Design and Implementation of Real-Time Cognitive Dynamic Spectrum Radio, Targeting the FM Radio Band with PHYDYAS FS-FBMC

A THESIS SUBMITTED TO
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By

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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy, which has been carried out at the Institute for Signals, Sensors and Communications of the Electronic and Electrical Engineering Department at the University of Strathclyde, Glasgow, UK.

Declaration

I declare that this thesis embodies my own research work and that it is composed by myself. Where appropriate, I have made acknowledgements to the work of others.

Kenneth W. Barlee

Acknowledgements

I would firstly like to thank my family, friends and colleagues for their support throughout the course of my work. I got there in the end! Thanks to the core 2016-2018 Postgraduate Society team for providing a fun and enjoyable environment to relax and socialise with other PhD students from across the University. You really brought me out of my shell, and of course inadvertently introduced me to my Wife! Laura, thank you for always supporting me, for pushing me to complete my thesis, and for putting up with my nocturnal engineering habits.

Thank you to my supervisors, Prof Bob Stewart and Dr Louise Crockett, for handing me an RTL-SDR back in the summer of 2013 and saying “figure out what this does”! Thank you for providing me the opportunity to research, implement and play with software defined radios over the last 7 years. Our group has come a long way from the early days of Dale and myself building FM Radio receivers with the RTL-SDR. We are now building ground breaking SDR-powered 5G mobile networks and getting to work with incredible new SDR devices like the Xilinx RFSoC; and it is testament to the hard work of the whole team in the Strathclyde SDR lab, and the leadership of Bob, Louise and Dr David Crawford.

Thanks to Neil, Phil, Ousman and other colleagues (/former colleagues) from the Glasgow MathWorks team. The internship they offered was an invaluable experience, without which I would never have been able to carry out the complex ZynqSDR targeting of my radio design. I would also like to thank the Xilinx University Program for the donation of the Xilinx ZC706 development board used in this research.

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Abstract

Demand for wireless connectivity is exponentially increasing. Allocated bands in the Radio Frequency (RF) spectrum are commonly presented as being nearly at capacity, but in reality, they are often under-utilised. New shared spectrum regulations, combined with Dynamic Spectrum Access (DSA) technologies and Software Defined Radio (SDR) allow third parties to access vacant spectrum that has been traditionally licensed to broadcasters and mobile network operators. Regulators and research institutions worldwide are actively exploring the sharing of finite spectral resources, driving a wireless revolution that will bring lower cost and ubiquitous connectivity.

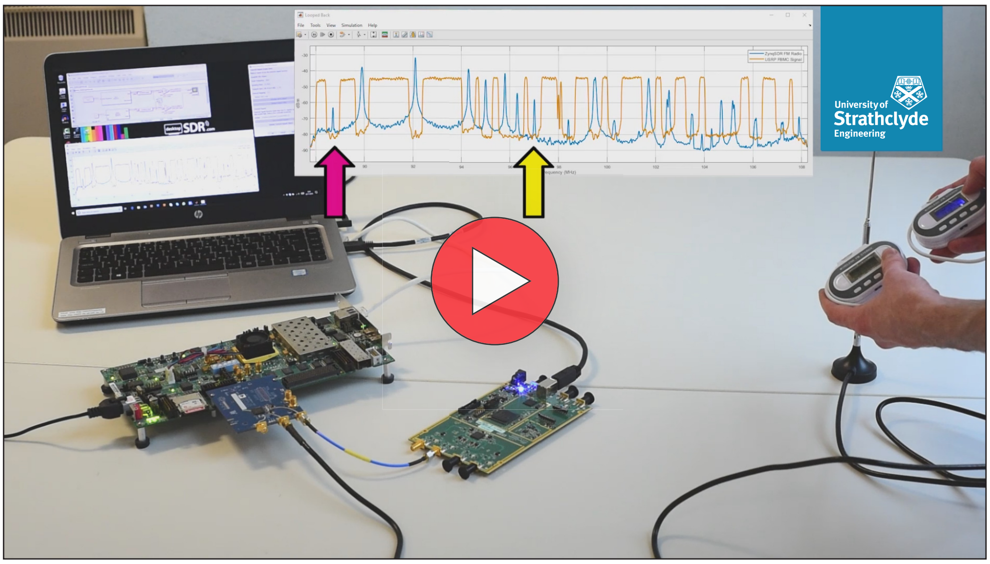
This thesis presents and validates a disruptive new spectrum sharing technique that facilitates access to the significant amount of vacant spectrum in the band traditionally used for analogue FM Radio broadcasting (88-108 MHz), providing a potential communications solution for load balancing and demand side management in smart grid networks. In this work, a novel, real-time DSA-enabled radio transmitter is designed, implemented, and targeted to programmable 'ZynqSDR' hardware, and investigations are carried out to determine whether it is capable of coexisting with incumbent FM Radio stations. The transmitter uses the Frequency Spread Filter Bank Multicarrier (FS-FBMC) modulation scheme—which has low levels of Out-Of-Band (OOB) leakage—and a non-contiguous subchannel mask, which can automatically reconfigure itself in real time to change the spectral characteristics of the output signal. It was developed using low level Digital Signal Processing (DSP) components from within MATLAB and Simulink.

The FBMC Secondary User (SU) radio was shown to cause minimal interference to FM Radio stations when 'transmitting' at low broadcast powers (e.g. 20 dBm) and using a 200 kHz guardband, indicating that an SU such as the one proposed in this thesis would be capable of legally coexisting with (and transmit alongside) incumbent FM Radio signals; provided radio spectrum regulations were modified to permit legal operation.

Graphical Abstract

A video presentation has been developed as a graphical abstract to this work. This explains how the novel Dynamic Spectrum Access (DSA) Frequency Spread Filter Bank Multicarrier (FS-FBMC) transmitter was developed and targeted to programmable 'ZynqSDR' Software Defined Radio (SDR) hardware, and introduces the series of experiments used to validate the design's 'cognitive' DSA capabilities. The reader can visualise how experiments were carried out, and view 'live' spectrum analyser windows that show the real time operation of the radio. The reader is strongly encouraged to view this before proceeding.

The video has been published and issued a DOI, and is available to download and watch at:
https://doi.org/10.15129/607b5dd7-1ab6-4efb-8a55-18876919714c
https://youtu.be/AZoS_-n-SsY (also available to watch on YouTube)



Screenshot from the companion video, demonstrating the FBMC signal dynamically adapting to the changing FM Radio environment in real time on the ZynqSDR at the University of Strathclyde in Glasgow city centre

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Acronyms and Units

The following acronyms are used throughout this thesis.

6LoWPAN	IPv6 Low-power Wireless Personal Area Networks
ACARS	Aircraft Communications Addressing and Reporting System
ACLR	Adjacent Channel Leakage Ratio
ADC	Analogue to Digital Converter
ADSL	Asymmetric Digital Subscriber Line
AGC	Active Gain Control
AM	Amplitude Modulation
AP	Access Point
ATSC	Advanced Television Systems Committee
AXI	Advanced eXtendable Interface
BER	Bit Error Rate
BPF	Bandpass Filter
DAB	Digital Audio Broadcast
DAC	Digital to Analogue Converter
DFT	Discrete Fourier Transform
DNO	Distribution Network Operator
DSA	Dynamic Spectrum Access
DSM	Demand Side Management
DSP	Digital Signal Processor
DTT	Digital Terrestrial Television
DTV	Digital Television
DVB-T2	Digital Video Broadcast - Terrestrial (version 2)
CDMA	Code Division Multiple Access (3G)
CFO	Carrier Frequency Offset
COM	Serial Port (on a computer)
CORDIC	COordinate Rotation DIgital Computer
CSMA	Carrier Sense Multiple Access
CP	Cyclic Prefix
CPU	Central Processing Unit
CR	Cognitive Radio
CWSC	Centre for White Space Communications (University of Strathclyde)
ECC	Error Correction Code

ETSI	European Telecommunications Standards Institute
EU	European Union
EV	Electric Vehicle
F-OFDM	Filtered OFDM
FAT	Frequency Allocation Table
FBMC	Filter Bank Multicarrier
FCC	Federal Communications Council
FIFO	First In First Out
FIR	Finite Impulse Response (Digital Filter)
FFT	Fast Fourier Transform
FM	Frequency Modulation
FMT	Filtered MultiTone
FPGA	Field Programmable Gate Array
FS	Frequency Spread
GSM	Global System for Mobile (2G)
GPS	Global Positioning System
HAN	Home Area Network
HD	Hybrid Digital
HDL	Hardware Definition Language
HN	Hidden Node
I	In Phase (signal)
ICI	Inter Carrier Interference
IDFT	Inverse DFT
IFFT	Inverse FFT
IoT	Internet of Things
IP	Intellectual Property
IQ	In Phase/ Quadrature Phase (signal)
ISI	Inter Signal Interference
ISM	Instrumentation, Scientific and Medical
ITU-R	International Telecommunications Union Radiocommunication Sector
JTAG	Joint Test Action Group (circuit board test and debug port)
LAL	Local Access Licence (Ofcom)
LFSR	Linear Shift Feedback Register
LTE	Long Term Evolution (4G)
LTE-A	Long Term Evolution-Advanced (4.5G)
LTE-APro	Long Term Evolution-Advanced Pro(4.9G)
LUT	Lookup Table
M2M	Machine to Machine (Communication)
MA	Multiple Access
MAC	Media Access Control Layer
MCM	MultiCarrier Modulation
MCS	Modulation Coding Scheme

MIMO	Multiple Input Multiple Output
MMS	Maritime Mobile Service
mmWave	Millimetre Wavelength (Signals)
MNO	Mobile Network Operator
NC	Non-Contiguous
NR	New Radio (5G)
NTSC	National Television System Committee
Ofcom	Office of Communications
Ofgem	Office of Gas and Electricity Markets
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OOB	Out Of Band (spectral leakage)
OQAM	Offset QAM
ORIT	Organisation Internationale de Radiodiffusion et de Télévision
OS	Operating System
PAPR	Peak to Average Power Ratio
PCI	Physical Cell Identity
PHY	PHYsical Layer
PHYDYAS	PHYsical layer for DYnamic AccesS
PMSE	Programme Making and Special Events
PMR	Professional Mobile Radio
PPN	PolyPhase Network
P/S	Parallel to Serial Operation
PSK	Phase Shift Keying
PU	Primary User
Q	Quadrature Phase (signal)
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RB	Resource Block
RBF-OFDM	Resource Block Filtered OFDM
RC	Raised Cosine
RDS	Radio Data Service
RF	Radio Frequency
RSI	Root Sequence Index
RTS	Radio Tele-switching Service
Rx	Receive
SAL	Shared Access Licence (Ofcom)
SDR	Software Defined Radio
SINR	Signal to Interference Noise Ratio
SIR	Signal to Interference Ratio
SISO	Single Input Single Output

SMETS2	Smart Metering Equipment Technical Specifications version 2
SNR	Signal to Noise Ratio
SoC	System on Chip
SOM	System On Module
SSH	Secure Shell
S/P	Serial to Parallel Operation
SU	Secondary User
TDMA	Time Division Multiple Access
TxRx	Transceive
TV	Television
TVWS	TV White Space
Tx	Transmit
UE	User Equipment
UFMC	Universal Filtered MultiCarrier
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunications Service (3G)
UN	United Nations
USRP	Universal Serial Radio Peripheral
V2G	Vehicle to Grid
VHF	Very High Frequency
WAN	Wide Area Network
WSDB	White Space Database
WTR	Wireless Telegraphy Register

The following SI Prefixes and units are used throughout this thesis:

µ	micro (10^-6)
m	milli (10^-3)
k	kilo (10^3)
M	Mega (10^6)
G	Giga (10^9)
Hz	Hertz
Sa	Sample
Sym	Symbol
b	bit
B	Byte
s	second
m	metre
/	‘per’, i.e. Sym/s = Symbols per second

Key Terms

The following key terms are used throughout this thesis.

Primary User	Primary user of the radio spectrum, normally the holder of a spectrum license from a spectrum regulator, such as TV broadcasters and cellular companies.
Secondary User	Secondary user of the radio spectrum, normally unlicensed and transmitting in shared spectrum at a low power.
Radio spectrum Channel	Individual communication channel, used by a primary user to transmit a signal.
Radio spectrum Band	A group of channels, often block allocated by a spectrum regulator for a particular type of use.
Shared Spectrum	Radio spectrum bands are normally licensed to primary users and reserved for a particular type of use. For various reasons though, often not all spectrum in these bands is fully utilised. Shared spectrum policies allow secondary users to make use of unused, often licensed, spectrum.
Dynamic Spectrum Access	A technology that enables secondary users partially or fully automated access to shared spectrum bands.
Software Defined Radio	A radio system where components typically implemented with dedicated hardware (e.g. mixers, filters, modulators, demodulators) are instead implemented with programmable radio hardware and software.
Hardware Targeting (in the context of this thesis)	The process of implementing a fixed point HDL design on programmable FPGA hardware.

Chapter 1

Introduction

The demand for wireless connectivity is exponentially increasing. The Radio Frequency (RF) spectrum is under pressure, yet licensed bands are often under-utilised. This research aims to investigate whether it would be possible for a third party to access and transmit in vacant parts of the band traditionally used for FM Radio broadcasting (88–108 MHz), without causing harmful interference to incumbent FM Radio signals. This band is rarely fully utilised, and the favourable radio propagation characteristics of this band make it an exciting candidate for spectrum sharing.

1.1 Secondary User Access to the Radio Spectrum

The RF spectrum is a part of the electromagnetic spectrum that exists between the frequencies 3 kHz and 300 GHz. It is used extensively for applications such as Television (TV), commercial radio stations, mobile/cellular, Wi-Fi and satellite communications. The RF spectrum is divided up into a number of frequency bands—each allocated for a particular purpose—and the allocation of bands is managed by government-owned spectrum regulators such as Ofcom (UK) and the FCC (USA). Primary Users (PU) such as TV broadcasters and cellular operators obtain licences from regulators, to reserve portions of the spectrum solely for their use. Additionally, swathes of the spectrum are reserved for use by the emergency services and the military. Generally speaking, it is illegal for any person or organisation to transmit in these bands without the consent of the licence holder.

It is possible to transmit in some parts of the spectrum on an unlicensed basis. Devices such as wireless doorbells, garage door remotes and car keyfobs utilise what are called Industrial, Scientific and Medical (ISM) bands. These were originally intended to provide free and unlicenced spectrum access for devices that only need to send and receive signals on an irregular basis. Due to the fact that these bands were open for unlicensed use, rather more intensive applications began to operate in them. Wi-Fi and Bluetooth are prime examples of everyday communications protocols that were developed to operate in the unlicensed 2.4–2.5GHz ISM band.

As technology has improved in the last few decades, the demand for wireless data continues to increase. People now have more smartphones, tablets and laptops than ever before. With the advent of 8k video, and streaming services such as YouTube, Netflix and Amazon Prime Video, an extraordinary strain is being placed on particular bands of the RF spectrum. Cisco predicts that, by 2021, over 50% of all Internet connected devices will be 'smart' devices, and that the volume of mobile Internet traffic will have reached a total of 125 Exabytes (134,217,728,000 GB) per month [19].

Spectrum is a valuable commodity and asset, and therefore licences for bands suitable for mobile and wireless communications often cost a significant amount of money. Despite this, PUs for various reasons often do not use all of their licensed spectrum in all licensed geographical areas, and this results in valuable spectral resources lying fallow. New shared spectrum initiatives are being introduced, enabling Secondary Users (SU) to access the spectrum, allowing for more efficient use of this finite resource [185]. The SU is an opportunistic user, which may or may not have a licence to broadcast, and can only transmit in parts of the spectrum which are unoccupied by the PU. Coupled with Dynamic Spectrum Access (DSA) technologies, SU radios are able to make use of these valuable spectral resources; providing additional communications channels to help ease the burden on existing services.

