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Performance Evaluation of CFO and Channel Estimation in Hybrid Tone OFDM Signals

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Abstract:

Introduction: There is a growing need for high-accuracy signal processing in 5G and future 6G networks. Reconfigurable Intelligent Surface (RIS)-assisted OFDM is a promising solution to enhance channel quality. Hybrid tone OFDM (HT-OFDM) introduces a new approach to improve carrier frequency offset (CFO) and channel estimation.

Objectives: This paper aims to develop an efficient method for joint CFO and channel estimation in HT-OFDM. The goal is to minimize the mean square error (MSE) and improve estimation accuracy.

Methods: The method starts with correlation and least-squares techniques to get initial CFO and channel estimates. A hybrid tone is then inserted into OFDM symbols. This step reduces noise and enhances accuracy by lowering MSE. Simulations and theoretical analysis validate the approach.

Results: At 20 dB SNR, the method reduces MSE to 0.02 when 100 RIS elements are used. The CFO estimation error drops to 0.005 for a CFO value of 0.5. Increasing pilot subcarriers to 32 at 30 dB SNR further lowers MSE to 0.01. Additional hybrid tone symbols show significant improvements in high-SNR conditions.

Conclusions: The proposed method effectively enhances CFO and channel estimation. It achieves significant MSE reduction and improves accuracy in RIS-assisted HT-OFDM systems. This makes it suitable for advanced 5G and 6G networks.

Keywords: RIS, OFDM, CFO, Channel Estimation, MSE, SNR.

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1. Introduction

RIS are transforming wireless communications. This technology enables intelligent radio environments by controlling electromagnetic wave propagation. It achieves these using surfaces embedded with passive reflecting elements. RIS technology is expected to play a crucial role in 6G networks by improving signal coverage, energy efficiency and reliability [1, 16]. To fully leverage RIS, accurate channel state information (CSI) is essential. With proper CSI, systems can optimize RIS reflection coefficients, enhancing overall performance.

Estimating CSI in RIS-aided OFDM systems presents significant challenges. RIS configurations typically involve many passive elements, complicating the process. Various methods have been proposed to address this. The on/off approach is a basic technique that activates one RIS element at a time. While simple, it does not utilize the RIS surface's full potential. Reflection pattern-based methods have also emerged, using predefined RIS reflection coefficients for estimation. These methods, however, often require some active RIS elements, which increase hardware costs. Recently, advanced techniques like enhanced extreme learning machine (ELM)-based methods have shown promise. ELMs address issues like insufficient cyclic prefix (CP) length and hardware imperfections. Despite their effectiveness. These methods involve prolonged training, making them less practical for real-time applications.

Another key issue in RIS-aided systems is carrier frequency offset (CFO). CFO occurs due to frequency mismatches between transmitter and receiver oscillators. This misalignment disrupts the orthogonality of subcarriers in OFDM systems causes inter-carrier interference (ICI) [2, 3]. CFO degrades system performance, making its estimation critical. Joint CFO and channel estimation techniques have been developed to tackle this. Some methods insert pilot symbols in the time domain to estimate CFO [4]. While effective, these approaches increase system complexity and rely on knowing the channel's maximum delay spread, which is often unavailable. To address these challenges, we propose a insertion of hybrid tone in OFDM symbols. It is specifically designed for CFO and channel estimation in RIS-aided OFDM systems [5, 6]. The protocol eliminates the need for prior knowledge of the channel's maximum delay spread. This makes it simpler and more efficient. The first phase involves correlation-based CFO estimation and least-square (LS)-based channel estimation. This provides initial estimates with low complexity. Next, noise effects are reduced, refining these initial estimates [7, 8].

The demand for faster and more reliable wireless communication has driven the development of advanced techniques in OFDM. Hybrid tone OFDM and RIS-assisted OFDM are among the latest innovations. These techniques address critical challenges like CFO and channel estimation. This literature survey highlights current research [9, 17]. CFO arises due to oscillator mismatches and Doppler effects. It disrupts subcarrier orthogonality and causes inter-carrier interference. Traditional CFO estimation techniques, such as Maximum Likelihood Estimation (MLE) and Least Squares (LS), are computationally intensive. Hybrid Tone OFDM improves these methods by adding pilot tones [10]. These tones serve as references for precise CFO estimation without adding significant overhead [11, 12]. Machine learning approaches have further enhanced accuracy in dynamic channels. Algorithms using neural networks adapt to changing CFO conditions better than conventional methods [13].

