Rohit Datta

Generalized Frequency Division Multiplexing in Cognitive Radio

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Generalized Frequency Division Multiplexing in Cognitive Radio

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Abstract

In today's scenario, radio spectrum is becoming scarce, and the intelligent use of the available spectrum by cognitive radio (CR) has become an important aspect of research in wireless communication. To cope with this huge demand for spectrum, regulatory bodies (such as FCC in the USA, BNetzA in Germany, and Ofcom in the UK) have recently opened up licensed spectrum for secondary unlicensed access. Unlicensed access in licensed bands should not create interference to incumbent users, and hence, new physical layer (PHY) designs and waveforms are being researched, which can fill in the TV white spaces (TVWS) in an opportunistic manner. One of the strict specifications for CR physical layer modulation design is that the opportunistic signal should have extremely low out-of-band radiation, so that incumbent signals are not disturbed, and co-existence is assured. Moreover, to cope with spectrum fragmentation, the receiver should be able to aggregate several TV white spaces (TVWS) by a single wide band signal. Hence, innovative waveform design with a new multicarrier modulation capable of interference mitigation has emerged as a very important topic of research.

The multiband Generalized Frequency Division Multiplexing (GFDM) is a 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, as the choice of pulse shaping filters makes the out-of-band leakage extremely small. Compared to OFDM, which has rectangular pulse shaping, GFDM with a choice of transmit pulse shaping, causes lesser interference to the adjacent incumbent frequency bands.

The thesis introduces the concept of GFDM and extends it towards cognitive radio applications. The basic GFDM transceiver chain is described in detail along with all its intricacies. The thesis analyses the adjacent channel leakage ratio of GFDM and compares them with traditional OFDM and other new waveforms like filter bank multi-carrier (FBMC) and interference avoidance partition frequency technique (IAPFT). The thesis studies the effects of different pulse shaping filters, like raised cosine and root raised cosine filters, to out of band leakage, and also, to the bit error rate performance. The thesis studies the adjacent channel leakage ratio (ACLR) of GFDM and introduces the concept of cancellation carrier insertion to GFDM. This method reduces the out of band leakage to match that of FBMC.

In a cognitive radio application, sensing the opportunistic signal is extremely important. Towards this, the thesis studies the sensing performance of GFDM. Along with theoretical analysis, simulation methods are explained and numerical studies have been performed. The thesis also introduces the idea of sensing opportunistic signals with GFDM sharper filters with a significant gain in performance.

Along with sensing, feature detection of an opportunistic signal is also an interesting and invigorating study. The thesis details the study of cyclostationary properties of GFDM and identifies

new correlative properties in the GFDM signals which give rise to additional cyclostationary peaks in the cyclostationary autocorrelation function. The thesis uses these additional peaks of correlative informations to improve the detection performance of a GFDM signal compared to OFDM.

The concept of GFDM data block and flexible pulse shaping filters to reduce the ACLR, however, introduces severe non-orthogonality between the subcarriers. This in-turn produces self interference which degrades the bit error rate (BER) performance of the GFDM system. The thesis implements a successive interference cancellation scheme which cancels out the self interference and matches the GFDM performance to theoretical studies and that of OFDM.

The thesis also describes an experimental testbed for GFDM as a cognitive radio waveform in a 4G LTE cellular whitespace. The GFDM waveform is transmitted with *SIGNALION* SDR testbed, and interference to the legacy LTE signal is calculated. Apart from which, a sensor, which proves the spectral efficiency of sharper GFDM waveform compared to traditional OFDM, has also been implemented. The prototype implementation proves the validity of GFDM as a suitable candidate for CR access beyond doubt.

