Development of a Novel Feedback Filtered Orthogonal Frequency Division Multiplexing Scheme for 5G Network and Beyond

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***Abstract*— Previous generations of wireless technologies from 0G through 4G used synchronous data transmission for multiple users, which made it difficult to accommodate recent wireless devices and increasing user demands. The Fifth Generation (5G) network standardized by the year 2020 was designed to harmonize the use of asynchronous transmission. This is to accommodate not only new devices and multiple users, but also different type of users. In this regard, so many mitigation schemes were developed to meet the 5G and 5G-A expectations but suffered one limitation or the other, such as Inter Symbol Interference (ISI), Inter Channel Interference (ICI), Peak to Average Power Ratio (PAPR), and more. Each limitation had serious damaging effect on the performance of the 5G network because the techniques were not appropriate. Hence, this paper, presented a novel Feedback Filtered Orthogonal Frequency Division Multiplexing (FF-OFDM) scheme with performance indices of Bit Error Rate (BER) and Signal to Noise Ratio (SNR) in an Additive White Gaussian Noise (AWGN) domain that provide solutions to these limitations. Simulation results of FF-OFDM showed a 54.4% reduction in the BER and a 17.0% improvement in the SNR, when compared with those of Cyclic Prefix Orthogonal Frequency Division Multiplexing (CP-OFDM) deployed in Long Time Evolution-Advanced (LTE-A) network. FF-OFDM signal waveform which is synonymous to that of Electromagnetic Wave (EMW) because of its orthogonal nature, is systematically designed to mitigate Inter Symbol Interference (ISI), Inter Channel Interference (ICI), and boost processing speed to achieve the 1 ms round trip latency expectation of 5G network and beyond.**

***Index Terms*—5G; BER; FF-OFDM; SNR.**

I. INTRODUCTION

The quest for wireless services and innovations has increased since the discovery of the EMW for transmitting information through radio wave resources bandwidth of about 3 kHz - 300 GHz, [1]. It is now evident that there are millions of radio signals existing in every radio wave and EMW induced domain. The evolution of the radio wave began in the early years of 1800, where many scientists participated in the invention of radio technology [2]. Experimental works on the connection of electrical and magnetic waves began around 1820 with the work of Hans Christion Orsted, which was improved by other scientists in the subsequent years. One of those scientists was James Clerk Maxwell, who published a Treatise on electricity and magnetism in 1873 that stimulate many scientists to start experimental works on wireless communications [2]. Maxwell's work which was proven correct using mathematical analogy to generate and transmit electrical and mechanical signals orthogonally placed on each other revolutionized the world of telecommunications to date.

The EMW when induced in the radio wave domain serves as a carrier to all kinds of signals for both short and long distance communication. This success brought about the breakthrough in the field of mobile communications, space exploration, military operations, aviation, seismic, medical, sonar, and many more [3]. The EMW, as a carrier is termed as a perfect signal because of its immunity to the internal signal friction caused by its orthogonal nature and signal difference, but the induced message signals do not have such immunity due to its linearity that results in the loss of signal strength due to friction caused by leakage current [4]. The need to proffer solution to this loss of signal strength leads to the development of so many mitigation techniques, in which one of them is the Orthogonal Frequency Division Multiplexing (OFDM). Although OFDM is one of the most widely deployed technologies in 4G and is considered as the one of the recent wireless communications systems, it is characterized by strings of limitations, which leads to transmission inefficiency [5]. In OFDM, the radio wave resources is not properly utilized due to side lobes effect that causes the loss of signal strength. These limitation leads to the development of special cases of multicarrier transmission such as CP-OFDM, Filtered-OFDM [6] and a novel FF-OFDM scheme, proposed in this work. The FF-OFDM signal waveform resembles that of EMW. This makes it possible for the message signal to be transduced in an EMW radio domain with minimal loss of both energy and information.