1.2 Research Aim and Objectives

This research aims to investigate the potential for a SU to operate inside the band traditionally used for FM Radio broadcasting (88–108 MHz), without causing harmful interference to PU FM Radio signals. As will be discussed in the coming chapters, the FM Radio band is not fully utilised, and the favourable RF propagation characteristics of this Very High Frequency (VHF) band make it an exciting candidate for spectrum sharing.

A novel, real-time, cognitive DSA-enabled radio transmitter Physical Layer (PHY) was designed, implemented and targeted to programmable Software Defined Radio (SDR) hardware in order to enable this investigation. This SU radio is able to establish data communication channels in vacant parts of the PU FM Radio spectrum using a MultiCarrier Modulation (MCM) scheme with a Non Contiguous (NC) channel mask, facilitating the transmission of data for Internet of Things (IoT)/ smart grid applications. Due to the lack of an existing spectrum sharing geolocation database for the FM Radio band, a spectrum sensing module was incorporated into the design that was capable of automatically generating a spectrum mask to control the transmitter, ensuring that no data is modulated into channels being used by a PU FM Radio station.

1.2.1 Design Specification

Design a DSA-enabled SU radio PHY that is capable of accessing and establishing communications links in vacant channels of the FM Radio band, that could be used to enable low data rate IoT and smart grid applications.

Design Requirements:

- The radio must cause minimal (–to no) noticeable interference to broadcast PU FM Radio channels (i.e. there should be a minimal loss in the audio quality of demodulated FM signals).
- The radio should use an adaptive NC-MCM scheme, and have suitably low Out-Of-Band (OOB) leakage power, such that it is capable of meeting speculated transmission and OOB leakage power levels for SUs operating in the FM Radio band.
- In the absence of a SU database, the radio should be capable of identifying vacant FM Radio channels independently, and automatically building a suitable NC-MCM channel mask complete with frequency guardbands that protect the PUs.
- The design should be prototyped on programmable SDR hardware to allow for real-time closed door testing to be carried out.

1.2.2 Review of Design Decisions

In line with the specified requirements, the following design decisions were taken:

- *The radio will use a Frequency Spread Filter Bank Multicarrier/Offset QAM (**FS-FBMC/OQAM**) PHY, with a **PHYDYAS** prototype filter.* As discussed in Section 3.3, the FS form of FBMC is better suited to DSA applications. While it is possible to utilise a mixed PolyPhase Network (PPN)/ FS radio pair, for this initial investigation, the decision was made to concentrate on one scheme only. The PHYDYAS prototype filter offers a good balance between design complexity and OOB attenuation, and should be capable of meeting the anticipated Adjacent Channel Leakage Ratio (ACLR) requirements.

- *The radio will use a **Matched Detector** for spectrum sensing.* Much research has been performed on cognitive sensing techniques, and the recurring findings from prior research suggest that, when there is prior knowledge about the type of signal expected to be present in a particular band, a matched detector will always provide the best detection results [61][124][156]. As this radio is being designed specifically to target the FM Radio band, all PU signals broadcast in the band should be FM modulated. Therefore, a matched detector in the form of an FM Radio demodulator will be used.

- ***Guardbands** will be required in the SU **channel mask** (introduced in Section 5.5).* Once sensing has been carried out, the radio will need to develop a channel mask that is capable of controlling the FS-FBMC transmitter. Suitable guardbands will be required in order to protect the PU signals. Research will need to be carried out with a prototype transmitter in order to establish a suitable size for the guardbands.

- *For a real system demonstration, the design will ultimately be targeted to a **ZynqSDR** (introduced in Section 2.5.1).* As such, the development will be carried out in Simulink, using low level components from the MathWorks *HDL Coder* library. This 'model-based design' approach used allows for rapid prototyping on real radio hardware.

1.3 Contributions

The following are considered to be the contributions made by the work presented in this thesis:

- A case study is presented of FM Radio band utilisation for Central Scotland. This is the first such study in the UK that allows comparison with the occupancy studies by Otermat [118] in the USA.
- A novel SU radio application that can utilise vacant spectrum in the band traditionally used for FM Radio is proposed, that would enable Distribution Network Operators (DNOs) to broadcast Demand Side Management (DSM) messages to consumer smart home equipment, providing an improved replacement to the ageing Radio Tele-switching Service (RTS) and a communications solution for load balancing in the smart grid.
- A novel, real-time, cognitive DSA-enabled radio transmitter PHY is designed, implemented and targeted to programmable SDR hardware. This is one of few published works exploring an FS-FBMC FPGA system level hardware implementation, and one of even fewer that is targeted to SDR hardware. The transmitter PHY is fully tailored for the application and target hardware, with a custom modulator architecture (and FBMC parameters) developed to meet the design constraints for ZynqSDR targeting.
- A module is developed to automatically generate a subchannel mask that controls the spectral output of the transmitter. This module identifies vacant spectrum using a series of matched detectors, and is shown to be capable of automatically constructing a subchannel mask complete with guardbands, based on detected PU activity, in a period of 320 ms. This is the first such mask generator for SU access to the FM Radio band reported in the literature.
- A series of investigations are carried out both in software and using the targeted SDR hardware to explore the effects the FBMC SU has on the quality of PU FM Radio signals when 'overlaid' on the FM spectrum (and vise versa, the effects that PU signals have on the SU), with various SU transmit powers and frequency guardband sizes. The FBMC SU was shown to cause minimal interference at low broadcast powers (e.g. 20 dBm). Recommendations are made of a minimum guardband size of 200 kHz to protect PU signals.

- Following investigations carried out in this work, an argument is presented that it would be possible for a SU to operate inside the FM Radio band without causing harmful interference to PU signals, using a radio transmitter such as the one developed in this thesis.

1.4 Related Works

Otermat *et al.* were the first to propose targeting the FM Radio band for low power SUs [116][117][118]. Their research provides strong evidence that the FM spectrum (in the USA) is not used as effectively as it could be, and presents the argument that the band could be used by SU devices to enable IoT applications. Ernesto [35] and Capela [17] discuss the propagation benefits of low frequency bands for Cognitive Radio (CR) applications. Ernesto presents a CR for voice communication in disaster recovery situations, that accesses vacant spectrum in the AM and FM Radio bands; while Capela demonstrates an NC OFDM based CR targeted at Maritime Mobile Service (MMS) frequencies (156–174 MHz).

Radios using a NC OFDM PHY layer for SU spectrum access have been presented by several other researchers; eg. Bindiganavile [13], Bobrowski [14], Capela [17], Iyer [73], Rajbanshi [121], Recio [124] and Sanker [128]. This scheme is the clear favourite in the literature when with comes to NC-MCM, however, it is unsuitable for the application in question. The drawback of NC OFDM’s excessive spectral leakage is identified by Recio, and suggestions are made in his work that either FBMC or Filtered MultiTone (FMT) based PHY layers may be more suitable alternatives for DSA scenarios. These findings are in line with those of Farhang-Boroujeny [41], Mahmoud [84], Ravindran [123] and Weiss [150].

Much of the material published around FBMC/OQAM for SU access focuses on system architecture proposals and the simulation and evaluation of FBMC waveforms, such as the work of Velamala [143] and Zhang [156]. They present PPN-FBMC radios suitable for general SU coexistence, with implementations limited to simulations. Of the few published FBMC hardware implementations, most of the focus has been on PPN-FBMC. Berg [12] proposes the use of NC PPN-FBMC for accessing vacant TV White Space (TVWS) bands, and presents an implementation of a transmitter on the Xilinx-based T-Flex Field Programmable Gate Array (FPGA) platform, and analyses the hardware resource requirements and utilisation after the place and route processes. Nadal [91] presents a low complexity FPGA implementation of the PPN-based approach that uses Fast Fourier Transform (FFT) pruning to reduce hardware processing requirements. Shaheen [133] discusses an FPGA implementation of a PPN-FBMC transmitter and receiver pair, with a focus on the resource utilization and power consumption of the design.

Initial comparisons between PPN-FBMC and the alternative architecture, FS-FBMC, are provided by Bellanger [9]. Varga [142] and Keerthana [75] compare the computational requirements of the two architectures, and more general comparisons of hardware resource requirements between various NC modulation schemes are presented in [52] by Gerzaguet. Carvalho [18] and Ferreira [47] perform analysis of the resource requirements and FPGA utilisation for a generic dynamic FS-FBMC transmitter using a ZedBoard (Zynq System on Chip (SoC) development board). Ferreira goes on to implement and compare reconfigurable OFDM, FS-FBMC and Universal Filtered MultiCarrier (UFMC) transmitters on Zynq FPGA hardware [48][49].

Kaushik and Wunsch [78][152] present an SDR FPGA demonstrator of a PPN-FBMC transmitter on a Universal Software Radio Peripheral (USRP), presented at the DySPAN conference, that uses energy detection and preamble detection algorithms to prevent it interfering with PU signals. This is similar to the work by Dziri [34] and Horváth [60]. Font-Bach's work [50] compares hardware implementations and coexistence capabilities of PPN-FBMC and cellular OFDM transmitters using the Xilinx ZC706 FPGA and Analog Devices FMCOMMS 3 SDR front end, for the application of SU access to Professional Mobile Radio (PMR) bands. Drozdenko presents an 802.11a SDR–Wi-Fi implementation targeted to the same hardware in [30]-[33], using the MathWorks model-based design workflow for SDR targeting featured in this thesis.

The only other publications of note that make use of the workflow are by Dang [25] and Cai [16], which review Quadrature Phase Shift Keying (QPSK) transmitter/ receiver examples created by MathWorks to demonstrate their tools [191][192]. Finally, a state of the art SDR prototyping platform using the Xilinx RFSoC R ZCU111 is discussed by Goldsmith in [55]. This is a single-chip SDR device that has direct support for all frequency bands across the range 0-6 GHz, with RF-ADCs and RF-

DACs (RF Analogue-to-Digital and Digital-to-Analogue Converters) operating at 4096 MSa/s (Mega samples per second) and 6554 MSa/s respectively. With the addition of appropriate RF signal conditioning stages, it could be argued that this new platform is a key enabler and solution for future DSA radios.

To the best of the author's knowledge, no other DSA radio has been developed to address the opportunity (and challenge) of enabling SU communication in the FM Radio band. This thesis is one of few published works that presents an FS-FBMC FPGA hardware implementation, and one of even fewer that is targeted to real-time programmable SDR hardware. The transmitter PHY is fully tailored to the application, with custom FBMC parameters and modulator implementations; and experiments are carried out to explore the effects that the signals it generates have on incumbent PU FM Radio signals.

1.5 List of Publications

Below is a list of publications resulting from work carried out during these studies. Publications [A]-[D] are focused specifically on this research, while the others can be grouped as publications on SDR. Further information about these publications is presented on page 145.

[A] K. W. Barlee *et al.*, "Rapid Prototyping and Validation of FS-FBMC Dynamic Spectrum Radio with Simulink and ZynqSDR" (journal), in IEEE Open Journal of the Comms. Soc. (OJ-COMS), Nov 2020.
Available: https://doi.org/10.1109/OJCOMS.2020.3039928

[B] K. W. Barlee, R. W. Stewart and L. H. Crockett, "Secondary User Access for IoT Applications in the FM Radio Band using FS-FBMC" (conference paper + presentation), in IEEE 5G World Forum (5GWF), Silicon Valley, CA, USA, Jul 2018.
Available: https://doi.org/10.1109/5GWF.2018.8517058
Available: https://www.slideshare.net/slideshow/embed_code/key/HFNDdTPleQcXeW

[C] K. W. Barlee, R. W. Stewart and L. H. Crockett, "Dynamic Spectrum Access: Secondary User coexistence in the FM band" (poster), Presented at New England Workshop on Software Defined Radio, Worcester, USA, May 2018.
Available: https://pureportal.strath.ac.uk/en/publications/dynamic-spectrum-access-secondary-user-coexistence-in-the-fm-band

[D] K. W. Barlee, "Glad to be Grey: The Power of Shared Spectrum" (magazine), in UK Government Department for Digital, Culture, Media and Sport (DCMS) 5G Innovation Briefing, no. 3, pp. 53-56, Jun 2020.
Available: https://flickread.com/edition/html/5f15a4240e557#53

[E] J. Goldsmith *et al.*, "Control and Visualisation of a Software Defined Radio System on the Xilinx RFSoC Platform Using the PYNQ Framework" (journal), in IEEE Access, vol 8, pp. 129012-129031, Jul 2020.
Available: https://doi.org/10.1109/ACCESS.2020.3008954

[F] R. W. Stewart *et al.*, "A low-cost desktop software defined radio design environment using MATLAB, Simulink, and the RTL-SDR" (journal), in IEEE Comms. Mag., vol. 53 no. 9, pp. 64-71, Sep 2015.
Available: https://doi.org/10.1109/MCOM.2015.7263347

[G] R. Stewart, K. Barlee, D. Atkinson, L. Crockett, "Software Defined Radio using MATLAB & Simulink and the RTL-SDR" (textbook), Strathclyde Academic Media, Sep 2015.
Available: www.desktopSDR.com/download

[H] K. W. Barlee, R. W. Stewart and L. H. Crockett, "The teaching and learning of DSP enabled Software Defined Radio using MATLAB & Simulink and the RTL-SDR" (poster), Presented at 8th New England Workshop on Software Defined Radio, Worcester, USA, May 2015.
Available: https://pureportal.strath.ac.uk/en/publications/the-teaching-and-learning-of-dsp-enabled-software-defined-radio-u

[I] H. Mohamed *et al.*, "Partial discharge detection using software defined radio" (conference paper), ICSAE'16, Newcastle upon Tyne, UK, pp. 373-376, Oct 2016.
Available: https://doi.org/10.1109/ICSAE.2016.7810220

[J] H. Mohamed *et al.*, "Partial discharge detection using low cost RTL-SDR model for wideband spectrum sensing" (conference paper), ICT'16, Thessaloniki, pp. 1-5, May 2016.
Available: https://doi.org/10.1109/ICT.2016.7500353

[K] H. Mohamed *et al.*, "Partial discharge localization based on received signal strength" (conference paper), in ICAC'17, Huddersfield, UK, pp. 1-4, Sep 2017.
Available: https://doi.org/10.23919/IConAC.2017.8082028

1.6 Thesis Organisation

The remainder of this thesis is organised as follows:

- **Chapter 2** presents a review of the role of spectrum regulators, spectrum allocation policies and licensing, new shared spectrum initiatives and dynamic spectrum access. SDR is presented as the DSA enabler, and the radio hardware used in this work is introduced.

- **Chapter 3** provides an overview of popular NC-MCM schemes, and presents an argument as to why FBMC/OQAM is the most suitable contender for a DSA-enabled SU radio.

- **Chapter 4** introduces FM Radio, worldwide broadcast variations and the (non-impending) digital switchover. Underutilisation of the band is discussed, and a case study is presented that explores FM band occupancy in Central Scotland. A new SU application for vacant FM spectrum is proposed.

- **Chapter 5** reviews the design and implementation of the FS-FBMC/OQAM modulator, developed for SU access in the FM Radio band. A high level overview of the full design is presented, alongside details of the transmitter protocol. A basic receiver is developed, and simulations are carried out to investigate interference effects caused by the radio to PUs, and also the effect that the SU radio has on the quality of PU FM Radio stations.

