

# SCALABLE NUMEROLOGY FOR EFFECTIVE ASYNCHRONOUS AND ORTHOGONAL SIGNAL WAVEFORMS USING FF-OFDM SCHEME

Zakka Augustine<sup>1,\*</sup>, Abdoulie Momodou Sunkary Tekanyi<sup>2</sup>, Aliyu Danjuma Usman<sup>2</sup>, Kabir Ahmad Abubilal<sup>2</sup>, Frederick Duniya Basaky<sup>3</sup>, Savior Douglas Dogo<sup>4</sup>

<sup>1</sup>Department of Computer Science, Federal University of Applied Sciences, Kachia, Nigeria

<sup>2</sup>Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Nigeria

<sup>3</sup>Department of Computer Science, College of Information and Communication Information, Salem University, Lokoja, Nigeria

<sup>4</sup>Department of Physics Education, Federal College of Education (Technical), Omoku, Rivers State, Nigeria

\*Corresponding Author: <sup>1,\*</sup>Zakka Augustine (Email: zakka.augustine@fuask.edu.ng, zax.austen@yahoo.com)

Co-Authors: <sup>2</sup>Abdoulie Momodou Sunkary Tekanyi (Email: amtekanyi@abu.edu.ng), <sup>2</sup>Aliyu Danjuma Usman (Email: aliyuusman1@gmail.com), <sup>2</sup>Kabir Ahmad Abubilal (Email: kabirahmed@abu.edu.ng), <sup>3</sup>Frederick Duniya Basaky (Email: frederick.basaky@fulokojia.edu.ng), <sup>4</sup>Savior Douglas Dogo (Email: dogodouglas83@gmail.com)

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**Abstract.** *Wireless systems are often affected by distortions at the physical layer, which hinder reliable performance. A key challenge is the limited ability to suppress interference at the receiver, preventing the achievement of the asynchronous and orthogonal signal waveforms required for efficient utilization of Fifth Generation New Radio (5G NR) resources. Poor asynchronicity and orthogonality primarily result from Adjacent Channel Interference (ACI), Inter-Symbol Interference (ISI), and Inter-Channel Interference (ICI). This work addresses these challenges using the Feedback Filtered Orthogonal Frequency Division Multiplexing (FF-OFDM) channel access technique. Simulation results at 60 kHz Subcarrier Spacing (SCS) show that Hann-Kaiser-based FF-OFDM achieves superior mitigation of ICI (-47.0 dBm) and ISI (-39.0 dBm) compared to Hann-Chebyshev-based FF-OFDM (-45.2 dBm*

*and -37.2 dBm, respectively). Conversely, Hann-Chebyshev-based FF-OFDM provides better ACI suppression (-27.5 dBm) than Hann-Kaiser-based FF-OFDM (-25.4 dBm). Similar trends were observed at 120 kHz SCS, where Hann-Kaiser-based FF-OFDM consistently produced more orthogonal signal waveforms, while Hann-Chebyshev-based FF-OFDM yielded safer asynchronous signal waveforms. The conventional and modified F-OFDM models were used as benchmarks for evaluating and validating these results.*

**Keywords:** 5G NR numerology; Effective asynchronous waveform; Effective orthogonal waveform; FF-OFDM system; System scalability.

# 1. Introduction

An essential requirement for effective asynchronous and orthogonal wireless transmission is the ability to share a wireless channel among multiple signals in such a way that each signal can be received without interfering with the others [1]. Orthogonal Frequency Division Multiplexing (OFDM) and Cyclic Prefix-OFDM (CP-OFDM) are well-established mobile communication techniques that marked a paradigm shift toward achieving reliable asynchronous and orthogonal wireless transmission. The Fourth Generation (4G) Long Term Evolution (LTE) and Long-Term Evolution Advanced (LTE-A) networks were successfully powered by OFDM and CP-OFDM schemes [2], achieving peak data rates of 400 Mbps and 1 Gbps, respectively.

Despite their success, OFDM and CP-OFDM waveforms cannot fully meet the requirements for effective asynchronicity and orthogonality needed for balanced transmission in Fifth Generation (5G) New Radio (NR). This shortcoming is primarily due to the presence of intrinsic and extrinsic interferences. Intrinsic limitations include large Out-of-Band Emissions (OoBE) and a high Peak-to-Average Power Ratio (PAPR), while extrinsic limitations include poor spectral confinement and inflexible waveform structures. These drawbacks make them insufficient for meeting the demands of 5G networks. Consequently, the limitations of these earlier Multi-carrier Channel Access (MCA) techniques have driven the development of more advanced access schemes to address modern wireless requirements. Within the context of 5G and beyond, Filtered-OFDM (F-OFDM) has emerged as one of the most promising MCA candidates [3]. Extensive studies and practical implementations have shown that F-OFDM mitigates some of the limitations of OFDM and CP-OFDM through the use of spectrum-shaping filters. However, F-OFDM still does not fully satisfy the stringent requirements of future wireless communications, leaving room for further enhancements. One notable drawback is the reintroduction of chunks of interference at the receiver side of the system [4, 5]. For example, a potential application of F-OFDM is the Internet-of-Things (IoT) but in this scenario, the subbands are narrowed, and

therefore, interference caused by the shortening or displacement of the CP can significantly degrade the performance of the system and should be taken into consideration seriously [5]. In this work, the focus is on improving system efficiency by mitigating three key sources of interference: Adjacent Channel Interference (ACI), caused by leakage of nearby frequencies within the filter passband; Inter-Symbol Interference (ISI), induced by the frequency selectivity of the channel due to CP removal; and Inter-Channel Interference (ICI), induced by Carrier Frequency Offsets (CFO) [6].

F-OFDM normally adopts a much longer filter, mostly a windowed Sinc filter with a length being half of the symbol duration [7, 8]. However, the filter tails (typically totally) extend to the adjacent symbols to keep the system overhead the same as the CP OFDM system [5, 9]. This overlapping is the cause for the system exhibiting more ISI and/or ICI, especially in a scenario wherein a subband occupies a small percentage of the whole bandwidth [9]. This drawback led to the adoption of a more scalable scheme known as the Feedback Filtered Orthogonal Frequency Division Multiplexing (FF-OFDM) scheme in this work to totally curtail these interferences [10]. The FF-OFDM system is an F-OFDM-improved architecture encompassing two paired windowed induced spectrum-shaping filter functions. In this work, pairing Hann-Kaiser and Hann-Chebyshev achieved the scalability required for effective asynchronicity and effective orthogonality to run advanced 5G NR numerologies.

The new 5G waveform must allow different numerologies to be mixed on the used carrier frequency, where the subcarriers of specified numerology interfere in the frequency domain with other subcarriers of another numerology [11]. Other interference mitigation schemes developed to suppress ACI, ISI, ICI, etc., to control synchronization error or phase error, are observed to be incapacitated in bandwidth management at the detriment of sacrificing time and power efficiency when compared to F-OFDM [12, 13]. The FF-OFDM is designed flexibly with a backward compatibility of creating an effective handshake with LTE/LTE-A systems and 5G NR systems and is projected for forward compatibility with

next generations of air interfaces. The motivations behind this research are the following:

- To develop scalable networks to improve wireless systems asynchronicity and orthogonality.
- To explore an improved access channel scheme of FF-OFDM to ascertain its scalability to drive network numerologies 0, 1, 2, 3, 4, and 5 for 5G NR systems and beyond.

The innovation in this research is in the development of a non-unity feedback module in the Channel Estimation Region (CER) of an FF-OFDM access scheme receiver, encompassing Hann-Kaiser induced filter for effective system orthogonality and Hann-Chebyshev induced filter for effective system asynchronicity. This has never been seen presented for any waveform modification, to the best of our knowledge.

