Experimental Testbed for Dynamic Spectrum Access and Sensing of 5G GFDM Waveforms

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Abstract—Generalized frequency division multiplexing (GFDM) is a new candidate waveform for 5G applications. With flexible pulse shaping filtering and tail-biting cyclic prefix, GFDM has lower out of band leakage and hence is more suitable as an opportunistic cognitive radio waveform. Improved adjacent channel leakage ratio (ACLR) of GFDM makes the coexistence of secondary signals easier, with lower adjacent channel interference to legacy users. This paper details the experimental validation of the coexistence study of this 5G waveform in an LTE system. The paper also highlights the improved sensing performance of GFDM-CR waveform compared to traditional OFDM. OFDM with implicit rectangular pulse shaping has higher out of band leakage and increases the probability of false alarm; while sharper GFDM waveform demonstrates substantial spectral efficiency and produces lesser number of false alarms.

Keywords: 5G Waveform; Coexistence; Cognitive Radio; Experimental Testbed; LTE waveform.

I. INTRODUCTION

Radio spectrum is getting very scarce, and increasing popularity of wireless devices is making the demand for it even higher. To cope with this huge demand for spectrum, worldwide regulatory agencies (like FCC in the USA and Ofcom in the UK) have recently opened up licensed spectrum for unlicensed access [1], [2]. Unlicensed access in licensed bands should not create interference to incumbent users, and hence new PHY designs and waveforms are being researched which can fill in the TV white spaces (TVWS) in an opportunistic manner.

The multiband Generalized Frequency Division Multiplexing (GFDM) [3], [4] is a relatively new idea for designing a multicarrier PHY. GFDM is block based multicarrier transmission scheme derived from filter bank approach, where the transmit data of each block is distributed in time and frequency and each subcarrier is pulse-shaped with an adjustable pulse shaping filter. GFDM is well suited for Cognitive Radio (CR), as the choice of pulse shaping filters makes the out-of-band leakage extremely small. Compared to OFDM, with implicit rectangular pulse shaping, GFDM with a choice of transmit pulse shaping causes lesser interference to the adjacent incumbent frequency bands. This technique improves the Adjacent Channel Leakage Ratio (ACLR) of the GFDM system by around 20 dB. Compared to Filter Bank Multi Carrier (FBMC), which has no cyclic prefix, GFDM with its tailbiting cyclic prefix [5], can address the synchronization issues that was problematic in FBMC [6], [7].

CR technology has been subject of research efforts for several years. Some of the existing work addresses CR-enabled LTE systems, such as LTE in TVWS, but so far mainly a theoretical study [8], [9] with only few experimental work, has been done. This paper extends the work done in [10], where an experimental framework for CR access in an LTE testbed was studied. This present paper, not only studies the co-existence of a 5G CR waveform in an existing LTE system, but also validates the spectral efficiency of this next generation 5G waveform. The paper also describes the experimental work of sensing the LTE whitespace and then transmitting the CR user (either OFDM or GFDM), within the detected frequency holes. The paper also shows that there are less false alarm events when the steeper GFDM pulse is transmitted compared to OFDM, thus highlighting the spectral efficiency of GFDM.

The remaining sections of the paper are structured as follows. Section II describes the GFDM transmitter model, Section III describes the theoretical sensing characteristics with its probability of false alarm and detection, Section IV gives an overview of the experimental testbed and Section V presents the measurement results.

II. GFDM TRANSMITTER MODEL

GFDM is a multicarrier system with flexible pulse shaping. In this section, the GFDM system model is described in detail as a basis for the experimental work in the next section. The GFDM transmitter structure is shown in Fig. 1.

