

# Feedback Filtered-OFDM Waveform Candidature for Interference Mitigation in 5G Networks and Beyond

Zakka Augustine<sup>1\*</sup>, Abdulmalik Shehu Yaro<sup>1, 2</sup>, Addoulie Momodou Sunkary Tekanyi<sup>1</sup>, Habeeb Bello<sup>1</sup>, Umar-Faruk Abdu-Aguye<sup>1</sup>, Ezekiel Ehime Agbo<sup>1</sup>

<sup>1</sup> Department of Electronics and Telecommunications Engineering, Faculty of Engineering, Ahmadu Bello University, Zaria, NIGERIA

<sup>2</sup> Department of Informatics and Quantitative Methods, Faculty of Informatics and Management, University of Hradec Kralove, Hradec Kralove, 500 03, CZECH REPUBLIC

\*Corresponding Author: [zax.austen@yahoo.com](mailto:zax.austen@yahoo.com)

DOI: <https://doi.org/10.30880/ijie.2025.17.01.027>

## Article Info

Received: 6 August 2024

Accepted: 6 November 2024

Available online: 30 April 2025

## Keywords

FF-OFDM technique, F-OFDM, interference mitigation, 5G NR, programmable non-unity feedback probe.

## Abstract

The ever-growing demand for more filtered waveforms to improve communication system's quality triggered the development of a novel Feedback Filtered-Orthogonal Frequency Division Multiplexing (FF-OFDM) Channels Access (CA) technique. This work presented some significant applications of FF-OFDM, which are the capability of mitigating Inter-Channels Interference (ICI), Inter-Symbols Interference (ISI), and Adjacent Channels Interference (ACI) better than previous CA techniques. This research introduced a paradigm shift from the traditional method of mitigating ICI, ISI, and ACI to a more advanced method using Artificial Intelligence (AI) coded non-unity feedback probe. At 60 kHz Subcarrier Spacing (SCS), the FF-OFDM obtained an interference power mitigation of 47.0 dB for ICI, 39.0 dB for ISI, and 27.0 dB for ACI, outperforming the conventional model of Filtered Orthogonal Frequency Division Multiplexing (F-OFDM) which realized 31.6 dB for ICI, 27.0 dB for ISI, and 22.0 dB for ACI. For the tests of the performance of the communication channel, the FF-OFDM achieved a Bit Error rate (BER) within  $10^{-6}$  at 27 dB Signal-to-Noise Ratio (SNR) better than  $10^{-5}$  realized by conventional and modified versions of F-OFDM. Effective interference mitigation to improved signal quality is a requirement by Third Generation Partnership Project (3GPP) for the Fifth Generation (5G) New Radio (NR) objectives.

## 1. Introduction

Each generation of wireless technology (air interface) has Channel Access (CA) techniques that propel them to accomplish the desired purpose they are built for [1]. These CA techniques are waveform modifiers set up from various modulation and coding schemes. The successive changes and demands from Equipment Users (EUs) and User Equipment (UE) led to increasing modifications of previous and existing techniques in order to meet the requirements of each air interface [2]. Currently, wireless mobile demands are not based on meeting multiple kind of users anymore but on how to achieve dissimilar kind of users also [3]. One of the focuses in achieving dissimilar communication is drastic mitigation of interference based on Third Generation Partnership Project (3GPP) for the Fifth Generation (5G) New Radio (NR) objectives [4]. This has been the challenge posed for 5G and post 5G wireless networks. For example, the most acceptable CA techniques conceived and developed (deployed

commercially) by various researchers, such as Orthogonal Frequency Division Multiplexing (OFDM), Cyclic Prefix-OFDM (CP-OFDM), Windowed OFDM (W-OFDM), Filter Bank Multi-Carrier (FBMC), Generalized Frequency Division Multiplexing (GFDM), Universal Filtered Multi-Carrier (UFMC), Filtered-OFDM (F-OFDM), and many more could not effectively mitigate interference that distorts wireless system efficiency [5]. These earlier techniques were incapacitated in mitigating interference because they both worked on constraint methods, where any signal optimization to increase bandwidth, data rate, and throughput do come up with a trade-off in favor of interference [6]. This causes serious havoc in present day communication system and also poses challenge for future wireless networks. Therefore, the need for the development of a novel CA technique that could further mitigate the effects of interference caused by filter tails interactions after the Cyclic Prefix (CP) removal in F-OFDM [6, 7], forms the basis of this work. This research developed an application of novel FF-OFDM CA technique with the sole target to mitigate ACI, ICI, and ISI better than previous CA techniques. This developed FF-OFDM technique takes its genealogy from the successes and limitations of F-OFDM, CP-OFDM, OFDM, and their variants [6].

There are so many factors that cause interference in wireless network, this work focuses on interference due to filter tail interactions and CP removal at the receiver side. Reviewed literatures and studies have proven that most of the transmission requirements for effective wireless system (in transmitter and channel) have been achieved to an appreciable level, except at the receiver side. For this reason, researchers are advised to focus attention on mitigating interference experienced at the receiver side of the wireless transceiver to improve communication efficiency. From this stated fact, this work is targeted to be deployed at the receiver side of the wireless transceiver, in order to present a received baseband signal that is nearly exact to that of it transmitted baseband. This is achieved by the deployment of the developed FF-OFDM waveform modifier probe at the receiver side of the transceiver [6]. The FF-OFDM technique is developed in conformity with 3GPP NR waveform modification requirements, focusing on mitigating the effects of ICI, ISI, and ACI which constitute serious challenges at the receiver side of a wireless communication system.

## 2. Related Works

The reviews focus more on researches conducted with the sole aim of mitigating interference experienced at the receiver side of a wireless transceiver.

In an attempt to address the problem of interference in 5G downlink cellular networks, where cell edge users may suffer from high interference, [8] adopted a method of an advanced receiver combined with a scheduling mechanism for cell assignment. The duty of the scheduling mechanism was to jointly determine serving UE and Channel State Information (CSI) using transmission and modulation schemes. Additionally, advanced receivers were also used to aid the CSI which further suppressed interference experienced in downlink cellular network. Simulation results showed improvement in SNR and throughput compared to the conventional method. The method lacked the capacity to drive higher SCS, as such, could only achieve interference cancellation within Long Term Evolution (LTE), LTE-Advanced (LTE-A), and 5G FR1 context. For the purpose of reducing the effect of interference at the receiver side of a wireless system, [9] proposed a novel Hann window function based low complexity Receiver Windowing-OFDM (RW-OFDM) method that is fully compatible with the frame structure of existing standards. The proposed method allowed superior ACI rejection and reduced guard bands without requiring ISI extensions. The Hann window effectively rejected unstructured ACI at the expense of structured and limited ICI across data carriers. This induced ICI was resolved based on simple Maximum Ratio Combining (MRC) and Successive Interference Cancellation (SIC) receiver using standard transmitters. [10] presented an iterative receiver for the Space Frequency Block Code-OFDM (SFBC-OFDM) system in order to solve the most eloquent problem in OFDM systems which have been dispensed as ICI and ISI. ISI which is normally caused by the infraction of the 'quasi-static' fading conjecture gives rise to medium's frequency and/or time selectivity problem. Furthermore, ICI is also caused by the medium's frequency offset or jittering that repercussion in reduction of orthogonality amongst the other subcarriers. Simulation results proved that, the SFBC-OFDM retrieved and mitigated interferences caused by OFDM side lobes but at the detriment of bandwidth and high-power demand. [11] achieved a localized frequency spectrum for narrow bandwidths while maintaining the ISI, ICI, Bit Error Rate (BER), and Peak to Average Power Ratio (PAPR) within an acceptable range using F-OFDM sub-band filtering agility. The research was purposed in achieving 5G attributes that a conventional OFDM scheme could not achieve in terms of mitigating interference. The impact of system parameters like filter length, CP length was analyzed on the F-OFDM system performance and compared with the simulated results of the proposed work in terms of the ICI and ISI power for F-OFDM system. The 5G NR requirement of total interference free network for advanced communication could not be obtained because the method has the demerits of retaining interferences at an undesirable level. The demand to relax synchronization to achieve the specifications of the next generation system, led to the development of numerous waveforms for the displacement of the OFDM/CP-OFDM synchronous waveform by [12]. These waveforms are based on novel methods of filtering, which are suggested to induce FBMC, GFDM, UFMC, F-OFDM, and more for 5G actualization. The novel filtering was achieved through hybridization and integration of different conventional filters which has the capacity of increasing SE better than individual