## 2. Research Significant Contributions

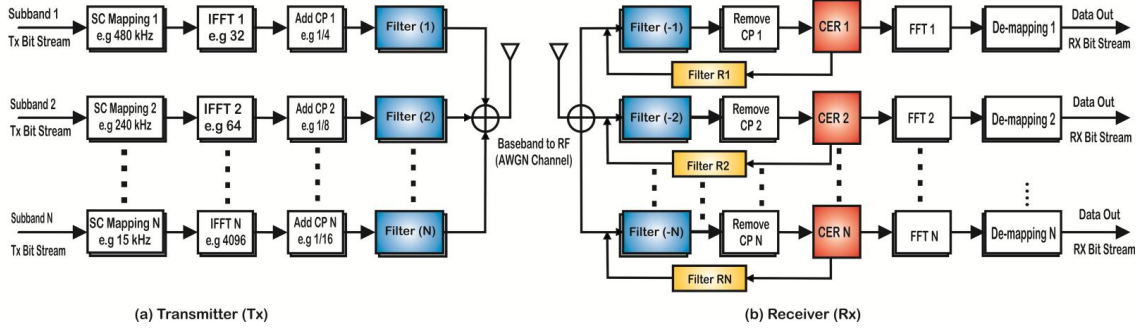
The key contributions of this research are as follows:

- Proposed an improved approach of mitigating interference on the receiver side of orthogonal access schemes, achieving better performance than previously reported in the literature.
- Demonstrated the effectiveness of the method in both 60-kHz and 120-kHz sub-carrier spacings (SCSs) in advanced 5G NR systems.
- Improved channel asynchronicity and orthogonality through the application of the FF-OFDM algorithm.
- Identified a slight increase in power consumption resulting from the incorporation of hybrid windowed filters in the FF-OFDM access scheme, highlighting the need for further research to reduce power overhead and enhance the overall efficiency of FF-OFDM waveforms.

## 3. Research Methodology

This research builds upon the orthogonality of OFDM and the interference resilience of CP-OFDM to derive the F-OFDM signal waveform. To address the inherent drawbacks of F-OFDM, an enhanced FF-OFDM waveform algorithm, as proposed, is presented in Figure 1. This proposed model is capable of generating effective asynchronous and orthogonal signals suitable for driving advanced 5G NR systems better than earlier Orthogonal Multiple Access (OMA) models. The innovation of this work lies in the modification caused by the FF-OFDM scheme through the use of hybridized adaptive filters, enabling support for scalable numerologies ( $\mu = 0, 1, 2, 3, 4, \text{ or } 5$ ). This approach overcomes the performance limitations observed in F-OFDM and its variants, particularly those experienced after the removal of the cyclic prefix (CP).

The FF-OFDM framework applies subband filtering to an OMA waveform and uses a non-unity block at the receiver. This non-unity loop continuously estimates and subtracts residual interference experienced at the receiver side of a wireless transducer, which is one of the drawbacks suffered by the traditional F-OFDM models. The improved non-unity module encompasses a spectrum-shaping filter version,  $F_{HW}^*(-n)$ , which serves as the error factor determinant to all received signal pulses. The demultiplexer is used for the Serial-to-Analog (S/A) conversion and for the removal of the CP burdens, the Channel Estimation (CER) for the system gain estimation, and the feedback region for complementing the signal attenuation. From the scope of this work, the received signal is constantly demultiplexed and complemented to correct transmission errors that are noticed. Satisfied received signals are transited through the FFT tool to be converted back into the frequency domain. At the CER of Figure 1, the system isolates error droplets caused by ACI, ISI, and ICI in accordance with the response of the improved non-unity model. To correct these remaining anomalies, the identified corrupted signal pulses at the output of the demultiplexer are continuously compensated by the feedback filter effects. Using a non-unity trans-



**Figure 1:** Workflow Diagram of an FF-OFDM Transceiver System (Link Level Round-Trip).

fer gain function, the feedback filter systematically accentuates the original signal from interference aberrations. This recursive feedback loop is designed to seamlessly process the signal by canceling out noise, suppressing interference, and narrowing the sidelobe effects of the sub-carrier. The final outputs are highly correlated and complemented signals before the final symbol de-mapping and data recovery.

In 5G NR, multiple numerologies are defined by the subcarrier spacing (SCS), which plays a critical role in mitigating interference while maintaining system asynchronicity and orthogonality. This study considers the deployment context of 100 MHz bandwidth in sub-6 GHz bands and 200–400 MHz bandwidth in mmWave bands, both within the 5G NR domain. The objectives and parameters adopted in this research aim to establish a robust framework for achieving reliable received signal waveforms, which are evaluated to enhance sensitivity, specificity, and accuracy in detecting and mitigating adjacent channel interference (ACI), inter-symbol interference (ISI), and inter-carrier interference (ICI).

### 3.1. Spectrum-shaping filters

Before going further, be reminded that the developed FF-OFDM waveform is filter-centric. It is a combination of Hanning, Kaiser, and Dolph-Chebyshev FIR filtered signals. The modified waveforms are obtained in the classes of Hanning-Kaiser and Hanning-Chebyshev induced FF-OFDM waveforms. These are finite impulse response (FIR) filters, which serve as modifiers but at the detriment of power con-

sumption. This is deliberate in order to explore and exploit all the SCS earmarked for 5G frequencies (FR1/FR2/FR2-2/FR2-A) by 3GPP NR (Release 15, 16, 17, and 18) and to meet International Telecommunication Union (ITU) standards.

In terms of frequency selectivity with moderate main-lobe width and stop-band attenuation, Hanning plays a better role than the others [14]. This is the simple reason it is assumed to be placed first at the output of the transmitter and its folded version placed at the input of the receiver, as demonstrated in Figure 1. Hanning types of window filters are known to have fewer side lobes. Another reason Hanning is considered at the output of the transmitter and input of the receiver instead of other windows (for example, Hamming filters) is because Hanning decays and touches zero at both ends, removing any discontinuity, making it suitable for the requirement in this work for 5G FR1. Hanning is the most commonly used window function for random signal sampling and image filtering because it provides good frequency resolution and leakage control with fair amplitude accuracy.

Considering an ideal low-pass Sinc filter function,  $h_{id}(n)$  as presented in Equation (1).

$$h_{id}(n) = \begin{cases} \frac{\sin[C_\omega(n - N_f)]}{\pi(n - N_f)}, & \text{for } n \neq N_f \\ & (0 \leq n \leq 2N_f) \\ \frac{C_\omega}{\pi} & n = N_f \end{cases} \quad (1)$$

where,  $N_f$  is the number of filter taps;  $C_\omega$  is the cut-off frequency and  $n$  is the subband length in time domain.

Its Hanning Windowed function,  $W_{HW}^*(n)$  is given as:

$$W_{HW}^*(n) = 0.5 \left[ 1 - \cos \left( \frac{2\pi n}{N_W} \right) \right]^\alpha \quad (2)$$

where,  $N_W$  is the length of the window and  $\alpha$  is the roll-off factor.

If the filter taps used are real values,  $N_f = N_W$  whenever the frequency response is symmetrical around  $f_0 = 0$  Hz.

The required Hanning Window filter impulse response,  $F_{HW}^*(n)$  is expressed as the multiplication of the ideal filter and the windowed function by Equation (3):

$$F_{HW}^*(n) = h_{id}(n)W_{HW}^*(n) \quad (3)$$

where,  $h_{id}(n)$  is the ideal low-pass Sinc filter function and  $W_{HW}^*(n)$  denotes the Hanning Windowed function.

