFO candidate with the largest ICS value is selected as the final estimate. The underlying principle of this processing chain is described below.

The key idea is that the comb-type frequency allocation of the TRS can be interpreted as an interleaved multiuser structure in the time domain. This interpretation enables the separation of the reference and data components through structured projections. Specifically, the interleaved mapping

of the TRS symbols in the frequency domain corresponds to an interleaved frequency-division multiple-access (IFDMA) structure [13]. Based on this interpretation, the received time-domain signal corresponding to the m^{th} reference symbol, $\mathbf{y}_m$, can be expressed as

$$\mathbf{y}_m = \mathbf{D}\mathbf{H}\mathbf{x}_m + \mathbf{z}_m \quad (8)$$

In this model, $\mathbf{x}_m$ denotes the transmitted time-domain sample vector, while $\mathbf{z}_m$ denotes additive white Gaussian noise (AWGN), with $\mathbf{z}_m \sim \mathcal{CN}(\mathbf{0}, \sigma^2 \mathbf{I})$. The impact of the frequency offset is captured by the CFO-dependent steering matrix $\mathbf{D} = \text{diag} \left(\left[1, e^{j\frac{2\pi\Delta f}{N}}, \dots, e^{j\frac{2\pi(N-1)\Delta f}{N}} \right] \right)$. Here, $\mathbf{H}$ is an $N \times N$ circular convolution matrix whose first column is $\mathbf{h} = [h_0, \dots, h_{L_c-1}, 0, \dots, 0]^T$, where the L_c non-zero complex coefficients represent the channel impulse response (CIR).

The transmitted OFDM symbol $\mathbf{x}_m$, typically obtained via an N -point inverse discrete Fourier transform (IDFT) of the frequency-domain symbols, can be equivalently represented using the IFDMA framework. As illustrated in Fig. 2, this representation interprets the comb-type TRS allocation as an interleaved multiuser structure, in which the TRS and the interleaved data are treated as P distinct streams. In the considered 5G TRS configuration, $P = 4$, corresponding to the comb factor, and with $N = 2048$, each stream contains $Q = N/P = 512$ samples. Each stream p is represented by the vector $\mathbf{d}_p^{(m)} = [d_{p,0}^{(m)}, d_{p,1}^{(m)}, \dots, d_{p,Q-1}^{(m)}]^T$, where the total number of subcarriers satisfies $N = PQ$. In this representation, the contribution of the p^{th} data stream to $\mathbf{x}_m \in \mathbb{C}^{N \times 1}$ consists of phase-rotated repetitions determined by the stream index p . Consequently, the time-domain symbol can be expressed as [11]:

$$\mathbf{x}_m = \sum_{p=0}^{P-1} \Phi_p \mathbf{x}_p^{(m)}, \text{ with } \mathbf{x}_p^{(m)} = \mathbf{F}_Q^H \mathbf{d}_p^{(m)} \quad (9)$$

where $\mathbf{F}_Q^H \in \mathbb{C}^{Q \times Q}$ is the IDFT matrix, and $\Phi_p \in \mathbb{C}^{PQ \times Q}$ is a user-specific matrix with PQ non zero entries [11], defined as

$$\Phi_p = \mathbf{a}_p \otimes \mathbf{B}_p. \quad (10)$$

TABLE I: Simulation parameters for the considered NTN configurations

Scenarios	f_c	BW	f_{SCS}	N	N_p	(m_1, m_2)	Capture range	True CFO	Channel profile
NTN-Cfg-1	2 GHz	10 MHz	15 kHz	2048	150	(4,8)	± 1.75 kHz	$[-5, 5]$ kHz	NTN-TDLC5
NTN-Cfg-2	2 GHz	20 MHz	15 kHz	2048	300	(4,8)	± 1.75 kHz	$[-5, 5]$ kHz	NTN-TDLC5

The vector $\mathbf{a}_p = [1, e^{j2\pi p/P}, \dots, e^{j2\pi p(P-1)/P}]^T$ is a blockwise phase-rotation vector of length P , while $\mathbf{B}_p = \text{diag}([1, e^{j2\pi p/N}, \dots, e^{j2\pi p(Q-1)/N}])$ represents the phase ramp across the samples within each block.

