Comparative Analysis on Interference Suppressive Transmission Schemes for White Space Radio Access

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Abstract — **With opening up of the TV white spaces for opportunistic access, designing a flexible physical layer (PHY) scheme has become an important focus for cognitive radio (CR) systems. Two possible PHY design solutions proposed are: generalized frequency division multiplexing (GFDM) and interference avoidance by partitioned frequency and time domain transmission (IA-PFT). Both of these methods extend the orthogonal frequency division multiplexing (OFDM) scheme to be applicable as a flexible CR PHY solution in a fragmented spectrum. In GFDM, introduction of pulse shaping filters reduces the out-of-band radiation of the opportunistic signals into the frequency band of the incumbent users; while in IA-PFT, simultaneous cancellation carrier insertion and time windowing technique suppress spectral leakage into the incumbent band of operation. In this paper, these two different approaches are compared in terms of interference suppression, transmission performance and processing complexity.**

Keywords- cognitive radio, white space, PHY design, intercarrier interference, multicarrier modulation

I. INTRODUCTION

Radio spectrum is a very limited resource and intelligent use of the available spectrum by cognitive radio (CR) [1] has emerged as an important aspect in wireless communication. To overcome the acute shortage in spectrum, regulatory bodies like Federal Commission for Communication (FCC) and Ofcom have recently opened up the TV white spaces for unlicensed access [2][3]. However, spectrum sharing by opportunistic users with licensed users need to be done meticulously in a controlled manner so that incumbent users are not disturbed.

One of the strict specifications for CR TV white space (TVWS) operations includes extremely low out-of-band radiation of the opportunistic signal into the incumbent band. The interference caused by the cognitive signals to the incumbent users in the adjacent channel should be as low as possible. The receiver should also have high sensitivity to detect even the weakest of the incumbent signals and must be able to flexibly exploit fragmented TVWS with one single wideband signal. Thus innovative waveform design with interference avoidance and mitigation techniques has emerged as a very hot topic of research for application in CR scenarios.

OFDM based multicarrier modulation scheme is an initial choice for white space cognitive radio applications. OFDM has been extensively studied and multicarrier OFDM can flexibly access frequency white spaces in the extremely fragmented TVWS spectrum [4]. But rectangular pulse shaping in OFDM causes extensive out-of-band interference to the adjacent incumbent bands. As a simple approach, time windowing (TW) has been proposed to suppress out-of-band emission. For example, IEEE802.11 standardization employs TW technique [5]. But to efficiently use the TVWS and at the same time to maintain the low out-of-band radiation, GFDM has been proposed as an advanced multicarrier modulation technique [6][7]. In GFDM a pulse shaping root-raised-cosine (RRC) filter shapes the data symbols. The RRC filter has lower side lobe in the frequency domain and causes less interference to the adjacent bands. The RRC pulse however causes self-interference with adjacent subcarriers, and hence in the receiver a serial interference canceller is needed to improve the system performance.

As an alternate approach, IA-PFT has been proposed where the transmitter employs a twin-inverse fast Fourier transform (IFFT) scheme for the opportunistic signal [8]. Then cancellation carriers (CC) insertion in frequency domain [9][10] and TW in time domain are carried out. Unlike GFDM, the proposed IA-PFT scheme does not have any additional requirements in the receiver side. But again, compared to IA-PFT, GFDM does not require any cancellation carriers to suppress the out-of-band interference. In this paper, these two different approaches are compared in terms of interference suppression, transmission performance and processing complexity. Different trade-offs between these two designs are explained and based on the comparison results applications of GFDM and IA-PFT are clarified.

The rest of the paper is organized as follows. Sections II and III describe the principles of GFDM and IA-PFT, respectively. Section IV compares the two transmission schemes. Finally, the conclusions will be given in Section V.