Similarly, Kaiser induced filter is known to give the lowest and most suitable side lobe width (when altered) compared to other window functions, which makes them more suitable for interference cancellation (that is, minimizing channel crosstalk) without a spill-over [15]. As such, it is used in this work to generate both 5G FR1/FR2 waveforms. Its attenuation values are larger with lower side-lobe levels; a wider main-lobe is provided, and vice versa. A Kaiser window also has an advantage over the other kind of FIR filters because it produces better main-lobe width and has the most flexible roll-off parameter configuration, but it is inferior in addressing stop-band attenuation. Kaiser filters' smallest main-lobe width means higher steepness as required for 5G FR1/FR2. So, in the filter design, applying Kaiser windowed function is more worthy in measuring bioelectric signals like Electro-Cardiogram (ECG) and Electro-Myogram (EMG). The Kaiser Windowed impulse response is computed within the boundaries of  $0 \leq n \leq N_W - 1$  by Equation (4) as:

$$W_{KW}^*(n) = \frac{I_0 \left[ \beta \sqrt{1 - \left( \frac{2n}{N_W} - 1 \right)^2} \right]}{I_0(\beta)} \quad (4)$$

where,  $\beta = \pi\alpha$ , is the attenuation function and  $I_0[\cdot]$  is the modified zero-order Bessel function.

The Kaiser-induced Windowed filter transfer function,  $F_{KW}^*(n)$  is obtained by multiplying Equations (1) and (4) as:

$$F_{KW}^*(n) = h_{id}(n)W_{KW}^*(n) \quad (5)$$

where,  $W_{KW}^*(n)$  denotes the Kaiser Windowed function.

Furthermore, the Dolph-Chebyshev window filters have greater performance with respect to stop-band attenuation, but their main lobe width is the widest one of the three filters [16]. Its responses suit the requirement of 5G NR releases 17 and 18 for satellite communication and AI integration to be deployed in FR2-2/FR2-A and 6G networks. It has a higher noise reduction capability than others but less steepness. So, the filter design using Dolph-Chebyshev window method is very much suitable for voice, video, and data transmission reception purposes. The impulse response of a Dolph-Chebyshev filter,  $W_{DW}^*(n)$  is obtained by Equation (6) as:

$$W_{DW}^*(n) = \frac{\cos \left( N_W \cos^{-1} \left[ \beta \cos \left( \frac{\pi n}{N_W} \right) \right] \right)}{\cosh \left[ N_W \cosh^{-1}(\beta) \right]} \quad (6)$$

Its window-induced filter transfer function,  $F_{DW}^*(n)$  is generated by Equation (7) as:

$$F_{DW}^*(n) = h_{id}(n)W_{DW}^*(n) \quad (7)$$

where,  $W_{DW}^*(n)$  denotes the Dolph-Chebyshev Windowed function.

On this note, the waveform modifier of this research uses Hanning window for the OoBE and PAPR waveform filtering to obtain 5G FR1 seamlessly, while Kaiser and Dolph-Chebyshev windows address the stop-band and pass-band attenuation problem in interference control and projecting to facilitate the main lobe width peculiarities for 5G FR1, FR2, FR2-2, and FR2-A. The Hanning induced FIR filter is used at the peak of transmission and at the trough of reception in order to cast off the CP burdens, while the Hann-Kaiser and Hann-Dolph-Chebyshev induced FIR filter responses are used

for the waveform modification to effectively improve the system asynchronicity and orthogonality using the non-unity feedback system.

### 3.2. System asynchronicity and orthogonality

In F-OFDM symbol transmission, ACI, ISI, and ICI do occur at the receiver due to inadequate filtering (caused by extraneous power from a signal in an adjacent channel and filter tails), delay spread (which is the difference between the maximum transmission latency in the longest path and the minimum transmission latency in the shortest path), and frequency offset (caused by Doppler shift, which means the difference between the transmitter and receiver frequency), respectively. The impact of ACI, ISI, and ICI has such a damaging effect on the wireless system scalability. The presence of ACI has a similar effect as noise in making the communication less reliable; ISI occurrence severely affects the transmission quality of digital signals, while ICI damages the orthogonality of the subcarriers in the F-OFDM system, thereby affecting the demodulation process at the receiver side. In order to avoid these in OFDM system, a CP copy extracted from the symbol head information is inserted between two OFDM symbols or channels in place of Guard Interval (GI) [17]. The CP is used to counter the effects of ACI, ISI, and ICI to avoid the effects of extraneous power, multipath propagation, and Doppler shift. It is kept at half the symbol period of the channel. The CP-OFDM is noted with the limitation of wasted bandwidth. In F-OFDM, these challenges are curtailed drastically using spectrum filters, but it is again observed to be emitting some chunks of interference at the receiver that impede the system from meeting its required objectives of effective asynchronous and orthogonal systems. The FF-OFDM tried to mitigate these drawbacks encountered by its predecessors. The mathematical expression of an FF-OFDM MCA symbol,  $X_k$  as proposed for 5G frequencies, is presented in Equation (8) as in [18, 19]:

$$X_K(n) = X_0, X_1, X_2, \dots, X_{(N-1)} \quad (8)$$

where,  $X_K(n)$  is the encoded subcarrier samples in the frequency domain and  $N$  is taken as the sample's length.

The symbols' length is taken as 4096 in conformity with the 3GPP standard for 5G NR systems. Experimental works have proven that the maximum numerology a 4G LTE/LTE-A system can service is 0 (that is 15 kHz SCS only), which is also the point of handoff between 4G and 5G FR1 frequencies [20]. It is also shown that some of the 5G NR access schemes have the scalability to drive numerologies 0, 1, and 2 (that is, 15 kHz, 30 kHz, and 60 kHz SCS) but could not drive higher. In order to fully meet up with the waveform parameters assignment framework for 5G NR and Sixth Generation (6G) in [21, 22]. The FF-OFDM access scheme considered in this research would be used to validate the effective handoff region between 5G FR1 and FR2 using numerology 2 and 3 of 60 kHz and 120 kHz, respectively.

Equation (9) is the generated mathematical formulation of a transmission waveform of an FF-OFDM system. This is derived from the concepts of F-OFDM transmission basics in the time domain using the Inverse Fast Fourier Transform (IFFT) tool and is expressed as [23]:

$$x(n) = \sum_{k=0}^{N-1} X_K(n) e^{j2\pi k \Delta f n T_s} \quad (9)$$

where,

- $x(n)$  is the transmitted signal waveform altered by  $F_{HW}^*(n)$  of the Equation (3).
- $k$  reflects the signal subcarrier index.
- $\Delta f$  denotes the subcarrier spacing, and
- $n$  is the symbol's time-discrete function.
- $T_s$  is the symbol period.
- $j$  refers to the imaginary unit  $\sqrt{-1}$  that alters the frequency shift.

The received signal impulse response,  $r(n)$  is subjected to circular convolution in the time domain in [24] as:

$$r(n) = h(n) * x(n) \quad (10)$$

where,  $h(n)$  is the channel gain and  $x(n)$  are the baseband carrier samples in the time domain.

In converse, its frequency domain translation,  $R(e^{j\omega})$  after transiting the Fast Fourier Transform (FFT) conversion is expressed by Equation (11) as:

$$R(e^{j\omega}) = H(e^{j\omega})X(e^{j\omega}) \quad (11)$$

where,

- $H(e^{j\omega})$  is the channel impulse representative in frequency domain.
- $X(e^{j\omega})$  refers to the information carrying signal in frequency domain.
- $e^{j\omega}$  is the frequency shift factor.

At this juncture, every discrete signal in the time domain is converted to a multiplication in the frequency domain. The goal of this research is to evaluate, detect, and complement subcarrier components with the higher likelihood of being corrupted by interference, which is experienced in an F-OFDM framework of  $X(n)$  samples after the removal of the CP.