- **Chapter 6** sees the design targeted to a ZynqSDR. Once implemented on the hardware, the transmitter is subjected to the various FM Radio environments sampled from around Central Scotland in a closed loop simulation. An investigation into SU guardband sizes is carried out, and interference effects are explored. Finally, the design is configured into full 'cognitive' mode, and is shown to be capable of dynamically adapting its NC transmitter mask in real time, so as to protect FM Radio signals that it detects off the air.

- **Chapter 7** presents a resume, key conclusions and future work.

- The full results of the Central Scotland FM Band occupancy study are presented in **Appendix A**.

Chapter 2

Spectrum Policy and Dynamic Spectrum Access

Wireless devices make use of the electromagnetic spectrum in order to communicate. Most (with the exception of those that use infrared or visible light) operate in the sub-300 GHz part, known as 'Radio' and 'Microwave' spectrum; more generally referred to as the 'RF' spectrum. In each country, this spectrum is normally managed by a spectrum regulator. Traditional spectrum policies have seen regulators categorise bands of RF spectrum for specific applications, and exclusively license these bands to particular 'users'. Spectrum is a valuable commodity, and therefore licences often cost a significant amount of money. Despite this, not all licensed spectrum is used. New shared spectrum initiatives taking place around the world are seeing this model change. Regulators are putting rules in place to allow third parties to access these unused bands on a shared/ dynamic scheduling basis, and many of them are looking to charge only a small administrative fee for the service.

Dynamic Spectrum Access takes shared spectrum a step further. Here, radios can access the spectrum and create communication channels dynamically. To do this, they must be spectrally aware, and use frequency agile modulation techniques in order to make use of available spectral resources. With large swathes of the spectrum underutilised, DSA has the potential to solve the spectral shortage 'crisis'.

2.1 Chapter Overview

This chapter reviews the role of spectrum regulators, their traditional spectrum allocation policies, and the shortfalls of these practices. An up-to-date analysis of new spectrum sharing technologies is presented. These technologies enable third parties to access unused frequencies, leading to more efficient use of the radio spectrum. DSA is introduced, and DSA radio requirements and DSA policy are reviewed. Finally, a brief introduction is made to Software Defined Radio, a DSA-enabling technology.

2.2 Regulators and Spectral Assignment

Every country has its own national spectrum regulator (e.g. Ofcom, the Office of Communications in the UK, and the FCC, the Federal Communications Council in the USA) which oversees the classification of bands and the licensing of spectral resources to particular users within their jurisdiction. These regulators do not have total control however, as they must obey rules set at an international level.

This section will discuss the spectral regulation hierarchy, introduce the static spectral assignment approach used by regulators, and present the shortcomings of this practise.

2.2.1 The Spectral Regulation Hierarchy

On a global scale, the International Telecommunications Union Radiocommunication Sector (ITU-R) of the United Nations (UN) is in overall charge of spectrum assignments. It was established in 1927 (originally named the International Radio Consultative Committee, CCIR), and develops radio regulations and procedures under an international treaty [87][187]. One of its main aims is coordination; to ensure the compatibility of radio technologies all around the world, and to prevent countries causing harmful interference to each other's spectrum [189]. Every member state[1] is encouraged to adopt the rules produced by ITU-R, and can only deviate as long as they prove that they will not cause interference to neighbouring countries. Example ITU-R regulations include the designation of the 2.4–2.5 and 5 GHz bands for 'ISM' [106] (used worldwide for Wi-Fi), and the 130 MHz band for 'ACARS' aeronautical communications.

In Europe, the next level of management is the European Telecommunications Standards Institute (ETSI). ETSI is an officially recognised standards organisation, which produces *harmonised standards* for the EU single market[2] [178]. It's main aim

1. *There are currently 196 member states of the ITU [188]*

is to ensure the inter-operability of technologies between countries across Europe. With these efforts, manufacturers are able to develop radio equipment which is suitable for use in many countries, meaning that consumers do not need to purchase individual User Equipment (UE) for use in each country [87]. ETSI was heavily involved in the development of 3GPP's 2G GSM, 3G CDMA/ UMTS and 4G LTE standards.

The latest ETSI *EU Radio Equipment Directive* [36] came into force in June 2017 [179]. This is a series of mandatory laws that must be adopted by all manufacturers developing radio products for commercial use within the EU. They ensure that all equipment conforms to ETSI standards, and that it meets all health, safety and emissions regulations; and therefore has the right to bear the EU CE symbol (CE).

On a local level, each country also has its own national regulator. They oversee the allocation and licensing of spectral resources to individual users, based on the rules passed down by the international bodies. In the UK, this task falls upon the Ofcom, (previously known as the Office of Telecommunications, Oftel, before 2003). The Communications Act of 2003 gave Ofcom permission to autonomously manage around 75% the UK's radio spectrum[3] [110]. This is a valuable market asset which, as of 2012, contributes over £50bn to the country's economy each year [27].

2.2.2 Static Spectral Assignment

Allocation in the UK (and in other countries) is rather static, and this is largely due to the way in which the spectrum has been managed in the past. Normally, regulators grant 'exclusive rights' licences to the highest bidder in a spectral auction [87]. The licence permits the owner to transmit certain types of radio signal in particular RF channels and across large geographical areas, for a fixed period of time (e.g. 15 years). Bidders tend to be state broadcasters or private companies; and when successful, they become the PU of the band in question.

With the static assignment rules, even when a PU does not fully utilise channels it 'owns' across 100% of the area in which it is allocated as the sole user, no other operator

2. ETSI has 856 members from 65 countries across 5 continents, not all in the EU [177]
3. The remaining 25% is viewed as 'crown' property, and is allocated by the government to public services and the military. This spectrum is not available on the open market.

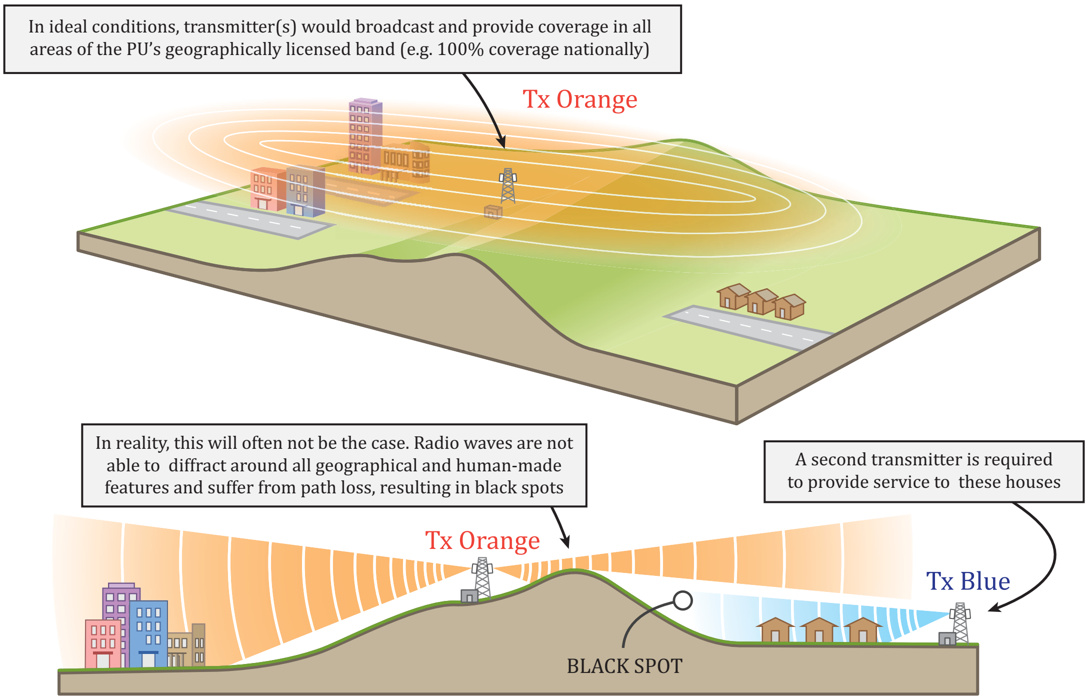

Figure 2.1: A PU black spot, resulting in underutilisation of the spectrum

is allowed to reuse them[4]; resulting in the spectral resources being wasted. (Licences in the UK are often national, so PUs are allowed to broadcast across the whole country). This situation can arise for a number of different reasons; such as when transmitted signals fail to diffract around geological and human-made features (e.g. hills and buildings) causing 'black spots' [163], when PUs hoard licensed spectrum for future use [182], or even when PUs opt not to use the spectrum they have paid for, because there is not a strong enough 'business case' for them to operate their service in a particular geographical area [138].

An example of the 'black spot' situation is shown in Figure 2.1. Here, the hill is preventing the *Tx Orange* PU signal from reaching the houses on the right. To serve these buildings, the PU will need to use another transmitter, *Tx Blue*, which may operate on an alternative frequency channel. This situation is all too familiar in large scale broadcast networks. With the static spectral assignment approach, no other user is allowed to make use of the *orange* frequency band within the black spot area, so the spectral resources of the *orange* band are essentially wasted here. This is a rather extreme example—normally broadcasters will perform calculations and modelling to

4. Unless there is an explicit sub-licensing agreement between the PU and the third party ensure that their transmitters are placed in the most optimal locations (e.g. at the tops of hills), however some black spots will always remain. Rural areas of the UK often suffer from very poor cellular coverage, and indoor coverage in cities is also an issue. A recent study by Arqiva (a large UK communications infrastructure company) found that 49% of people polled experienced poor coverage or dropped calls inside their workplace due to black spots [163]. (This will, in all likelihood, be partly due to the Faraday Cage effect associated with foil backed insulation, metal, and other building materials [125]).

With the static assignment approach, it is also common for large bands (containing numerous channels) to be reserved for a particular type of use, regardless of whether there is actually a PU signal in each individual channel. Prime examples of these are the VHF FM Radio (88–108 MHz) and UHF Digital Terrestrial Television (DTT) (470–790 MHz) bands, and the large *crown* spectrum bands designated for government, military and emergency services use. In theory there can be up to 100 individual FM radio channels (x100 200 kHz channels in the UK) and 40 DTT multiplexes (x40 8 MHz multiplex channels in the UK, each of which can contain up to ~12 Digital TV (DTV) + 10 Digital Audio Broadcast (DAB) stations); yet signals are not normally transmitted in every one of these. One reason for this is because of geographical guard bands/ minimum distance separations (i.e. protected radii around transmitters); but even when these geographically protected coverage areas are accounted for, there are still many usable channels left empty. To give an example, the DTT transmitters for central Scotland are shown in Figure 2.2, along with a list of the channels used at each location. It is clear that not every UHF channel is used (UHF channels 21–60 relate to the 470–790 MHz band); and upon examining the approximate service area of each transmitter (see Figure 2.3), it is obvious that a high number of channels sit empty in many locations.

Regulators frequently publish *Frequency Allocation Tables* (FATs) that provide details about the types of radio service allocated in each band. Links to FATs for various countries around the world are provided in [170].

2.2.3 The Shortcomings of Static Assignment Policy

On paper, the radio spectrum is nearly at capacity. The extremely crowded FATs of the UK [114] and USA [45] highlight the fact that very few unallocated bands remain, and

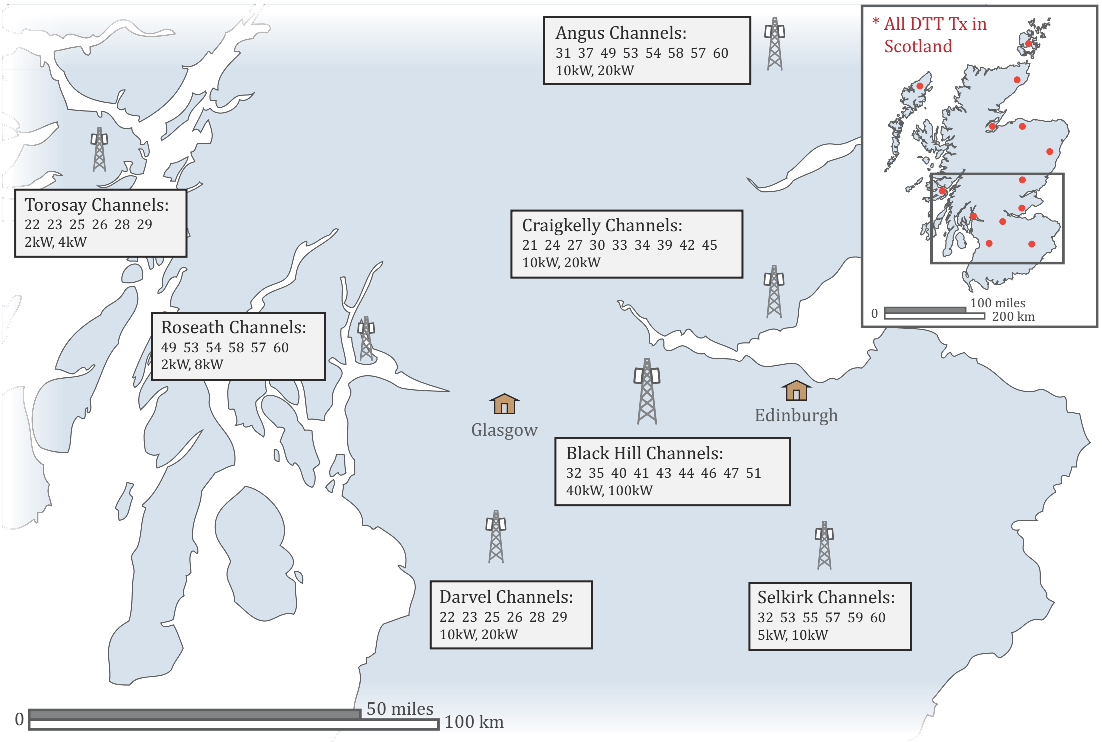

Figure 2.2: DTT DTV and DAB transmitters located in central Scotland, and the UHF channels they broadcast in

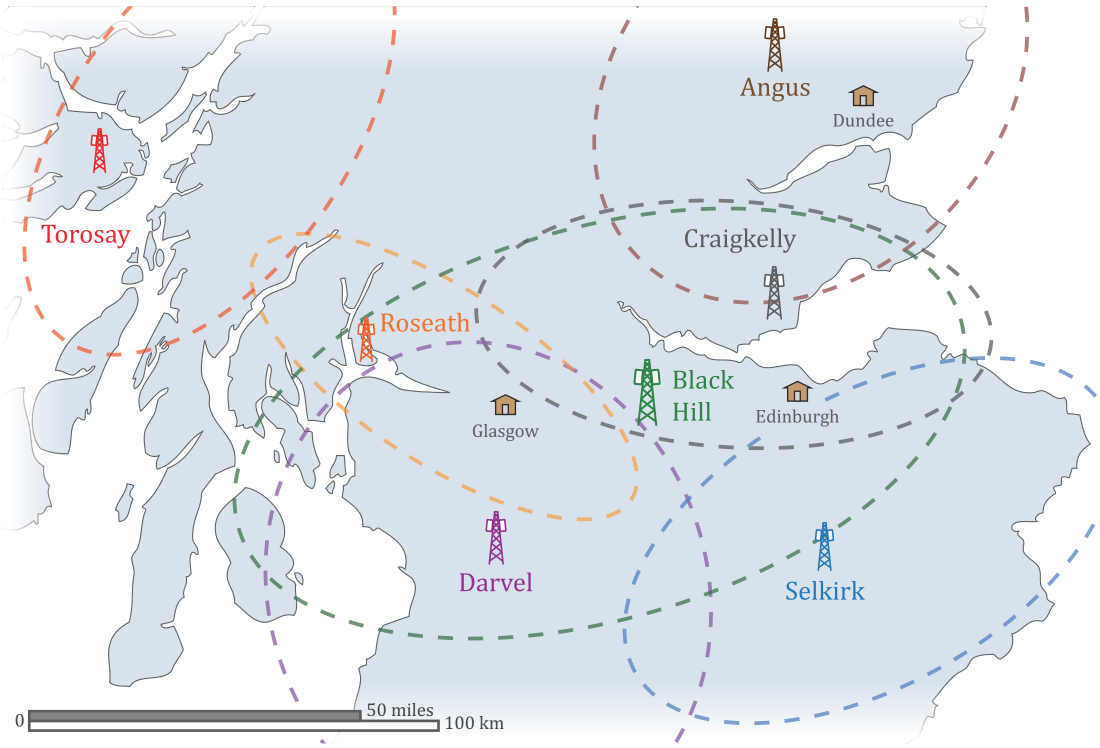

Figure 2.3: A rough plot of the broadcast service area for each of central Scotland's DTT transmitters

licences for those that are available are expensive. Licence fees at the most recent cellular frequency auction in the UK (for the 3.4–3.6 GHz 5G band) totalled £1.37 billion [97] (which works out at an average cost of £7.2 million per MHz). These high prices themselves are a result of spectrum scarcity. Yet upon inspection, large parts of the spectrum are actually underutilsed or not in use at all. As *Zhao* so elegantly puts it in [158], the spectrum shortage 'paradox' is actually caused by the static spectral allocation policy, rather than a physical shortage of available spectrum.