II. GENERALIZED FREQUENCY DIVISION MULTIPLEXING

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

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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 complex valued data symbols. Each such sequence $d[\ell]$, $\ell = 0 \cdots KM-1$ is spread across K subcarriers and M time slots for transmission. The data can be conveniently represented by means of a block structure

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

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

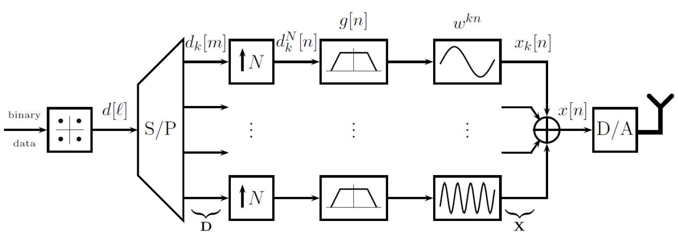

Fig. 1: GFDM Transmitter Block

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

$$d_k^N[n] = \sum_{m=0}^{M-1} d_k[m]\delta[n-mN], \quad n = 0, \ldots, NM-1 \quad (2)$$

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

$$x_k[n] = (d_k^N \circledast g)[n] \cdot w^{kn} \quad (3)$$

where $\circledast$ denotes circular convolution and $w^{kn} = e^{j\frac{2\pi}{N}kn}$.
Similar to (1), the transmit signals can be expressed in a block structure

$$X = \begin{pmatrix} x_0 \\ x_1 \\ \vdots \\ x_{K-1} \end{pmatrix} = \begin{pmatrix} x_0[0] & \cdots & x_0[MN-1] \\ \vdots & & \vdots \\ x_{K-1}[0] & \cdots & x_{K-1}[MN-1] \end{pmatrix} \quad (4)$$

The transmit signal for a data block D is then obtained by summing up all subcarrier signals according to

$$x[n] = \sum_{k=0}^{K-1} x_k[n] \quad (5)$$

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 $\hat{d}_k^{(i),N}[n]$, where

$$\hat{y}_k[n] = y[n] \cdot w^{-kn} \quad (6)$$

$$\hat{d}_k^{(i),N}[n] = (\hat{y}_k \circledast g)[n] \quad (7)$$

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

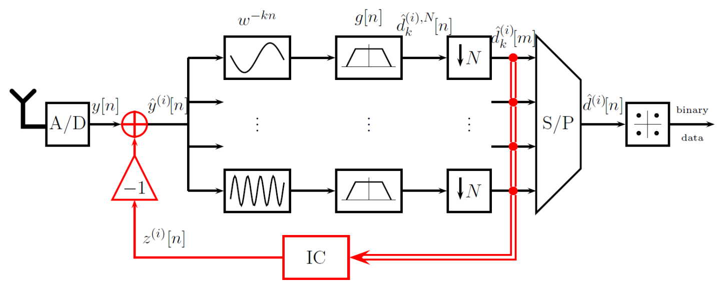

Fig. 2: GFDM Receiver Block

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.

III. INTERFERENCE AVOIDANCE-PARTITIONED FREQUENCY AND TIME-DOMAIN TECHNIQUE

In this section, the principle of IA-PFT is described. To enhance the suppression effect by CCs, IA-PFT utilizes zero padding (ZP) for a certain number of sub-carriers on behalf of cyclic prefix (CP). Therefore, IA-PFT transmitter employs two IFFT processing structure (i.e., one IFFT is used for ZP appended sub-carriers, the other IFFT is used for CP appended sub-carriers).

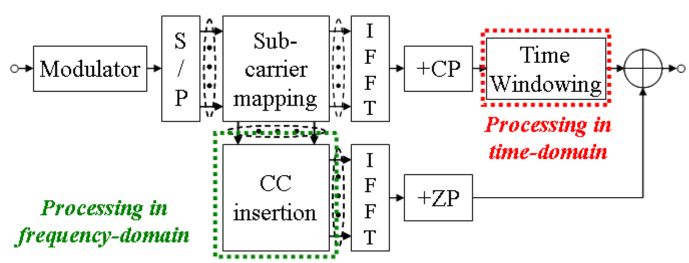

Fig. 3: IA-PFT Transmitter Block

Fig. 3 shows the transmitter block of IA-PFT. The modulated symbols are separated into time-windowing processed stream and CC insertion processed stream. For the time-windowing processed stream, CP and tail window are appended to each OFDM symbol after IFFT. Then the extended OFDM symbols are shaped in time-domain to reduce the out-of-emission. On the other hand, as for the CC insertion processed stream, CCs are inserted to the original symbols in frequency domain to cancel out side-lobes in the interference avoidance band. And then, IFFT is performed followed by ZP insertion. The reason of ZP appendix is to enhance the suppression effect by matching the peak-point between side-lobes of CCs sub-carriers and side-lobes of the original sub-carriers in frequency domain. Finally, both of the two streams are multiplexed.