Based on this transmitter representation, joint CFO estimation and multi-access interference (MAI) suppression can be performed at the receiver by exploiting the structure of Φ_p [11]. Assuming that the p' -th data stream represents the target time-domain TRS component, demultiplexing is performed by left-multiplying the received signal by $\Phi_{p'}^H$, yielding

$$\Phi_{p'}^H \mathbf{y}_m = \Phi_{p'}^H \mathbf{D} \mathbf{H} \mathbf{x}_m + \mathbf{z}'_m, \quad (11)$$

where $\mathbf{z}'_m = \Phi_{p'}^H \mathbf{z}_m$. By substituting $\mathbf{x}_m$ from (9), we can rewrite [11] as:

$$\begin{aligned} \Phi_{p'}^H \mathbf{y}_m &= \Phi_{p'}^H \mathbf{D} \mathbf{H} \sum_{p=0}^{P-1} \Phi_p \mathbf{x}_p^{(m)} + \mathbf{z}'_m \\ &= \Phi_{p'}^H \mathbf{D} \mathbf{H} \left(\Phi_{p'} \mathbf{x}_{p'}^{(m)} + \sum_{p \neq p'}^{P-1} \Phi_p \mathbf{x}_p^{(m)} \right) + \mathbf{z}'_m \end{aligned} \quad (12)$$

As illustrated in Fig. 2, the ambiguity-resolution stage iterates over all CFO candidates in the set $\hat{\mathcal{F}}$ obtained from (7). For each candidate, the received signal is first de-rotated and then processed through the IFDMA demultiplexing stage to compute the corresponding ICS metric. Suppose that $\hat{\mathcal{F}}$ contains J CFO candidates. For the j -th candidate, denoted by $\hat{\Delta}f_j$ with $j \in \{1, \dots, J\}$, the corresponding phase de-rotation matrix is defined as $\mathbf{D}_j = \text{diag}([1, e^{-j2\pi \hat{\Delta}f_j/N}, \dots, e^{-j2\pi (N-1) \hat{\Delta}f_j/N}])$. Applying $\mathbf{D}_j$ to $\mathbf{y}_m$ compensates for the phase rotation associated with the j -th CFO candidate. The resulting estimate of the target component $\mathbf{x}_{p',j}^{(m)}$ is then given by

$$\begin{aligned} \mathbf{x}_{p',j}^{(m)} &= \Phi_{p'}^H \mathbf{D}_j \mathbf{y}_m \\ &= \Phi_{p'}^H \mathbf{D}_j \mathbf{D} \mathbf{H} \left(\Phi_{p'} \mathbf{x}_{p'}^{(m)} + \sum_{p \neq p'}^{K-1} \Phi_p \mathbf{x}_p^{(m)} \right) + \mathbf{z}'_m \end{aligned} \quad (13)$$

For the correct CFO candidate, i.e., when $\mathbf{D}_j = \mathbf{D}^*$, the phase distortion is ideally compensated for, resulting in constructive alignment and MAI suppression [10, eq. 6]. Furthermore, for multipath channels dominated by the strongest path, i.e., $h_0 \gg h_l$ for $l \in \{1, \dots, L_c - 1\}$, the contributions of the remaining paths can be neglected. Therefore, $\mathbf{H}$ can be approximated

by the scalar gain h_0 . If the estimate at the matching CFO candidate is denoted as $\hat{\mathbf{x}}_{p'}^{(m)}$, then

$$\begin{aligned} \hat{\mathbf{x}}_{p'}^{(m)} &\approx h_0 \Phi_{p'}^H \mathbf{D}^* \mathbf{D} \Phi_{p'} \mathbf{x}_{p'}^{(m)} + \mathbf{z}'_m \\ &\approx P h_0 \mathbf{x}_{p'}^{(m)} + \mathbf{z}'_m \end{aligned} \quad (14)$$

which equals the true $\mathbf{x}_{p'}^{(m)}$, scaled by an unknown complex gain $P h_0$. In the case of TRS, only $\mathbf{x}_{p'}^{(m)}$ is known at the receiver. For the remaining unknown candidates, leakage into the MAI term reduces the correlation between $\mathbf{x}_{p',j}^{(m)}$ and $\mathbf{x}_{p'}^{(m)}$. Because of the unknown scaling factor in (14), the cosine similarity for both reference symbols is used as an ICS. This similarity provides a normalized measure of the correlation between the estimates $\mathbf{x}_{p',j}^{(m)}$ and the reference $\mathbf{x}_{p'}^{(m)}$. The CFO candidate index j_{CFO} corresponding to the largest ICS is obtained as

$$j_{\text{CFO}} = \arg \max_{j \in \{1, \dots, J\}} \left(\sum_{m \in \{m_1, m_2\}} \frac{|(\mathbf{x}_{p'}^{(m)})^H \mathbf{x}_{p',j}^{(m)}|}{\|\mathbf{x}_{p'}^{(m)}\| \cdot \|\mathbf{x}_{p',j}^{(m)}\|} \right) \quad (15)$$