conventional filtering techniques. Simulation results showed that the proposed filters outperformed previous waveform designs in terms of spectral efficiency, which improved dramatically by releasing the synchronization overhead. All these techniques when deployed have the requisite to drive above 5G FR1 data rate requirement. The new product of wireless communication systems, the 5G, promises higher data rates and SE enhancements to support the communication of heterogeneous services, as such, [13] proposed a novel F-OFDM design waveform. The research adopted a first time four sub-bands in equal and unequal sub-band sizes of seven kinds of window sinc filters and a variety of numerology designs to observe SE enhancement. Simulation results showed that F-OFDM reduced Out-of-Band Emission (OoBE) and achieved SE higher than conventional OFDM for equal and unequal sized sub-bands, by optimizing the guard band between the designed sub-bands, which achieved 5G guard band requirements. The options in filtering did increase system efficiency but interference caused by CP removal were ignored, this again affected the system overall SE. New radio waveforms of existing wireless communication systems need further improvement in order to support future wireless communications, [14]. NR is the radio air interface technology proposed by the 3GPP for 5G. Some of the NR filtering techniques are; F-OFDM, FBMC, and UFMC. NR waveforms require performance improvement when high reliability, massive connectivity, lower power consumption, and time-critical applications are required. Areas of improvement are Power Spectral Density (PSD), BER, Signal to Interference Ratio (SIR), Doppler Diversity (DD), and PAPR. The method developed a novel Prototype Filter (PF) to be deployed in F-OFDM for PSD, FBMC for OoBE, and UFMC for interference was observed. To meet the requirement of the data rate and improvement in SE, the concept of hybridization of F-OFDM and Cognitive Radio (CR) was proposed by [15]. This is because, the present communication system is not efficient enough for the data rate requirement for the real-time applications like video conferencing and file sharing. Again, a hybrid filter detection technique is proposed for the Multi-User Multiple Input Multiple Output (MU-MIMO) F-OFDM system where multiple users are served with the same time and frequency resource to improve signal strength. The study also evaluated spectral efficiency to offer optimum detection at acceptable complexity levels for low Signal to Noise Ratio (SNR) signals and found that the performance of the proposed technique compared with the existing techniques, was better and can effectively improve the detection accuracy of the signal with low SNR. Using optimal filters could make this work more efficient.

It is evident from the reviews that the waveform modification methods conducted by previous researchers and the techniques used to achieve interference mitigation mostly results in drawbacks due to reintroduction of network burdens and leftover interference. These drawbacks and more have posed serious threats on the advanced attribute of 5G NR. It is also vivid from the reviewed literatures that interference cancellation at the receiver side of the communication system poses challenge that is required of experts to solve in order to improve communication channels efficiency. This research focuses on development and deployment of the FF-OFDM technique at the time-frequency domain of the receiver side. This is targeted at presenting a received baseband signal that is nearly exact to that of its transmitted baseband.

### 3. Proposed Technique

This section presents the procedures followed to achieve the objectives of this work. The F-OFDM drawbacks of reintroducing ICI, ISI, and ACI after the removal of CP [11], are the core lacunae of this research. These interferences were detected at the channel estimation region after the CP removal at the receiver and mitigated to desirable levels using the synergies of Hann-Kaiser or Hann-Chebyshev induced FIR filters, separately. The Kaiser and Chebyshev filters serve as reagent at the signal attenuation region of a non-unity feedback probe while the Hanning filter complements the received signal. The entire probe is coded using Machine Learning (ML) algorithm of Artificial Intelligence (AI), where the receiver has the capability to accurately predict the transmitted parameters and modify its received information to suit the desired signal using the synergized filters agility. These reagents modify the waveforms of every received signal to obtain a fully developed FF-OFDM waveform that could serve in present and advanced wireless system for both short and long-distance communications.

#### 3.1 FF-OFDM Workflow Building Blocks

Figure 1 demonstrates a workflow diagram from OFDM blocks that laid the footing for the developed FF-OFDM technique. The characteristics of each building blocks to obtain an expected FF-OFDM waveform are not detailed in this work. Many CA techniques such as W-OFDM, UFMC, GFDM, and FBMA also built their branches on OFDM orthogonal milestone and limitations [12]. This OFDM orthogonality gave the breakthrough for the frequency equalization of successful implementation in the 4G LTE standard, but was limited by High Side Lobes (HSL) emission and PAPR [2]. The CP-OFDM built on OFDM limitation to achieve an LTE-A waveform with data transmission of about 1Gbps, but was over weighted with the CP, thereby resulting to bandwidth wastage, power consumption, and time delay [16]. These CP-OFDM drawbacks led to another stepping stone known as F-OFDM. The F-OFDM also adds its blocks based on OFDM and CP-OFDM limitations to obtain frequency-time localization waveform, targeted at meeting the demand of 5G and next generation. This was achieved by the insertion of filters at the peak of transmission and the trough of reception to mitigate the challenges in previously laid blocks [3].

Consequently, its waveform was also characterized by a series of interference. The FF-OFDM is developed to mitigate interference experienced by the F-OFDM technique and by extension CP-OFDM and OFDM while retaining its advantages in order to improve wireless system performance, as such, meet the 5G NR requirements for advanced wireless communications [6].

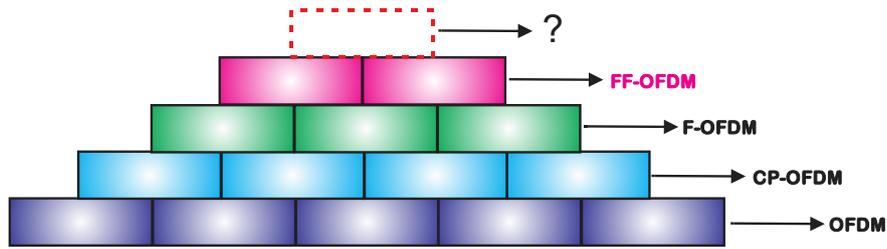


Fig. 1 Orthogonal waveform footings and building blocks

### 3.2 Modelling of FF-OFDM Waveform Modifier

A threshold is set at the output of the de-multiplexer, if any form of interference is noticed, the signal packet,  $Y_2(n)$  that contain the interference is extracted treated, and fed-back to the filter,  $F_\phi^*(-n)$  via a systematic design adaptive filter (soft-truncated sinc filter),  $H(n)$  which is easily employed in various applications with different parameters [17], using non-unity feedback model of Figure 2. The feedback system is designed with adjustable or adaptive stop-band filter capable of accentuating the desired signal from the ICI, ISI, and ACI. That is, the FF-OFDM waveform has the capacity to mitigate the drawbacks F-OFDM and other CA methods could not effectively curtail.