The CC vector is expressed as

$$\mathbf{h} = -\left(\mathbf{P}_1^T \mathbf{P}_1\right)^{-1} \mathbf{P}_1^T \mathbf{P}_\mathbf{S} \mathbf{X} \tag{8}$$

where $\mathbf{P}_\mathbf{s}$ and $\mathbf{P}_\mathbf{1}$ are the matrix of the extraction of the matrix $\mathbf{P}$ [8]. The equation (8) is based on a minimum mean-squared error solution. Matrix $\mathbf{P}$ consists of the conversion function, expressed as

$$P(l,k) = \sum_{n=0}^{N-1} \exp\left(j2\pi \frac{n}{N}\left(k - \frac{l}{M_{CC}} \right)\right) \tag{9}$$

where l and M_{CC} are respectively the up-sampled frequency position and the up-sampling ratio for the CC vector calculation.

For the receiver side of IA-PFT, a normal OFDM receiver can be used. The receiver does not require additional processing such as interference cancellation.

IV. Comparative Analysis

A. Evaluation Parameters

Parameters for the comparable evaluation on IA-PFT and GFDM are shown below in Table 1. The IA-PFT system is simulated in an additive white Gaussian noise (AWGN) channel with un-coded transmission. QPSK and 16 QAM modulation schemes have been implemented with 564 active subcarriers, 32 carriers in the interference avoidance notch and another 4 sub carriers used as CC. FFT size is set to 1024. For time windowing, a Root-raised-cosine (RRC) filter with the roll-off factor α = 0.03 is considered. 72 samples are assumed for cyclic prefix (CP) and zero padding (ZP).

Table 1

Parameter	IA-PFT	GFDM
FFT size	1024 (2^{10})	16384 (2^{14})
Data Block, M	1	15
Number of effective sub-carriers	564	564
Number of sub-carriers in interference avoidance notch	32 (4 sub-carriers are used for CCs)	36
Pulse shape	RRC (α = 0.03) for TW	RRC (α = 0.3)
CP (ZP) sample	72	No CP for AWGN
Modulation scheme	QPSK, 16QAM	QPSK, 16QAM
Channel model	AWGN	AWGN

The GFDM system is also simulated in an AWGN channel with un-coded transmission. QPSK and 16 QAM modulations schemes have been implemented with number of subcarriers, K = 600, with 36 subcarriers switched off for the interference avoidance band. Samples per symbol considered is N = 64 and block size considered is M = 15. The FFT size is the next higher power of 2 of KM = 9000. Here we have FFT of 2^{14} i.e. 16384 points. Root-raised-cosine (RRC) filters are chosen with roll-of-factor α = 0.3. As an AWGN channel environment is simulated here, cyclic prefix is not considered in the simulation setup also.

B. Power Spectrum Density

In Fig. 4, the power spectrum density of GFDM and IA-PFT is plotted and compared to OFDM. It is observed that GFDM has lower leakage into the incumbent frequency band compared to OFDM. With RRC pulse shaping, the frequency profile is sharper and steeper and the second power lobe of GFDM is at – 23 dB, while that of OFDM is at – 13 dB. The stop band attenuation of GFDM is lower than that of OFDM by about 10 to 12 dB. In IA-PFT, insertion of CC degrades the spectrum efficiency, but achieves even lower stop band attenuation. IA-PFT achieves better incumbent protection with interference to the incumbent users at –35 dB compared to GFDM which is at –28 dB. Fig. 4 shows that GFDM and IA-PFT are better at maintaining lower interference level to the incumbent frequency bands and thus protecting the adjacent channel primary system from opportunistic users.