The terms *white*, *grey*, and *black* space have been coined to classify the state of any and every band of the RF spectrum [58]. At any particular location, channels that are continuously occupied by PU signals can be classed as black spaces. Under no circumstances should a another party, a SU, consider accessing these channels to transmit their own signal. White space channels are ones which are not in use at a particular location. These may be empty because they are being used as guard bands to prevent possible interference with other PU signals, or it may just be that the channels have not been used, even though they could have been. There are white spaces all throughout the spectrum (TV, radio, cellular bands etc.), and these are ideal for sharing by SUs, as long as the SU transmissions do not interfere with PU transmissions. Permission to use white spaces may have to be granted from the relevant parties, and an example of this will be discussed further in Section 2.3.1.

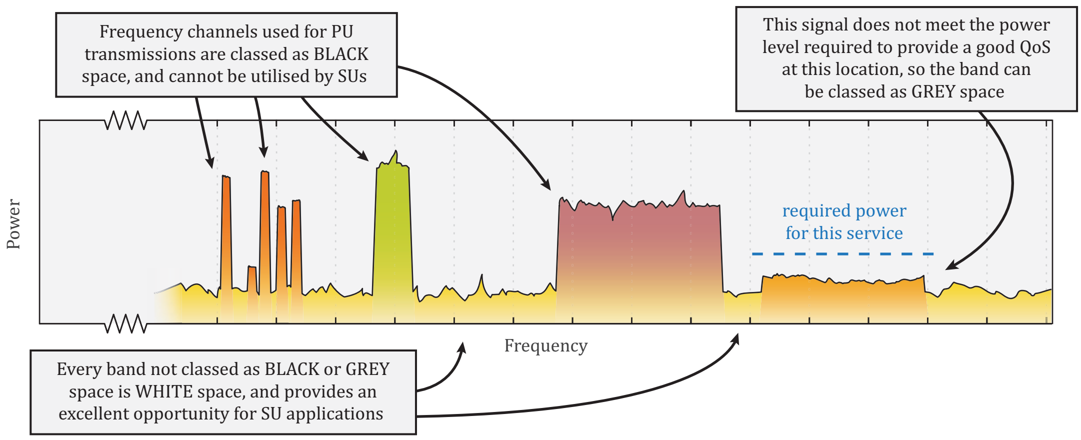

Figure 2.4: A sketch of the RF spectrum highlighting white, grey and black spaces

Finally, grey spaces are channels that are in use on a part time basis, or channels where a received PU signal broadcast from a location far away is too weak to provide the required Quality of Service (QoS) to customers, as shown in Figure 2.4. The weak PU signals may be classed as high powered noise in these situations. Grey spaces pose the greatest challenge to SUs, because in order to operate in them, SU radios must be highly dynamic and able to reconfigure themselves to vacate the band whenever legitimate PU signals are detected. And, if the SU broadcasts over the top of a weak PU signal, it must ensure that it transmits at a sufficiently low power not to cause interference in surrounding areas where the PU's signal can in fact be received. The sharing of grey space in particular is a contentious issue when it comes to spectral politics. Those PUs who have paid for a licence to transmit will not want other users to have the option of using their channels, despite the fact that they are not necessarily even providing a usable service at the location in question.

Under standard static assignment rules, any user who wishes to make use of spectral resources in a band which is not license-exempt (i.e. bands other than those designated for 'ISM') must obtain a licence from the local regulator, or come to an agreement with the PU that 'owns' it. Regulators must always act in the interest of their license-holding customers (PUs such as TV broadcasters and cellular/ Mobile Network Operators (MNOs)), in order to protect the integrity of the channels they have paid for. This means it is highly unlikely that a regulator would grant a black or grey space licence, and a significant amount of valuable white space will be left empty in order to act as guard bands, to protect PU signals. Even if suitable bands are identified from whatever spectrum occupancy databases the regulator has to hand, newcomers will need to pay in order to access them. Under static assignment the concept of SUs is basically non-existent.

In the early 2000s, a number of bodies (governments, regulators and research institutions) around the world began to accept that the way in which spectrum was managed needed to change [20][44][68][135][141][204]. They realised that, by developing new policies incorporating new spectral access concepts such as shared spectrum, finite spectral resources could be used in a far more efficient way.

2.3 The Shift Towards Shared Spectrum

Ofcom ran a consultation on its spectral policy between October 2013 and January 2014 [109], seeking the views of a number of interested parties (cellular operators, national broadcasters, military, energy providers and equipment manufacturers) on issues such as spectrum sharing, international spectrum management rulings (i.e. the

ITU-R and ETSI designations), and for comments on a new spectrum management approach they proposed. Many of the parties who responded were very supportive of the idea of sharing spectral resources, however others were less so. The BBC (one of the main broadcasters in the UK), whose primary concern is the UHF DTT band, responded that it supported the concept of sharing, but on the basis that no harm came to terrestrial BBC services transmitted on neighbouring UHF channels. They also stated that costs associated with reallocating any BBC services should be borne by those who benefit from the bands rather than the BBC—"*Broadcasters, multiplex operators and consumers should not bear the burden of additional costs of a process from which they derive no benefit*" [166]; and suggested that the costs associated with 'spectrum recycling' (i.e. changing the use of specific bands of the spectrum) could be considerably higher than any value gained—"*We would also suggest that Ofcom takes full account on the costs of repurposing services as these costs can often exceed the benefits of introducing the nominally "more valuable" service*" [166].

Feedback drawn from the responses was incorporated into Ofcom's 10 year plan, which was ultimately published in April 2014 [110]. Ofcom stated in this plan that it "*expects to see an increase in shared access to spectrum among different uses*" and pointed out that it has been "*exploring the opportunities*" that sharing could bring [110]. Additionally, Ofcom stated that it would assess over the coming years whether there was the need to develop new regulations specifically focusing on the sharing of spectrum, in order to support the ever growing demand for connectivity from the Machine-to-Machine (M2M) and IoT fields.

2.3.1 TV White Space

One example of channel sharing to have recently taken off in the UK, USA, India and parts of Africa is TVWS–white space in the UHF TV broadcast band. A lot of TVWS channels have been created in the UK in recent years, thanks to the switch from analogue to digital TV. This compacted the spectral requirements of broadcasting whilst adding more services through the use of multiplexing. Since 2007, Ofcom has been exploring the possibility of allowing unlicensed SUs access to TVWS. The RF propagation characteristics of the sub-1 GHz part of the UHF band are very appealing. Signals broadcast in this frequency band are able to travel further with the same transmit power than those broadcast at higher (GHz) frequencies; due to free space path loss [126]. Sub-1 GHz waves are good at diffracting around hilly terrain, so are excellent for non line of sight communications [71]. They are also better able to penetrate through buildings than higher frequency waves, which means they have the potential to solve indoor blackspot issues—such as Wi-Fi blackspots [195].

A series of pilots [113] were run in several parts of the UK to confirm the feasibility of the TVWS concept, and some of these were hosted by the Centre for White Space Communications (CWSC) at the University of Strathclyde. CWSC projects include providing rural broadband to various remote communities in Scotland via TVWS, and testing the deployment of new TVWS-compliant Wi-Fi equipment (802.11af) in homes around Glasgow. Ofcom used the findings from the various trials carried out by the CWSC and other research institutions around the UK to finalise its TVWS policy, published in 2015 [104]. This is very similar to the policy that has been adopted by the FCC [46].

The end result is that SUs are now freely allowed to use TVWS bands, but on one condition. Their radios must first contact a White Space Database (WSDB) in order to establish which bands they are permitted to use at a particular location, and what power levels they are allowed to transmit at. This of course means that TVWS devices must have an existing Internet connection (to query the database), and knowledge of their latitude and longitude via GPS or hard-coding. The WSDB is 'read only', so all TVWS devices looking to access the spectrum at a particular location will be provided with the same list of channels and the same maximum transmit power value for each channel. There is no option of 'checking out' a licence to a particular channel, so TVWS users need to compete with one another when gaining access.

2.3.2 Barriers to Sharing

Ofcom ran a consultation in 2016 focused specifically on developing a framework for spectral sharing, thanks to the success of TVWS. Ofcom stated that there were no regulations preventing something similar across other bands, and wanted to identify what licence holders and potential opportunistic users saw as 'barriers' to more widespread sharing. A number of factors were identified, as listed below [95]:

- Availability of real time spectral information
- Market barriers

- The impact on the value of existing licenses
- Technological challenges
- Authorisation constraints and the impact of regulatory delay

Many of the stakeholders who responded stated that access to real time information about spectrum use was required [95]. In response, Ofcom released the entire Wireless Telegraphy Register (WTR), which provides information about every spectral licence allocated in the UK. Stakeholders said this did not go far enough, and that detailed information on actual spectral use (i.e. details about which bands are actually in use, rather than those licensed) was required in order to make informed decisions about which bands would be worth exploring for sharing opportunities. Ofcom judged that this would be too expensive a task, so would not be considering it at the time (2016).

Ofcom stated it considered that "*uncertainty about the future*" (rollout of 5G, 6G etc. and associated requirements) may "*discourage* [PU] *licensees from pursing sharing arrangements*" [95]. PUs sharing their licences may result in situations in the future where they are not left with enough resources to implement new technologies themselves. This view was shared by a number of stakeholders. Additionally, concerns were raised that the value of their spectrum might be reduced by permitting sharing to take place in their bands [95]. One solution suggested was that the licence fee of licence holders could be partially reimbursed for agreeing to sharing.

Coexistence was the main technical concern. Being overly cautious about interference risks would obviously reduce sharing opportunities, but PUs do not want their transmissions to be interfered with. The terms specified in existing licences were also identified as a barrier. Questions were raised about whether restrictions on sharing would result because of the wording in the licences granted by Ofcom—i.e. if a licence is granted for a particular type of signal to be transmitted, would opportunistic users have to transmit that signal type too [95]? Stakeholders also criticised Ofcom for being overly cautious during the introduction of TVWS, which, they argue, had a negative impact to date in the development of sharing technologies.

2.3.3 Sharing for 4G/5G Mobile

Despite barriers against it, momentum for shared spectrum has been growing steadily in the UK and around the world in the last 2 years. This has been partially led by the drive to implement 4G and 5G mobile networks [176]. Baig *et al.* [4] were the first to propose deploying unlicensed 4G LTE signals in TVWS shared spectrum channels. They argue that the communications protocols used by TVWS devices (which are designed around Wi-Fi) are not suitable for long distance links, and that using LTE technologies in these shared bands instead would result in increased throughput and efficiency [4]. Building on this, and past work in shared spectrum and TVWS, the team at the University of Strathclyde deployed an R14 LTE mobile network on the Scottish Orkney Islands in *5G RuralFirst*[5], to demonstrate new cellular shared spectrum technologies in the 700 MHz 5G band [169]. Some photographs of project installations are presented in Figure 2.5. One of the key deliverables of the project was a whitepaper addressing the need for introducing shared spectrum to cellular bands, in order to allow third party community operators to build and run SU mobile networks in rural areas experiencing PU market failure, where no service was being provided [138].

Following the release of the whitepaper, Ofcom opened a series of consultations in December 2018, focused on the upcoming 5G spectrum auctions and the topics of shared spectrum, local licensing and PU coverage obligations [99][100][101][111]. New shared bands in cellular spectrum were proposed, along with a new licensing model that would support SUs accessing channels that were already licenced to MNOs.

Figure 2.5: Photographs of shared spectrum basestation sites from the 5G RuralFirst project

5. 5G RuralFirst was a UK government funded testbed, part of the '5G Testbeds and Trials' programme. The project ran from June 2018 – September 2019, and was the UK's largest testbed (at the time) for connectivity in rural areas [159].

Stakeholders, in general, responded very positively to the proposals, with statements being made such as "*Ofcom is to be congratulated for proposing such a radical shift in terms of access to spectrum*"–techUK [206]. This has since resulted in Ofcom announcing the "*airwaves* [being] *opened up to support* [the] *wireless revolution*" [96].

From the 9th December 2019, Ofcom made parts of the 1800 and 2300 MHz 4G cellular bands, the whole of 3.8-4.2 GHz, and also the 26 GHz 5G mmWave band, all available for indefinite sharing through the Shared Access Licence (SAL) [108]. In addition to this, Ofcom will now consider localised SU sharing requests for all other MNO licensed bands, in locations where they are not being used by the licence holder, through the Local Access Licence (LAL) framework [105]. Applicants for the SAL are issued rolling 1 year lite-licences on a first come, first served basis; while applications for the LAL are issued 3 year lite-licences on a first come, first served basis.

2.4 Dynamic Spectrum Access

While there has been great traction in developing policy to support more widespread shared spectrum access in the UK, Ofcom currently appears to be far from allowing true DSA. DSA takes shared spectrum to the next level; this is a method of spectrum sharing where SU nodes and networks are able to access the spectrum and establish communication channels of their own accord, on an unlicensed (or lite-licensed[6]) basis [59]. Subject to a new regulatory framework, DSA would see licensed PUs encouraged to share all bands they are not fully using, allowing the spectrum to be used more efficiently. DSA-enabled SUs would ideally be spectrally aware, meaning that they are capable of identifying bands using spectrum sensing techniques that are suitable for use (without generating unacceptable levels of interference to incumbent PUs) [155]. The logical processing and radio flexibility that this requires could be met by cognitive SDR systems [58].

After identifying a band, DSA-enabled nodes must continue scanning the spectrum on a real-time basis in order to ensure that, if the state of the spectrum changes, they adjust their RF parameters accordingly (e.g. swapping to a different frequency band as soon as an incumbent licensed PU is detected) [62]. System parameters could also be

6. Lite-licensed spectrum arrangements will see SUs request permission from the regulator to access a particular band. The SU may need to pay a small administrative fee for the service.

modified in real time if the requirements or objectives of the radio node change, or if the node moves. This is no simple task, especially on a network-wide scale, and innovation in the field is made more difficult by the concerns that spectrum stakeholders and regulators have with the concept [95].

