Improved CR Spectrum Sensing Performance with Lower ACLR GFDM Signals

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Abstract Generalized Frequency Division Multiplexing (GFDM) with its flexible pulse shaping filters can provide extremely low out of band leakage to adjacent legacy channels. This makes it an attractive choice for a PHY layer of cognitive radios operating in fragmented TV white spaces. Introducing zero padding to the transmission data block significantly reduces the said out of band leakage even further. Primary, incumbent signals can now be protected with a geo-location database query mechanism. Even then, sensing opportunistic users operating in the same frequency band is important in cognitive radio operations. In this paper, a simulation based study has been performed to compare GFDM matched filter based sensing characteristics with traditional orthogonal frequency division multiplexing (OFDM) sensing receiver operating characteristic (ROC) curves. Sensing with a GFDM based cognitive radio receiver shows better sensing performance. If we incorporate the improved lower ACLR pulse, then the sensing characteristic curves become even better.

Key words Cognitive Radio, Flexible PHY, Low ACLR, Opportunistic Access, Spectrum Sensing

1. Introduction

Radio spectrum is becoming a very scarce resource, and an increasing popularity of wireless devices is making the demand for it even higher. To cope with this huge demand for spectrum, regulatory bodies (like FCC in USA and Ofcom in UK) have recently opened up licensed spectrum for unlicensed access [1]. 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.

When incumbent users or opportunistic users are inactive over a portion of the spectra, only then other opportunistic users will be allowed to transmit and receive data. A strict specification for such innovative cognitive radio (CR) PHY design is that the opportunistic signal should have extremely low out-of-band radiation into the adjacent incumbent frequency bands. In the 2010 FCC and Ofcom ruling, requirements of spectrum sensing for protection of incumbent users were eliminated, and a geo-location database mechanism was proposed [2]. Information about incumbent users at a particular position is stored in these geo-location databases. Opportunistic users communicate in the white spaces only and thus provide necessary protection to incumbent users.

The multiband Generalized Frequency Division Multiplexing is a new idea for designing a multicarrier PHY [3]. GFDM is very well suited for a cognitive radio PHY modulation scheme, as pulse shaping filters makes the out-of-band leakage into the adjacent incumbent band extremely small. This makes it well suitable for TVWS transmission. Filter Bank Multicarrier (FBMC) [4],[5] is another option for CR-TVWS transmission, which has been well studied; but comparing sensing performance between GFDM and FBMC is out of the scope of this paper.

Compared to OFDM, which has rectangular pulse shaping, GFDM with flexible pulse shaping filters, for example, root-raised-cosine (RRC), causes less interference to the adjacent incumbent frequency bands [6]. An improvement of the existing filter for GFDM was done in [7], where adding zero padding to the GFDM block reduces the out of band leakage by significant amount.
The pulse shaping filters, however, introduces self intercarrier interference (ICI) to the adjacent subcarriers. This degrades the bit error rate performance. Recent works in [8] have shown that a successive interference canceller can mitigate the ICI and improve the GFDM system performance.

To protect opportunistic users, GFDM signals need to be sensed reliably, so that any other CR signal is not transmitted when a GFDM signal is present in the frequency band of operation. An extensive work has already been done in sensing OFDM signals based on the energy detection principle [9, 10] and in this paper, we evaluate the sensing performance of GFDM signals. Other spectrum sensing techniques like cyclostationary feature based detection [11] are more computationally intensive than simple energy detection and a comparison of these two methods is out of the scope of this paper.

In this paper we use a standard GFDM receiver for sensing an opportunistic signal. Whenever GFDM is used for CR TVWS transmission, it is convenient to use the GFDM receiver as a sensing device for other CR signals. Complementary ROC curves are obtained for sensing with a GFDM sensor and compared with ROC curves of an OFDM sensor.

Another work done in this paper is the evaluation of sensing performance improvement, when a sharper filter with lower out of band leakage is incorporated into the GFDM system. It will be shown that, with sharper filters, the complementary ROC curves for sensing performance improves significantly.

The rest of the paper is organized as follows. In Section 2, the GFDM system model is described. Section 3 evaluates the performance of the GFDM sensing as compared to OFDM sensing, and finally the conclusions are given in Section 4.

2. System Model

A relatively new PHY design technique, GFDM [2], [3], has the flexibility of shaping the pulses so that these have lower out-of-band radiations to cause interference to the incumbent signals in the adjacent frequency bands. The pulse shaping root raised cosine (RRC) filter however, introduces inter-carrier interferences (ICI) which degrades the performance of the GFDM transmission and reception.