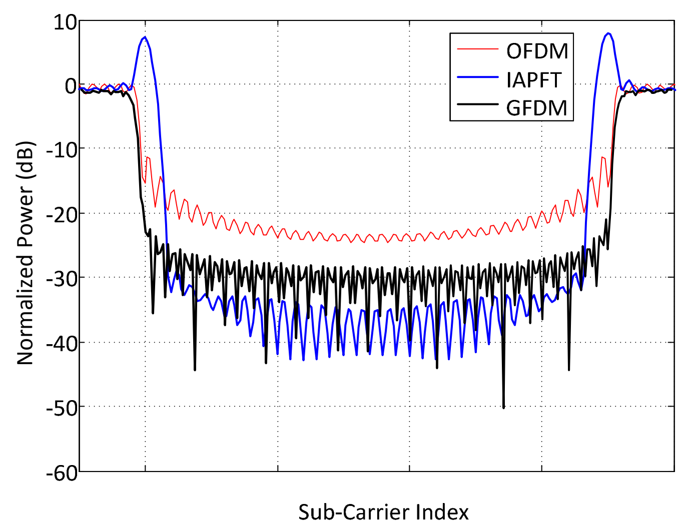

Fig. 4: GFDM and IA-PFT Power Spectrum Density

FCC, Ofcom and other regulatory bodies are currently discussing the specifications of the spectral mask, especially for the TV white space devices, to be around -50 dB. The new innovative multicarrier systems like GFDM and IA-PFT can lower the spectral mask from -23 dB, for traditional OFDM schemes to around -30 dB to -35 dB. Applying cancellation carrier insertion to GFDM or optimizing the time domain windowing pulse can further lower the spectral mask.

C. Transmission Performance

The un-coded BER performance of the GFDM system with double sided serial interference cancellation technique is shown in Fig. 5. The double sided scheme now mitigates the inter carrier interference from neighbouring subcarriers as is evident in the improved BER performance compared to [5] and the BER performance almost matches the theoretical OFDM bit error rate performance. In case of 16 QAM scheme, the double sided SIC uses 3 iterations to completely cancel the inter-carrier-interference (ICI) and matches the theoretical AWGN BER curve.

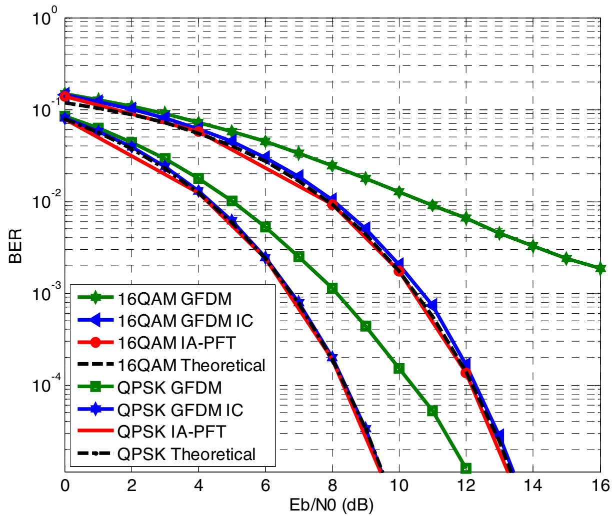

Fig. 5: DSIC GFDM and IA-PFT BER Performance in AWGN

The un-coded BER performances of IA-PFT are almost same as those of theoretical performances in both of QPSK and 16 QAM. It can be seen that IA-PFT does not induce any ICI in AWGN channel.

D. Computational Complexity

A comparison of computational complexity is done in this section between GFDM and IA-PFT. The number of real multiplications required to detect a symbol is considered as a measure of complexity.

Computational complexity of GFDM

An evaluation of the computational complexity of GFDM is presented here. For the transmitter side, the total number of multiplications required to generate M symbols is 2MNLK, where L is the length of the pulse shaping filter. For the receiver side, the total number of multiplications comes out to be 2MNLK. Now with the implementation of double sided SIC, the number of multiplications involved is 6MNLK. So the total complexity comes out to be 10MNLK for M symbols. Therefore for 1 symbol, and with oversampling factor, $N = K$, the complexity comes out to be

$$\mu_{gfdm} = 10N^2L. \tag{10}$$

For a different IFFT-FFT based implementation method [15], the GFDM complexity can be made lower.