As shown in [11], when all transmit samples are collected in a vector $\mathbf{x} = [x_0, \ldots, x_{K-1}]^T$, the GFDM transmitter, described in [3], can be formulated as

$$\mathbf{x} = \mathbf{A} \mathbf{d}. \quad (1)$$

Herein, $\mathbf{A}$ is a $NM \times KM$ complex valued modulation matrix with elements based on the parameters $M$, $K$, $N$ and $g[n]$. The matrix $\mathbf{A}$ contains all transmit signal processing operations and is given by

$$\mathbf{x} = \mathbf{W}^H_{NM} \sum_{k=0}^{K-1} \mathbf{P}^{(k)} \mathbf{Gamma}_{L_k}^{(L)} \mathbf{R}^{(L)} \mathbf{W}_M \mathbf{d}_k, \quad (2)$$

where the data symbols $\mathbf{d}_k$ on the $j$th sub-carrier are first transformed to frequency domain by multiplication with an $M \times M$ discrete Fourier transform (DFT) matrix $\mathbf{W}_M = \{w_{i,j}\}_{M \times M}$, where $w_{i,j} = e^{-j2\pi \frac{i}{M}}$ with $i = 0, \ldots, M - 1$ and $j = 0, \ldots, M - 1$. 


matrices \( \mathbf{I} \) is its band pass representation. Lower part of the base band spectrum of the sub-carrier onto elements. This matrix shifts and exchanges the upper and lower part of the base band spectrum of the sub-carrier onto its diagonal, and zeros elsewhere. Finally, the \( k \)-th sub-carrier is up-converted to its respective sub-carrier frequency with the permutation matrix \( \mathbf{P}(b) \), which can be constructed according to

\[
\mathbf{P}^{(0)} = \begin{pmatrix}
\mathbf{I}_{LM/2} & 0_{LM/2} & \cdots & 0_{LM/2} & 0_{LM/2} \\
0_{LM/2} & \mathbf{I}_{LM/2} & \cdots & 0_{LM/2} & 0_{LM/2} \\
0_{LM/2} & 0_{LM/2} & \cdots & \mathbf{I}_{LM/2} & 0_{LM/2} \\
0_{LM/2} & 0_{LM/2} & \cdots & 0_{LM/2} & \mathbf{I}_{LM/2}
\end{pmatrix}^{tr},
\]

\[
\mathbf{P}^{(1)} = \begin{pmatrix}
0_{LM/2} & \mathbf{I}_{LM/2} & \cdots & 0_{LM/2} & 0_{LM/2} \\
0_{LM/2} & 0_{LM/2} & \cdots & \mathbf{I}_{LM/2} & 0_{LM/2} \\
0_{LM/2} & 0_{LM/2} & \cdots & 0_{LM/2} & \mathbf{I}_{LM/2} \\
\mathbf{I}_{LM/2} & 0_{LM/2} & \cdots & 0_{LM/2} & 0_{LM/2}
\end{pmatrix}^{tr},
\]

etc. with \( 0_{LM/2} \) being an \( \frac{LM}{2} \times \frac{LM}{2} \) matrix containing zero elements. This matrix shifts and exchanges the upper and lower part of the base band spectrum of the sub-carrier onto its band pass representation.

After that, the signals of all \( K \) sub-carriers are super-positioned and the result is transformed back to the time domain with \( \mathbf{W}^{NM} \).

Tail biting [12], has been applied to GFDM and this has been used to reduce the length of the CP. It is used to maintain the circular structure within each block. This tail biting concept exploits the digital implementation of the filters to perform circular convolution. \( \bar{x}[n] \) is then passed to the digital-to-analog converter and sent over the channel. The GFDM receiver is described in detail in [3], including interference cancellation schemes that remove the self-ICI generated by the non-orthogonal GFDM subcarriers.

III. THEORETICAL ANALYSIS OF SENSING GFDM SIGNAL

The goal of sensing the spectrum now, is to determine, if the licensed frequency band is currently occupied any user or not. Extensive work has already been done for OFDM sensing [13], [14], and these are extended here to calculate the sensing characteristics of the opportunistic GFDM signal.