The most obvious advantage of adopting DSA is that it permits the spectrum to be used in a far more efficient way. If a DSA-enabled SU identifies a frequency band that is not in use at a particular location, establishes that it is suitable for use and has permission from the licensed PU or regulator to use it, the SU will use it. With DSA, radio channels could be spatially reused for low power transmissions nationwide. Black spots, white and grey spaces could all be exploited, as shown in Figure 2.6. SUs using DSA techniques would need to ensure that they did not interfere with the PUs of the band when exploiting available spectrum.

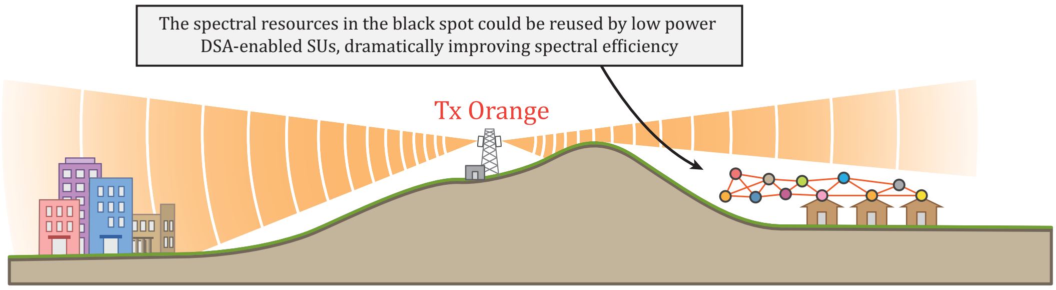

Figure 2.6: Spectral resources of a PU black spot being reused by a DSA-enabled SU network

Networking could potentially be made a little more complicated in a DSA environment. If a DSA-enabled node is to join a DSA-enabled network, it must search for a control channel or similar, communicate with it and request resources in order to gain access. This is not too dissimilar from what happens in cellular or Wi-Fi networks; nodes turn on and search for an Access Point (AP, e.g. a cell tower or a Wi-Fi router) and establish a connection to it. Cellular and Wi-Fi networks have defined frequency channels however, meaning that smartphones and other devices know which frequencies to probe when searching for an AP. But with DSA at play, these control channels could be at any frequency. Nodes would potentially need to scan a large amount of the spectrum in order to find one of them, and even then, finding the control channel of a network they are permitted to connect to could take even longer.

2.4.1 Identifying Spectrum Opportunities

One of the key requirements of a DSA-enabled radio is an ability to identify bands that are suitable for use. The most common methods that have been suggested to do this are to use sensing technologies to scan the spectrum, or to consult a geolocation database which contains information about which channels are available at a particular location [59]. Having the ability to log spectrum availability information through time could allow radios to make informed predictions about future use as well [158], potentially cutting down on the amount of sensing/ database contact required.

There are various techniques that can be used for sensing, such as Energy Detection [157], Cyclostationary Feature Detection [129], Automatic Modulation Classification with Deep Learning [148] and Coherent/ Matched Detection [61]. If the radio has knowledge about what types of signal are expected to be found in each band, the processes used in sensing stages can be tailored to help make them more reliable as the most suitable sensing technique can be chosen [61]. This could be achieved with a database, populated with information from the local regulator and its PUs. The cyclic prefix of OFDM signals can easily be detected using correctly configured matched filters, for example; and the high-powered pilot tone broadcast with American ATSC DTV[7] can be detected with a simple bandpass energy detector.

It is common for single-node sensors to succumb to the effects of channel fading, meaning that they are unable to detect ambient signals from their particular location whilst sensing nodes located a few metres away are able to receive them[8]. DSA-nodes connected together in a DSA-enabled network could use cooperative, network-wide sensing campaigns to increase the reliability of their sensing results [59]. Some form of protocol would be required for nodes to share their sensing results, and it would need to be designed in a way that kept the overhead to a minimum.

As an alternative to sensing, a geolocation database (similar to the one used for TVWS) could be established to serve a large portion of the spectrum. The benefits of a database

7. In the USA, the broadcasting standard ATSC is used for DTV. This differs from that broadcast in the UK, and it uses a different modulation scheme called 8VSB. This contains a Vestigial Sideband (VSB) and a high-powered pilot tone, which makes transmitted ATSC signals far simpler to detect than the UK's OFDM-based DVB-T signals. WSDs being developed for use in the USA could potentially use sensing systems designed to search for these pilots [146].

8. This is known as the Hidden Node (HN) problem [149] are that PUs are likely to be better protected, because there is the guarantee that only empty white space bands will be listed, and maximum transmit powers can be set for each of them. Additionally, if PU broadcasters had the capability to identify when their signals were being interfered with, they could, subject to agreement from their national spectrum regulator, arrange for the permitted transmit power values to be modified accordingly, thereby effectively reducing the transmit power of the SU in real time [95]. One disadvantage of the database approach is that no grey space bands will be identified, while they potentially would be with a sensing scheme [147]. Bands that are used on a part time basis are unlikely to be listed, so will sit empty most of the time, and in situations where the PU signal does not provide the required QoS, the spectrum will not be recycled. This trade-off of PU protection vs. availability for SUs will ultimately result in less efficient use of the spectrum than could be achieved with sensing.

Responders to the Ofcom framework for spectral sharing consultation agreed that "*sensing offered new opportunities for spectrum sharing in conjunction with geolocation database technologies*"; however many were concerned that there were some "*limitations*" on sensing technologies [95]. It would be possible, for example, to factor receive-only devices into a database (such as DTV receivers or wireless microphone receivers), but unless the receivers transmitted beacons they would not be detected by a sensing campaign [95]. A SU which only used sensing techniques, it was pointed out, could transmit in a frequency band that contains active PU receivers. There are clearly advantages and disadvantages with both approaches, and it is likely that a hybrid approach will need to be found between them for DSA to really take off [147].

2.4.2 Exploiting Spectral Opportunities

After establishing which bands are available for use, the DSA-enabled radio needs to decide on 'whether and how' to exploit them [158]. It must trade off the possibilities of collisions with PU and other SU broadcasts against the DSA-node's data throughput requirements. The main factors here are the interference constraints (i.e. the maximum interference power that PUs may be subjected to) and spectral masks. Spectral masks must be defined to clarify acceptable OOB spectral leakage levels, and will be set either by a regulatory policy, or potentially even as a feature of a database.

The greatest task for an 'exploitation' module in a cognitive DSA radio would be deciding how to make use of available bands. If a large bandwidth is required by the

DSA-node, channel aggregation might need to be used in order to combine multiple smaller bands into a larger communication channel. Often these smaller bands will be NC, meaning that they are not positioned next to each other in the spectrum. They are likely to be interspersed between other PU and SU channels, in a fragmented manner. Aggregation of NC channels poses a significant design challenge, and requires the use of particular modulation techniques in the radio's PHY. NC modulation schemes will be reviewed in Chapter 3.

A DSA policy with some sort of penalty will need to be created to manage the etiquette of SUs exploiting the spectrum [59]. If unrestrained, greedy SUs could cause significant problems to other users by transmitting with a high power and high bandwidth, disrupting PU broadcasts and preventing any other SUs from gaining access. The policy must throttle the radio in order to ensure that some spectral resources are left unused, so that some remain for other SU applications. There was discussion in the Ofcom framework for spectral sharing consultation about how PU policy could be changed too, to include 'use it or share it' rules to prevent inefficient hoarding and help to encourage sharing [95].

In the future it is likely that multiple SUs will be active in each band at the same time, and so will need to exert care not to interfere with one another. There are existing protocols that deal with the sharing of communications channels, using Carrier Sense Multiple Access (CSMA) techniques to gauge when nodes should broadcast their messages [132]. A prime example of this is Wi-Fi, where devices listen to identify when the channel becomes free before transmitting. If a collision occurs during the transmission, devices wait for a backoff period before trying to communicate again [67]. These techniques could be recycled in standards that are developed for DSA.

A few recent IEEE standards (such as 802.11af, 802.15.4, 1900.7 and 802.22 [63][64][65][66]) have been developed with DSA in mind, and include details about procedures and timescales that must be followed when PUs' signals are detected in a band that is being used by an opportunistic user. All of these standards focus on slightly different scenarios and use cases, and this is largely because they are additions to existing standards and must remain back-compatible. Bodies such as the Dynamic Spectrum Alliance[9] have been working on 'suggested' regulations for DSA [29],

9. The Dynamic Spectrum Alliance is a cross-industry organisation working with regulators and governments globally to help develop laws and regulations that support DSA [173] although these are yet to be ratified in standards. Some African nations have however begun work to adopt the these suggestions for their own DSA policies [22].

2.4.3 DSA Spectrum Access Policy

Ofcom has stated that there are no regulations preventing the sharing of existing licenced spectral bands [95], while acknowledging, however, that some changes regarding how spectrum access is managed may have to take place. A tiered access system was suggested by Ofcom (also referred to as a shared use model in [59]). With this model, different users of the spectrum would be assigned different access priorities [95]. Figure 2.7 compares the proposed tiered access model and the current static assignment model with TVWS and LAL/SAL provisions.

Long term PU licence holders such as TV broadcasters and cellular operators would reside at Tier 1. Tier 1 users have the highest priority when it comes to accessing the spectrum, because they have paid for licences. If a new Tier 1 PU was to turn on, it

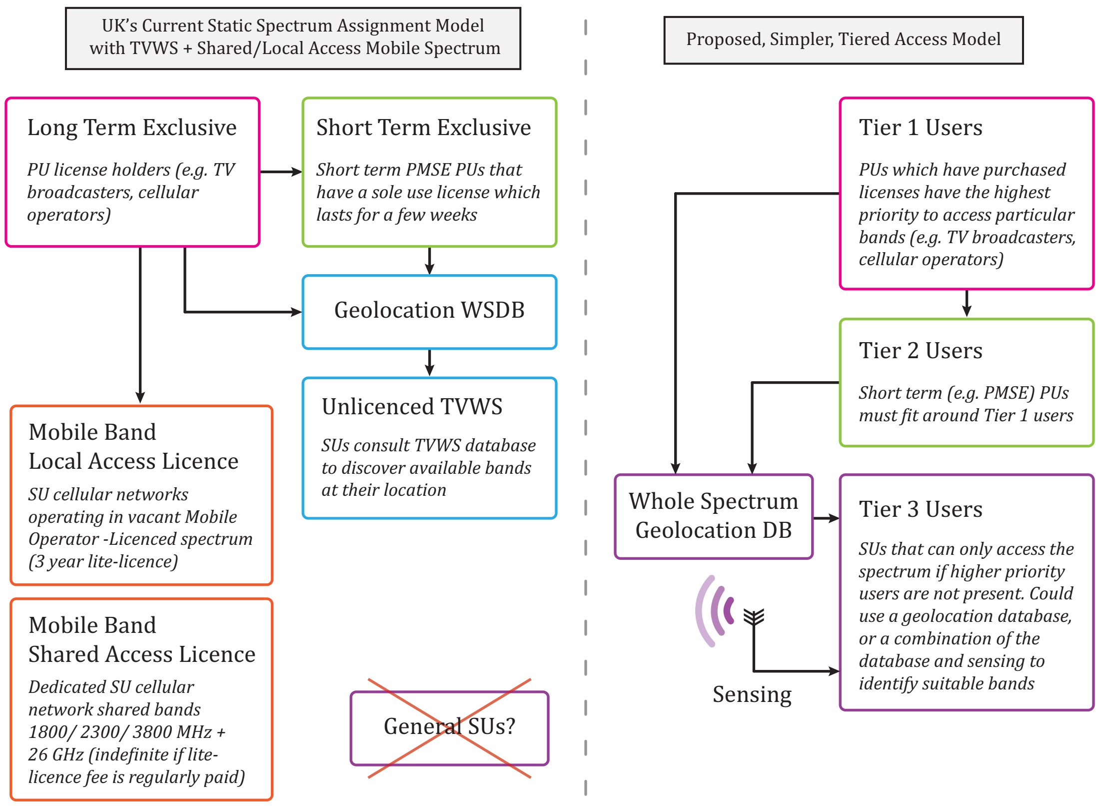

Figure 2.7: A comparison of the UK's current static assignment/ TVWS + shared mobile spectrum access model with the proposed tiered access model, based on descriptions from [95][102]

could potentially displace lower-tiered users to other bands. Short term 'PMSE' licence holders would sit at Tier 2. These licences tend to be granted for a few weeks, generally to allow setup and operation of equipment at concerts, theatres and sporting events. All remaining users would reside at Tier 3. These users would have the lowest priority and no guarantee of spectral access.

Tier 1 and 2 licencees would feed their spectrum utilisation information into a 'whole spectrum' geolocation database (which would either be operated by Ofcom or a registered third party as has happened with TVWS). Tier 3 users including SUs would, theoretically, be able to request access to any channels listed as 'vacant' in the database [95].

To evaluate the benefits the tiered model offers to the shared spectrum cause, it is worth reflecting how sharing is managed in the current static assignment model with TVWS and the LAL/SAL.

The cellular spectrum LAL is the closest the UK currently has to widespread SU spectrum sharing. Ofcom indicated to Strathclyde that they currently run the LAL application process manually, and that they must contact MNOs to query the current and planned deployment state of each frequency channel requested in a LAL application every time an application is made. (MNOs can take weeks to respond to queries). Ofcom must do this because it does not have access to information about how licenced spectrum is really being utilised—there is no obligation for PU licence holders to provide data to Ofcom about their spectrum use [95]. A similar issue exists from the SU's point of view: unless SU applicants have insider knowledge or have conducted measurement campaigns to ascertain what equipment MNOs have deployed, they will not know what spectrum is vacant in any particular area. There is no up-to-date publicly available source of information discussing MNO deployments[10], and no information is published about future deployment plans either. (Short term estimates can be made based on mast planning permission applications submitted to local councils). SUs must therefore request 3 year local access licences blindly, and applications are proving unsuccessful as a result [103].

10. Data was regularly published for a brief period on the (now deleted) Ofcom Sitefinder website, however this was suspended in 2012 due to market competition concerns.

With the tiered access model, this problem would not exist. MNOs (and other PUs from all across the spectrum) would enter information about current and planned deployments into the whole spectrum geolocation database. Ofcom, for the first time, would be able to easily see which channels were in use, and in which locations. Some of this data could be made publicly available (e.g. current deployments), meaning SUs would be able to make informed LAL sharing requests. There is also the potential for Ofcom to make use of this data when analysing MNO network coverage, as it does for the Connected Nations reports and online coverage prediction tools [98][199]. (The current Ofcom MNO coverage datasets rely on a combination of RF simulation data provided by operators, and random confirmatory RF sampling through drive testing [98]).

Cellular spectrum SAL lite-licences are issued by Ofcom on a first come first served basis. Once a licence has been issued to a SU in a particular geography, all other SU licence applications for that same area will be rejected [108]. In real world cellular networks, neighbour cells for a particular operator will tend to broadcast on exactly the same frequencies as each other, as operators have limited access to spectrum. Higher layer techniques have been developed to allow support for overlapping neighbour cells. By lowering the User Equipment (UE, e.g. a smartphone) Modulation Coding Scheme (MCS) and ensuring neighbouring cells' Physical Cell Identity (PCI) and Root Sequence Index (RSI) do not conflict, the effects of Inter-Cell Interference can be mitigated [127]. The 'first come, first served' lite-licencing approach of the SAL prevents this neighbour overlap situation from occurring, in turn protecting the channel quality for the SU that is using it. It does, however, prevent any other SUs from requesting lite-licences and gaining access to the same channel in the same area; despite the UE and basestation equipment being inherently designed to support this feature. The SAL, it could be argued, is too protective of the SU licencee. This is in complete contrast to the system that exists for TVWS, where it is likely that multiple geographically neighbouring SUs, on contacting the WSDB, will all receive the same response; and all end up broadcasting in the same channel as each other (likely causing some SU:SU interference). It can be argued there are flaws with both of these approaches.