II. SYSTEM MODELING

In EMW radio environment, binary bits are collected in a digital system to be sampled, quantized, and encoded to obtain convolutional codes for channel coding scheme. Subsequently, the diversity gain is obtained by interleaving coded date bit stream using 16QAM, 32QAM, 64QAM and so on, as well as mapped with the relative bit in an eye-to-sight pattern. In this reference, the bits are serial. At this time, the individual carrier signals are mapped with the message signals to obtain the modulated data stream. The application of a serial to parallel conversion followed by the Inverse Fast Fourier Transform (IFFT) operator are performed on each of this parallel complex data to convert it from frequency domain to time domain. The number of required subcarriers transmission is obtained by grouping the transformed data again. At this point, it is observed that the orthogonal generated signal creates some frictions as they wobble on each other due the large side loops. To mitigate this effect, a Cyclic Prefix (CP) is introduced on each block of data according to the system specifications and then multiplex with the OFDM to generate a CP-OFDM signal. However, the insertion of the CP tends to cause ripples on the main lobe, which again affects the Spectrum Efficiency (SE). A Finite Impulse Response (FIR) filter is modulated with the CP-OFDM to suppress the side lobes effect and smoothen the main lobe to produce the required asynchronous F-OFDM signal. A Digital/Analog Converter (DAC) is used to transform the digital data into time domain analog data. Radio Frequency (RF) modulation is performed and the signal is up-converted to the required transmission frequency. When transmitted by the antenna, the F-OFDM signals go through all the impairments of the wireless channel. The analog signal is down-converted at the receiver and reconverted to a digital signal using an Analog/Digital Converter (ADC). The F-OFDM received signal is de-multiplex to remove the CP. The removal of the CP causes a little ISI and ICI droplets due to the length of the CP. To correct the anomalies of side lobes friction, ISI, and ICI, a feedback system is introduced at the output of the de-multiplexer to obtain a novel FF-OFDM waveform. The Fast Fourier transform (FFT) operator is used to demodulate the FF-OFDM signal into the frequency domain. Finally, demodulated pilots are performed using channel estimation to obtain the complex received data, which is de-mapped according to the transmission constellation diagram. To recover the originally transmitted bit stream, the de-interleaving and Forward Error Correction (FEC) decoding or Channel Coding (CC) are used.

III. CONVENTIONAL OFDM MODEL

OFDM is a multicarrier modulation scheme that splits a high data rate modulating stream into slowly modulated narrowband, close-spaced subcarriers and orthogonally placed as illustrated in Figure 1. OFDM has been deployed for many LTE/LTE-A standards like Digital Video Broadcast (DVB), Wi-Fi, and Digital Radio Modulation (DRM) [7][8]. The main advantages of the OFDM are its immunity to selective fading caused by its orthogonal waveform [4].

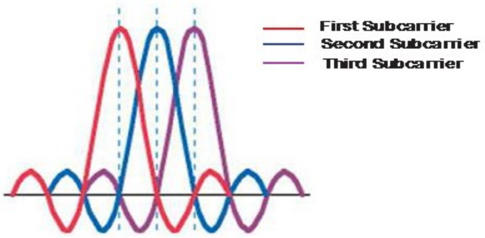

Figure 1: OFDM Subcarrier Signal [7]

OFDM is a tool that can deal with the delay spread of broadband wireless channels because FFT is used to effectively simplify the complications in the current 4G wireless communication systems and standards [9]. OFDM split the data symbol stream into several lower rate streams and are transmitted on different subcarriers. Due to splitting data, it increases the symbol duration by the number of orthogonally aliasing subcarriers. This also causes multipath echoes to affect only a small portion of the neighboring symbols. Using OFDM method, it reduces the need for complex equalizers and mitigates the dispersion effect of multipath channels encountered with high data rates. Other merits of OFDM include scalability, high spectral efficiency, robustness against Narrowband Interference (NBI), signal waveform shaping, as shown in Figure 2, and the ease of implementation using FFT [4].