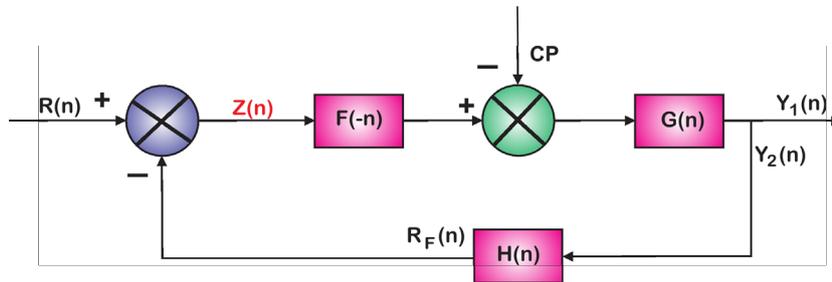


Fig. 2 FF-OFDM signal modifier

Starting from equation (1), the received signal across the subcarrier is written as:

$$R(n) = h(n) * S_\phi(n) \tag{1}$$

where,  $h(n)$  is the channel impulse response and  $S_\phi(n)$  is the received data symbols.

The error factor,  $E$  of the model is computed as:

$$E = Z(n) = R(n) - R_F(n)Y_1(n) \tag{2}$$

where,  $Y_1(n)$  is the desired signal waveform to be accentuated from interference and  $R_F(n)$  is the modified waveform reagent.

The open loop gain of the signal modifier,  $G(n)$  is formulated as:

$$G(n) = \frac{Y_1(n)}{R(n)} \tag{3}$$

To properly treat the extracted signal to achieve the desired information free of interference, a portion of the F-OFDM asynchronous symbols with the likelihood of being characterized by interferences is fed-back to the receiver filter,  $F_\phi^*(-n)$  via a close lobe transfer attenuation function,  $H(n)$  in order to accentuate the original signal from ICI, ISI, and ACI. It is then formulated here as:

$$Y_1(n) = G(n)Z(n) \quad (4)$$

From equation (4), the close-loop transfer of this signal modifier is determined.

By substituting equation (2) into equation (4) yields:

$$\begin{aligned} Y_1(n) &= G(n)[R(n) - R_F(n)Y_1(n)] \\ &= G(n)R(n) - G(n)R_F(n)Y_1(n) \end{aligned} \quad (5)$$

$$\begin{aligned} G(n)R(n) &= Y_1(n) + G(n)R_F(n)Y_1(n) \\ &= Y_1(n)[1 + G(n)R_F(n)] \end{aligned} \quad (6)$$

Hence, the signal quality estimation of this developed waveform modifier is also obtained as:

$$G(n) = F(-n) - CP \quad (7)$$

where,  $G(n)$  is the system gain and  $F(-n)$  is the folded version of the spectrum shaping filter.

Whereas, the attenuated signal reagent is:

$$R_F(n) = H(n)Y_2(n) \quad (8)$$

This increases signal strength, bandwidth, and invariably improves quality to obtain the targeted asynchronous waveform. Finally, the model equation of the expected FF-OFDM received signal waveform,  $Y_1(n)$  that is accentuated from ICI, ISI, and ACI is generated as follows:

$$Y_1(n) = \frac{[F(-n) - CP]R(n)}{1 + [F(-n) - CP]R_F(n)} \quad (9)$$

where,

- $R_F(n)$  is the feedback output component or the signal reagent components,
- $R(n)$  denotes the received signal across sub-carriers, and
- $Y_1(n)$  represents composite FF-OFDM symbols that mitigates interference.

Finally, the desired output waveform of the developed FF-OFDM scheme that is free of interference to be deployed in 5G networks and beyond is expressed as:

$$\hat{Y}(e^{jw}) = \sum_{k=0}^{N-1} Z_k(e^{jw}) K e^{jwk\Delta f t} \quad (10)$$

where,

- $Z_k(n)$  is the baseband samples,
- $K$  reflects the signal coefficient,
- $e^{jw}$  represent the frequency shift factor,
- $\Delta f$  denotes the subcarrier spacing, and
- $t$  corresponds to the symbols time.

### 3.3 FF-OFDM Receiver Process

Figure 3 presents the FF-OFDM receiver probe which comprises the folded version of the Hanning induced filter,  $F(-n)$  the CP waveform modifier copies, the Channel Estimation Region (CER) for the desired and undesired data sampling, the filtered signal waveform reagent,  $R_F(n)$  for interference cancelation and for waveform negotiation, the FFT region that convert signals from time domain to frequency domain, and the demodulator which is used to de-map the complex received data according to the transmission constellation diagram in order to recover the original transmitted bit stream.

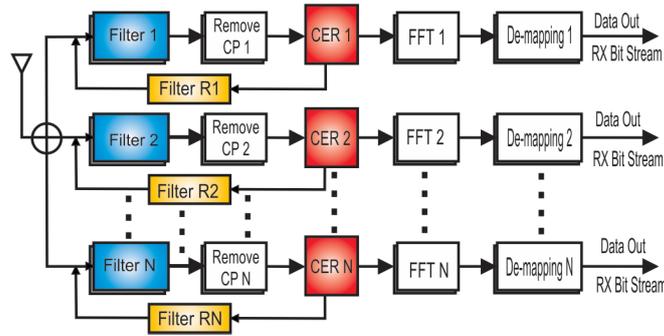


Fig. 3 FF-OFDM receiver probe

### 3.4 Developed FF-OFDM Flowchart

The operational principle of the proposed FF-OFDM model is a fraction or a modified workability function from the limitation of the previous multiple access and coding schemes and is demonstrated in Figure 4. The model demonstrates various waveforms workflow from OFDM, CP-OFDM, F-OFDM, and the expected FF-OFDM technique. The threshold frame and the Hop (signal reagent/modifier) serves as the heart and center of activities in obtaining an effective FF-OFDM waveform.

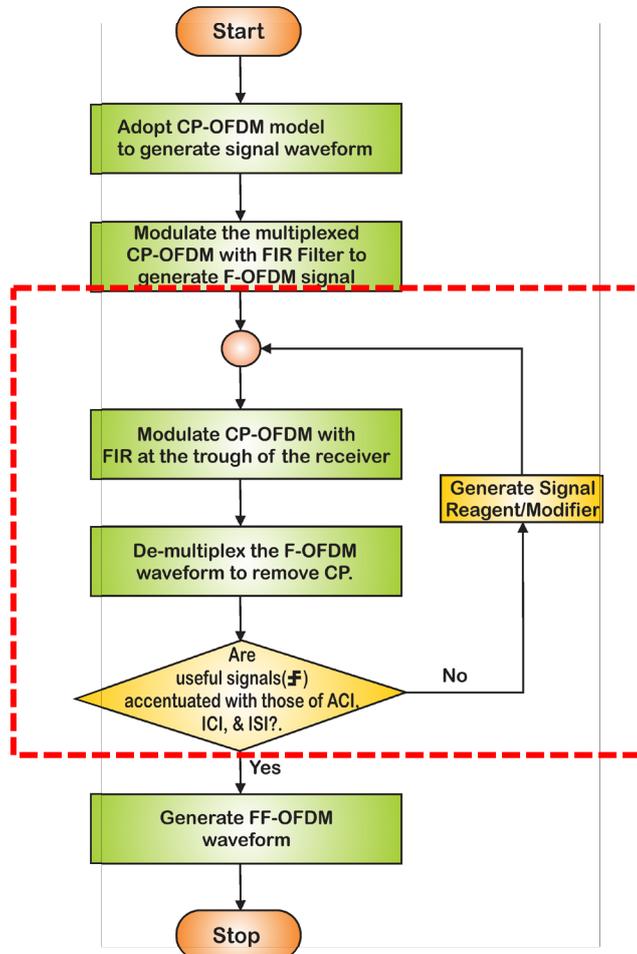


Fig. 4 FF-OFDM waveform generation flowchart

#### 4. Research Parameters

This section provides the parameters used for the computer simulation using Pycharm Integrated Development Environment (IDE) of Python 3.10.8. The research explored the 5G NR IFFT/FFT sample size of 4K ( $N = 4096$  subcarriers of 3300 payloads), 80 subband of 48/4 subcarriers bandwidth size/index each. The subbands arrays are organized as, (0)1 – 47, (1) 48 – 95, (2) 96 – 143, ..., (80) 3791 – 3839, while the first subband bandwidth,  $M$  tagged (0) is taken as the worst scenario capable of encountering interference anomalies more than any other cluster, as such it is used for this analysis as demonstrated results obtained. The subcarriers mapping is taken as 256 Quadrature Amplitude Modulation (QAM) scale, CP size of 256, where  $F(-n) \geq CP$ . The comparisons are made with those of the works of [11] and [5] for the ICI, ISI, and ACI sensitivity/mitigation, and of the model works of [4], [3], and [12] for BER improvement. The final results for the interference power of this research work are obtained using equations (11) through (15), as:

$$\% \text{ Increase in } I_{Sen/Mit} = \frac{I_{Mod/Adv} - I_{Conv}}{I_{Conv}} \times 100\% \quad (11)$$

$$\text{Average \% Increase in } I_{Sen/Mit} = \frac{\sum_{i=0}^{N-1} (I_{Mod/Adv} - I_{Conv}) \times 100\%}{I_{Samp}} \quad (12)$$

where;

$I_{Sen/Mit}$  is the interference sensitivity/mitigation in dB.

$I_{Conv}$  represents conventional method of sensing/mitigating interference of F-OFDM in dB.

$I_{Mod}$  means version of interference sensitivity/mitigation by modified F-OFDM in dB.

$I_{Adv}$  reflects the newly developed advanced method of sensing/mitigating interference by FF- OFDM in dB.

$I_{Samp}$  corresponds to the number of index samples per sub-band.

The average interference power,  $I_{Average}$  is determined using the summation of total units' power divided by the number of sample index.

$$I_{Average} = \frac{\sum_{k=1}^M I_{Total}}{I_{Samp}} \quad (13)$$

The final interference sensitivity/mitigation result is obtained by comparing the  $I_{Adv}$  against  $I_{Mod}$  at 60 kHz SCS as:

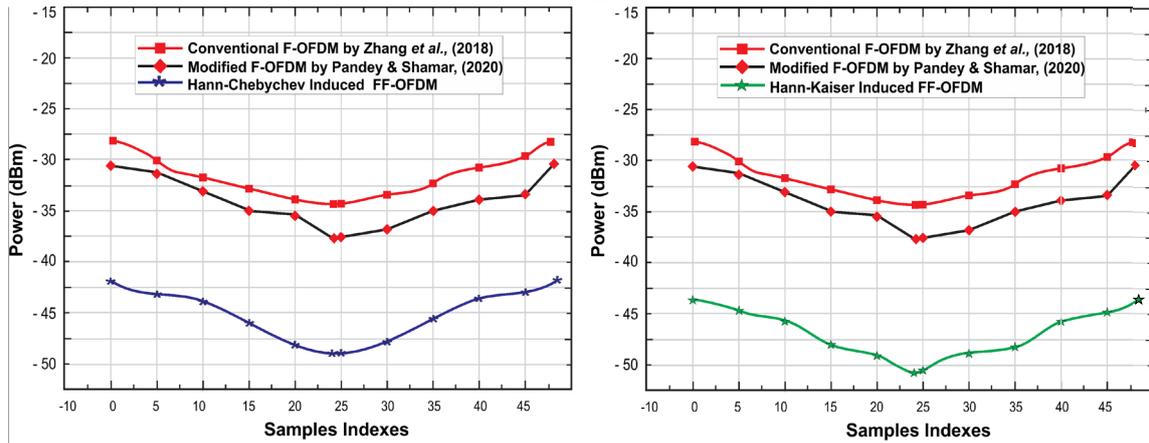
$$\text{Average \% Increase in } I_{Sen/Mit} = \frac{\sum_{i=0}^{N-1} (I_{Adv} - I_{Mod}) \times 100\%}{I_{Samp}} \quad (14)$$

Furthermore, at 120 kHz SCS it is gotten as:

$$\text{Average \% Increase in } I_{Sen/Mit} = \frac{\sum_{i=0}^{N-1} (I_{Adv} - I_{Conv}) \times 100\%}{I_{Samp}} \quad (15)$$

##### 4.1 ICI Mitigation Results

The graphical results of Figure 5 (a & b), interpreted in Tables 1 and 2 show how aggressive the FF-OFDM system senses/mitigates ICI at 60 kHz SCS better than F-OFDM systems. The results present the modified F-OFDM version by [11] senses and mitigates interference by 8.4% over the conventional F-OFDM model developed by [5]. In Figure 5 (a), it is obvious that the newly developed Hann-Chebyshev induced FF-OFDM outperform the conventional F-OFDM model and modified F-OFDM version by 43.4% and 32.3%, respectively. Figure 5 (b) also shows the Hann-Kaiser induced FF-OFDM performing better than the conventional F-OFDM model and modified F-OFDM version by 49.1% and 36.6%, respectively.



(a) ICI mitigation of Hann-Chebyshev induced FF-OFDM versus conventional and modified F-OFDM models

(b) ICI mitigation of Hann-Kaiser induced FF-OFDM versus conventional and modified F-OFDM models

Fig. 5 ICI mitigation at 60 kHz SCS

Table 1 ICI sensitivity/mitigation of Hann-Chebyshev induced FF-OFDM against modified and conventional F-OFDM at 60 kHz SCS

$I_{Sen/Mit}$ Technique	Average Interference Power ( $I_{Average}$ ) (dBm)	Average % Improvement over Conv. F-OFDM	Average % Improvement over Modified F-OFDM
Conventional F-OFDM	31.6		
Modified F-OFDM	34.2	8.4%	
Hann-Chebyshev FF-OFDM	45.2	43.4%	32.3%

Table 2 ICI sensitivity/mitigation of Hann-Kaiser induced FF-OFDM against modified and conventional F-OFDM at 60 kHz SCS

$I_{Sen/Mit}$ Technique	Average Interference Power ( $I_{Average}$ ) (dBm)	Average % Improvement over Conv. F-OFDM	Average % Improvement over Modified F-OFDM
Conventional F-OFDM	31.6		
Modified F-OFDM	34.2	8.4%	
Hann-Kaiser FF-OFDM	47.0	49.1%	36.6%

At 120 kHz SCS, presents simulation results in Figure 6 (a & b) which is summarized in Tables 3 and 4. It show the newly developed Hann-Chebyshev induced FF-OFDM model outperformed the conventional F-OFDM model by 30.6% in Figure 6 (a) and in Figure 6 (b), it is also evident that the Hann-Kaiser induced FF-OFDM performed better than the conventional F-OFDM model by 34.2%. This is because the non-unity feedback probe incorporated in the FF-OFDM system has a backup information of the transmitter parameters, thereby modifying its receiver information in nearly conformity. This has an advantage in mitigating the frequency offset or Doppler shift (jittering) that causes ICI between two or more independent channels of data streams better than F-OFDM system and other previous CA and modulation techniques.