A simplified model of the FF-OFDM symbols with the likelihood of being distorted by interference after the removal of the CP is expressed in Equation (12). Which explains that effective interference investigation is better visualized, performed, and achieved in the frequency domain as [25]:

$$X(e^{j\omega}) = \frac{R(e^{j\omega})}{H(e^{j\omega})} \quad (12)$$

Equation (13) expresses the mathematical formulation of the non-unity module used for detecting and complimenting defaulted signal pulses, which is either a combined filtering effect of Hann-Kaiser or that of Hann-Chebyshev. Incorporating this module in an FF-OFDM model will modify the entire output pulse to match those transmitted. The non-unity model functions as policing the gateway from time domain to frequency domain by constantly identifying/complementing error signal pulses that do not match the transmitted signal pulse.

$$y_S(n) = \frac{[F_{HW}^*(-n)]r(n)}{1 + [F_{HW}^*(-n)]R_S(n)} \quad (13)$$

where,

- $F_{HW}^*(-n)$  is the folded version of the FF-OFDM spectrum-shaping filter at the receiver side.
- $R_S(n)$  reflects the defected signal pulses reverted for error correction.
- $S$  is HKW or HCW, which is the combined filtering effect on the received signal waveform.

Depending on the waveform requirement, the individual HKW or HCW responses are formulated to either enable 5G FR1, FR2, or FR-A.

From these stated facts in Equations (12) and (13), the modified asynchronous waveform response,  $\hat{Y}_k(e^{j\omega})$  in frequency domain that is altered by the non-unity model of an FF-OFDM scheme is expressed in Equation (14) as:

$$\hat{Y}_k(e^{j\omega}) = \sum_{K=0}^{N-1} X_K(e^{j\omega})e^{j\omega t} \quad (14)$$

Its orthogonal nature,  $X(e^{j\omega})$  takes the following form:

$$X(e^{j\omega}) = \frac{1}{T_q} \int_0^{T_q} \hat{Y}_k(e^{j\omega})e^{-j\omega t} dt \quad (15)$$

where,  $T_q$  is the symbol's timing limit;  $e^{j\omega}$  represents the frequency shift factor;  $\omega$  is the angular frequency given as  $2\pi k\Delta f$ .

The system would fully satisfy its orthogonality if  $T_q\Delta f = 1$ .

In 4G LTE/LTE-A frequencies, the transmitted waveform,  $x(n)$  has 7 symbols, while the 5G NR frequencies contain 14 symbols in the same reference numerology 0. By considering numerologies 2 and 3 for the analysis in the work, the expected transmission symbols to explore for the validation of FF-OFDM system scalability as compared to F-OFDM are taken at 60 kHz SCS and 120 kHz SCS per each  $14 \times 12$  subcarrier block.

## 4. Results and Discussions

This section presents the parameters, the equations, and the simulation obtained in this

**Table 1:** Research Parameters.

| Parameters                          | Specifications                                                                       |
|-------------------------------------|--------------------------------------------------------------------------------------|
| Software                            | Pycharm IDE of Python Library                                                        |
| Filter Window                       | Hanning, Kaiser, Dolph-Chebyshev Windowed Sinc                                       |
| Air interfaces                      | 5G FR1, 5G FR2/FR2-2/FR2-A                                                           |
| Bandwidths                          | 5G FR1 bands [100 MHz (sub-6G)], 5G FR2/FR2-2/FR2-A bands [200 MHz–400 MHz (mmWave)] |
| Channel Access Scheme               | F-OFDM, FF-OFDM                                                                      |
| FFT/IFFT size, $N$                  | 4096 (3840 useful, 256 CP)                                                           |
| Number of useful subcarriers, $N_S$ | 3840 (3300 effective data subcarriers ( $N_E$ ), 540 pilots ( $N_P$ ))               |
| Number of subbands, $N_K$           | 80                                                                                   |
| Subband bandwidth, $M$              | 48 subcarriers                                                                       |
| Sample Index, $N_x$                 | 12                                                                                   |
| Defected Subcarriers, $N_d$         | 2,016 (1,680 undesired, 336 Pilots)                                                  |
| Defected Subband                    | 42                                                                                   |
| Modulation scheme                   | 256 QAM                                                                              |
| Bits per symbol                     | 8 bits                                                                               |
| Prioritized Numerologies            | 2, 3                                                                                 |
| Tone Space                          | 60 kHz, 120 kHz                                                                      |
| Sampling frequency, $f_s$           | 4.8 MHz, 9.6 MHz                                                                     |
| Sampling time, $T_c$                | 208.33 ns, 104.16 ns                                                                 |
| Energy bits, $E_b/N_0$              | –35 dB to 1 dB                                                                       |

work. The obtained research results are compared with recent research works in terms of Interference Power (IP) and Spectrum Efficiency (SE). The research parameters used are stated in Table 1. For the purpose of achieving effective 5G FR1, 5G FR2, and post-5G waveforms, this research proposes the use of signal antidotes, such as Hann-Kaiser induced FF-OFDM and Hann-Chebyshev induced FF-OFDM algorithms, respectively. The raw signal will be generated and processed from the OFDM orthogonal footing, while the Rayleigh Distribution (RD) channel model is also suggested to be used in this work because of its properties to model multipath fading with no Line of Sight (LoS) path. This is for the purpose of observing the signal impulse response at the receiver side.

#### 4.1. Interference mitigation results

To authenticate the viability of this work, its upshots in terms of ACI, ISI, and ICI power detection and mitigation are compared with those obtained from recent research works of [9]

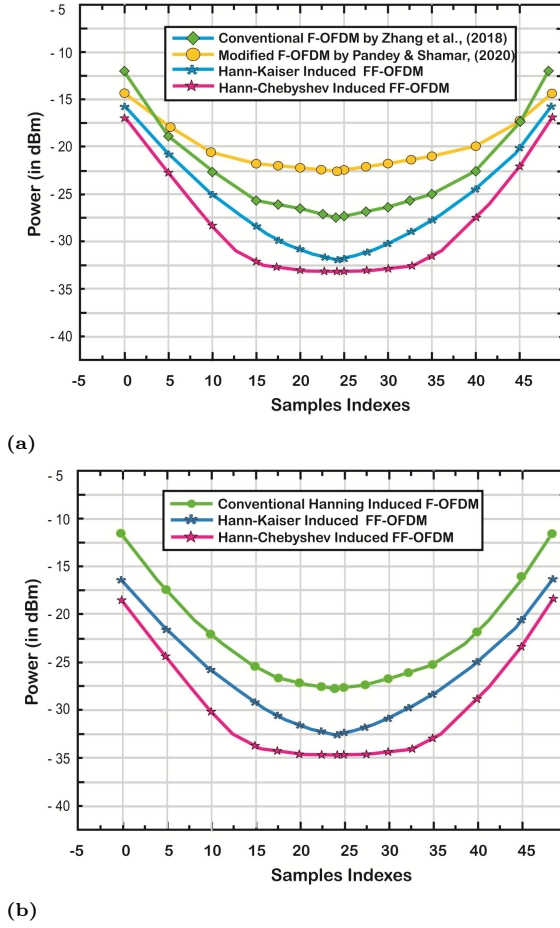
and [26] in order to achieve effective evaluation and validation. The results obtained in Figure 2, 3, and 4 are summarized in percentage improvement in Tables 2 through 7.

The performance evaluation of this work is carried out using Equation (16) through Equation (18) to determine the average interference power  $I_{Average}$  in dBm. The significant improvement of the developed FF-OFDM CA technique over F-OFDM techniques developed/presented by recent research works in terms of ACI, ISI, and ICI power detection/mitigation is evaluated and compared in this work as:

$$I_{Average} = \frac{\sum_{k=1}^M I_{Total}(k)}{I_{Samp}} \quad (16)$$

where,  $I_{Total}$  is the total interference unit power;  $I_{Samp}$  is the number of sample indices and  $M$  represents the subband bandwidth.