Let \( \xi \) be the number of GFDM multi-carrier symbols detected, then the total number of transmitted data symbols detected is \( \xi M \). The sensor collects measurements over \( \xi \) successive GFDM symbol period to determine if the narrow band interference is present. At the end of the measurement period, the transceiver has sensed a total of \( \xi M \) transmitted symbols. The in-phase and the quadrature components of the received signal are arranged such that the first \( \xi M \) values are the in-phase while the next \( \xi M \) components are the quadrature values. Thus the transceiver constructs a \( 2\xi M \times 1 \) vector for every point in the up-converted frequency bins.

Given that the opportunistic user is transmitting signal actively, then under the null hypothesis \( (H_0) \), the receiver measures only noise in the frequency bins. Under the alternate hypothesis \( (H_1) \), the receiver measures the opportunistic transmission along with the noise. Expressed as a binary hypothesis testing problem [15], [16], we have

\[
r(n) = \begin{cases} 
  w(n) & H_0 \\
  h(n) \ast x(n) + w(n) & H_1
\end{cases}
\]

(3)

where, \( r(n) \) is the signal received by the sensor, \( x(n) \) is the GFDM based CR’s transmitted signal, \( h(n) \) is the channel response and \( w(n) \) is the additive white Gaussian noise (AWGN). The SNR is defined as \( \gamma = \frac{P}{\sigma_n^2} \) with \( P \) as the opportunistic signal power detected at the receiver and \( \sigma_n^2 \) as the noise power.

Using Neyman-Pearson (NP) test [17], [18], the statistics and the decision rule can be expressed as:

\[
L = \sum_{i=1}^{2\xi M} r_i^2(n) \geq \tau_{th}
\]

(4)

where the threshold is denoted as \( \tau_{th} \). The test statistic, defined in equation (4), is the sum of squared output of the signal vector. Hence, the test statistic follows a central chi-squared distribution with \( 2\xi M \) degrees of freedom under \( H_0 \) and non-central chi-square distribution with a non-central parameter of the SNR \( \gamma \), under \( H_1 \).
The probability density function of the test statistic $L$, under the null hypothesis, $H_0$ is given in [19], [20], as

$$p(L|H_0) = \begin{cases} L^{K-1} e^{-\frac{L}{2\sigma_n^2}} \left( \frac{1}{\sigma_n^2} \right)^{\frac{1}{2}} \frac{2^{\frac{K}{2}} \Gamma \left( \frac{K}{2} \right)} {2^{\frac{K}{2}} \Gamma \left( \frac{K}{2} \right)} x \geq 0 \\ 0 & x < 0 \end{cases} \tag{5}$$

where $\Gamma(x)$ is the Gamma function.

The probability of a missed detection is defined as the probability that the signal level exceeds the decision threshold, when $H_0$ is true, in any one of the $K - 1$ bands that is not occupied by the opportunistic GFDM cognitive radio transmission. Mathematically, it can be expressed as

$$P_m = \text{Prob} \left( L > \tau_{th} \mid H_0 \right)$$

$$= 1 - \int_0^{\tau_{th}} L^{K-1} e^{-\frac{L}{2\sigma_n^2}} \left( \frac{1}{\sigma_n^2} \right)^{\frac{1}{2}} \frac{2^{\frac{K}{2}} \Gamma \left( \frac{K}{2} \right)} {2^{\frac{K}{2}} \Gamma \left( \frac{K}{2} \right)} dL$$

$$= 1 - \Gamma_{inc}^{K-1} (\tau_{th}, \xi M) \tag{6}$$

where $\Gamma_{inc}$ is Pearson’s incomplete Gamma function [21], $\Gamma_{inc}(a, b) = \frac{1}{\beta^a} \int_0^\infty e^{-\beta t} t^{b-1} dt$.