Computational complexity of IA-PFT

For the transmitter side of IA-PFT, additional complexity is required in addition to a normal OFDM. The number of multiplications per OFDM symbol is expressed as

$$\mu_{IA-PFT}^{Tx} = N\log_2 N + 2L_{OV} + N_{CC}N_{edge}Q \tag{11}$$

where N, L_{OV}, N_{CC}, N_{edge}, and Q are respectively FFT size, the number of overlapping samples for TW, the number of CCs, the number of spectrum edges, and the number of sub-carriers processed by CC. For example, the parameter sets, $N=1024$, $L_{OV}=30$, $N_{CC}=2$, $N_{edge}=2$, $Q=15$, are used for the evaluations in Figure 4 and 5.

For the receiver side of IA-PFT, the normal OFDM receiver can be applied. Except for the channel estimation and the weight calculation, the number of multiplications per OFDM symbol is expressed as

$$\mu_{IA-PFT}^{Rx} = \frac{N}{2}\log_2 N \tag{12}$$

From the above complexity analysis of IA-PFT, it can be considered that the complexity of IA-PFT transmitter is increased because two IFFTs are employed. On the other hand, the complexity of IA-PFT receiver is same as that of the normal OFDM which is implemented with low complexity.

E. Discussions in Practical Utilities

Both the PHY designs discussed and compared above are extremely suitable for application in white space cognitive radio environment. For GFDM, having a pulse shaping filter reduces the spectral leakage of the opportunistic signal into the incumbent frequency band. However, RRC filters induce self-interferences within the system and these need to be cancelled at the receiver to match theoretical AWGN BER performance. Interference cancellation measures increase the complexity of the system, but ICI is completely eliminated.

IA-PFT compared to OFDM and GFDM has even lower interference to the incumbent band. Cancellation carrier insertion makes the frequency mask steeper compared to OFDM, but it slightly decreases the spectral efficiency of the system. In comparison to GFDM, IA-PFT does not require any interference cancellation schemes at the receiver. All these trade-offs need to be considered when selecting one PHY scheme over the other.

Several scenarios like fixed rural broadband, machine to machine communication, cellular extension in mobile environments and etc are under consideration for application of white space cognitive radio[14]. GFDM can be applicable to cognitive fixed rural broadband and also to backhaul CoMP with higher transmit and receiver processing power. IA-PFT, with its simple receiver implementation, is suitable for cognitive mobile environments i.e. as in cellular extension.

V. Conclusion

GFDM and IA-PFT are two of the most innovative PHY designs for cognitive radio PHY applications in white spaces. Both these multicarrier schemes come with the flexibility of accessing the frequency holes in the spectrum extremely selectively. GFDM with its pulse shaping filters makes the spectral mask extremely sharp and decreases the interference caused by the opportunistic signal into the adjacent incumbent bands. IA-PFT, on the other hand, combines time domain windowing technique and cancellation carrier insertion to lower the interference in the incumbent band even lower. Both these cognitive PHY design schemes have their individual pros and cons and different CR scenarios are suitable for these two schemes depending upon receiver processing power and implementation complexity. In this paper, these two PHY designs are compared in terms of interference suppression, BER performance and processing complexity. Future work will involve incorporating cancellation carrier insertion in GFDM to lower the inherent low spectral mask even further. Designing a better time domain windowing technique with optimized filter might be another avenue to look, to lower the spectral mask in IA-PFT. The work highlights spectral shaping properties of these recent flexible multicarrier schemes, especially designed for cognitive radio PHY operating in an extremely fragmented frequency spectrum. With lowered spectral leakage into the incumbent band of operation, these two PHY modulation schemes can co-exist with the primary users without degrading their performance. The analysis and comparison of different performance parameters of these two multicarrier designs have shown that they are very suitable to be adopted as flexible multicarrier CR PHY modulation schemes.

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