The effective asynchronicity results of the two systems are finally obtained by comparing the average interference mitigation,  $I_{Mitigation}$  of



**Figure 2:** ACI of FF-OFDM versus ACI of F-OFDM: (a) at 60 kHz and (b) at 120 kHz SCS.

$I_{Mit}(hc)$  and  $I_{Mit}(hk)$  as:

$$\begin{aligned} & \text{Average \% Increase in } I_{Mitigation} \\ &= \frac{\sum_{k=1}^M \left( \frac{I_{Mit}(hc) - I_{Mit}(hk)}{I_{Mit}(hk)} \times 100\% \right)}{I_{Samp}} \quad (17) \end{aligned}$$

Also, the effective orthogonality results of the system are finally obtained by comparing the interference mitigation,  $I_{Mitigation}$  of  $I_{Adv}(hk)$  and  $I_{Adv}(hc)$  as:

$$\begin{aligned} & \text{Average \% Increase in } I_{Mitigation} \\ &= \frac{\sum_{k=1}^M \left( \frac{I_{Mit}(hk) - I_{Mit}(hc)}{I_{Mit}(hc)} \times 100\% \right)}{I_{Samp}} \quad (18) \end{aligned}$$

where,  $I_{Mit}(hc)$  is the interference mitigation of the FF-OFDM system induced by Hann-Chebyshev filtering and  $I_{Mit}(hk)$  is the interference mitigation of the FF-OFDM system induced by Hann-Kaiser filtering.

Among other waveforms, F-OFDM is known for an effective numerology of driving 15 kHz, 30 kHz, and 60 kHz subcarrier spacing but is not scalable enough to run further. Experimental results obtained in Figures 2 to 7 have shown that it could only be deployed to drive 5G FR1 maximum. As illustrated in the results, FF-OFDM, on the other hand, has overcome this limitation by driving above 60 kHz and is proposed to be deployed in 5G FR1, FR2, and FR2-Advanced. This is as a result of its effective interference mitigation. The effective orthogonal and asynchronous waveform results are presented in the categories of effective filter tail interaction control, effective delay spread relegation, effective frequency offset mitigation, and spectral power density. The null options, 0 obtained in Tables 2 to 7, are a result of the research scope as presented in Equations (17) and (18), which are basically for percentage increase analysis, not decrease.

## 1) Effective Filter Tail Interaction Control

The FF-OFDM scheme is compared with the conventional model and modified F-OFDM versions in terms of ACI mitigation. 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 2a presented in Table 2 prove that the modified F-OFDM model performs poorer compared with the conventional model with about a 12.1% reduction in ACI mitigation. This has clearly spelled 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 and Hann-Chebyshev FF-OFDM models overcome that limitation of the modified version by outperforming the conventional model with about 16.8% and 26.7%, respectively. The Hann-Kaiser and Hann-Chebyshev FF-OFDM models are also realized to perform better than

**Table 2:** Filter Tail Interaction Control of Hann-Chebyshev FF-OFDM versus Hann-Kaiser FF-OFDM, Modified F-OFDM, and Conventional F-OFDM at 60 kHz SCS.

| $I_{\text{Sen/Mit}}$<br>Technique | Average Inter-<br>ference Power<br>( $I_{\text{Average}}$ ) in<br>dBm | Average % Im-<br>provement over<br>Conventional F-<br>OFDM | Average % Im-<br>provement over<br>Modified<br>F-OFDM | Average % Im-<br>provement over<br>Hann-Kaiser<br>FF-OFDM |
|-----------------------------------|-----------------------------------------------------------------------|------------------------------------------------------------|-------------------------------------------------------|-----------------------------------------------------------|
| Conventional F-OFDM               | 22.0                                                                  | 0                                                          | 0                                                     | 0                                                         |
| Modified F-OFDM                   | 19.7                                                                  | -12.1%                                                     | 0                                                     | 0                                                         |
| Hann-Kaiser FF-OFDM               | 25.4                                                                  | 16.8%                                                      | 27.1%                                                 | 0                                                         |
| Hann-Chebyshev FF-OFDM            | 27.5                                                                  | 26.7%                                                      | 38.3%                                                 | 8.2%                                                      |

**Table 3:** Filter Tail Interaction Control of Hann-Chebyshev FF-OFDM versus Hann-Kaiser FF-OFDM and Conventional F-OFDM at 120 kHz SCS.

| $I_{\text{Sen/Mit}}$ Technique | Average Inter-<br>ference Power<br>( $I_{\text{Average}}$ ) in<br>dBm | Average % Im-<br>provement over<br>Conventional F-<br>OFDM | Average % Im-<br>provement over<br>Hann-Kaiser<br>FF-OFDM |
|--------------------------------|-----------------------------------------------------------------------|------------------------------------------------------------|-----------------------------------------------------------|
| Conventional F-OFDM            | 21.6                                                                  | 0                                                          | 0                                                         |
| Hann-Kaiser FF-OFDM            | 25.8                                                                  | 21.7%                                                      | 0                                                         |
| Hann-Chebyshev FF-OFDM         | 28.8                                                                  | 32.9%                                                      | 11.9%                                                     |

**Table 4:** Delayed Spread Relegation of Hann-Kaiser induced FF-OFDM versus Hann-Chebyshev FF-OFDM, Modified F-OFDM, and Conventional F-OFDM at 60 kHz SCS.

| $I_{\text{Sen/Mit}}$<br>Technique | Average Inter-<br>ference Power<br>( $I_{\text{Average}}$ ) in<br>dBm | Average % Im-<br>provement over<br>Conventional F-<br>OFDM | Average % Im-<br>provement over<br>Modified<br>F-OFDM | Average % Im-<br>provement over<br>Hann-<br>Chebyshev<br>FF-OFDM |
|-----------------------------------|-----------------------------------------------------------------------|------------------------------------------------------------|-------------------------------------------------------|------------------------------------------------------------------|
| Conventional F-OFDM               | 27.0                                                                  | 0                                                          | 0                                                     | 0                                                                |
| Modified F-OFDM                   | 30.0                                                                  | 11.5%                                                      | 0                                                     | 0                                                                |
| Hann-Chebyshev FF-OFDM            | 37.2                                                                  | 37.1%                                                      | 24.1%                                                 | 0                                                                |
| Hann-Kaiser FF-OFDM               | 39.0                                                                  | 43.6%                                                      | 29.8%                                                 | 4.6%                                                             |

**Table 5:** Delayed Spread Relegation of Hann-Kaiser induced FF-OFDM versus Hann-Chebyshev FF-OFDM and Conventional F-OFDM at 120 kHz SCS.

| $I_{\text{Sen/Mit}}$ | Technique              | Average Inter-<br>ference Power<br>( $I_{\text{Average}}$ ) in<br>dBm | Average % Im-<br>provement over<br>Conventional F-<br>OFDM | Average %<br>Improvement<br>over Hann-<br>Chebyshev<br>FF-OFDM |
|----------------------|------------------------|-----------------------------------------------------------------------|------------------------------------------------------------|----------------------------------------------------------------|
|                      | Conventional F-OFDM    | 34.0                                                                  | 0                                                          | 0                                                              |
|                      | Hann-Chebyshev FF-OFDM | 44.5                                                                  | 31.7%                                                      | 0                                                              |
|                      | Hann-Kaiser FF-OFDM    | 45.3                                                                  | 33.2%                                                      | 1.4%                                                           |

**Table 6:** Frequency Offset Mitigation of Hann-Kaiser induced FF-OFDM versus Hann-Chebyshev FF-OFDM, Modified F-OFDM, and Conventional F-OFDM at 60 kHz SCS.

| $I_{\text{Sen/Mit}}$ | Technique              | Average Inter-<br>ference Power<br>( $I_{\text{Average}}$ ) in<br>dBm | Average % Im-<br>provement over<br>Conventional F-<br>OFDM | Average %<br>Improvement<br>over Modified<br>F-OFDM | Average %<br>Improvement<br>over Hann-<br>Chebyshev<br>FF-OFDM |
|----------------------|------------------------|-----------------------------------------------------------------------|------------------------------------------------------------|-----------------------------------------------------|----------------------------------------------------------------|
|                      | Conventional F-OFDM    | 31.6                                                                  | 0                                                          | 0                                                   | 0                                                              |
|                      | Modified F-OFDM        | 34.2                                                                  | 8.4%                                                       | 0                                                   | 0                                                              |
|                      | Hann-Chebyshev FF-OFDM | 45.2                                                                  | 43.4%                                                      | 32.3%                                               | 0                                                              |
|                      | Hann-Kaiser FF-OFDM    | 47.0                                                                  | 49.1%                                                      | 36.6%                                               | 4.0%                                                           |