A potentially more favourable solution could be achieved using a combination of the tiered access model's database with SU spectrum sensing. Tier 3 devices would initially contact the whole spectrum database to receive information about what spectrum was vacant at their location. They could then perform sensing in order to find out which of the 'available' channels was least occupied by other Tier 3 SUs. This process could be aided by mandating Tier 3 devices transmit a known identifier, so that their signals could be easily detected by other SUs using sensing techniques, similar to the detection process used during an LTE cell search [23]. If a Tier 3 user had to channel share with other Tier 3 users, they could synchronise their transmissions using Time Division Multiple Access (TDMA) -style time slots, and then take it in turns to broadcast, resulting in a far higher throughput all round as their transmissions would not constantly collide. Research has shown that time-synchronising independent (but channel-sharing) Wi-Fi APs can increase throughput by up to 35% [51].

In summary, while it would likely take some time and effort to implement, this alternative tiered access framework places a minimal burden on PUs, and has the potential to enable support for the sharing of vacant channels across the entire radio spectrum. As there would be a single mechanism for SUs to apply for/ acquire access to shared spectrum, the administration overhead both for the SU and Ofcom would be greatly reduced. Best practice DSA remains an open policy and research issue. This tiered access approach is a potential solution that might result in the best situation for SUs looking to access the spectrum.

2.5 Software Defined Radio: The DSA Enabler

SDR is a generic term which refers to radio systems in which some or all of the PHY components typically implemented with dedicated hardware (e.g. mixers, filters, modulators, demodulators) are instead implemented using Digital Signal Processing (DSP) algorithms in software or on programmable hardware [88], [89], [203]. In DSA applications, where radios have to be able to adapt operating parameters on the fly, SDRs are an attractive option. They are truly the most flexible type of radio, as they can be used to transmit and receive any type of waveform [137].

The 'ultimate' SDR (shown at the top of Figure 2.8) has a minimal analogue RF front-end. The transmit side simply consists of a Digital to Analogue Converter (DAC) (ideally operating at multiple GHz), an RF amplifier, RF filter and an antenna; and the receive side comprises an antenna, RF filter and amplifier, and an Analogue to Digital Converter (ADC). This radio performs direct RF conversion digitally, and can transmit and receive a wide band of radio frequencies. All of the modulation/demodulation processes required in the radio stack are performed using DSP algorithms [140]. This architecture first became realisable as a single chip solution in mid-2018 with the release of the Xilinx Zynq UltraScale+ RFSoC [215][55].

Prior to this point, it was more common for SDRs to feature DACs and ADCs that operated at tens or hundreds of MHz, and for them to contain mixer stages implemented in dedicated hardware, that shift signals between RF and baseband prior to digitisation. The architecture of the 'RF Mixer' SDR sees RF signals downconverted to baseband in a single stage using a complex mixer; i.e. a mixer with both Sine and Cosine components. Ultra low-cost SDRs (such as the RTL-SDR [137]) will commonly feature an 'Intermediate Frequency (IF) Mixer', and perform downconversion over multiple stages, in a manner similar to a superheterodyne receiver.

2.5.1 ZynqSDR (Xilinx Zynq + Analog Devices SDR)

One of the popular 'RF Mixer' SDR hardware platforms for development purposes is the ZynqSDR. This comprises a Xilinx Zynq-based SoC development board and an Analog Devices AD9361/ AD9363/ AD9364 SDR front end. Zynq is a heterogeneous processing system that combines both a dual core Arm processor and a high speed Xilinx FPGA on a single piece of silicon. The AD936x are widely used SDR front ends,

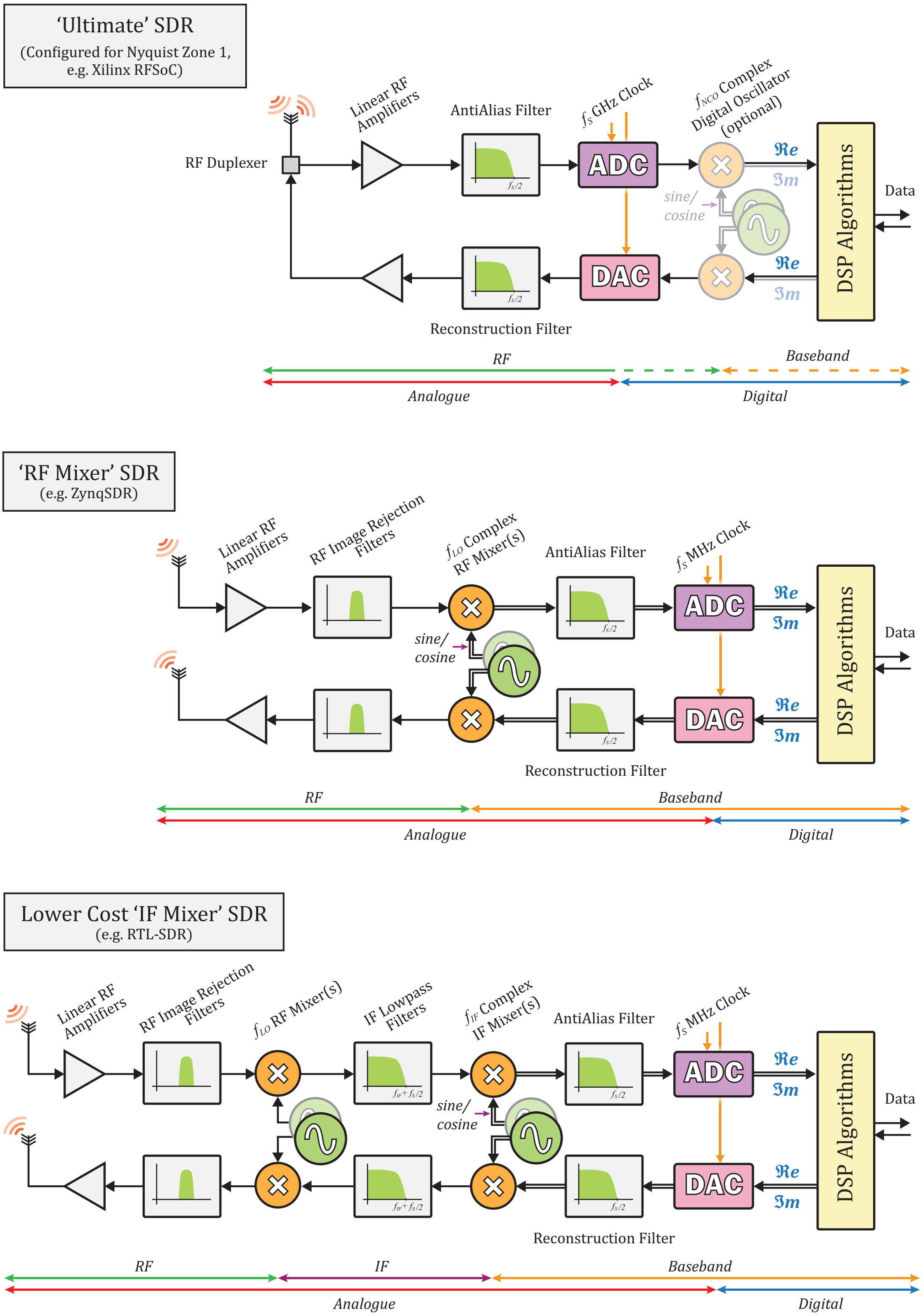

Figure 2.8: The components of the 'ultimate' SDR (top), the more standard 'RF mixer' SDR (middle), and low cost 'IF mixer' SDR (bottom)

and are featured principally on the Analog Devices FMCOMMS range of RF daughterboards [160] and other Analog Devices radio modules [161][162], some USRP radios [180] and the PicoZed SDR [164]. The Zynq SoC/ AD936x radios can be used to implement powerful and wideband Transmit/ Receive (Tx/ Rx) SDR systems with a significant amount of programmable resource.

ZynqSDR hardware configurations include:

- ZedBoard + FMCOMMS 3/4 [165]
- PicoZed SDR (a single board with a Zynq/ AD9361 combination) [164]
- ADALM PlutoSDR (a single board with a Zynq/ AD9363 combination) [161]
- ADRV9361-Z7035 System-On-Module (SOM) (single board with Zynq/ AD9361 combination) [162]
- ZC706 Development Board + FMCOMMS 3/4 [214]

Hardware Configuration: ZC706 and FMCOMMS

Of the ZynqSDR hardware configurations, the most powerful is the ZC706 Development Board/ FMCOMMS. The ZC706 uses the Xilinx XC7Z045 SoC, which boasts a dual core Arm CPU and a large FPGA with 900 DSP slices. The FMCOMMS connects directly to the ZC706, as shown in Figure 2.9. It uses the AD936x SDR front

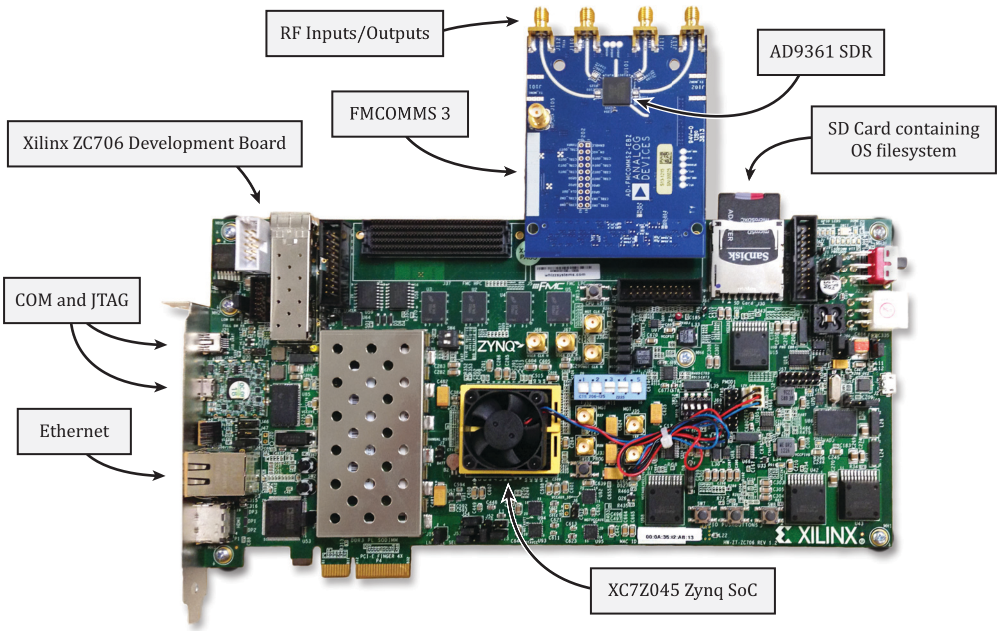

Figure 2.9: ZC706 Development Board/ FMCOMMS 3 ZynqSDR combination

end, which features a 12-bit 640 MSa/s ADC and a 12-bit 320 MSa/s DAC, and operates across the frequency range 70 MHz to 6 GHz. It supports full duplex operation, has a maximum system sampling rate of 61.44 MHz, and maximum bandwidth of around 56 MHz. The FMCOMMS 3 (which uses the AD9361) supports 2x2 MIMO (Multiple Input Multiple Output), while the FMCOMMS 4 (AD9364) is 1x1 SISO (Single Input Single Output).

The Xilinx RFSoC ZCU111, for contrast, is a single-chip 8x8 MIMO SDR device that has direct support for all frequency bands across the range 0-6 GHz, with RF-ADCs and RF-DACs operating at 4096 MSa/s and 6554 MSa/s respectively [216]. This falls into the category of the 'Ultimate SDR', as shown in Figure 2.8. The quad core Arm CPU is coupled to a significantly larger UltraScale+ FPGA with 4272 DSP slices. It costs more than double the price of the ZC706 and FMCOMMS ZynqSDR combination (around £8800 – Dec 2020), however it could be argued that the ZCU111 is much better value for money. What the RFSoC platform currently lacks is a software development environment that can be used to rapidly prototype radio designs. It is simply too new.

As will be described in the following paragraphs, the ZC706 and FMCOMMS ZynqSDR has well established and mature support in the leading technical development software. On weighing these pros and cons, and considering the compute and RF resources required for the ultimate aim of the work presented in this thesis, it was decided that the 'RF Mixer' based ZC706 and FMCOMMS ZynqSDR would be used during the radio development phase.

Model Based Design Environment

MATLAB and Simulink, software tools developed by MathWorks, have in recent years become one of the standard technical computing programming languages and development environments used by engineers worldwide. A variety of add-ons are available (such as the DSP System, HDL Coder and Embedded Coder Toolboxes), alongside Hardware Support Packages that enable additional features and provide support for third party hardware integration. With the MathWorks ecosystem, it is possible to take a floating point Simulink model, readily convert it to fixed point implementation, and then automatically generate Hardware Definition Language (HDL) and/or C code; which can the be used to program the FPGA and processor of a device such as a Zynq, respectively [193]. This is an incredibly powerful prototyping environment, that can rapidly speed up development times.

The hardware support package for Zynq-Based Radio [194] enables support for ZynqSDR in Simulink, making it possible to target block-based designs onto the programmable radio hardware. As highlighted in Figure 2.10, the base radio design features a 'Tx/Rx User Logic' module on the FPGA (connected in-line as part of the transmit and receive paths), as well as the option to run software on the Arm processor.

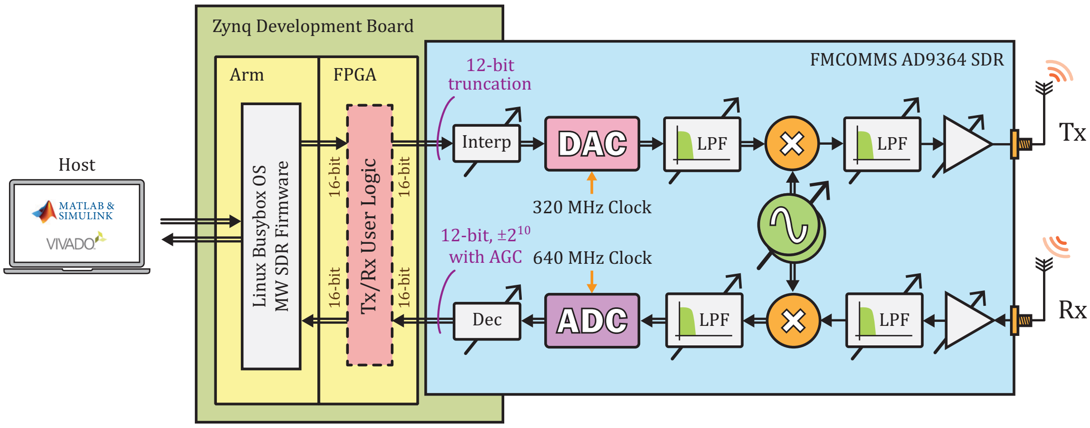

Figure 2.10: High level diagram of the ZynqSDR, featuring numerous tunable components

Transmitter/ Receiver Chain

When using the ZynqSDR as a receiver, the AD936x downconverts received signals from RF to baseband by mixing them with the output of a complex local oscillator. After passing through a programmable analogue filter stage, the signals are sampled by an ADC. Decimation takes place, and the signals (now samples), are transferred to the Zynq device. Once the samples enter the FPGA of the Zynq, they pass through a User Logic module, as shown in Figure 2.10. When the FPGA is configured with the default MathWorks bitstream, this simply acts as a passthrough, meaning that the samples are not modified in any way. Users have the option, however, to target this area with their own receiver designs. While certain design constraints must be followed, the user otherwise enjoys full flexibility when implementing a radio design in the module area.