As a major outcome, the results clearly indicate the suitability of GFDM as an opportunistic waveform for application in fragmented TVWS cognitive radio environments. The thesis studies the applicability of GFDM in cognitive radio not only in respect to its out of band leakage but also to its robust sensing performance. The new results of low ACLR in GFDM and improved sensing performance for GFDM makes it very suitable for CR applications. Additional correlative properties found in its cyclostationary autocorrelative functions improves its detection performance and also hints at ease of synchronization of GFDM in this direction. The results from the thesis highlights the overall applicability and suitability of GFDM as a next generation flexible waveform for cognitive radio application in fragmented spectrum scenarios.

Zusammenfassung

In heutigen Mobilfunkanwendungen ist Bandbreite eine knappe Resource und die intelligente Nutzung des verfügbaren Spektrums durch Cognitive Radio (CR) Systeme ist zu einem bedeutenden Aspekt der Erforschung drahtloser Kommunikation geworden. Um den hohen Bandbreitnanforderungen nachzukommen, haben Regulierungsbehörden (z.B. FCC in den USA, BNetzA in Deutschland und Ofcom in Großbritannien) seit Kurzem für Mobilfunk lizensierte Frequenzen für eine weitere Nutzung durch unlizensierten Zugriff freigegeben. Unlizensierter Zugriff in lizensierten Frequenzbändern sollte keine Interferenz für die existierenden Nutzer erzeugen, wodurch ein neuer Entwurf der physikalischen Schicht (PHY) samt Wellenform zu einem Forschungsschwerpunkt geworden ist, insbesondere um TV White Spaces (TVWS) in geeigneter Weise zu nutzen. Eines der strengsten Kriterien des CR-Modulationsentwurfs ist eine extrem niedrige Außerbandstrahlung, so dass existierende Signale nicht gestört werden und gleichzeitiges Bestehen von ursprünglichen und opportunistischen Signalen sichergestellt wird. Um mit der Fragmentierung des Spekturms umgehen zu können sollte der Empfänger in der Lage sein, mehrere TVWS in ein einziges Breitbandsignal zusammenzufügen. Dabei hat sich ein innovativer Wellenformentwurf mit einer neuartigen interferenzunterdrückenden Mehrträgermodulation als ein bedeutsames Forschungsfeld herausgestellt.

Generalized Frequency Division Multiplexing (GFDM) ist eine neue Idee für den Entwurf eines Mehrträger-PHY. GFDM ist ein blockbasiertes Mehrträgerübertragungsschema, das vom Filterbankansatz abgeleitet wurde. Bei diesem Schema sind die übertragenen Daten eines jeden Blocks in Zeit und Frequenz verteilt und jeder Unterträger wird mit einem veränderlichen Pulsformungsfilter gebildet. GFDM ist gut geeignet für CR, da die geeignete Wahl der Pulsformungsfilter die Außerbandstahlung extrem gering halten kann. Verglichen mit Orthogonal Frequency Division Multiplexing (OFDM), welches Rechteckpulsformung verwendet, verursacht GFDM mit der Wahl der Pulsformung weniger Interferenz für bestehende Frequenzbänder.

Diese Dissertation führt das Konzept von GFDM ein und erweitert es auf CR Anwendungen. Die grundlegende GFDM Übertragungsstrecke wird in ihren Feinheiten detailliert beschrieben. Diese Arbeit analysiert das Nachbarkanalstörungsverhältnis (Adjacent Carrier Leakage Ratio - ACLR) von GFDM und vergleicht es mit traditionellem OFDM und anderen Wellenformkonzepten wie Filter Bank Multi-Carrier (FBMC) und Interference Avoidance Partition Frequency Technique (IAPFT). Es wird der Effekt von verschiedenen Pulsformungsfiltern wie Raised Cosine und Root Raised Cosine auf die Außerbandstrahlung und die Bitfehlerrate untersucht. Neben der Analyse des ACLR von GFDM wird in dieser Dissertation das Konzept des Cancelation-Carrier-Einschubs für GFDM vorgestellt, welches die Außerbandstrahlung auf den Wert von FBMC reduziert.