**Table 7:** Frequency Offset Mitigation of Hann-Kaiser induced FF-OFDM versus Hann-Chebyshev FF-OFDM and Conventional F-OFDM at 120 kHz SCS.

| $I_{\text{Sen/Mit}}$ | Technique              | Average Inter-<br>ference Power<br>( $I_{\text{Average}}$ ) in<br>dBm | Average % Im-<br>provement over<br>Conventional F-<br>OFDM | Average %<br>Improvement<br>over Hann-<br>Chebyshev<br>FF-OFDM |
|----------------------|------------------------|-----------------------------------------------------------------------|------------------------------------------------------------|----------------------------------------------------------------|
|                      | Conventional F-OFDM    | 38.8                                                                  | 0                                                          | 0                                                              |
|                      | Hann-Chebyshev FF-OFDM | 50.6                                                                  | 30.6%                                                      | 0                                                              |
|                      | Hann-Kaiser FF-OFDM    | 52.0                                                                  | 34.2%                                                      | 2.6%                                                           |

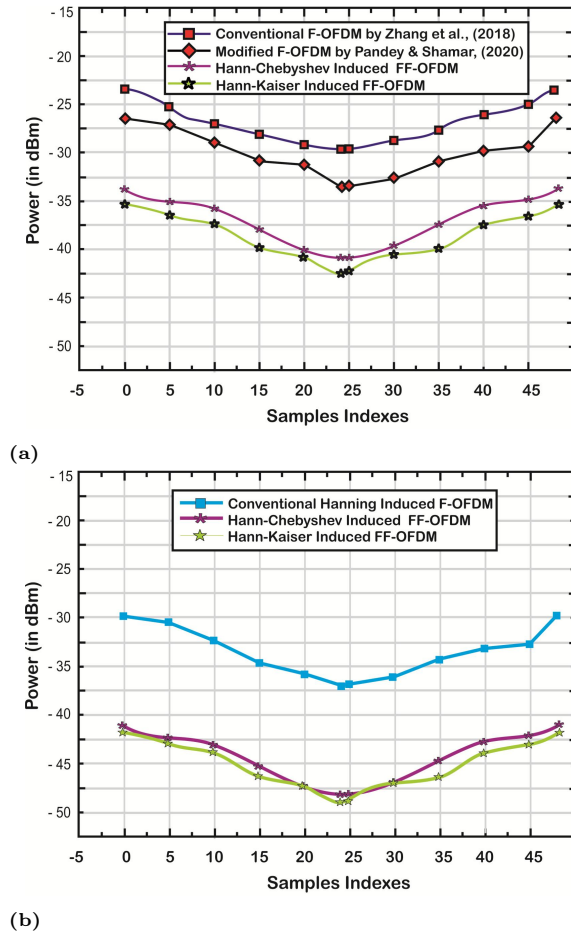
the modified F-OFDM by 27.1% and 38.3%, respectively.

When subjected to self-evaluation, the Hann-Chebyshev FF-OFDM is observed in both Figure (2a & 2b), summarized in Tables 2 and 3, and seen to outperform Hann-Kaiser by 8.2% and 11.9% in both 60 kHz and 120 kHz SCS, respectively. It is concluded that the Hann-Chebyshev FF-OFDM achieves effective asynchronous waveform requirement better than Hann-Kaiser FF-OFDM, modified F-OFDM, and conventional F-OFDM. This is because the Hann-Chebyshev FF-OFDM waveform combines all the advantages of Hanning Windowed and Chebyshev Windowed functions with wider bands (which helps in distant communication) and fewer sidelobes (which mitigates spectral leakage).

## 2) Effective Delay Spread Relegation

Similarly, the FF-OFDM agility in mitigating ISI is also compared with conventional and modified F-OFDM versions in order to prove its effectiveness in meeting the 5G NR requirement for orthogonality. Results in Figure 3a, summarized in Table 4, show the modified F-OFDM mitigating ISI better than the conventional F-OFDM model by about 11.5%, while the Hann-Chebyshev and Hann-Kaiser FF-OFDM versions are noted to be better than the conventional F-OFDM model by 37.1% and 43.6%, respectively. It is also interesting to note that the Hann-Chebyshev and Hann-Kaiser FF-OFDM outperform the modified F-OFDM version by 24.1% and 29.8%. These show how good the new scheme is in mitigating ISI caused by delay spread and/or frequency/time selectivity problems.

The results in Tables 4 and 5, deduced from Figure (3a & 3b), are subjected to self-evaluation between Hann-Chebyshev and Hann-Kaiser FF-OFDM at 60 kHz and 120 kHz SCS. This time, the reverse is the case as compared to ACI relegation, in which the Hann-Kaiser FF-OFDM is seen to mitigate ISI caused by symbols interfering with their predecessor(s) or successor(s) better than Hann-Chebyshev FF-OFDM by 4.6% and 1.4% in both cases. This is because

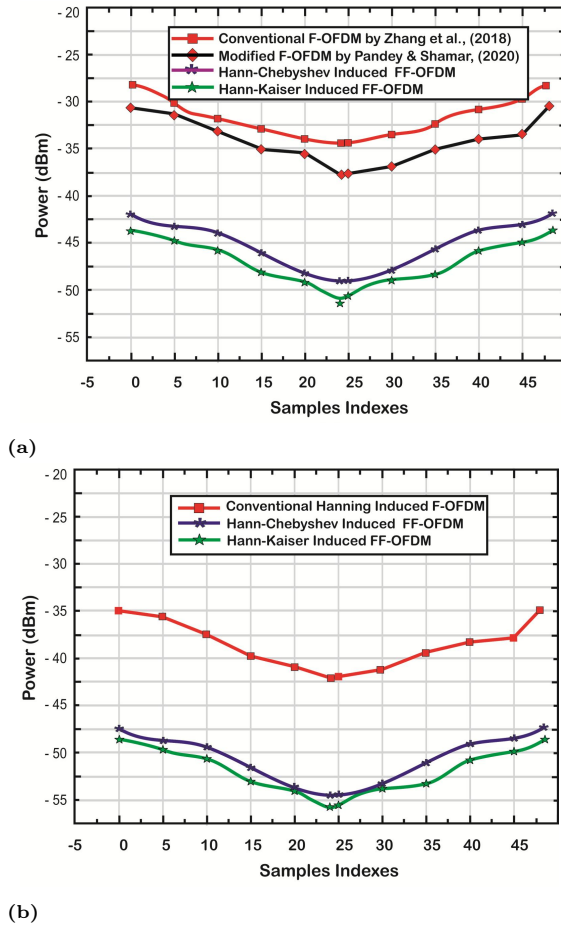


**Figure 3:** ISI of FF-OFDM versus ISI of F-OFDM: (a) at 60 kHz and (b) at 120 kHz SCS.

of the Hann-Kaiser FF-OFDM agility in obtaining much lower and fewer sidelobes in its waveform, which aids in mitigating spectral friction. This is also relative to the system's improved orthogonality.