The binary data is modulated and divided into sequences of KM valued data symbols. Each such sequence \(d[\ell], \ell = 0 \ldots KM - 1\) is spread across K subcarriers and M time slots for transmission. The data can be conveniently represented by means of a block structure

\[
D = \begin{pmatrix}
d_0 \\
d_1 \\
\vdots \\
d_{K-1}
\end{pmatrix}
\begin{pmatrix}
d_0[0] & \cdots & d_0[M-1] \\
\vdots & \ddots & \vdots \\
d_{K-1}[0] & \cdots & d_{K-1}[M-1]
\end{pmatrix}
\]  

(1)

where \(d_k[m] \in \mathbb{C}\) is the data symbol transmitted on the k-th subcarrier and in the m-th time slot.

![Fig. 1: GFDM Transmitter Block](image)

The GFDM transmitter structure is shown in Fig. 1. After up-sampling the complex data symbols \(d_k[m]\), \(m = 0, \ldots, M-1\) by factor N, we get

\[
d_k^N[n] = \sum_{m=0}^{M-1} d_k[m] \delta[n - mN], \quad n = 0, \ldots, NM - 1
\]

(2)

The root raised cosine (RRC) pulse shaping filter \(g[n]\) is applied to the sequence \(d_k^N[n]\), followed by digital subcarrier up conversion. The resulting subcarrier transmit signal \(x_k[n]\) can be mathematically expressed as

\[
x_k[n] = (d_k^N \circ g)[n] w^{kn}
\]

(3)

where \(\circ\) denotes circular convolution and \(w^{kn} = e^{j2\pi kn/N}\).

Similar to (1), the transmit signals can be expressed in a block structure.
The transmit signal for a data block \( D \) is then obtained by summing up all subcarrier signals according to
\[
x[n] = \sum_{k=0}^{K-1} x_k[n]
\]
(5)
This is then passed to the digital-to-analog converter and sent over the channel.

The receiver structure is shown in Fig. 2. After analog-to-digital conversion the received signal is denoted as \( y[n] \). The subcarrier received signal, \( \hat{y}_k[n] \) is obtained after digital down conversion. After convolving with the receiver matched filter \( g[n] \), the signal is defined as
\[
\hat{d}_k^{(i)}[n] = (\hat{y}_k @ g)[n]
\]
(7)

The received data symbols \( \hat{d}_k^{(i)}[m] \) are obtained after down sampling \( \hat{d}_k^{(i)}[n] \) according to \( \hat{d}_k^{(i)}[m] = \hat{d}_k^{(i)}[n = mN] \).

Finally the received bits are obtained after demodulation.

Fig. 2: GFDM Receiver Block

The receiver structure in Fig. 2 shows the interference cancelation unit.

If RRC filters are used as transmit and receive filters, then, only the adjacent subcarriers interfere, causing ICI. This is the underlying reason why the GFDM bit error rate (BER) performance was found out to be worse than that of the OFDM in [3]. A double sided serial interference cancellation has been implemented which cancels out the self-ICI [13] and GFDM BER performance now matches the theoretical AWGN curve.

### 2.1 Low ACLR Response

GFDM has flexible pulse shaping filters, and in this paper, root raised cosine filters with roll off factor = 0.3 is considered. This is the reason why GFDM has lower pulse shaping compared to OFDM, as shown in Fig 3. The out of band leakage of a simple GFDM signal is around 10 dB lower than that of OFDM.

In [7], the authors have shown that adding zero padding to the GFDM data block reduces the out of band leakage significantly. The Fig. 3 shows that increasing the zero padding to the GFDM block reduces the out of band leakage monotonically. In a GFDM block of \( M = 15 \), we get very low out of band leakage for having two zeros on both sides of the GFDM data block, i.e. with \( M_O = 11 \).

![Fig. 3: Lower Out of Band Leakage of different pulses Times](image)

### 3. Performance Evaluation

The detailed block diagram of the energy detector is shown in Fig. 4. The GFDM receiver demodulates the received data and the data block \( D \) is passed through a square law device. The summer adds up the energy values of each of the samples along one subcarrier to compute the energy in each of the subcarrier bins. This sensing measurement is compared with a decision threshold to decide whether the subcarrier is empty or occupied. The vector \( H \) contains the decisions, either \( H_0 \) or \( H_1 \) for all the subcarriers in the CR system.
The scenario simulated in this paper is where the primary incumbent signals are protected with geo-location database query mechanism, but the opportunistic users in the TV white space need to be sensed before another signal can be transmitted in the same frequency band of operation. The system is simulated with $K = 128$ subcarriers, where the TVWS is present in subcarriers $K = 33$ to $K = 96$, where the whitespace is in the center of the frequency band and 32 subcarriers on the left as well as on the right side carry opportunistic data. The adjacent subcarriers to the stop band, i.e. the transition band, are not for transmission and hence are not considered in the calculation of the probability of false alarm and that of detection. The simulation parameters are tabulated in Table 1. Multipath channels and cyclic prefix were not considered in the setup.