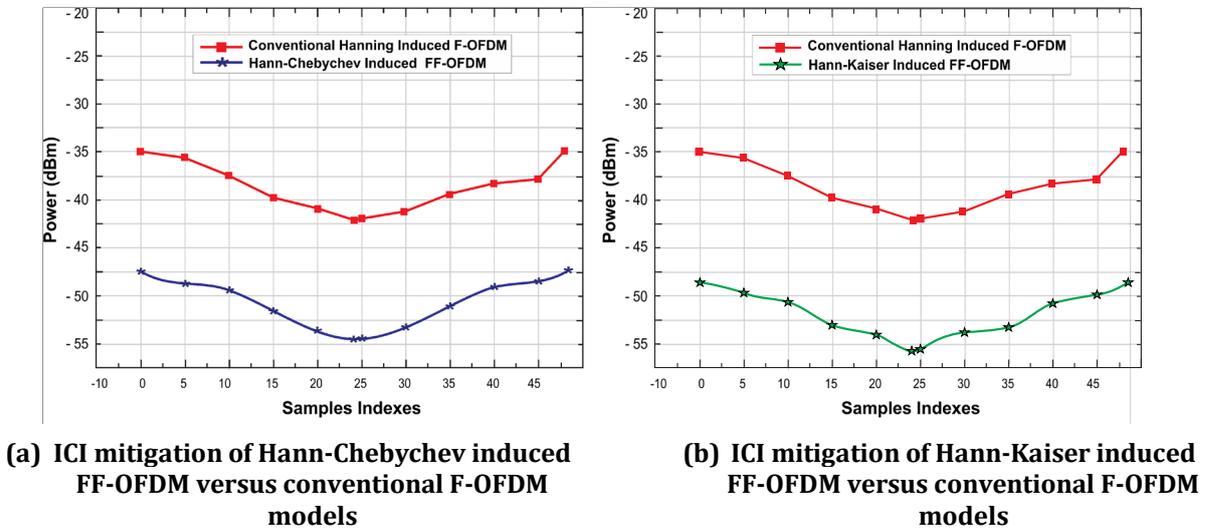


Fig. 6 ICI mitigation at 120 kHz SCS

Table 3 ICI sensitivity/mitigation of Hann-Chebyshev induced FF-OFDM against conventional F-OFDM at 120 kHz SCS

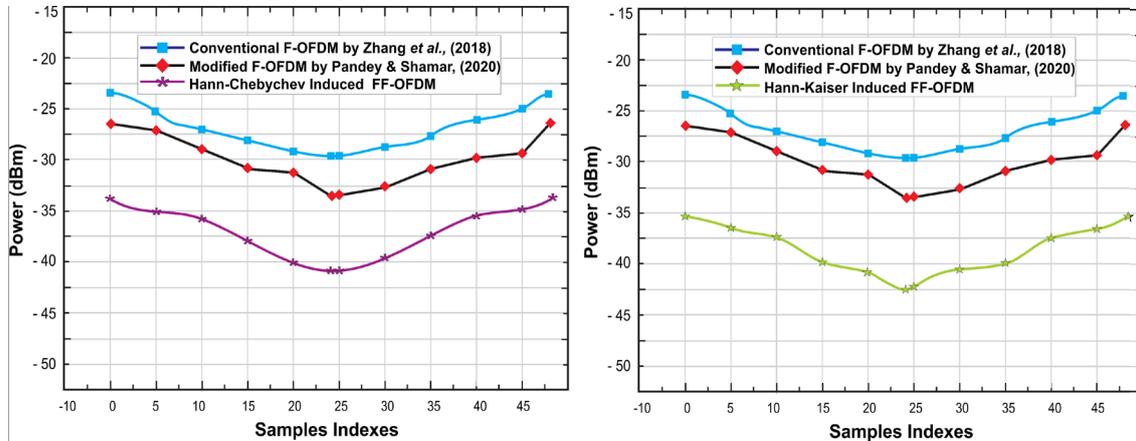
$I_{Sen}^{Mit}$ Technique	Average Interference Power ( $I_{Average}$ ) (dBm)	Average % Improvement over Conv. F-OFDM
Conventional F-OFDM	38.8	
Hann-Chebyshev FF-OFDM	50.6	30.6%

Table 4 ICI sensitivity/mitigation of Hann-Kaiser induced FF-OFDM against conventional F-OFDM at 120 kHz SCS

$I_{Sen}^{Mit}$ Technique	Average Interference Power ( $I_{Average}$ ) (dBm)	Average % Improvement over Conv. F-OFDM
Conventional F-OFDM	38.8	
Hann-Kaiser FF-OFDM	52.2	34.2%

### 4.2 ISI Mitigation Results

Similarly, the FF-OFDM agility in mitigating ISI is also compared with conventional F-OFDM model and modified versions of F-OFDM in order to prove its effectiveness in meeting up the 5G NR requirement for orthogonality at 60 kHz SCS. Results in Figure 7, summarized in Tables 5 and 6 show the modified F-OFDM mitigating ISI better than conventional model with about 11.5%, while the Hann-Chebyshev FF-OFDM model is observed to be better than the conventional and modified model of F-OFDM by 37.1% and 24.1%, respectively. It is also interesting to note that Hann-Kaiser FF-OFDM outperforms the conventional model and modified version of F-OFDM by 43.6% and 29.8%, respectively.



(a) ISI mitigation of Hann-Chebyshev induced FF-OFDM versus conventional and modified F-OFDM models

(b) ISI mitigation of Hann-Kaiser induced FF-OFDM versus conventional and modified F-OFDM models

Fig. 7 ISI mitigation at 60 kHz SCS

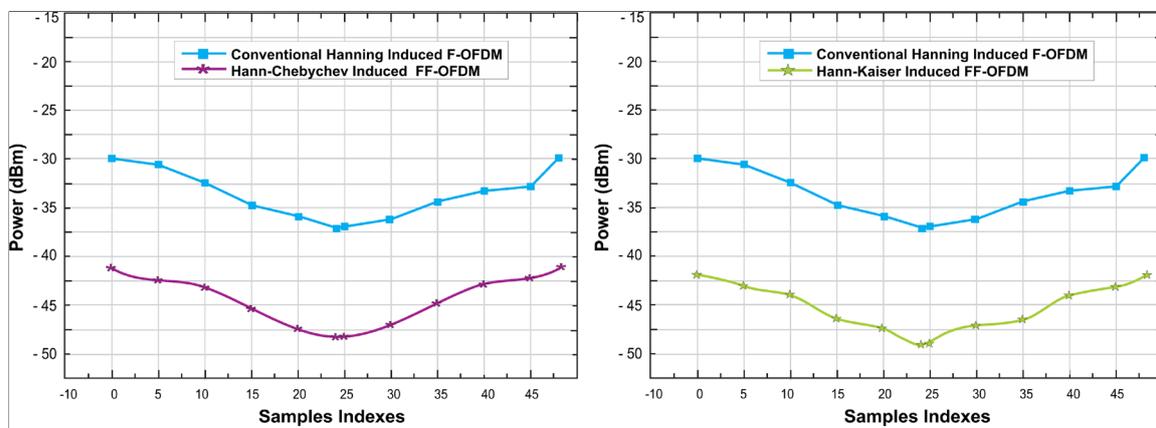
Table 5 ISI sensitivity/mitigation of Hann-Chebyshev induced FF-OFDM against modified and conventional F-OFDM at 60 kHz SCS

$I_{Sen/Mit}$ Technique	Average Interference Power ( $I_{Average}$ ) (dBm)	Average % Improvement over Conv. F-OFDM	Average % Improvement over Modified F-OFDM
Conventional F-OFDM	27.0		
Modified F-OFDM	30.0	11.5%	
Hann-Chebyshev FF-OFDM	37.2	37.1%	24.1%

**Table 6** ISI sensitivity/mitigation of Hann-Kaiser induced FF-OFDM against modified and conventional F-OFDM at 60 kHz SCS

$I_{Sen/Mit}$ Technique	Average Interference Power ( $I_{Average}$ ) (dBm)	Average % Improvement over Conv. F-OFDM	Average % Improvement over Modified F-OFDM
Conventional F-OFDM	27.0		
Modified F-OFDM	30.0	11.5%	
Hann-Kaiser FF-OFDM	39.0	43.6%	29.8%

Figure 8 summarized in Tables 7 and 8 present ISI mitigating at 120 kHz SCS. Simulation results obtained in Figure 8 (a) show Hann-Chebyshev FF-OFDM model performs better than conventional model by about 31.7%. It is also observed in Figure 8 (b) that Hann-Kaiser induced FF-OFDM outperforms the conventional model of F-OFDM by 33.2%.