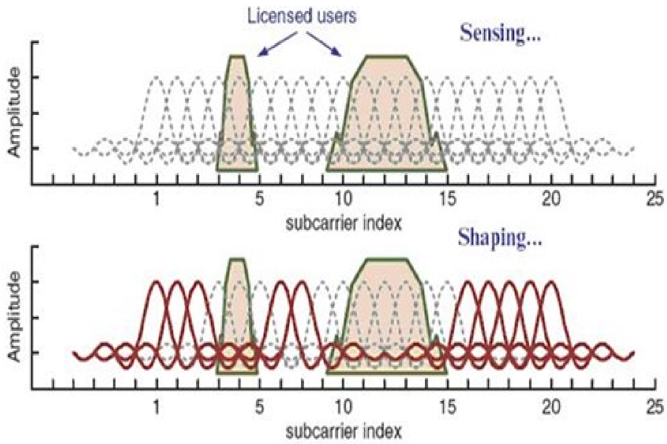

Figure 2: Signal Waveform Shaping using OFDM [10].

Since the OFDM signal is time-limited and the Out of Band (OoB) leakage or Side Lobes (SL) is high, it can only be deployed in LTE/LTE-A. This is because in a typical 5G network, users are arranged in an asynchronized nature [6][11]. In an attempt to overcome these challenges, a guard bands or Guard Intervals (GIs) are placed in between the signals of two adjacent symbols in the frequency domain, in addition to CPs in the time domain. This arrangement proved to be better but affects the Spectral Efficiency (SE) of OFDM. For instance, in the LTE fixed 256 subcarrier system, it has a bandwidth wasted of about 11.2% due to the placement of CPs [7]. The remaining ISI, PAPR, and ICI limitations are mitigated by multiplexed CP-OFDM symbol. The 5G network supports not only several number of users but also dissimilar types of users with high demands and different expectations [6]. For example, asynchronous transmission to accommodate different kinds of users in massive Machine Type Communication (mMTC) and other expectations cannot be satisfied by conventional OFDM and CP-OFDM [6][11]. Therefore, a novel modulation technique with much lower OoB leakage, which invariably mitigates the effects ISI, PAPR, and ICI is needed. This new technique is also expected to consider backward compatibility with conventional OFDM systems and lower generation of networks [12].

IV. OFDM MODELING

For $0 \leq n \leq N-1$, the serial samples of an OFDM are generated as follows [13].

$$z(n) = z(0)\ z(1)z(2) \ldots \ldots \ldots z(N-1), \tag{1}$$

For the same range of $0 \leq n \leq N-1$, these serial samples are converted into parallel samples and IFFT is applied to each sample to obtain its transform as:

$$Z(n) = Z(0)\ Z(1)\ Z(2) \ldots \ldots \ldots Z(N-1) \tag{2}$$

For $0 \leq t \geq T_q$, the composite OFDM mapped signal is expressed as:

$$Y(t) = \sum_{k=0}^{N-1} Z(t) K e^{j2\pi k \Delta f t} \quad (3)$$

where:

Y(t) denotes the OFDM signal.
Z(t) represents the IFFT signal.
Δf is the gap between carriers.
t stands for the symbols time.
K depicts the signal coefficient.
N corresponds to the number of subcarriers.

According to [8], the orthogonal signal is ascertained if Tq Δf = 1 and also equation (4) ensures that the orthogonal condition holds and the transmitted symbols are recovered without distortion:

$$Z(t) = \frac{k}{Tq} \int_{0}^{Tq} Y(t) e^{-j2\pi k \Delta f t} . dt \quad (4)$$

where, Tq is the symbols timing limit.

To mitigate the friction caused by samples aliasing, CPs are added between the symbols' samples on an OFDM system to mitigate the ISI and ICI effects [14]. Therefore, CP-OFDM modulated signal obtained to be transmitted is defined by [5] as:

$$\sum_{k=0}^{N-1} Z(t) K e^{j2\pi k \Delta f t} + cp \quad (5)$$

Consequently, the introduced CP mitigates the high side lobes friction, ISI, and ICI. However, it causes ripples on the main lobe and bandwidth wastage, which in turn affects the CP-OFDM signal strength and makes it difficult to attain the required SE for 5G expectations [15].