## 3) Effective Frequency Offset Mitigation

The pictorial results of Figure (4a & 4b), interpreted in Table 6 show how sensitive and 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 [26] that senses and mitigates interference by 8.4% over the conventional F-OFDM model developed by [9]. From Fig-



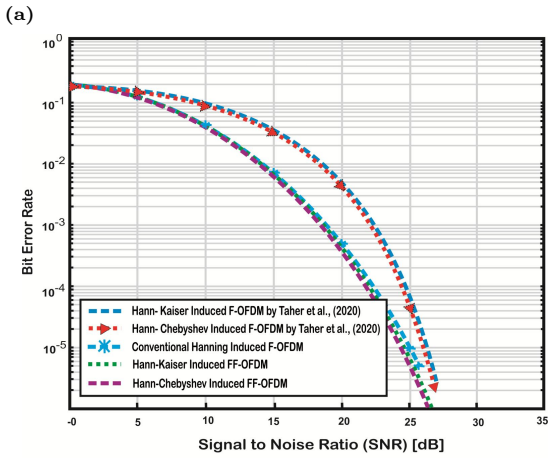
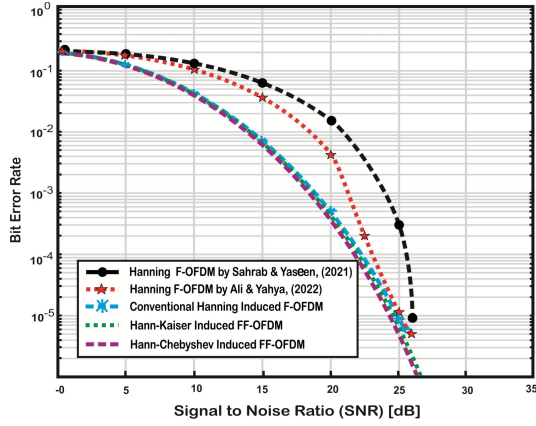
**Figure 4:** ICI of FF-OFDM versus ICI of F-OFDM: (a) at 60 kHz and (b) at 120 kHz SCS.

ure 4a, it is obvious that the newly developed Hann-Chebyshev induced FF-OFDM and Hann-Kaiser induced FF-OFDM outperform the conventional F-OFDM version by 43.4% and 49.1% and also outperform the modified F-OFDM version by 32.3% and 36.6%, respectively. This is because the feedback probe incorporated in the FF-OFDM system has backup information of the transmitter parameters, thereby modifying its receiver information to near 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 the F-OFDM system and other previous CA schemes and modulation techniques.

Tables 6 and 7 are the summary of results of the FF-OFDM systems' self-evaluation at 60 kHz and 120 kHz SCS. In Figure 4a, the Hann-Kaiser induced FF-OFDM outperforms Hann-Chebyshev FF-OFDM by 4% in terms of ICI mitigation at 60 kHz SCS. The same parameters were stepped up for 120 kHz SCS as illustrated in Figure 4b, it is also seen that Hann-Kaiser FF-OFDM performs better than Hann-Chebyshev FF-OFDM by 2.6%. It is concluded that Hann-Kaiser has a better ICI mitigation effect than Hann-Chebyshev FF-OFDM. This is relative to the system's effective orthogonality.

## 4.2. BER Improvement

The worthiness of this FF-OFDM multicarrier channel access technique is also subjected to a comparison of its BER with those of the conventional work of using a 256 QAM mapping scale [9] and modified models of [11, 27, 28]. This is to further ascertain how good the quality of the signal realized by the FF-OFDM scheme is. It is observed in the results of Figure 5a that both conventional F-OFDM and its modified versions obtained BER within  $10^{-5}$  threshold at 27 dB SNR 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 a lower BER within  $10^{-6}$  scale at 27 dB, which outperforms those achieved by the conventional F-OFDM and its modified versions. Figure 5b 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 [27]. Simulation results presented show Hann-Kaiser and Hann-Chebyshev F-OFDM obtained a BER improvement better than that of conventional F-OFDM but still fall within the confines  $10^{-5}$ . On the other hand, the Hann-Kaiser and Hann-Chebyshev FF-OFDM prove to outperform the conventional F-OFDM and modified F-OFDM with better BER by achieving improvement within  $10^{-6}$  BER threshold. The quality of the signal generated by FF-OFDM is further subjected to self-evaluation, where simulation results show that the Hann-Chebyshev FF-OFDM

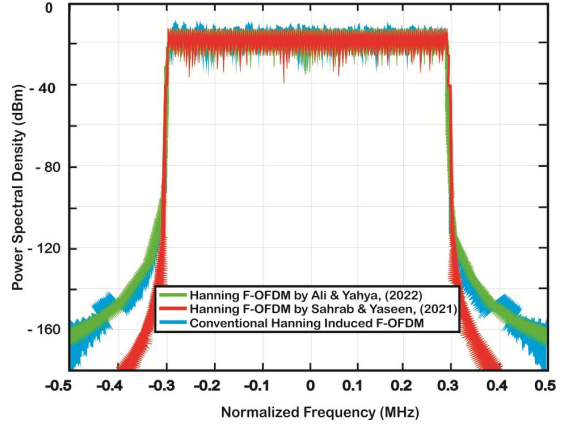


**Figure 5:** BER at 60 kHz SCS of: (a) FF-OFDM versus Traditional Hanning-enable F-OFDM and (b) FF-OFDM versus F-OFDM using Hanning, Hann-kaiser, Hann-Chebyshev Filters.

produces a better BER 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.

### 4.3. Power Spectral Density Efficiency

To further substantiate this work, the spectral power contents of this work, successively obtained, are validated with those achieved in the works of [27], [28], and [11]. The imagery in Figures 6 and 7 clearly proves beyond reasonable

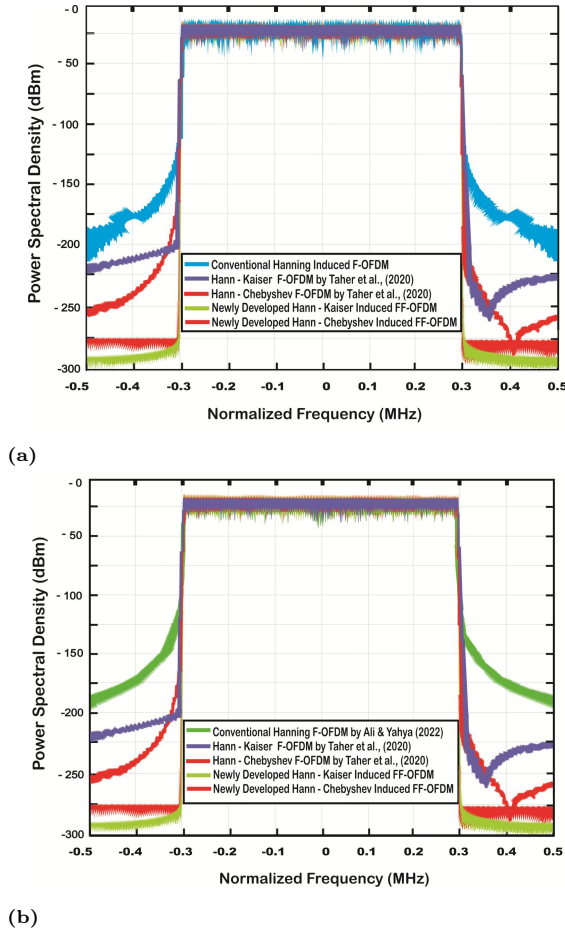


**Figure 6:** Spectral Efficiency of Conventional F-OFDM versus its Variants.

doubt that the signal waveform obtained by the newly developed FF-OFDM scheme achieved better spectral efficiency than those achieved by recent research works in literature.

Figure 6 is the presentation of spectral power content of conventional F-OFDM step-up at 60 kHz SCS and replicated by this work against its modified versions achieved by [11] and [28]. Simulation results show that the conventional model achieved interference/noise control from  $-38$  dBm to  $-160$  dBm, while the modified version by [11] achieved interference/noise control within  $-50$  dBm to  $-160$  dBm. The F-OFDM version developed by [28] obtains better spectral power content with interference/noise control within  $-50$  dBm to  $-180$  dBm. This is because of the systematic modification carried out on the Hanning-induced FIR filter targeting to achieve advanced versions of the 5G FR.