Channel estimation is vital for reliable communication. It ensures accurate equalization at the receiver. Pilot-assisted techniques like LS and Minimum Mean Square Error (MMSE) are common. They balance computational complexity and accuracy [14, 15]. Hybrid Tone OFDM improves channel estimation by embedding pilots strategically among data tones. New methods using compressed sensing reduce the need for extensive pilots, enhancing efficiency in sparse channels [16, 18]. However, these techniques face challenges in highly dynamic environments. RIS is a new technology that uses programmable surfaces to control electromagnetic waves. RIS reflects signals with adjustable phases, improving signal quality and propagation. When combined with OFDM, RIS mitigates CFO effects and enhances channel estimation. It creates favourable signal paths, boosting spectral efficiency and reliability. Studies show RIS-OFDM systems are energy-efficient and ideal for 6G networks. However, they require complex optimization algorithms for RIS phase configurations.

Recent research explores joint frameworks for CFO estimation, channel estimation and RIS configuration. These approaches aim to optimize overall system performance. For example, deep reinforcement learning has been used to optimize RIS configurations and CFO simultaneously [9]. Integrating RIS with hybrid tone OFDM shows potential for overcoming multipath and CFO issues. However, implementation challenges, such as hardware limitations and computational overhead, must be addressed. Despite advancements, challenges remain. CFO estimation must adapt to fast-changing scenarios. Channel estimation should minimize pilot overhead while maintaining accuracy. RIS optimization needs simpler algorithms for real-time applications.

2. Objectives

This scheme ensures high estimation accuracy and reliability, even under challenging channel conditions. The proposed protocol offers several benefits. It enhances both estimation accuracy and spectral efficiency. By avoiding reliance on complete knowledge of the delay spread, it reduces system complexity and resource requirements. This makes the solution scalable and suitable for large-scale 6G deployments. RIS, as a passive technology, aligns well with the goals of green and sustainable communication. It reflects and scatters signals to improve link quality and extend coverage without consuming significant energy. The proposed protocol complements these features, providing efficient and reliable joint CFO and channel estimation tailored for dynamic environments. Our work contributes to the field in multiple ways.

- We have introduced a hybrid tone with two distinct phases for joint CFO and channel estimation.
- System employed a correlation-based technique for CFO estimation to reduce the complexity and improve the accuracy.
- Estimated the channel without requiring prior knowledge of its length, it makes adaptable to real-world scenarios.
- Finally, the protocol's MSE performance is derived and analysed under various SNR levels to ensures a strong theoretical foundation for practical applications.

3. Hybrid Tone OFDM System Model

The proposed scheme describes the transmission and reception process in a wireless communication system is shown in Figure (1). It utilizes an IRS to enhance signal quality. It consists of three main sections: the transmitter (Base station), the IRS-assisted propagation path (Channel) and the receiver (User).

At the transmitter, random bits are generated as the source data. These bits are first converted into modulated symbols using a modulation block. Here, constellation mapping, such as QAM, is performed. After modulation, the data is separated into three categories: pilot data, hybrid tone, and OFDM data. The pilot data is essential for channel estimation, hybrid tones assist in correcting CFO and OFDM data contains user information. These components are inserted into the appropriate positions in the OFDM frame. The frame then undergoes an inverse fast Fourier transform (IFFT) operation to convert it into the time domain. A cyclic prefix is added to mitigate inter-symbol interference (ISI) caused by multipath propagation. The time-domain OFDM signal is then transmitted to the propagation medium. The transmitted signal encounters obstacles, such as buildings, and trees.

This may degrade signal quality. The IRS acts as an intermediary to improve signal propagation. It uses passive reflecting elements to dynamically adjust the signal's phase and direction. Its ensures that the signal reaches the user despite obstacles.

At the receiver, the signal undergoes cyclic prefix removal and an FFT operation to transform it back to the frequency domain. This is followed by CFO & channel estimation; it corrects frequency offsets and estimates the channel response. The channel equalization block then compensates for distortions caused by the propagation channel. Afterward, the demodulation block performs de-mapping to recover the original transmitted bits. The system improves transmission reliability by addressing signal degradation due to obstacles and channel impairments.