The probability density function of the test statistics under the alternate hypothesis, $H_1$ is given as

$$p(L|H_1) = \begin{cases} L^{K-1} e^{-\frac{L}{2\sigma_n^2}} \left( \frac{1}{\sigma_n^2} \right)^{\frac{1}{2}} \frac{2^{\frac{K}{2}} \Gamma \left( \frac{K}{2} \right)} {2^{\frac{K}{2}} \Gamma \left( \frac{K}{2} \right)} x \geq 0 \\ 0 & x < 0 \end{cases} \tag{7}$$

The probability of a missed detection is defined as the probability that the signal level in a frequency band does not exceed the decision threshold given that the opportunistic GFDM signal is actually present (i.e. under $H_1$). It is given as

$$P_m = \text{Prob} \left( L < \tau_{th} \mid H_1 \right)$$

$$= \int_0^{\tau_{th}} L^{K-1} e^{-\frac{L}{2\sigma_n^2}} \left( \frac{1}{\sigma_n^2} \right)^{\frac{1}{2}} \frac{2^{\frac{K}{2}} \Gamma \left( \frac{K}{2} \right)} {2^{\frac{K}{2}} \Gamma \left( \frac{K}{2} \right)} dL$$

$$= \Gamma_{inc} \left( \frac{\tau_{th}}{1 + \gamma}, \xi M \right) \tag{8}$$

From equation (6), the decision threshold $\tau_{th}$ can be expressed in terms of target probability of false alarm, $P_f$ as

$$\tau_{th} = \Gamma_{inc}^{-1} \left( 1 - P_f \right) \frac{1}{\xi M} \tag{9}$$

Based on the equations (8), (9), the probability of detection for a target false alarm probability $P_f$ is hence given by

$$P_d = 1 - \Gamma_{inc} \left( \frac{1}{\xi M}, \Gamma_{inc}^{-1} \left( 1 - P_f \right) \frac{1}{\xi M} \right) \tag{10}$$

The probability of false alarm is a parameter of quality of service. The threshold of the sensor varies with the probability of false alarm.

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IV. EXPERIMENTAL FRAMEWORK FOR 5G GFDM CR WAVEFORMS

The LTE/LTE-A testbed, developed by the Vodafone Chair Mobile Communications Systems at the TU Dresden, is an experimental wireless testbed to study cognitive radio experiments in cellular systems. The testbed, as described in [10], [22], is equipped with SIGNALION (a National Instruments company) test hardware. It basically consists of an FPGA powered baseband unit and a radio frontend unit. Depending on the firmware the equipment can either be configured as Evolved Node B (eNB) or user equipment (UE).

Fig. 2 illustrates the testbed setup. The primary user downlink (DL) is connected from eNB to UE. The UE uplink (UL) signal is added to the CR UL signal via a power combiner. This combined signal is afterwards divided into one signal for the eNB and one for the spectrum analyzer by a power splitter. The eNB receive port has a 20 dB attenuator to prevent clipping. In this work the power difference between the primary and

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Fig. 3: Out of band leakage of OFDM and GFDM
TABLE I: System parameters (valid only for GFDM)

<table>
<thead>
<tr>
<th>Parameters of the primary system.</th>
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<tr>
<td>FFT size</td>
<td>2048</td>
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<tr>
<td>Bandwidth</td>
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</tr>
<tr>
<td>Subcarrier spacing</td>
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</tr>
<tr>
<td>Modulation</td>
<td>QPSK</td>
</tr>
<tr>
<td>Uplink (UL) frequency</td>
<td>1.99 GHz</td>
</tr>
<tr>
<td>Downlink (DL) frequency</td>
<td>2.18 GHz</td>
</tr>
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<td>Used PRBs</td>
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</tr>
<tr>
<td>Waveform</td>
<td>OFDM</td>
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</table>

<table>
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<th></th>
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</thead>
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<tr>
<td>Bandwidth</td>
<td>20 MHz</td>
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<tr>
<td>GFDM Blocksize</td>
<td>15</td>
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<tr>
<td>Modulation</td>
<td>QPSK</td>
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<tr>
<td>Waveform</td>
<td>OFDM or GFDM</td>
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<tr>
<td>Allocated subcarriers</td>
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</tr>
<tr>
<td>Roll-of-factor*</td>
<td>0.1</td>
</tr>
<tr>
<td>Cyclic prefix*</td>
<td>With tail biting</td>
</tr>
<tr>
<td>Filter*</td>
<td>Raised Cosine</td>
</tr>
</tbody>
</table>

secondary user is of more interest than the exact power levels.