The spectral efficiency of the newly developed FF-OFDM technique is examined at 120 kHz SCS in comparison with the conventional F-OFDM model and modified F-OFDM version of the work of [26]. Results obtained in Figure 7 presents that the conventional F-OFDM obtained spectral control from  $-45$  dBm to  $-180$  dBm, in which the Hann-Chebyshev F-OFDM and Hann-Kaiser F-OFDM developed by [27] achieved better spectral content of  $-120$  dBm to  $-230$  dBm and  $-120$  dBm to  $-270$  dBm, respectively. Lastly, the Hann-Chebyshev induced FF-OFDM and Hann-Kaiser



**Figure 7:** PSD: (a) Desired FF-OFDM versus Undesired F-OFDM Waveforms and (b) Desired FF-OFDM versus Desired F-OFDM Waveforms.

induced FF-OFDM spectral efficiencies developed by this work superseded all cases presented with spectral control from  $-240$  dBm to  $-280$  dBm and  $-240$  dBm to  $-190$  dBm, respectively, where the Hann-Kaiser gave the best spectral content. This is because of the non-unity casual module developed and built in the FF-OFDM system.

It is evident that the results in Figure 7 also present the discrepancy between Nyquist sampling theory and the 5G NR sampling standard recommended by 3GPP. The simulation results show the 3GPP sampling having an edge in spectral content over the Nyquist sampling requirement.

## 5. Research Significant Contributions

In conclusion, the Hann-Kaiser induced FF-OFDM demonstrates superior orthogonality compared to the Hann-Chebyshev induced FF-OFDM, while the Hann-Chebyshev variant achieves better asynchronicity than Hann-Kaiser FF-OFDM. These results indicate that each filter combination offers complementary advantages: the Hann-Kaiser waveform produces steep, narrow-band signals suitable for 5G NR deployments requiring high orthogonality, whereas the Hann-Chebyshev waveform generates wide-band signals optimized for long-distance 5G NR communications.

The proposed FF-OFDM scheme has also proven to be highly scalable, effectively supporting a range of 5G NR numerologies beyond the limits of conventional F-OFDM and its modified variants. This scalability enables deployment across both FR1 and FR2 bands with improved interference mitigation, orthogonality, and spectral efficiency.

However, the enhanced performance comes at the cost of increased power consumption due to the paired-filter architecture employed in the waveform design. This limitation highlights the need for further research aimed at improving system energy efficiency while maintaining high spectral and interference performance. Such efforts would fully align with the 3GPP standards for next-generation wireless systems and contribute to the development of more sustainable and efficient 5G and post-5G networks.

## Declarations

### Competing interests

The authors declare they have no competing interests.

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## About Authors

**Zakka Augustine** received his B.Eng. degree in Electrical and Electronics Engineering from Abubakar Tafawa Balewa University (ATBU), Bauchi, Nigeria in 2011. He obtained his M.Sc. and Ph.D. degrees in Telecommunications Engineering from Ahmadu Bello University (ABU), Zaria, Nigeria in 2019 and 2024, respectively. He is currently affiliated with the Federal University of Applied Sciences Kachia (FUASK), Nigeria, as an academic lecturer. He also works as a remote research consultant with the Department of Informatics and Quantitative Methods, Faculty of Informatics and Management, University of Hradec Kralove, Hradec Kralove, Czech Republic. He has authored many scientific publications, including SICE and ESCI articles of WEB-of-SCIENCE data base, Conference Proceedings, Book Chapters in both National and International venues. He is a member of renowned professional bodies, including Nigerian Institute of Electrical and Electronics Engineers (NIEEE), Council for Regulatory of Engineers in Nigeria (COREN), International Association of Electrical, Electronics, & Energy Engineers (IAEEE), and International Association of Engineers (IAENG), among others. His research interest includes Wireless Mobile Communications, Satellite Communications, Informatics, IoT, AI, and Optical Communications. He could be reached via email: [zax.austenc@yahoo.com](mailto:zax.austenc@yahoo.com).

**Abdoulle Momodou Sunkary Tekanyi (PhD)** obtained his B. Eng. (Hons) degree in Electrical Engineering from University of Sierra-Leone (USL), Freetown in 1990. His M.Sc. degree in Computer Networks from Middlesex University (MDX), London in 2001, and his PhD degree in Electrical Engineering from Ahmadu Bello University (ABU), Zaria in 2014. He is a Professor of Telecommunications Engineering, Ahmadu Bello University, Zaria. He has to his credit many recognized National and International publications of peer-reviewed journals and conference proceedings. He is Registered Fellow of Institute of Policy Management Development (FIPMD), Member of the Council for the Regulation of Engineering in

Nigeria (COREN), Member of Nigerian Society of Engineers (MNSE), Member of International Association of Engineers (MIAEng), Member of the International Research Development Institute (MIRDI). His research interest is in Telecommunications Engineering, with emphasis on finding out problems associated with WCAN, wireless, and heterogeneous networks and their resolutions, particularly, finding out factors affecting efficient bandwidth utilization, channel congestion, traffic delivery delay, and traffic loss in networks. Professor Tekanyi could be reached via email: [amtekanyi@abu.edu.ng](mailto:amtekanyi@abu.edu.ng).

**Aliyu Danjuma Usman** is currently a Professor of Telecommunications & Electronics Engineering from Ahmadu Bello University (ABU), Zaria, Nigeria. Has over 25 year's cognate working experience in tertiary educational institutions. He has published many peer reviewed National and International Journals/Conferences and authored many books and book Chapters. A recipient of national Patent and many research grants locally and internationally. He is a visiting scholar and external examiner to many institutions, including examiner to Universite Federale Toulouse France, Pan African University of Science and Technology, Kenya, University Putra Malaysia, among others. He is a resource person and serve in so many national and international committees, among which are: Nigerian Communication Commission (NCC), National University Commission (NUC), National Board for Technical Education (NBTE), Nigerian Society of Engineers (NSE), Council for the Regulations of Engineering in Nigeria (COREN), Nigerian Institute of Science Laboratory Technology (NISLT) and Technical and Vocational Education Training (TVET) centers, among others. His other research interest include; Teletraffic Engineering, Network access technologies, Fiber to the last mile, IoT, and 5G and beyond. He could be reached at email: [aliyuuusman1@gmail.com](mailto:aliyuuusman1@gmail.com).

**Kabir Ahmad Abubilal** was born in Zaria City, Nigeria. He received B.Eng.; M.Sc.; and PhD in Electrical Engineering from Ahmadu Bello University (ABU), Zaria, Nigeria. He has published many Journal Articles, Con-

ference Papers, Books and Book Chapters in National and international Platforms. He is currently a Professor of Electronics Engineering in Ahmadu Bello University, Zaria, Nigeria. His research interest is in Electronics and Mechatronics. He can be contacted at email: [kabirahmed@abu.edu.ng](mailto:kabirahmed@abu.edu.ng).

**Frederick Duniya Basaky** was born in Sako, Kaduna State in Nigeria. He received his Master's in Information Technology from National Open University Nigeria (NOUN) in 2000. He is currently pursuing his second PhD in Computer Science (Artificial intelligence) at Ahmadu Bello University, Zaria, Nigeria. He is presently working with the Federal University Lokoja, Nigeria. His fields of interest include Cyber Security, I.T Engineering, and Computer Science. He could be contacted using the email: [frederick.basaky@fulokoja.edu.ng](mailto:frederick.basaky@fulokoja.edu.ng).

**Dogo Douglas Saviour** got his bachelor degree in Physics from University of Jos, Nigeria in 2012. He also obtained an M.Sc in Mechatronic Engineering in Near East University, Cyprus between 2016-2018. He is presently running a Ph.D program in Nuclear and Radiation Physics in Nigerian Defense Academy. He is currently a lecturer with Federal College of Education (Technical) Omoku, Rivers State, Nigeria. He has been involved in few researches in area of Elemental Analysis using Neutron Activation Analysis (NAA). He can be reached via email: [dogodouglas83@gmail.com](mailto:dogodouglas83@gmail.com).