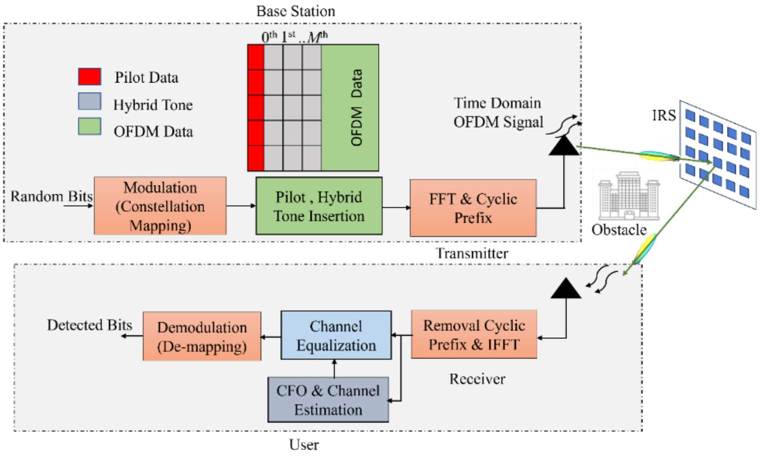

Figure 1: Block diagram of hybrid tone OFDM System with assisted IRS Equipment

In this model, we examine an OFDM system with N subcarriers that operates over a frequency-selective fading channel. The system uses a RIS with M passive elements to improve signal quality. Here, both the channel and the CFO are considered stable within each transmission frame. The RIS is strategically positioned to enhance the uplink communication between a user and a Base Station. Both the user and the BS have single antennas. This setup involves the estimation of $M+1$ channels. A direct channel between the user and the BS.M cascaded channels between the user, the RIS, and the BS. A pilot frame with $M+1$ blocks is used for both CFO and channel estimation. Each frequency-domain OFDM symbol, represented in equation (1) [12].

$$s_k = [s_k(0), s_k(1), \dots, s_k(N-1)]^T \quad \in \mathbb{C}^{N\times 1} \tag{1}$$

The sequence consists of two main parts: A pilot sub-sequence of length N_P used for estimating both the CFO and Channel Impulse Response (CIR). A data sub-sequence of length $N_D = N - N_P$. This is reserved for data transmission. The total transmission power P_t is uniformly spread across all subcarriers. Each RIS element has a normalized magnitude, represented by equation (2).

$$\phi_k = [\phi_{0,k}, \phi_{1,k}, \dots, \phi_{M,k}]^T \quad \in \mathbb{C}^{(M+1)\times 1} \tag{2}$$

Here, $|\phi_{m,k}| = 1$ for all indices *k* and *m*. In this model, the direct path is denoted by path *(0, k)* with a unit reflection coefficient, $\phi_{0,k} = 1 \quad \forall k$ .The channel impulse response for each path *m* is represented by equation (3)

$$\mathrm{g}_m = [g_m(0), g_m(1), \ldots, g_m(L-1)]^T \tag{3}$$

Here, $g_m(l)$ follows a complex Gaussian distribution, $g_m(l) \sim \mathcal{CN}(0, \sigma_l^2)$, with a power delay profile $\sum_{l=0}^{L-1} \sigma_l^2 = 1$. The channel frequency response for each path *m* is computed using the fast Fourier transform is mathematically represented as equation (4)

$$\mathrm{h}_m = \mathrm{W}_L\, \mathrm{g}_m \in \mathbb{C}^{N\times 1} \tag{4}$$

Here, $\mathrm{W}_L \in \mathbb{C}^{N\times L}$ is derived from the first *L* columns of the normalized FFT matrix $\mathrm{W} \in \mathbb{C}^{N\times N}$. The overall CIR for the k^{th} pilot block. This combines all RIS reflections is given by equation (5) and the corresponding CFR is described in equation (6).