In einer CR Anwendung ist es sehr wichtig, das opportunistische Signal aufzuspüren (Sensing). Dementsprechend wird in dieser Arbeit die Sensing-Leistungsfähigkeit für GFDM untersucht. Neben theoretischen Analysen werden Simulationsmethoden erklärt und numerische Un-

tersuchungen durchgeführt. Weiterhin wird die Idee, opportunistische Signale mit schärferen GFDM Filtern aufzuspüren präsentiert, wodurch ein bedeutender Gewinn an Leistungsfähigkeit erzielt wird.

Neben Sensing ist die Merkmalsdetektion eines opportunistischen Signals ebenfalls eine interessante und vielversprechende Studie. Diese Arbeit beschreibt die Untersuchung zyklostationärer Eigenschaften von GFDM und identifiziert neue übereinstimmende Merkmale von GFDM Signalen, welche zusätzliche Maxima der zyklostationären Autokorrelationsfunktion hervorrufen. Diese Maxima übereinstimmender Informationen werden in dieser Arbeit verwendet, um die Leistungsfähigkeit der Detektion eines GFDM Signals im Vergleich zu einem OFDM Signal zu verbessern.

Das Konzept von GFDM Datenblöcken und flexiblen Pulsformungsfiltern zur Reduktion des ACLRs bringt jedoch starke Nichtorthogonalitäten zwischen Unterträgern mit sich. Dies verursacht Eigeninterferenz, welche die Bitfehlerrate eines GFDM Systems erhöht. In dieser Arbeit wird ein Successive Interference Cancelation Schema realisiert, welches die Eigeninterferenz beseitigt und die Leistungsfähigkeit von GFDM mit theoretischen Studien in Übereinstimmung bringt und somit an jene von OFDM anpasst.

Die vorliegende Arbeit beschreibt einen Versuchsaufbau zur experimentellen Überprüfung ausgesuchter theoretischer Ergebnisse. GFDM wird dabei als sekundäres Cognitive Radio in einem 4G LTE System eingesetzt. Während LTE mithilfe dezidierter Hardware emuliert wird, kommt für GFDM eine flexible Software-Defined-Radio-Plattform zum Einsatz. Dieser Aufbau erlaubt es den Einfluss von GFDM bzw. OFDM auf ein primäres LTE - System zu untersuchen. Ein Spektrumanalysator zeigt die bessere spektrale Effizienz von GFDM gegenüber OFDM und bestätigt somit GFDM zweifelsfrei als geeigneten Kandidaten für CR-Zugang.

Als wesentliches Resultat dieser Dissertation zeigen die Ergebnisse eindeutig die Tauglichkeit von GFDM als opportunistische Wellenform für Anwendungen in fragmentierten TVWS-CR-Umgebungen. Die Arbeit untersucht nicht nur die Anwendbarkeit von GFDM bezüglich Außerbandstrahlung sondern auch hinsichtlich seiner robusten Sensing-Leistungsfähigkeit. Die neuen Ergebnisse von geringem ALCR für GFDM und der verbesserten Sensing-Leistungsfähigkeit untermauert die Eignung von GFDM für CR Anwendungen. Zusätzliche übereinstimmende Merkmale, welche in der zyklostationären Autokorrelationsfunktion gefunden wurden, verbessern die Detektionsleistungsfähigkeit und weisen auf eine mögliche Vereinfachung der Synchronisierung für GFDM hin. Die Ergebnisse dieser Dissertation unterstreichen die allumfassende Anwendbarkeit von GFDM als die Wellenform der nächsten Generation für CR Anwendungen in Szenarien mit fragmentiertem Spektrum.

Acknowledgement

> “ Where the mind is without fear and the head is held high;
> Where knowledge is free;
> Where the heart has not been broken down into fragments,
> By narrow restrictive walls ...”

These lines by Rabindranath Tagore (Nobel Laureate, 1913), aptly sum up my experiences during the last four years in Dresden. The following few lines are not enough to acknowledge all those who have helped me with this Doctoral process. Forgive me if I miss some of you.