The next part of the experimental setup was sensing the white space available for opportunistic transmission. In our experiment setup, we have kept the threshold at $-70$ dB. Once the sensor detects a whitespace, it communicates with the CR telling it to transmit in that particular frequency range. The CR then transmits in that frequency range either OFDM or GFDM waveform.

V. MEASUREMENT RESULT

Fig. 3 depicts the different out of band leakage levels of Orthogonal Frequency Division Multiplex (OFDM) and GFDM measured at the spectrum analyzer. GFDM performs up to 30 dB better than OFDM. This result exemplifies that GFDM is a promising candidate for cognitive radio coexistence between incumbent communication techniques.

The next part of the experiment was that of sensing. A simple energy detector was implemented with an NI’s USRP device. Initially, the LTE signal was transmitted, considering it as a primary signal; and its frequency whitespace was detected, as shown in Fig. 4.

Then the OFDM cognitive radio signal is transmitted and subsequently sensed. The energy detector identifies which part of the spectrum is occupied (whether with LTE or with OFDM-CR signal), and which part of the spectrum is free. Now, OFDM-CR signal is replaced with GFDM-CR signal. The transmitted GFDM-CR signal is then sensed by the energy detector. The sensor identifies which frequencies are occupied and which are free. As is evident from Fig. 5 and Fig. 6, GFDM, being a sharper filtered signal than OFDM, shows higher and better spectral efficiency.

The total bandwidth of the setup is 20 MHz with 625 subcarriers, with subcarrier spacing of $20$ MHz/625 = 32 KHz. The LTE primary signal is occupying a bandwidth of 6.4 MHz (i.e.,
200 subcarriers). The LTE whitespace is 20 MHz − 6.4 MHz = 13.6 MHz (i.e., 425 subcarriers).

When OFDM-CR is transmitted and subsequently sensed, the total occupied bandwidth (including primary and CR signals) is found out, from Fig. 5, to be 17.76 MHz. The OFDM-CR waveform is then calculated to occupy 17.76 MHz − 6.4 MHz = 11.36 MHz (i.e., 355 subcarriers).

Now, when GFDM-CR waveform is transmitted and subsequently detected, the total occupied bandwidth (including primary and CR signals) is found out, from Fig. 6, to be 10.40 MHz. The GFDM-CR waveform, hence, occupies or is detected in 10.4 MHz − 6.4 MHz = 4 MHz (i.e., 125 subcarriers). As is evident in Fig. 6, there is no false detection of CR waveforms when GFDM waveform is used as the CR signaling modulation. Moreover, the spectral efficiency gain of GFDM compared to OFDM is 4 MHz/11.36 MHz × 100% = 35.21%. Compared to other recent flexible multicarrier waveforms like FBMC [23], or Spectrally Efficient FDM (SEFDM) [24], GFDM shows really spectacular spectral efficiency gain over OFDM.

VI. CONCLUSIONS

GFDM with its flexible pulse shaping filters has lower out of band leakage which makes it suitable for CR applications. This paper describes in detail the experimental validation of GFDM as a CR waveform. With improved ACLR properties, compared to OFDM, GFDM-CR waveform has lower interference to adjacent primary system. The experiment with the sensor proves that GFDM is spectrally efficient compared to OFDM. Based on the experimental work, it can be concluded that GFDM with lower out of band leakage compared to GFDM is more suitable as a next generation CR waveform to access frequency holes in an LTE cellular system.

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