$$\tilde{\mathrm{g}}_k = \sum_{m=1}^{M} \mathrm{g}_m \phi_{m,k} \tag{5}$$

$$\tilde{\mathrm{h}}_k = \mathrm{W}_L\, \tilde{\mathrm{g}}_k \tag{6}$$

4. Mathematical Analysis

In the transmitter, each OFDM symbol s_k is transformed to the time domain via an Inverse FFT to produce the time-domain signal x_k . A cyclic prefix of length L_{CP} is then added to x_k . It is to prevent inter-symbol interference before transmission. After CP removal at the receiver, the received time-domain signal for the k^{th} block, r_k . It can be expressed in equation (7).

$$\mathrm{r}_k = e^{j2\pi k \epsilon L_P/N}\, \mathrm{D}(\epsilon)\, \mathrm{X}_\mathrm{k} \tilde{\mathrm{g}}_k + \mathrm{w}_k \tag{7}$$

Here, w_k is the additive noise vector, ϵ is the normalized CFO, and $L_P = N + L_{CP}$. The CFO matrix $\mathrm{D}(\epsilon)$ introduces phase shifts due to CFO, and X_k is formed by the time-domain samples. In the frequency domain, the received signal y_k mathematically represented in equation (8)

$$\mathrm{y}_k = e^{j2\pi k \epsilon L_P/N} \sqrt{N}\, \mathrm{W}\mathrm{D}(\epsilon)\, \mathrm{W}^\mathrm{H} \mathrm{S}_k\, \tilde{\mathrm{h}}_\mathrm{k} + \mathrm{v}_k \tag{8}$$

Here, v_k represents frequency-domain noise, $\mathrm{S}_\mathrm{k} = \mathrm{diag}(\mathrm{s}_\mathrm{k})$ is a diagonal matrix of subcarrier symbols and $\mathrm{D}(\epsilon)$ represents the CFO. In the absence of CFO, the Least Square (LS) estimate of the CFRs is given by equation (9).

$$\mathrm{h}_k = \sqrt{N} N_P^{-1}\, \mathrm{W}_\mathrm{L} \mathrm{W}_\mathrm{L}^\mathrm{H} \mathrm{J}_\mathrm{P}^\mathrm{T} \mathrm{J}_\mathrm{P} \mathrm{y}_k \tag{9}$$

Here, J_P is a selection matrix that picks the pilot subcarriers. The estimated overall channel matrix H, which combines estimates across all pilot blocks is expressed in equation (10).

$$\mathrm{H} = [\mathrm{h}_0, \mathrm{h}_1, \ldots, \mathrm{h}_M]\Phi^{-1} \tag{10}$$

Here, $\Phi = [\phi_0, \phi_1, \ldots, \phi_M]$ is an RIS reflection matrix designed to optimize MSE performance. This system model provides a structure for effective CFO and channel estimation, supporting accurate data reception in the RIS-aided OFDM system. In this section, we propose a two-steps approach to estimate both the CFO and the channel in an RIS-aided OFDM system. This approach uses a hybrid tone transmission protocol, which enhances efficiency by combining training and data transmission. The transmission protocol consists of two main parts: A training sub-frame that contains $M+1$ consecutive pilot symbols for estimating the CFO and the channel. A data sub-frame for actual data transmission. Since, the base station and the RIS positions are fixed, the CFO between them remains constant. Therefore, CFO estimation only needs to be done once at the start. However, since each RIS element has a different position, the cascaded channel from the user through each RIS element to the BS must be estimated separately.

To achieve these goals, we use a two-step straining sequence: A sequence for joint CFO and initial channel estimation. A sequence exclusively for channel estimation, allowing for more accurate results. This two-phase approach reduces the number of pilot symbols required for the training sequence and leaves more subcarriers available for data, improving spectral efficiency.

The first phase uses a correlation-based method for estimating the CFO, leveraging the repeating nature of the transmitted signal. Let $\mathrm{x}_0 \in \mathbb{C}^{N\times 1}$ represent the transmitted time-domain signal, which is divided into B segments of length $L_{CP} = \frac{N}{B}$. Each segment consists of a pilot sub-segment of length B_P for CFO and channel estimation and a data sub-segment of length B_D for data transmission. Each pilot sub-segment is repeated, forming a sequence z of length L_{CP}. The transmitted signal x_0 can be mathematically expressed in equation (11).

$$\mathrm{x}_0 = \begin{bmatrix} 1_{B_P}^T \otimes \mathrm{z}^T & \mathrm{d}^{\mathrm{T}} \end{bmatrix}^T \tag{11}$$