First of all, I express my heart-felt gratitude to my supervisor Prof. Gerhard Fettweis for his enthusiastic, indispensable and continuous support and encouragement throughout this research work. He has always gone the extra mile to give me time from his ever busy schedule. The minutes – running into hours – he spent with us either in the lab or in his office, pondering over some problems, or to discuss some innovative ideas, really taught me how to think out of the box.

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I thank all my friends in Dresden Staatschauspielhaus, specially Miriam, Nane and Joanna for including me in a stage production and tolerating my singing ‘Freude schöner Götterfunken ...’ in German with heavy Bengali accent accompanied by Indian head-bobs.

I would like to conclude by saying that four years ago, when I met Gerhard at IIT Kharagpur, he promised me that the next years were going to be an adventure. He was not wrong at all!!

Contents

Chapter 1

Introduction

Radio frequency spectrum is a scarce resource in wireless communications. With proliferation of large screen smart wireless devices, innovative services and growing number of mobile users, a huge demand for radio spectrum has made this scarcity more stark. To cope with this, regulatory bodies like the Federal Commission for Communication (FCC) in the US and the Electronic Communications Committee within the European Conference of Postal and Telecommunications Administrations (ECC CEPT) in Europe have recently published some regulatory rules to make the unused spectrum in the TV bands available for unlicensed broadband wireless devices [FCC10], [FCC11]. Spectrum utilization at any given location, frequency, and time is highly inefficient [AIM10] and interest in allowing opportunistic users to access licensed spectrum has been growing tremendously among regulatory bodies (e.g. FCC in US and Ofcom in UK) and standardization groups such as IEEE802.16h, IEEE802.11af, P1900.4a, etc [ALVM06].

1.1 Cognitive Radio in White Space

Since Cognitive Radio (CR) was defined in 1999 by Joseph Mitola III [MM99], there has been extensive research on its application and on related enabling techniques [WGC11]. One of the most promising applications of cognitive methods is opportunistic spectrum access [ALVM08], [ZP05]. Opportunistic access in licensed frequency bands should be controlled such that they do not create any harmful interference to legacy primary licensed users, and hence, novel PHY waveform designs have been identified as a key requirement of cognitive radio [Tan05], [CB05]. Opportunistic users will be allowed to transmit data over the frequency spectrum when incumbent users, or other opportunistic users, are inactive. The opportunistic PHY should be extremely sensitive to detect even the weakest incumbent signal.

A traditional orthogonal frequency division multiplexing (OFDM) system can initially be thought of as a natural choice for a multicarrier cognitive radio PHY. Although OFDM offers efficient equalization [FABSE02], [SKJ95], [WG00] and is very robust to frequency selective channels [JCC99], [VALM+01], it is not well suited for next generation cognitive radio waveform designs. In presence of carrier frequency offsets, the orthogonal subcarriers of OFDM are extremely vulnerable to interference which makes the entire OFDM system very sensitive [CTY04], [MTGB01], [RB05]. OFDM with rectangular pulse shaping has quite high out