### 3.1 Synchronous Receiver

Assuming perfect synchronization at the receiver, this system is simulated, once with OFDM and then with GFDM as cognitive opportunistic signals. The OFDM and GFDM systems are sensed with respective OFDM and GFDM sensors and ROC performance curves are obtained. The complementary ROC curves for GFDM match the complementary ROC curves for OFDM.

![Fig. 6: Complementary ROC curves for synchronous GFDM and OFDM with varying SNR.](image)

The self interference generated in the GFDM system is considered a component of the signal and is not present when the GFDM signal is not present (H0). These simulated curves follow the theoretical curves from (14) as shown in Fig. 6. This shows that the sensing performance with a GFDM sensor is comparable to ROC curves obtained from traditional OFDM sensors in synchronous systems. The SNR is varied from 0 dB to 4 dB in steps of 1 dB.

### 3.2 Asynchronous Receiver

A more realistic scenario is where we consider a frequency offset at the receiver. The worst case setup with an offset of half the subcarrier spacing is considered. The OFDM and GFDM signals are sensed by their respective OFDM and GFDM sensors and the complementary ROC is obtained. It is observed in Fig. 7, that the GFDM complementary ROC plots are better compared to OFDM ROC curves. Over the considered range of SNR and $P_f$, the

![Fig. 7:](image)
probability of missed detection for an OFDM signal is higher than that of a GFDM signal. It is also observed that for higher values of SNR, the improvement of the complementary GFDM ROC curves over OFDM ROC curves is larger. This implies that GFDM signals can be better detected as compared to an OFDM signal in asynchronous systems as OFDM is more prone to frequency offset. Hence GFDM sensing is more robust compared to OFDM sensing in more realistic scenarios. The SNR is varied from 0 dB to 4 dB in steps of 1 dB.

3.3 Sensing with GFDM Receiver

In this simulation setup, we have considered an asynchronous CR system. All combinations of transmitting OFDM as well as GFDM and using an OFDM or GFDM receiver for sensing are considered. Based on this we have compared ROC curves for OFDM and GFDM receivers. These are shown in Fig. 8. From the above figure, we see that the sensing ROC performance is best when a GFDM transmission is sensed by a GFDM receiver. The conventional ROC performance curves for OFDM sensing by a traditional OFDM based sensor is also shown here, and its performance is worse than that of the GFDM sensor. The most interesting observation from this study is that when OFDM transmission is sensed by GFDM sensor, then the ROC is better than that of an OFDM based sensor.

Fig. 7: Complementary ROC curves for asynchronous GFDM, GFDM+ and OFDM with varying SNR

If we incorporate the steeper GFDM pulse, as shown in Fig. 3, then the sensing performance of the GFDM system in asynchronous environment is as shown in Fig. 7. It is observed that the complementary ROC curves for the improved GFDM pulse is better by about 3 dB compared to a normal GFDM RRC pulse with roll-off factor, $\alpha = 0.3$.

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Fig. 8: Complementary ROC for sensing with OFDM and GFDM+ receivers at SNR = 5 dB and 8 dB.

In Fig. 8, it is observed that sensing a GFDM+ signal with the corresponding matched filter improves the sensing performance quite significantly. Using the improved GFDM signal with steeper fall and lower out of band leakage, improves the complementary ROC curves by about 6 dB. Hence we see that, incorporating a sharper filter improves sensing performance. The steep spectral shape of the GFDM filters improves the sensing performance of a OFDM opportunistic transmission. It is also clear from the above figure that with higher SNR, sensing with GFDM receiver performance improves. It is also clear from the results shown in this subsection that having a sharper filter improves sensing performance.

4. Conclusion

It is extremely important that the cognitive radio reliably detects not only incumbent active transmissions but also other opportunistic signals. GFDM is an extremely attractive multicarrier modulation scheme suitable for cognitive radio PHY as it has a low
out-of-band radiation into the adjacent frequency bands. Traditional OFDM signal detection techniques and algorithms can be applied to GFDM as well. In this paper, energy detection based spectrum sensing is simulated for the scenarios where OFDM and GFDM are used as opportunistic signals. It is observed that complementary ROC curves for GFDM are better than OFDM and GFDM can be better sensed than OFDM in an asynchronous cognitive radio system. Deriving the theoretical performance in case of asynchronous detection is a work in progress and is kept as an outlook of the simulation study done here. It is also evident that using a GFDM receiver as a sensor also improves the ROC characteristics of a traditional OFDM system. These simulation studies show that compared to conventional OFDM, GFDM is more suitable for cognitive radio PHY, not only because of better spectral shaping, but also because of better sensing characteristics. An important contribution of this paper is the point that the sensing performance improves significantly if a sharper filter is used in the GFDM system. The complementary ROC curves improves by about 6 to 7 dB by incorporating a sharper GFDM filter.

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6. References