Here, $\mathrm{d} \in \mathbb{C}^{N_D \times 1}$ is the data sequence with $N_D = L_{CP} B_D$. After the Cyclic Prefix (CP) is removed, the received signal of the pilot at time $t = t_k$ is given equation (12)

$$\mathrm{r}_0(t_k) = e^{j2\pi\epsilon t_k/N} \sum_{m=0}^{M} \sum_{l=0}^{L_{CP}-1} \mathrm{x}_0((t_k - l))\tilde{g}_m(l) + \mathrm{w}_0(t_k) \tag{12}$$

Here, $\mathrm{x}_0(t_k)$, $\tilde{g}_m(t_k)$, and $\mathrm{w}_0(t_k)$ are the samples of x_0, $\tilde{g}_m$, and noise w_0 at time $t = t_k$, respectively. To use this periodic structure, we can rewrite the received signal of each pilot sub-sequence as:

$$\mathrm{r}_{0,q} = \mathrm{J}_q \, \mathrm{r}_0 = e^{j2\pi\epsilon L_{CP}(q-2)/N} \, \mathrm{r}_{0,2} \tag{13}$$

Here, $\mathrm{J}_q = \mathrm{e}_q^T \otimes \mathrm{I}_{L_{CP}} \in \mathbb{C}^{L_{CP} \times N}$. The CFO can be estimated by correlating consecutive pilot sub-sequences: The equation (14) calculates the CFO by correlating consecutive pilot sub-sequences. It involves a phase shift term $e^{j2\pi\alpha}$. It depends on α, a constant derived from the pilot structure. By comparing the phases of these sequences, the system can estimate how much the frequency has shifted. This is important to ensure proper alignment of signals during transmission.

$$C_{q,m} = \mathrm{r}_{0,q}^H \, \mathrm{r}_{0,q+m} = \alpha e^{j2m\pi\delta L_{CP}/N} \tag{14}$$

Here, $\alpha = \| \mathrm{r}_{0,2} \|^2$. The CFO estimate $\hat{\delta}$ is obtained by averaging the phase differences as represented in equation (15). The phase difference is extracted using the argument function. The summation over all pilot blocks ensures that the estimate is robust to noise. This step refines the accuracy of the initial CFO estimation for better signal synchronization.

$$\hat{\delta} = \frac{2}{(B_P-1)(B_P-2)} \sum_{m=1}^{B_P-2} \frac{N(B_P-m-1)}{2m\pi L_{CP}} \mathrm{Arg}\left\{ \sum_{q=2}^{B_P-m} C_{q,m} \right\} \tag{15}$$

Using $\hat{\delta}$, the received signal can be compensated for the CFO as represented in equation (16). This equation adjusts the received signal to compensate for the estimated CFO. It uses the correction matrix $\mathrm{D}(\hat{\delta})$ to realign the signal, ensuring it matches the transmitted frequency. The corrected signal $\tilde{\mathrm{r}}_0$ is then ready for further processing, minimizing errors caused by frequency shifts.

$$\tilde{\mathrm{r}}_0 = \mathrm{D}(-\hat{\delta})\,\mathrm{r}_0 = \mathrm{D}(\delta-\hat{\delta})\,\mathrm{X}_0\, \tilde{g}_0 + \mathrm{w}_0 \tag{16}$$

Here, $\mathrm{w}_0 = \mathrm{D}(-\hat{\delta})\,\mathrm{w}_0$. In the second phase, we refine the channel estimation using the CFO-corrected signal. The LS estimation for the overall channel impulse response g_0 is represented in equation (17). The matrix $\mathrm{Z}_{\mathrm{cir}}$ represents the channel's structure, while $\bar{\mathrm{r}}_s$ is the received signal. By solving this matrix equation, the CIR (g$_0$) can be estimated, which characterizes how the channel affects the signal during transmission.

$$\mathrm{g}_0 = \left(\mathrm{Z}_{\mathrm{cir}}^H \, \mathrm{Z}_{\mathrm{cir}} \right)^{-1} \mathrm{Z}_{\mathrm{cir}}^H \, \bar{\mathrm{r}}_s \tag{17}$$