Eventually, the IQ (In Phase/ Quadrature Phase) samples are passed to the Arm Cortex A9 processor (which is running the Linux Busybox Operating System, OS). Here they are acquired by the MathWorks SDR driver, optionally processed with custom software, and passed out over the Ethernet interface back to the host computer.

Users have the option of adding programmable registers to their user logic designs, which can be used to change the way in which a design functions; for example, to instruct the receiver to swap between demodulator ‘A’ and demodulator ‘B’. These registers can be programmed in real time via ‘COM’ or ‘SSH’ Terminal connections, or from a Simulink model running in ‘external mode’.

The transmit process is similar, but in reverse. Complex samples are passed down to the FPGA via the Arm processor from the host computer. The samples pass through the User Logic module, which can again be targeted with a transmitter design. Next, the samples enter the AD936x and are interpolated up to the DAC rate. The samples are converted to an analogue signal, which is filtered, mixed with a complex local oscillator and transmitted.

Design Constraints

As the MathWorks tools provide a base design that contains a ‘targetable’ User Logic module, there are some design constraints that must be met. These are outlined below.

The wordlengths of the I and Q input and output ports must all be signed, 16-bit values, despite the wordlength of the ADC/DAC pair being only 12-bits. On the receive side, when the Automatic Gain Control (AGC) of the AD936x is in use, samples will have an average value of around $\pm 2^{10}$. This is convenient, as it means engineers will always know the approximate amplitude of samples when creating their designs. The full 16-bit interface may be used between the FPGA programmable logic and the Arm processor on both the receive and transmit paths. On the transmit side, 16-bit signals are truncated to 12-bits prior to the AD936x.

The sampling rate of the user logic areas must match the baseband sampling rate configured in the AD936x front end. The rate can be reduced to a smaller value inside the user logic designs; however the rate at all ports must be consistent with the SDR.

The number of FPGA resources (flipflops, Lookup Tables (LUTs), DSP48 slices etc.) available for use is also dependent on the Zynq development board used. Design optimizations or partitioning may be required in order to fit the user's design into the resources available within the target FPGA.

Hardware Configurations

There are three main modes in which this hardware can be used: Tx only, Rx only, and Tx/Rx. There is also functionality called `transmitRepeat()` where a burst of data can be repeatedly broadcast contiguously, and there are options of FPGA or AD936x internal loopbacks in addition to using the external RF interfaces. Finally, there is a feature called 'Burst Mode', which can be used to ensure that contiguous bursts of data are transferred between the Zynq and the host computer (with no dropped samples). These many configuration options make it a very attractive platform for SDR prototyping.

2.6 Chapter Summary

This review chapter has presented the role of spectrum regulators, their traditional spectrum allocation policies, and the shortfalls of these practices. PUs, for various reasons, often do not use all of their licensed spectrum, and this results in valuable spectral resources lying fallow. Regulators are beginning to implement new rules that allow third parties access to these unused bands. Implementing spectrum sharing will result in the radio spectrum being used more efficiently, and will enable a host of new SU radio technologies to be developed.

DSA was introduced as the next level of spectrum sharing. Here, radios can access the spectrum and create communication channels of their own accord. Requirements and capabilities of DSA radios were reviewed, and a recently proposed spectrum access model was presented that could enable DSA in the future. Finally, a brief introduction to SDR, in particular the ZynqSDR, was presented. This flexible radio platform is an excellent candidate for prototyping new DSA-radio designs. As such, it was used during the development work presented later in this thesis.

Chapter 3

Dynamic Non Contiguous (NC) Modulation

Non Contiguous - MultiCarrier Modulation (NC-MCM) schemes can be used by SUs to generate signals that contain spectral 'holes' (i.e. gaps in the spectra of their transmissions that contain little to no energy). This allows SU transmitters to 'mold' around PU signals, and fill up all available spectral fragments. The main consideration when choosing an NC scheme is the ACLR. This is the ratio between the power in active ('on') parts of the signal's spectra, and the power that leaks into disabled ('off') parts; i.e. the OOB leakage. Different NC schemes have different ACLR values.

3.1 Chapter Overview

This chapter provides an overview of the most popular NC-MCM schemes[11]: OFDM, RBF-OFDM/ UFMC, and FBMC/OQAM (also known as OFDM/OQAM). These are already well reviewed in the literature [40][52][123]; so the focus in this chapter is on system level design, and the waveforms they produce. An argument is presented as to why FBMC/OQAM is the most suitable contender for a DSA-enabled SU radio.

3.2 Orthogonal Frequency Division Multiplexing (OFDM)

One of the most commonly used digital modulation schemes is OFDM. It is used in IEEE 802.11a/g/n/ac Wi-Fi, IEEE 802.16 WiMAX, 4G LTE, 5G NR, DVB-T and DVB-T2 DTV, DAB digital radio, and ADSL broadband standards, to name a few. In OFDM, the communications channel is split into a number of narrowband subchannels, each

11. The modulation scheme acronyms will be defined in the coming sections.

with their own subcarrier. Data transmitted using the scheme is divided across them, meaning that signals are better able to deal with the effects of multipath and frequency selective fading in the channel [136]. OFDM is well suited to Multiple Access (MA) scenarios, and the OFDMA (Orthogonal Frequency Division Multiple Access) extension permits multiple nodes to communicate in a channel at once. Large MIMO antenna arrays are achievable in OFDM, and it is speculated that these will be used in combination with beamforming in new, high data rate 5G mmWave systems.

3.2.1 OFDM Signal Structure

OFDM symbols are generated by modulating complex data symbols onto a series of orthogonal subcarriers [190]. These subcarriers take the form of *sinc* functions, which have a period of T seconds and zero crossings at multiples of $1/T$ Hz. Spacing these carriers $1/T$ Hz apart results in there being zero Inter-Carrier Interference (ICI) between them, as shown in Figure 3.1. The Discrete Fourier Transform (DFT) is conveniently able to produce tones with these properties from a rectangular pulse T seconds in length. For this reason, the DFT and Inverse DFT (IDFT) operations are therefore core elements of an OFDM system; and they are commonly implemented using the efficient Fast Fourier Transform (FFT) and Inverse FFT (IFFT) algorithms.

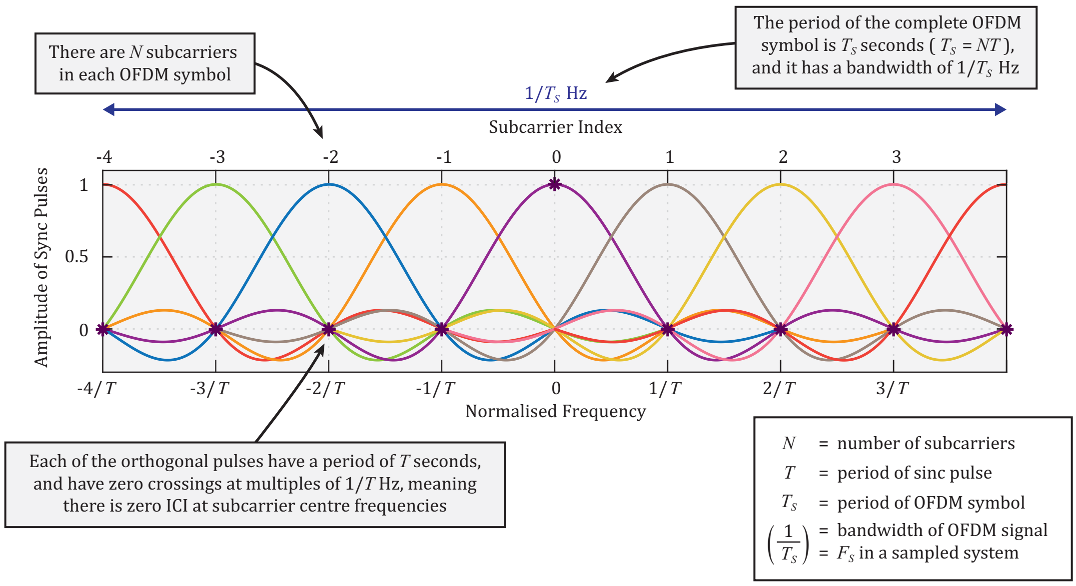

Figure 3.1: The fundamental properties of an 8-point OFDM symbol and its constituent sinc pulses, shown in the frequency domain

3.2.2 OFDM Modulation

The standard form of an OFDM transmitter is shown in Figure 3.2. Here, an input data stream is divided into a series of $\delta \times N$ sized blocks, where δ represents the M-ary modulation order. Next, complex data symbols are created by performing M-ary modulation (e.g. 4QAM, 8PSK, 16QAM etc.) on the groups of δ bits. Once N of these complex data symbols are created, they are input to the IFFT. This 'modulates' each of the complex symbols onto an OFDM subcarrier. The IFFT converts the array of complex symbols on the subcarriers from the frequency domain to the time domain, creating an OFDM symbol $s_{OFDM}(t)$.

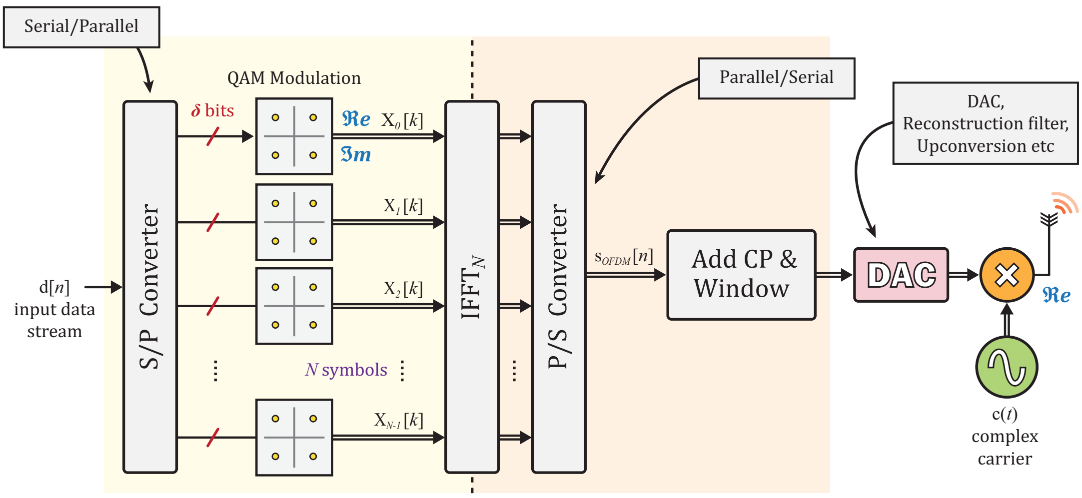

Figure 3.2: OFDM modulator and transmitter architecture

Waves propagating through RF channels often suffer from the effects of multipath interference. It is essential to combat this in OFDM, because zero ICI must be maintained in order to successfully convey information. The solution is to add a Cyclic Prefix (CP) to the OFDM symbol that is larger than the channel delay spread, as shown in Figure 3.3. This acts like a time domain guard band, lengthening the period of the symbol from T_s to $T_s + T_{cp}$ so that the effects of the multipath channel are mitigated. To address the discontinuities between OFDM symbols (which can cause problems in power amplifiers [74]), windowing is often performed. The window normally takes the form of a Raised Cosine (RC) filter, and it smooths the transitions between the symbols. As the symbols have been extended in length by the CP, no information is lost as a result of the windowing process. Once the OFDM symbol has a CP and windowing has been performed, the digital signal is passed through a DAC, mixed with a complex carrier, and transmitted.

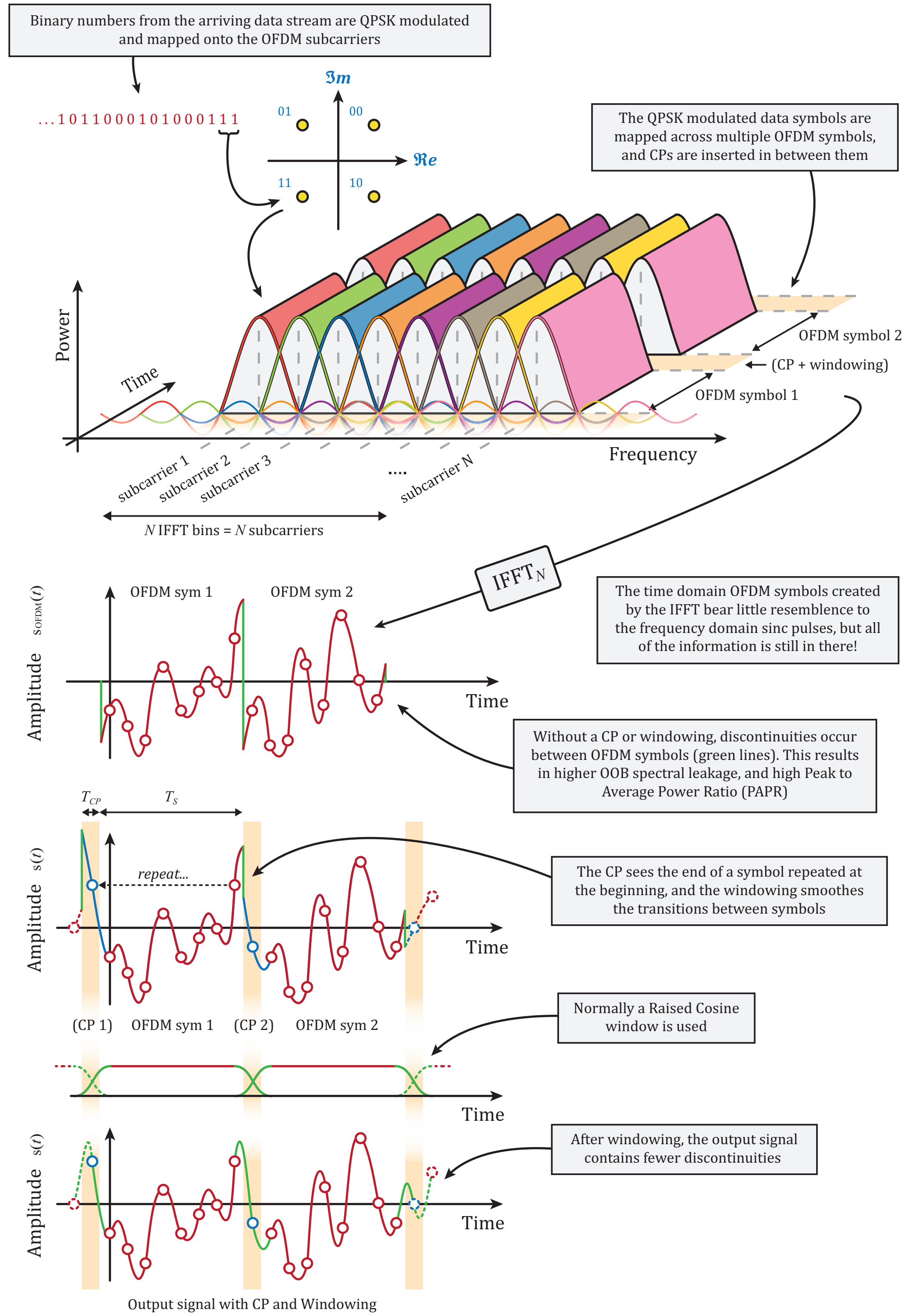

Figure 3.3: Example OFDM waveforms in the frequency and time domains, highlighting the cyclic prefix and the windowing process

3.2.3 OFDM Demodulation

An OFDM receiver is presented in Figure 3.4. The signal of interest is mixed down to baseband, and digitised with an ADC. In an ideal world, no synchronisation would be required; so the digitised signal could simply be processed by an FFT to extract the complex data symbols from their orthogonal carriers. These could be M-ary demodulated to recover the binary data stream. In reality however, things are a little more complicated.