(a) ISI mitigation of Hann-Chebyshev induced FF-OFDM versus conventional F-OFDM models

(b) ISI mitigation of Hann-Kaiser induced FF-OFDM versus conventional F-OFDM models

**Fig. 8** ISI mitigation at 120 kHz SCS

**Table 7** ISI sensitivity/mitigation of Hann-Chebyshev induced FF-OFDM against conventional F-OFDM at 120 kHz SCS

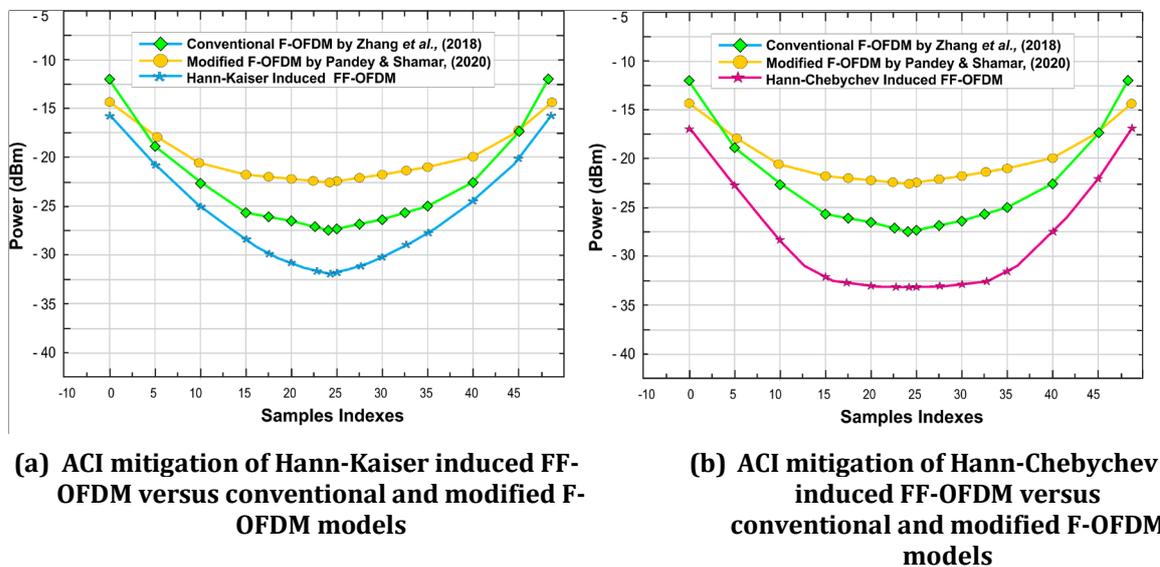
$I_{Sen/Mit}$ Technique	Average Interference Power ( $I_{Average}$ ) (dBm)	Average % Improvement over Conv. F-OFDM
Conventional F-OFDM	34.0	
Hann-Chebyshev FF-OFDM	44.5	31.7%

**Table 8** ISI sensitivity/mitigation of Hann-Kaiser induced FF-OFDM against conventional F-OFDM at 120 kHz SCS

$I_{Sen/Mit}$ Technique	Average Interference Power ( $I_{Average}$ ) (dBm)	Average % Improvement over Conv. F-OFDM
Conventional F-OFDM	34.0	
Hann-Kaiser FF-OFDM	45.3	33.2%

### 4.3 ACI Mitigation Results

The FF-OFDM scheme is compared with conventional and modified F-OFDM in terms for ACI mitigation at 60 kHz SCS. This is for the purpose of acknowledging its ability in achieving better asynchronicity which is a factor of ACI. Both analytical and simulation results in Figure 9 presented in Tables 9 and 10 prove that the modified F-OFDM model performs poorer as compared with the conventional model with about -12.1% reduction in ACI mitigation. This has clearly spelt the limitation of the modified F-OFDM model whose system works in achieving an increase in ISI and ICI but to the detriment of ACI. It is vivid from the results that the Hann-Kaiser FF-OFDM model overcomes that limitation of the modified F-OFDM version by outperforming the conventional model and the modified version by 16.8% and 27.1%, respectively. The Hann-Chebyshev FF-OFDM model is also realized to perform better than the conventional model and modified version of F-OFDM by 26.7% and 38.3%, respectively.



**Fig. 9** ACI mitigation at 60 kHz SCS

**Table 9** ACI sensitivity/mitigation of Hann-Kaiser induced FF-OFDM against modified and conventional F-OFDM at 60 kHz SCS

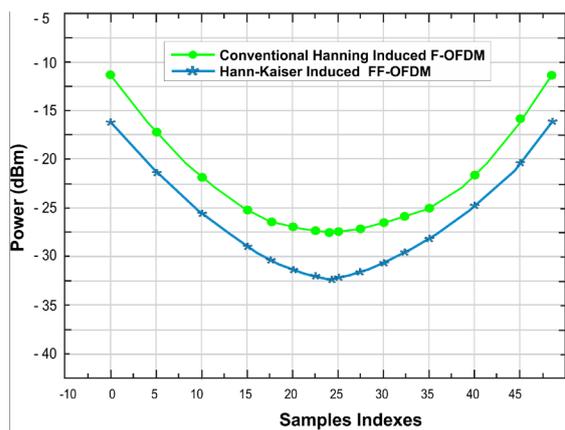
$I_{Sen/Mit}$ Technique	Average Interference Power ( $I_{Average}$ ) (dBm)	Average % Improvement over Conv. F-OFDM	Average % Improvement over Modified F-OFDM
Conventional F-OFDM	22.0		
Modified F-OFDM	19.7	-12.1%	

Hann-Kaiser FF-OFDM	25.4	16.8 %	27.1%
------------------------	------	--------	-------

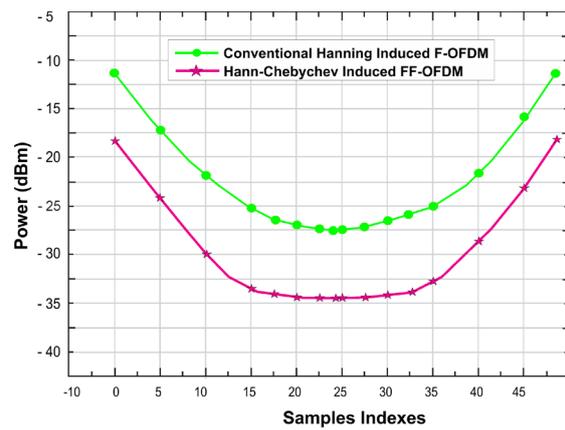
**Table 10** ACI sensitivity/mitigation of Hann-Chebyshev induced FF-OFDM against modified and conventional F-OFDM at 60 kHz SCS

$I_{Sen/Mit}$ Technique	Average Interference Power ( $I_{Average}$ ) (dBm)	Average % Improvement over Conv. F-OFDM	Average % Improvement over Modified F-OFDM
Conventional F-OFDM	22.0		
Modified F-OFDM	19.7	-12.1%	
Hann- Chebyshev FF-OFDM	27.5	26.7%	38.3%

In the same manner, the results in Figure 10 at 120 kHz SCS presented in Tables 11 and 12 show that the Hann-Kaiser induced FF-OFDM model outperformed the conventional model of F-OFDM by 21.7%, while the Hann-Chebyshev FF-OFDM model is also realized to perform better than the conventional model of F-OFDM by 32.9%.