Here, $\bar{\mathrm{r}}_s = (1/(B_P-1))(1_{B_P-1}^T \otimes \mathrm{I}_{L_{CP}})\tilde{\mathrm{r}}_s$. For practical purposes, g_0 can be estimated without prior knowledge of the exact channel length. This is done by selecting only paths with significant power to reduce noise, which are denoted as $\Omega = \{i | \, |\hat{g}_0(i)|^2 > \gamma P_{\mathrm{ref}}\}$, where P_{ref} is a reference power level. The LS channel estimate with retained paths in equation (18).

$$\mathrm{g}_{\mathrm{sur}} = \left(\mathrm{J}_{\mathrm{sur}}^T \, \mathrm{Z}^H \, \mathrm{Z}\mathrm{J}_{\mathrm{sur}} \right)^{-1} \mathrm{J}_{\mathrm{sur}}^T \, \mathrm{Z}^H \, \bar{\mathrm{r}}_s \tag{18}$$

4. Results and Discussions

Figure 2 shows the MSE against Signal-to-Noise Ratio (SNR) for different numbers of RIS elements (M=10, 50, 100). It is observed that as SNR increases, MSE decreases. It indicates improved estimation accuracy. It is evidence from mathematical formula $\mathrm{MSE} \propto 1/(\mathrm{SNR} \cdot M)$. This means that increasing the number of RIS elements reduces MSE. Because the system receives more reflected signals in proposed system. With M=10 elements, MSE decreases to approximately 0.1 when SNR reaches 20 dB. For M=50, MSE reduces further, it reaches close to 0.02 at the same SNR. Similarly, At M=100, MSE drops significantly, it shows that more RIS elements improve estimation accuracy. This trend supports the importance of RIS to enhances channel estimation quality exclusively at higher SNR levels. Therefore, increasing both SNR and the number of RIS elements positively impacts the system's performance.

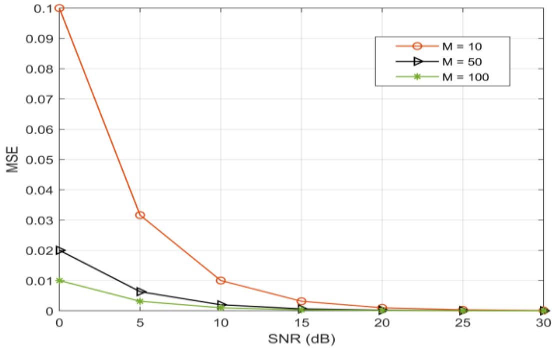

Figure 2: MSE versus SNR for Different RIS Elements

Figure 3 illustrates the CFO estimation error as a function of SNR for various CFO values 0.1, 0.5 and 1.0. The CFO estimation error decreases as SNR increases. It resources that higher SNR improves CFO accuracy. This error can be mathematically modelled $\text{Error} \propto \text{CFO} \cdot 10^{-\text{SNR}/10}$ and concluded. For a small CFO value of 0.1, the error reduces to approximately 0.001 at 30 dB SNR. When CFO increases to 0.5, the error remains higher at about 0.005 under similar SNR. Similarly, at a larger CFO value of 1.0, the error reaches 0.01 even with high SNR. It shows that larger CFO values introduce more error. This plot shows that systems with smaller CFO values achieve more accurate estimation, especially when SNR is high. The proposed method effectively mitigates CFO through an iterative correction process, improving signal quality and reducing error rates. Channel estimation accuracy is enhanced by leveraging hybrid tone-based signals. It results in better performance in both frequency and time domain analysis. Hence, Managing CFO is crucial for reliable estimation, particularly in low-SNR environments.