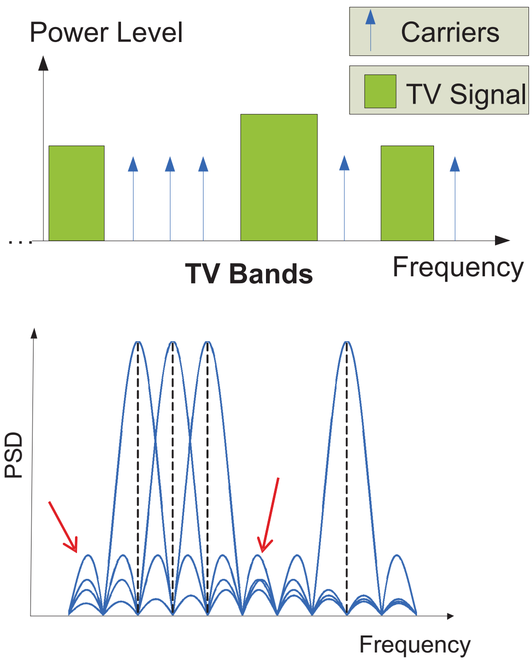

Fig. 1.1: *Opportunistic access in TVWS*

of band leakage which makes it unsuitable for cognitive radio applications in fragmented white space applications [GLAG10], [Sch10], and the requirement of a cyclic prefix limits its spectral efficiency [CGNT07]. New multicarrier schemes are being investigated, and among them, filter bank multicarrier (FBMC) [BRIdR10], [MLRR$^+$12] is extremely popular. FBMC with its prototype filter can satisfy regulatory requirements in its out of band leakage performance but, without a cyclic prefix, it suffers from severe limitations in the synchronization front [FPT08]. The multiband generalized frequency division multiplexing (GFDM) is a relatively new idea for designing a multicarrier PHY [FKB09], [DMLF12]. With flexibility of pulse shaping and a tail-biting cyclic prefix, GFDM shows interesting properties which make it extremely suitable for CR applications in fragmented spectrum.

1.2 Thesis Outline and Contribution

This thesis details the development of a new flexible multicarrier modulation scheme called generalized frequency division multiplexing (GFDM). GFDM is block based multicarrier transmission scheme derived from the filter bank approach where 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, as the choice of pulse shaping filters makes the out-of-band leakage extremely small. Compared to OFDM, which has rectangular pulse shaping, GFDM with a choice of transmit pulse shaping causes lesser interference to the adjacent incumbent frequency bands. This pulse shaping technique improves the adjacent channel leakage ratio (ACLR) of the GFDM system by around 20 dB. Another feature of GFDM is a tail biting cyclic prefix (CP). This feature is useful in cyclostationary detection [PDF12], [DPF12]. Compared to FBMC, which has no cyclic prefix, GFDM, with its shortened CP, could address the synchronization issues that were problematic in FBMC [FPT09].

The contributions of the thesis is summarized below. The transceiver chain is described here in detail. The application of GFDM in cognitive radio is studied and various performance metrics are evaluated. The adjacent channel leakage ratio of GFDM is evaluated and improved. Sensing an opportunistic waveform is an important function in a cognitive radio; and therefore, GFDM sensing performance is analysed and evaluated. GFDM with its tail biting cyclic prefix has interesting cyclostationary properties. These have been studied for the first time and utilized to improve GFDM waveform detection. GFDM with its pulse shaping flexibility introduces self intercarrier interferences between adjacent subcarriers. A novel double sided interference cancellation scheme has been implemented to improve the bit error performance of GFDM. All these studies, undertaken for the first time, examine the suitability of GFDM as a next generation cognitive radio PHY.

The outline of this thesis is as follows: In Chapter 2, we introduce OFDM principles and explain the essential building blocks. We evaluate the performance of OFDM as a cognitive radio opportunistic waveform and introduce other flexible waveforms like filter bank multicarrier modulation (FBMC) [IVSR10b], [VIS+06], and interference avoidance partition frequency technique (IAPFT) [QWJ10], [HH09] [FA12], [Yam04]. We also introduce the basic GFDM transceiver system model and explain its intricacies. Chapter 3 analyses the adjacent channel leakage ratio of GFDM and explores methods to improve them further. In Chapter 4, the sensing performance of GFDM is detailed. Simulation methods are explained. We also introduce the idea of sensing with GFDM sharper filters with a significant gain in performance. Chapter 5 details the study of cyclostationary properties of GFDM and uses them to improve the detection performance compared to OFDM. Chapter 6 investigates interference cancellation procedures, and robustness of the GFDM system to carrier frequency offset. The final contributory Chapter 7 details the validation of opportunistic GFDM CR access in an LTE experimental hardware testbed. The conclusion is given in Chapter 8 which also details the future work to be done.