**(a)** ACI mitigation of Hann-Kaiser induced FF-OFDM versus conventional F-OFDM models



**(b)** ACI mitigation of Hann-Chebyshev induced FF-OFDM versus conventional F-OFDM models

**Fig. 10** ACI mitigation at 120 kHz SCS

**Table 11** ACI sensitivity/mitigation of Hann-Kaiser induced FF-OFDM against conventional F-OFDM at 120 kHz SCS

$I_{Sen}^{Mit}$ Technique	Average Interference Power ( $I_{Average}$ ) (dBm)	Average % Improvement over Conv. F-OFDM
Conventional F-OFDM	21.6	
Hann-Kaiser FF-OFDM	25.8	21.7%

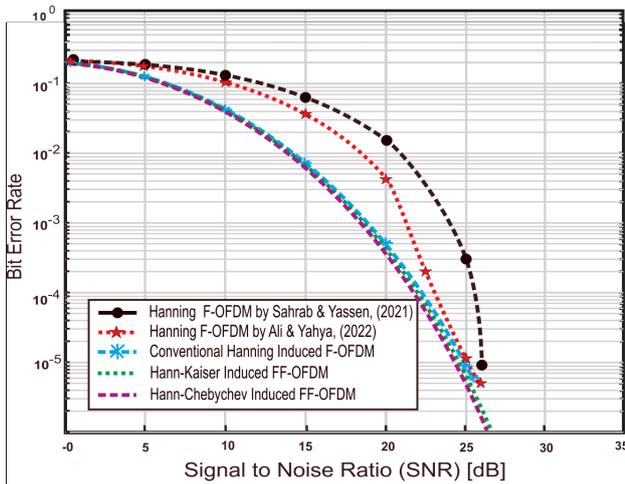
**Table 12** ACI sensitivity/mitigation of Hann-Chebyshev induced FF-OFDM against conventional F-OFDM at 120 kHz SCS

$I_{Sen}^{Mit}$ Technique	Average Interference Power ( $I_{Average}$ ) (dBm)	Average % Improvement over Conv. F-OFDM
Conventional F-OFDM	21.6	
Hann-Chebyshev FF-OFDM	28.8	32.9%

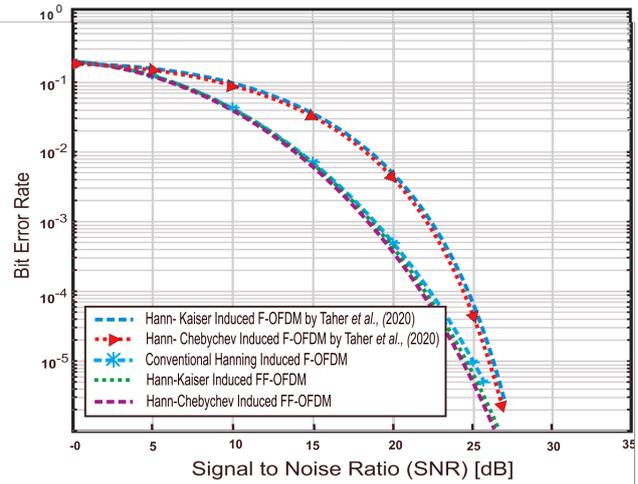
### 5. BER Improvement Results

BER is the measure of the difference between original transmitted signals and received signals at the receiving end [18]. The worthiness of this FF-OFDM multicarrier channel access technique is subjected to comparison of its results for BER and SNR using 256QAM mapping scale with those of the conventional work of [5] and modified models of [12] and [4]. This is to further ascertain the quality of the signal realized by the FF-OFDM scheme. It is observed in the results of Figure 11 (a) that both conventional F-OFDM and its modified versions obtained BER within  $10^{-5}$  and SNR slightly above 26 dB each when transmitted at 60 kHz SCS. This is within the required standard for 5G FR1 waveform. The Hann-Kaiser induced FF-OFDM and Hann-Chebyshev FF-OFDM are observed to have relegated BER within  $10^{-6}$  scale with SNR above 27.5 dB better than those achieved by the conventional F-OFDM and its modified versions.

Figure 11 (b) is also a comparison of the BER mitigation of Hann-Kaiser FF-OFDM and Hann-Chebyshev FF-OFDM to those of Hann-Kaiser F-OFDM and Hann-Chebyshev F-OFDM of the work of [12]. Simulation results presented show Hann-Kaiser and Hann-Chebyshev F-OFDM mitigate BER within the confines  $10^{-5}$  and SNR of about 27 dB better than that conventional F-OFDM with SNR of 26 dB. On the other hand, the Hann-Kaiser and Hann-Chebyshev FF-OFDM obtaining BER beyond  $10^{-5}$  prove to outperform the conventional F-OFDM and modified F-OFDM schemes.



(a) BER of FF-OFDM versus F-OFDM at 60 kHz SCS

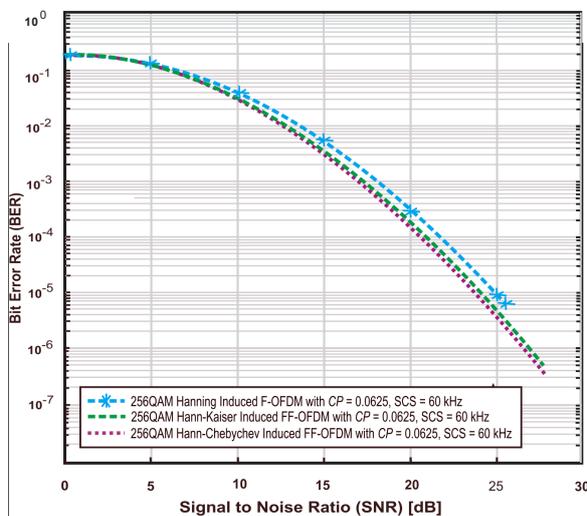


(b) BER of FF-OFDM versus F-OFDM using Hanning, Hann-Kaiser, and Hann-Chebyshev filters at 60 kHz SCS

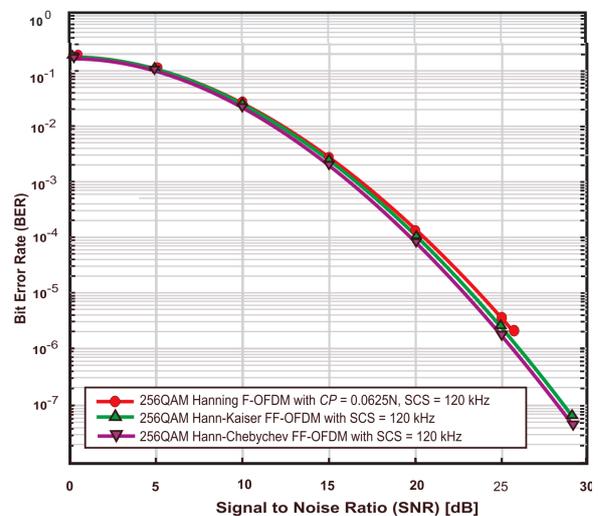
Fig. 11 BER of FF-OFDM versus conventional and modified F-OFDM versions at 60 kHz SCS

Analytical and experimental works have proven that, the lower the BER the better SNR quality. From this stated fact, the performance of the two simultaneous waveforms generated by FF-OFDM technique were again put to test in comparisons with those of F-OFDM under varying SCSs of 60 kHz and 120 kHz. It was observed in Figure 12 (a & b) that the FF-OFDM agility in generating more useful data bit than un-useful ones did better than F-OFDM in all cases. The results read that the FF-OFDM generated BER within the confines of  $10^{-6}$  and  $10^{-7}$  at 60 kHz and 120 kHz SCSs, respectively. Figure 12 (a) show the results of BER of FF-OFDM waveform against F-OFDM waveform at 60 kHz SCS, in which the two simultaneous FF-OFDM waveforms developed by this work are seen to be attained BER within  $10^{-6}$  dB better than F-OFDM which recorded BER within  $10^{-5}$ . It is also viewed in Figure 12 (b) that the FF-OFDM schemes proves beyond doubt its capability in driving higher SCSs in which it achieved BER of  $10^{-7}$  at 120 kHz SCS, thereby degrading the F-OFDM performance which still fell within  $10^{-5}$ . This is a clear proof that F-OFDM waveform does not service above 60 kHz SCS to drive higher 5G NR requirement, its scalability reduced with every increase in data at 120 kHz SCS.