V. Feedback Filtered Orthogonal Frequency Division Multiplexing Scheme

FF-OFDM scheme is a promising waveform generated for 5G and beyond to enable a more efficient network slicing, spectrum efficient network, and multi-service system. The 5G and next generational networks are to offer better asynchronous channel characteristics slicing [16]. FF-OFDM is expected to prevail over these challenges CP-OFDM to fulfill the expectation of the 5G and upcoming generations of cellular network [17][18].

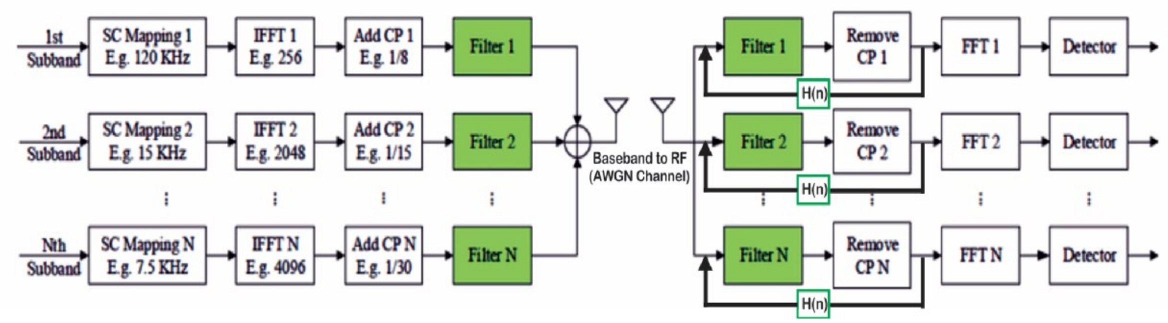

Figure 3: Block Diagram of FF-OFDM Transceiver System

Figure 3 denotes the block diagram of a modified F-OFDM transceiver, which is designed with a filter at the peak of transmission and at the peat of reception with a feedback system. The functions of the filters are to suppress the OoB, narrow the guard intervals between subcarriers, and remove ripples on the main lobes caused by CP insertion [19]. The system bandwidth is segmented into individual sub-bands to a specific length and each sub-band is filtered separately [17]. The feedback system is to set a threshold to mitigate ISI and ICI caused by the removal of the CP. The FF-OFDM scheme gives all the merits displayed by OFDM, CP-OFDM, and F-OFDM such as simple channel equalization, flexible frequency multiplexing, and easy combination with multi antenna transmission [10]. FF-OFDM also offers the following six benefits [10][12].

1. Efficient utilization of the spectrum.
2. Reduction of guard interval consumption to the minimum level.
3. Possibility to integrate other waveforms, such as Filter Bank Multicarrier (FBMC), Generalized Frequency Division Multiplexing (GFDM), Universal Filtered Multicarrier (UFMC), and many more.
4. Use of better technique such as Multiple Input Multiple Output (MIMO).
5. Backward and forward compatibility with schemes used in other generations of networks.
6. Support asynchronous transmission.
7. Waveform is shaped by turning off some subcarriers where primary users exist.

VI. FF-OFDM Signal Waveform Generation

The discrete time representation of OFDM symbol samples is multiplexed with a CP to give a CP-OFDM [7] as illustrated in equation (5). The mathematically analogy of an FF-OFDM sample is as illustrated in equations (6) through (9). Equation (5) is first of all modulated with an Finite Impulse Response (FIR) filter to generate an Filtered OFDM transmitted signal using convolution matrix and is formulated by [15][16] as follows:

$$Y_{\varphi}(n) = Y_{cp}(n) * F_{\varphi}(n) \quad (6)$$

where:

$Y_{cp}(n)$ is the CP-OFDM discrete signal
$F_{\varphi}(n)$ represents its FIR filter

Y_φ(n) denotes conventional F-OFDM transmitted signal.

The spectrum shaping filter, F_φ(n) is appropriately designed to suppress only the OoB emissions [15][16]. Its folded version $F_\varphi^*(-n)$ is to narrow the GI, remove CP, and invariably erase the ripples on the main lobes. It means that it should have a central frequency in the middle of the assigned sub-carriers and the bandpass of the filter should include all the sub-carriers of the OFDM symbol.