The index j_{CFO} identifies the CFO candidate whose signature best aligns with the separated time-domain reference signal $\hat{\mathbf{x}}_{p'}^{(m)}$. The final CFO estimate is then obtained as $\hat{\Delta}f = \hat{\Delta}f_{j_{\text{CFO}}}$, which resolves the ambiguity among the candidate set $\hat{\mathcal{F}}$.

The proposed method has a low computational complexity. Beyond legacy CFO estimation, the additional receiver processing consists primarily of a small number of vector operations, resulting in computational complexity of $\mathcal{O}(NJ)$.

IV. SIMULATION RESULTS

The performance of the proposed ICS method is evaluated through numerical simulations in a 5G NTN scenario. Two waveform configurations are considered to illustrate the trade-off between estimation accuracy and frequency-resource utilization. The time-frequency allocation of the paired OFDM reference symbols follows the 5G TRS specifications in [2]. The OFDM reference symbols span the full allocated bandwidth, with unknown user data transmitted on the subcarriers between the reference subcarriers. To model realistic propagation conditions, the channel follows the 3GPP NTN-TDLC5 profile specified in [14, Table B.2.1-3]. The true CFO is assumed to lie in the range $[-5000, 5000]$ Hz. The detailed simulation parameters, including the carrier frequency f_c , the channel bandwidth (BW), the subcarrier spacing f_{SCS} , the DFT length N , and the number of reference subcarriers N_p , are summarized in Table I.

Performance is evaluated in terms of the failure rate, defined as the percentage of simulation trials in which the CFO

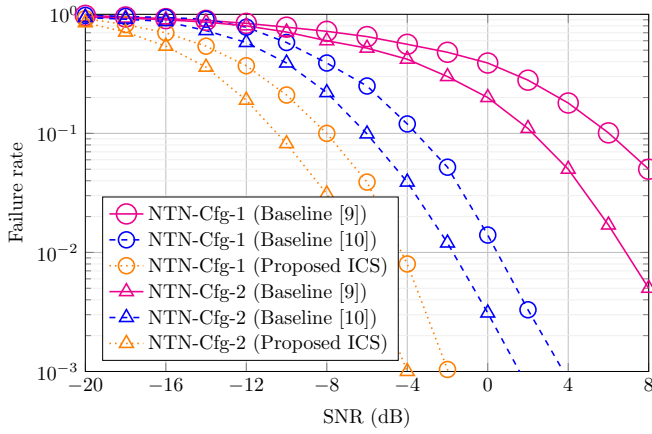


Fig. 3: Synchronization failure rate as a function of the received SNR

estimation error after ambiguity resolution exceeds 0.05 parts per million (ppm) of the carrier frequency. For example, when $f_c = 2$ GHz, a trial is counted as a failure if the absolute CFO estimation error after de-ambiguity processing exceeds 100 Hz, corresponding to 0.05 ppm at 2 GHz. The proposed ICS method is compared with the de-ambiguity techniques in [9], [10]. To ensure a fair comparison, the same preprocessing is used to generate the ambiguous CFO candidates for all methods; only the ambiguity resolution step differs.

Fig. 3 shows the failure rate for both NTN configurations. The proposed ICS method achieves a substantially lower failure rate than both baseline techniques in the both simulated configurations. Compared with the method in [10], the superior performance of the proposed approach is attributed to its use of clean time-domain phase-ramp information, which enables more effective suppression of noise and ICI. In addition, time-domain phase estimation offers finer frequency resolution than frequency-domain approaches, whose resolution is limited by the DFT bin spacing. In contrast to [9], the ICS method avoids the windowing operation that divides a single OFDM symbol into multiple sub-symbols. This windowing severely degrades the orthogonality between the reference and adjacent data subcarriers. Because these adjacent subcarriers carry unknown data, the resulting leakage creates interference within the sub-symbols that can exceed the CFO-induced ICI, thereby degrading the classification performance of the baseline. Consequently, in both configuration, the proposed ICS method provides gains of more than 5 dB over [10] and more than 12 dB over that in [9].