The quality of the signal generated by FF-OFDM is further subjected to self-evaluation, where simulations results show the Hann-Chebyshev FF-OFDM produces better BER and SNR than Hann-Kaiser induced FF-OFDM. This is simply because the Hann-Chebyshev induced FF-OFDM waveform is wider with fewer side-lobes in nature which makes it less distorted by noise/interference.



(a) BER of FF-OFDM versus F-OFDM at 60 kHz SCS



(b) BER of FF-OFDM versus F-OFDM at 120 kHz SCS

Fig. 12 BER of FF-OFDM versus conventional F-OFDM scheme versions at 60 kHz and 120 kHz SCS

## Conclusion

It will interest the reader to note that, the comparisons of the performance of this research work were done within 60 kHz and 120 kHz SCS because those are the thresholds and the handover region for 5G FR1 and FR2 as designated by 3GPP. Simulation results realized have shown that the newly developed FF-OFDM has overcome those limitations of F-OFDM by being able to service higher SCSs effectively by virtue of effective ICI, ISI, and ACI mitigations which invariably amount to improvement in signal quality. At 60 kHz SCS, results showed that FF-OFDM CA achieved an interference mitigation of 47.0 dB for ICI, 39.0 dB for ISI, and 27.0 dB for ACI, outperforming the conventional model of F-OFDM which obtained 31.6 dB for ICI, 27.0 dB for ISI, and 22.0 dB for ACI interference power. Similarly, at 120 kHz SCS the results also showed the FF-OFDM obtained an interference mitigation of 52.2 dB for ICI, 45.3 dB for ISI, and 28.8 dB for ACI, better than the conventional model of F-OFDM which achieved 38.8 dB for ICI, 34.0 dB for ISI, and 21.6 dB for ACI interference power. For the test of the performance of the communication signal quality at 60 kHz SCS, the FF-OFDM achieved a BER within  $10^{-6}$  at 27 SNR better than  $10^{-5}$  realized by conventional and modified versions of F-OFDM of previous researches. When comparing the BER of Hanning induced FF-OFDM and Hanning induced F-OFDM at 120 kHz SCS, it was also seen that the FF-OFDM obtained an improved BER above  $10^{-6}$  better than F-OFDM scheme which still operate within  $10^{-5}$  because of scalability factor. In this research findings, the F-OFDM waveform and its variants did transmit maximally and effectively at 60 kHz SCS for 5G FR1 but at 120 kHz SCS the F-OFDM performances degraded with every increase in data which made it difficult to meet the requirement for 5G FR2. Final results proved that FF-OFDM CA technique has amicably solved these problems encountered by F-OFDM system in terms of effective interference mitigation and improvement in communication signal quality.

## Acknowledgement

The authors of this research sincerely give credit to the entire staff team of the department of Electronics and Telecommunications Engineering, Ahmadu Bello University Zaria, Nigeria, for their constructive critiques and support towards ensuring this piece of work become a reality.

## Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

## Author Contribution

*The authors are responsible for the study conception, research design, data collection, data analysis, result interpretation and manuscript drafting.*

## References

- [1] Santiago, C. R., Szydełko, M., Kliks, A., Foukalas, F., Haddad, Y., Nolan, E. K., Kelly, Y. M., Masonta, T.M., & Balasingham, I. (2015). "5G: *The Convergence of Wireless Communications*." *Wireless Pers Commun*, 83:1617–1642.
- [2] Hussain, G. A., Wahhab, H. A., & Harbi, Y. J. (2023). Filtered OFDM System Improvement Using Hamming Code. *Journal of Communications*, 18(4).
- [3] Sahrab, A. A. & Yaseen, D. A. (2021), "Filtered orthogonal multiplexing scheme for improved 5G systems," *Bulletin of Electrical Engineering and Informatics*, 10(4), 2079-2087.
- [4] Ali, D. M., & Yahya, Z. Z. (2022). Flexible Sub-bands F-OFDM Configured for Spectrum Efficiency Enhancement in 5G System. *J. Commun.*, 17(3), 203-209.
- [5] Zhang, L., Ijaz, A., Xiao, P., Molu, M. M., & Tafazolli, R. (2018). Filtered OFDM systems, algorithms, and performance analysis for 5G and beyond. *IEEE Transactions on Communications*, 66(3), 1205-1218.
- [6] Augustine, A., Tekanyi, A.M. S., Sani, S. M., Usman, A. D., Yaro, A.S. (2021) "Development of a Novel Feedback Filtered Orthogonal Frequency Division Multiplexing Scheme for 5G Network and Beyond." *Journal of Telecommunication, Electronic & Computer Engineering (JTEC)*, Malaysia. 13(4)
- [7] Cai, Y., Qin, Z., Cui, F., Li, G. Y., & McCann, J. A. (2018). Modulation and multiple access for 5G networks. *IEEE Communications Surveys & Tutorials*, 20(1), 629-646.
- [8] Chalaliya, A. H., Dave, T. N. & Dastoor, K. S. (2018). "Interference Mitigation Technique for Downlink Cellular Network by Advanced Receiver and Scheduling Mechanism." *International Journal of Engineering Research & Technology (IJERT)*, 7(2), 330-335.
- [9] Peköz, B., Ankaralı, Z. E., Köse, S., & Arslan, H. (2019). Non-redundant OFDM receiver windowing for 5G frames and beyond. *IEEE Transactions on Vehicular Technology*, 69(1), 676-684.
- [10] Somasekhar, A., Kishore, C. S., Sai, R. T. D., Asha, C. H, Manasa, A. & Nalanda, C. (2020). "Inter Carrier Interference Mitigation in Space Frequency Block Code MIMO-OFDM System." *International Journal of Advanced Science and Technology*, 29(9), 3305-3314.

- [11] Pandey, A. & Sharma, D. (2020). "Filtered-OFDM for 5G Wireless Communication Narrow-band IoT Systems." *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*, 15(3), 24-3.
- [12] Taher, M. A., Radhi, H. S., & Jameil, A. K. (2021). "Enhanced F-OFDM candidate for 5G applications." *Journal of Ambient Intelligence and Humanized Computing*, 12(1), 635-652.
- [13] Ali, D. M., & Yahya, Z. Z. (2022). An Experimental Study of F-OFDM Spectrum Efficiency for 5G Applications. *International Journal of Microwave & Optical Technology*, 17(1).
- [14] Baki, A. K. M. (2023). Comparison of different New Radio (NR) waveforms for wireless communications. *Plos one*, 18(4), e0283886.
- [15] Algriree, W., Sulaiman, N., Isa, M., Sahbudin, R. K., Hassan, S. L., & Salman, E. H. (2023). Validation hybrid filter detection for Multi-User multiple input multiple output F-OFDM by Universal software radio Peripheral. *Alexandria Engineering Journal*, 74, 241-268.
- [16] Ramadhan, A. J. (2019). "Implementation of a 5G Filtered-OFDM Waveform Candidate." *International Journal of Engineering Research and Technology*, 12(4), 500-507.
- [17] Zhang, X., Jiay, M., Chen, L., May, J. & Qiu, J. (2021). "Filtered-OFDM -Enabler for Flexible Waveform in the 5th Generation Cellular Networks." *IEEE Globecom*, 1-6.
- [18] Pandey, R., Awasthi, A., & Srivastava, V. (2013, April). Comparison between bit error rate and signal to noise ratio in OFDM using LSE algorithm. In *Proceedings of the conference on advances in communication and control systems* (pp. 463-466).