At the receiver side, the signal received has the following expression [13][14]:

$$\sum_{n=0}^{M} Y_\varphi(\mathrm{n}) * h_\varphi(n) + w_\varphi(n) \tag{7}$$

where:

M is the number of received signals in time domain.
$h_\varphi(n)$ represents the channel gain.
$w_\varphi(n)$ depicts the channel noise.

The impulse response, r(t) is passed through the folded version of the filter, $F_\varphi^*(-n)$, which is matched with each transmitter filter, F_φ as follows:

$$r_\varphi(\mathrm{n}) = r(n) * F_\varphi^*(-n) \tag{8}$$

To increase the signal strength, the length of the filter is kept smaller than that of the CP, thereby narrowing the length of the GI.

To totally mitigate ISI and ICI caused by the CP removal and achieve proper filtering, the signal at the output of the de-multiplexer is fed-back to the filter, $F_\varphi^*(-n)$ using closed lobe transfer function process of equation (9) and it is demonstrated in Figure 4.

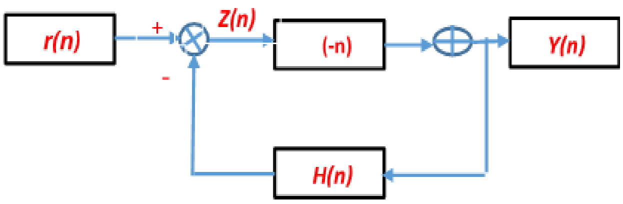

Figure 4: FF-OFDM Receiver Signal Model

This process is repeated until the Feedback Filter (FF) accentuates the original signal from ISI, ICI, smoothen the main lobe and carefully narrowing GI to increase signal strength and invariably improve SE.

Finally, the FF-OFDM received signal waveform is generated as:

$$Y(n) = \frac{F_\varphi^*(-n) r(n)}{1 - F_\varphi^*(-n) H(n)} \tag{9}$$

where, *Y(n)* is the signal accentuated from ISI, ICI, and $H(n)$ is the feedback filter coded with a minimum threshold.

VII. Results and Discussion

This section discusses the parameters used for the simulation of an FF-OFDM signal waveform using MATLAP R2018a, while Figure 5 depicts a diagrammatical presentation of the step-by-step procedure for generating an FF-OFDM waveform. The Rayleigh distribution was used because of its properties to model multipath fading with no Line of Sight (LoS) path [20][21]. The filter type was FIR. The Hanning window type was chosen over other FIR windows because of its fewer side lobes magnitude response. Experimental bandwidth, W was 10 GHz, modulation was 64 Amplitude Pulse Shift Keying (APSK), CP length was (1/4)*4096, filter order was 256, number of subcarriers was 200, and environmental noise level at -75dB worse scenario in AWGN domain.

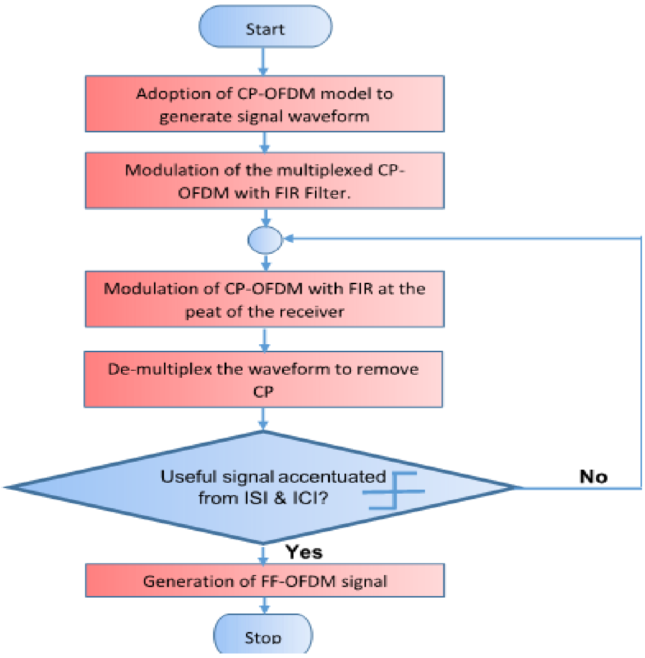

Figure 5: FF-OFDM Signal Waveform Generation Flowchart

A performance measure to evaluate SE using FF-OFDM scheme is the BER given as: received SNR over an AWGN channel or the ratio of error in the received signal to the total transmitted signal [13] as:

$$BER = \frac{Error\ in\ received\ signal}{Total\ transmitted\ signal} \tag{10}$$

where, error is the noise in the received signal, while the SNR which is the difference between the received signal and the background signal floor, is an estimation technique based on the maximum likelihood of the signal amplitude when observed against the AWGS, and is given [22] as follows:

$$Q = 20 \log \left(\frac{A_m}{\sigma_n(\sqrt{2})} \right) \tag{11}$$

Q is the SNR achieved value.
A_m is is the signal magnitude.
σ_n is the noise variance.

The results of this research were computed in percentage using the values from the Received Signal strength Indicator (RSSI). The percentage improvement of FF-OFDM scheme over CP-OFDM in both performance metrics was obtained as follows:

$$\text{Percentage Improvement} = \frac{\Sigma New\ Scheme - \Sigma Old\ Scheme}{\Sigma old\ Scheme} \times 100\% \quad (12)$$

Equations (5) through (9) were used to generate the FF-OFDM signal waveform. Simulations were carried out using parameters stated and MATLAP 2018a to obtain the corresponding results in Figures 6 and 7. With reference to 10^{-1}dB, the performance of FF-OFDM waveform was examined and the results were compared with those of CP-OFDM. A validation of the error probability was also conducted, which was presented by the BER of FF-OFDM and BER of CP-OFDM with reference to the various modulation levels from 4APSK to 256APSK modulation. The FF-OFDM presented a net gain in all cases simulated in this research when compared to the CP-OFDM system. It was evident that FF-OFDM using 64APSK with different number of subcarriers had better BER over CP-OFDM with approximately 4 dB at a BER of 10^{-1} dB. A percentage reduction of 54.4% BER of FF-OFDM over CP-OFDM was obtained, which was also applied to a normalized frequency domain in Figure 7, to obtain the FF-OFDM output signal waveform. It was deduced that the decrease of Power Spectral Density (PSD) in the OoB region due to the filtering and feedback processes used in FF-OFDM simply mitigated sub-bands friction that cause ISI and ICI as illustrated in Figure 7. The mitigation of ISI and ICI induced by side lobes friction was clear indications that an FF-OFDM waveform is a good candidate for deployment in 5G networks and beyond.