Fig. 4 compares the error vector magnitude (EVM) performance of all methods at an SNR of -2 dB. The maximum EVM permitted for QPSK modulation, as specified by 3GPP [15, Table 6.4.2.1-1], is indicated by a horizontal dashed line. Notably, the proposed ICS method is the only method whose cumulative distribution function (CDF) reaches 100% within the required threshold in both NTN configurations. This indicates that the proposed ICS framework can support reliable communication even below 0 dB SNR, which is important for NTN systems because of the high path loss. Fig. 5 further shows the probability density functions (PDFs) of the CFO estimation error at an SNR of -2 dB for *NTN-Cfg-1*. In

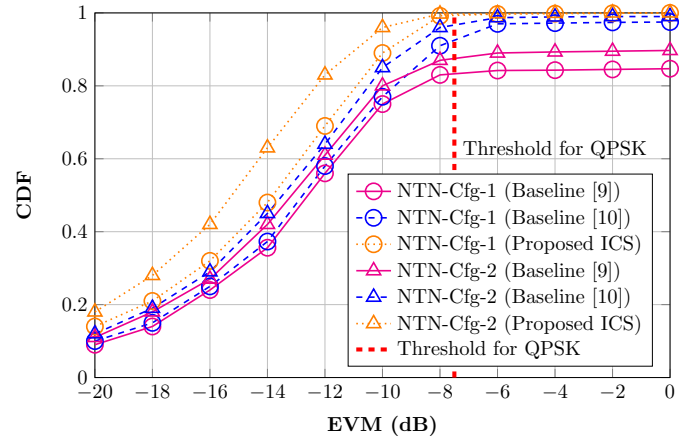


Fig. 4: CDF of the EVM at the received SNR of -2 dB

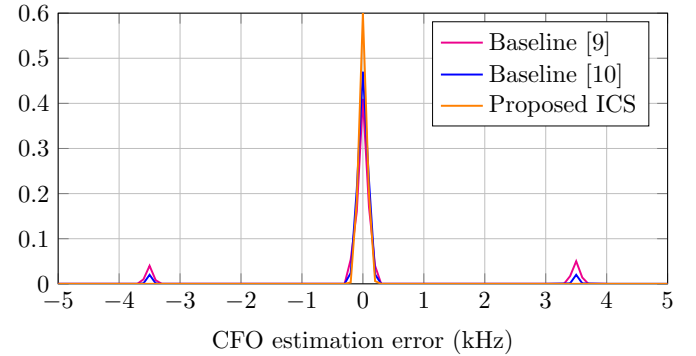


Fig. 5: PDF of the residual CFO estimation error at the received SNR of -2 dB

contrast to the baseline methods, the absence of outliers for the proposed ICS method indicates error-free ambiguity resolution in the simulation trials. In addition, within the correctly classified cluster, the proposed ICS method exhibits a smaller standard deviation than the baseline techniques. This shows that the proposed ICS approach not only resolves the CFO ambiguity effectively but also achieves a superior fractional CFO estimation accuracy.

Overall, the results demonstrate that the proposed ICS method resolves CFO ambiguities more reliably than the considered baseline methods. In NTN scenarios, reliable low-SNR performance is crucial, and the proposed ICS method provides gains of more than 6 dB in both configurations. The comparison between the two configurations also highlights the classical trade-off between estimation accuracy and frequency-resource usage. *NTN-Cfg-2* uses twice the frequency resources of *NTN-Cfg-1* and therefore achieves an additional gain of approximately 3 dB across the evaluated SNR range.

V. CONCLUSIONS AND FUTURE WORK

This paper proposes an ICS method for resolving CFO ambiguity in high-mobility OFDM systems. By exploiting the structural equivalence between comb-type 5G TRS and IFDMA waveforms, we drive a closed-form ambiguity-free signature that enables reliable selection of the correct CFO

candidate. Simulation results demonstrate that the proposed ICS method significantly outperforms the baseline techniques, especially under low-SNR conditions. The structural similarity between comb-type OFDM reference configurations and sparse antenna-array geometries also suggests that the proposed approach could be extended to angular ambiguity resolution in large-aperture arrays. Future work includes evaluating the proposed method under mobility scenarios with non-line-of-sight (NLOS) channel models.

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