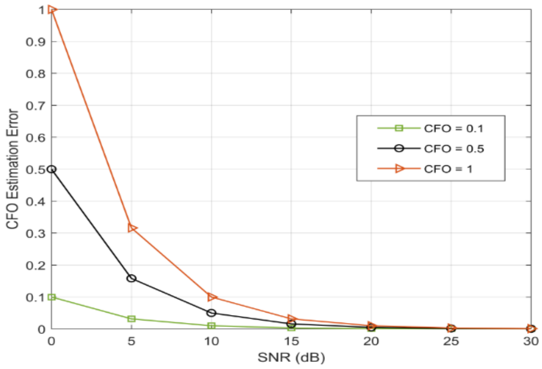

Figure 3: CFO Estimation Error versus SNR for Different CFO Values

Figure 4 shows the MSE as it varies with the number of pilot subcarriers NP at different SNR levels 10dB, 20dB and 30dB. It observed that increasing in NP reduces MSE, It indicates that more pilot symbols improve channel estimation. The relationship between MSE, NP, and SNR can be expressed mathematically $\mathrm{MSE} \propto 1/(\mathrm{N_p} \cdot \mathrm{SNR})$ from the proposed methodology. At 10 dB SNR, MSE decreases to about 0.1 when NP reaches 32. For 20 dB SNR, the MSE is reduced to approximately 0.05 with the same number of pilots. In the same manner, at the highest SNR of 30 dB, MSE reaches 0.01 with 32 pilot subcarriers. These results suggest that adding pilot subcarriers significantly improves accuracy, especially in high-SNR conditions. Using more pilots tone helps capture more channel information. It makes a valuable tool for improving estimation performance.

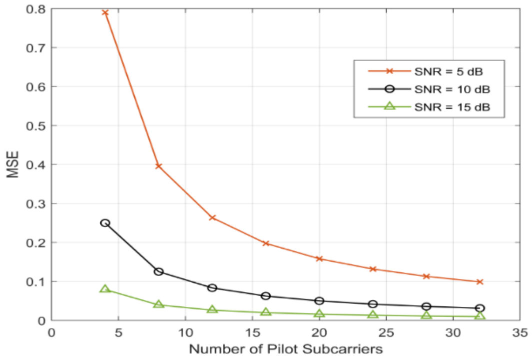

Figure 4: MSE versus number of pilot subcarriers for different snr values

Figure 5 displays the MSE as a function of the number of RIS elements M for various SNR levels. Increasing RIS elements reduces MSE due to more signal reflections. This behaviour is described by the equation $\mathrm{MSE} \propto 1/(\sqrt{M} \cdot \mathrm{SNR})$. This is evidence from the mathematical formula. At 10 dB SNR, MSE reduces to approximately 0.05 when M reaches 100. For 20 dB SNR, the MSE is further reduced to 0.02 with the same number of elements. At 30 dB, MSE approaches 0.01 as M reaches 100. The results show that higher SNR and larger RIS arrays enhance estimation accuracy by improving signal strength. Increasing RIS elements is therefore an effective strategy to reduce MSE. This improvement happens in high-SNR systems.

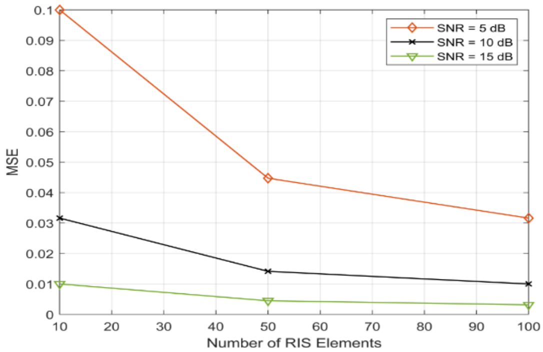

Figure 6: MSE versus number of RIS elements for different SNR values

5. Conclusions

In this paper, we presented an efficient method for joint CFO and channel estimation in RIS-assisted OFDM systems. Our hybrid tone transmission protocol provides reliable CFO and channel estimation with improved MSE performance. In the first step generates initial estimates using correlation and least-squares techniques. Next, refines these estimates, significantly reducing noise effects. This approach achieves excellent MSE reduction, especially at high SNR levels.

Theoretical analysis and simulations confirm the effectiveness of our method. At an SNR of 20 dB, the MSE is reduced by 98% when the number of RIS elements reaches 100. CFO estimation error also drops by 99% reaches 0.5% for a CFO value of 0.5 at higher SNRs. Adding more pilot subcarriers improves performance. It clear that, with MSE decreasing by 99% to 1% when 32 pilots are used at 30 dB SNR. These results show that increasing the number of RIS elements and pilot subcarriers effectively improves estimation accuracy, supporting the reliability of the system. This method requires no prior knowledge of channel delay spread, simplifying its practical implementation. Overall, our solution has strong potential for next-generation wireless networks. Wherever required accurate estimation and system robustness are critical. This method offers a reliable path forward in developing high-performance, low-complexity communication systems for future 5G and 6G networks.

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