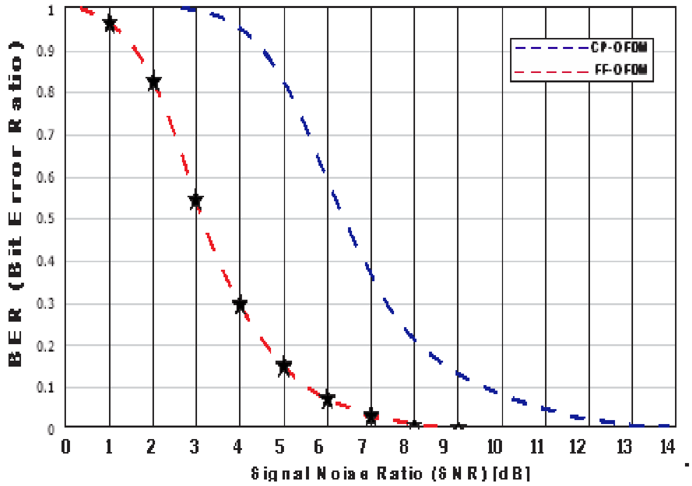

Figure 6: Plot BER versus SNR

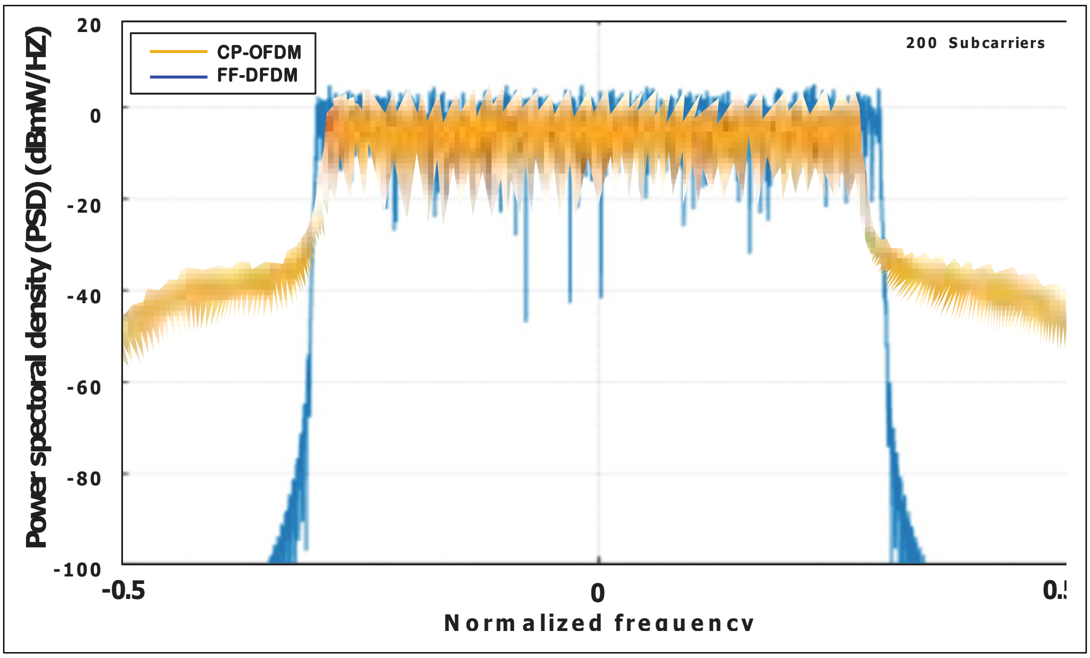

Figure 7: Comparison of Generated FF-OFDM and CP-OFDM Waveforms

The percentage reduction of FF-OFDM over CP-OFDM in terms of BER was computed using equation (12) and the following result in Table 1 was obtained.

Table 1
Percentage reduction of FF-OFDM over CP-OFDM in terms of BER

Scheme	Average BER (dB)	BER Reduction
CP-OFDM	7.44	54.4%
FF-OFDM	3.39	

Furthermore, the SNR using FF-OFDM novel scheme was observed to increase higher than that of CP-OFDM scheme with every reduction in BER. The Percentage Improvement of FF-OFDM over CP-OFDM in terms of SNR was also computed using equation (12) and the following result was achieved as shown in Table (2).

Table 2
Percentage Improvement of FF-OFDM over CP-OFDM in terms of SNR

Scheme	Average SNR (dB)	SNR Improvement
CP-OFDM	41.0	17.0%
FF-OFDM	48.0	

VIII. Conclusion

In this paper, a novel FF-OFDM technique was developed and succeeded in mitigating the limitations in traditional OFDM and other advance Orthogonal Multiple Access (OMA) techniques like W-OFDM, CP-OFDM, and F-OFDM. The developed technique was able to produce a signal waveform that mitigated the effect of side lobes friction, leakage current, ICI, ISI, and many more related signal distortion problems. The developed FF-OFDM novel waveform was compared and validated with that generated by CP-OFDM because both schemes aimed at eliminating the effects of ISI, ICI caused by adjacently placed signals lobes, in which the FF-OFDM waveform outperformed that of CP-OFDM to satisfy 5G asynchronous transmission requirement in 5G and beyond. The FF-OFDM signal waveform presented here in this work is really an enabler to 5G and 5G - Advanced technologies because of its promising and prospective flexibility in meeting the expectations of recent and future wireless technologies and devices.

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