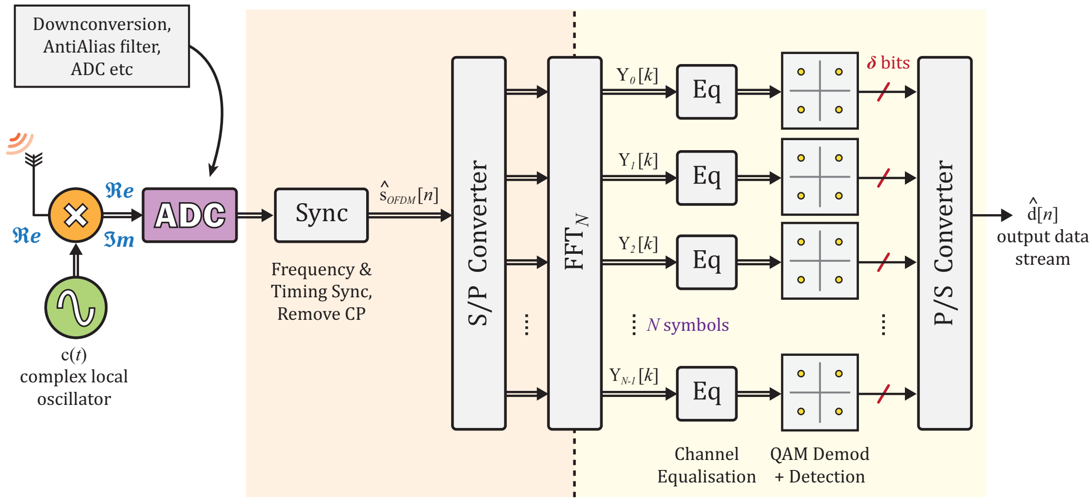

Figure 3.4: OFDM receiver and demodulator architecture

Normally a transmitter and a receiver will not have a common clock, so frequency and timing synchronisation stages are required. These ensure that there are minimal frequency, timing, and sampling offsets between the transmitter and receiver (in order to prevent the receiver experiencing ICI and Inter-Symbol Interference (ISI)). Training symbols are used at the beginning of an OFDM burst to allow coarse synchronisation to be performed. Next, fine synchronisation is carried out on a symbol-by-symbol basis. The CP is used to aid in this process, as it provides a reference as to where each symbol begins and ends in time.

Because RF channels normally have frequency selective fading and multipath issues, equalisation must also be performed to recover the true amplitudes of each of the complex data symbols, prior to M-ary demodulation. Distributed pilot tones are used to obtain channel estimates, allowing equalisation to be performed using a series of single tap gain blocks in the frequency domain.

3.2.4 Non Contiguous OFDM (NC OFDM)

NC OFDM is one of the most popular NC schemes presented in the literature [13][14][17][40][52][82][122]. Here, groups of subcarriers are disabled to create spectral holes. A subcarrier can be disabled by inputting a stream of complex symbols with the value (0+0j) to the transmitter's corresponding IFFT bin [13]. Because OFDM modulation uses rectangular pulse shaping, it suffers from very high OOB power levels [14].

Figure 3.5 shows a single OFDM subcarrier (with rectangular windowing) in the frequency domain, both with linear and logarithmic power scales. The sinc pulse crosses zero at multiples of $1/T$ Hz, which in normalised terms is equivalent to multiples of 1 subcarrier spacing. The carrier emits no energy at these zero crossings, and hence there is zero ICI. Between the zero crossings, however, there are sidelobes that contain a significant amount of energy [124].

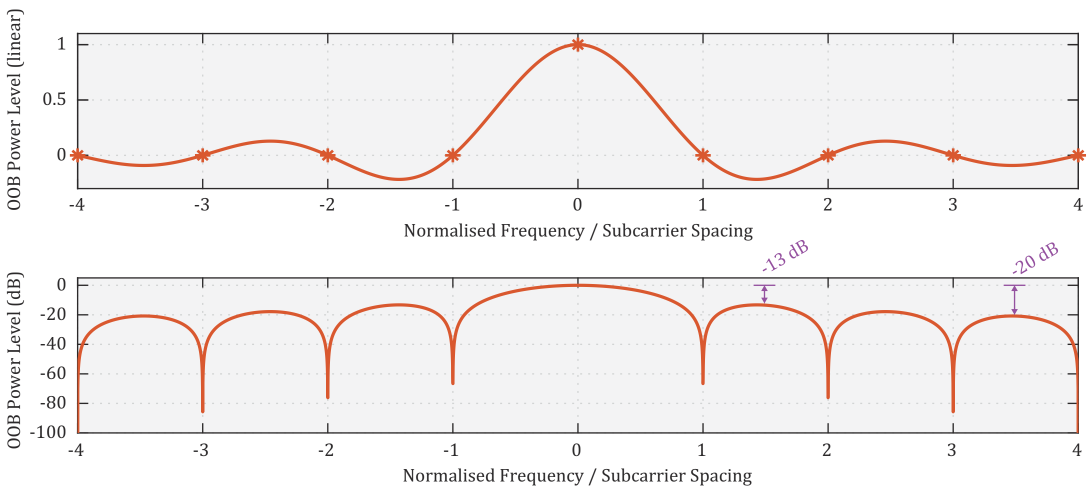

Figure 3.5: Power spectrum of an OFDM sinc pulse (with rectangular windowing), highlighting OOB leakage

The OOB leakage power within one subcarrier spacing is only 13 dB lower than in-band power level; and within three subcarrier spacings, this only drops to 20 dB. The result is that, when a group of subcarriers are disabled to create a spectral hole, a significant amount of energy is actually still present (and therefore transmitted) within the hole [52]. Standard NC OFDM has no additional filter stages that can attenuate this OOB leakage [41]. It is therefore highly likely that an SU transmitting an NC OFDM signal would cause interference to the PU signal it was aiming to protect [84][124].

3.2.5 Resource Block Filtered-OFDM (RBF-OFDM) / Universal Filtered MultiCarrier (UFMC)

In an effort to address the OOB leakage problems experienced with OFDM, a filter can be added to the transmitter. With this filter it is possible to decrease the OOB emissions dramatically, resulting in a signal with better spectral containment [3][153]. A visual comparison between OFDM and Filtered-OFDM (F-OFDM) for a contiguous band of subcarriers is presented in Figure 3.6 (subcarriers above and below the contiguous band are disabled). The filter used here is a lowpass, configured to cut off at the normalised frequency $f = \pm 0.28$. Note that the OOB leakage is significantly attenuated by the filter, F-OFDM could be used to target NC spectrum fragments.

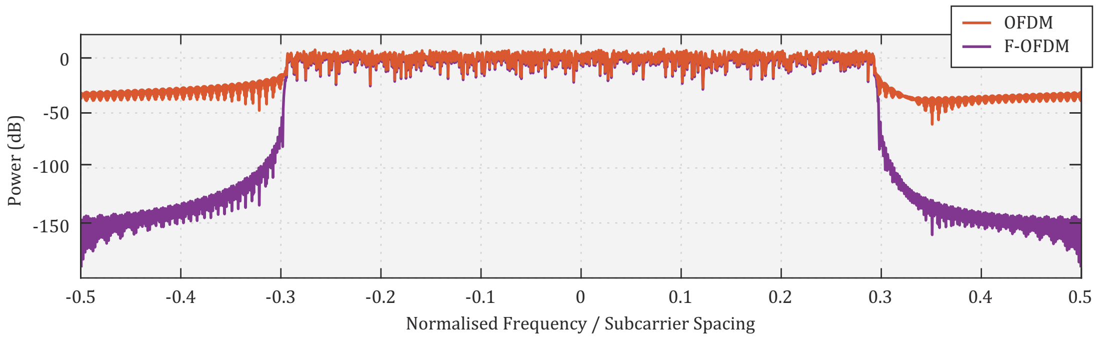

Figure 3.6: Comparison between wideband OFDM and F-OFDM LTE signals, generated using the MathWorks LTE System Toolbox

A transmitter chain with a single multi-bandstop digital filter would suffice; however the filter would be large and computationally expensive, and it would have to be re-designed and re-implemented every time the spectral environment changed; which could be every few seconds. Real time filter design would involve a significant processing overhead in the transmitter, even with techniques such as the frequency sampling method [7][83]. Widths of transition bands would need to be considered, as these in turn would effect the length of the filter, and the overall attenuation in stop-bands/ ‘off’ parts of the output signal’s spectrum.

A workaround to this issue is to opt for a frequency ‘Resource Block’ (RB) approach (similar to what is used in OFDMA situations, like in LTE), as proposed in [82]. Interestingly, the NC modulation technique proposed here by Li *et al.* is almost identical to what was later proposed by Vakilian *et al.*, and named Universal Filtered Multi-Carrier (UFMC) [144][130].

With a RBF-OFDM transmitter, the spectral band is divided up into i blocks, and i (parallel) transmitter branches are required. Each of the transmitter branches feature their own individual NC OFDM modulator and Bandpass Filter (BPF) [82][93], leading to the architecture shown in Figure 3.7. The filters in this design are fixed, and do not need to be redesigned every time the PU spectral environment changes.

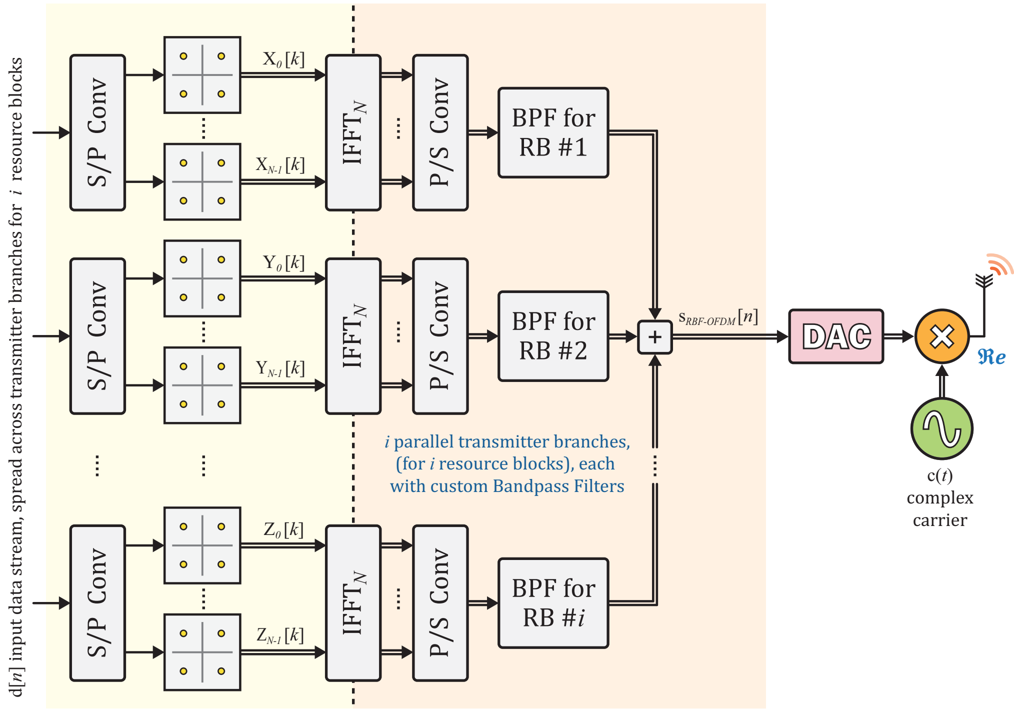

Figure 3.7: An example RBF-OFDM modulator and transmitter configuration

Each of the RBF-OFDM transmitter branches relate to a single resource block; and therefore, in each branch, information is only modulated onto subcarriers that are part of the resource block. Zeros are inserted to other subcarriers, as with NC OFDM. Transmitter branches are only activated when the entirety of the spectrum that their resource block targets is available for use [2][82]. The bandpass filters (identical, but frequency shifted) are designed to meet ACLR limits for the target RF channel.

The disadvantage to this approach is that it will often not be possible to utilise all available spectral fragments, due to the coarse frequency resolution of the resource blocks. The design also has significant additional complexity, in the order of i times the computational resources required for standard OFDM. NC signals generated with this transmitter do achieve the aim of far lower OOB leakage than standard OFDM though, making the transmitter more suited for DSA applications [82].

3.3 Filter Bank Multicarrier (FBMC)

In Filter Bank Multicarrier (FBMC), a communication channel is split up into M subchannels by a bank of filters. If the passbands of filters are spectrally separated, different modulation schemes can be used simultaneously across the set of subchannels [9]. Frequency overlapping FBMC is more spectrally efficient, more efficient in fact than OFDM [134], but requires the use of an orthogonal modulation technique called Offset Quadrature Amplitude Modulation (OQAM). OQAM orthogonality is achieved by inputting the real and imaginary components of complex QAM symbols individually to the IFFT, and transmitting them with a time offset of half a symbol [41]. In a practical sense, this means doubling the symbol rate and alternately inputting the real and imaginary components to even-indexed and odd-indexed subchannels (IFFT bins) [8]. Rather confusingly, FBMC/OQAM is often referred to as OFDM/OQAM in the literature [41][82][86][134], despite fundamentally being an FBMC scheme!

One of the benefits that FBMC/OQAM systems have over OFDM/QAM is that they do not require a CP to be added to protect the orthogonality of the subchannel carriers [86], meaning there is no constant efficiency loss per symbol [52]. The real prototype filter[12] used for FBMC/OQAM results in excellent frequency and time localisation, meaning that it is less susceptible to ICI and ISI [131]. Another advantage becomes clear in the MA scenario. Here, groups of subchannels are aggregated together, and allocated to different users (as in LTE). With OFDM/MA, it is critical that all of the users' signals are received at the same time and at the correct frequencies in order to maintain orthogonality conditions in the receive FFT. In contrast, once an empty OQAM subchannel is left between groups, transmitter synchronisation between MA nodes is not required when transmitting to an FBMC/OQAM basestation [8]. This is an important point, since it can drastically simplify the architecture of transmit-only radio nodes; for example IoT nodes that only broadcast sensor readings.

Two of the more common architectures of FBMC that feature in the literature are the Polyphase Network (PPN-FBMC) and Frequency Spreading (FS-FBMC). Configured with equivalent parameters and prototype filter designs, both of these architectures will achieve the same spectra [85]; and, as will be discussed, there are advantages and

12. The prototype filter's frequency response is used as the basis of all filters in the bank disadvantages to each of them. The filter bank exists either in the time-domain (PPN) or frequency-domain (FS), depending upon which architecture is chosen.

3.3.1 PPN-FBMC/OQAM Architecture

Figure 3.8 shows the architecture of the PPN-FBMC/OQAM transmitter. Here, M modulated OQAM symbols ($M/2$ complex QAM symbols) are input to an IFFT, and the output is passed to a time-domain polyphase filter bank network. The network contains M parallel polyphase filters, and the prototype filter (on which the bank is modelled) is designed based on an overlapping factor, K [145]. This filtering process creates the FBMC time domain symbol, which is then modulated and transmitted.

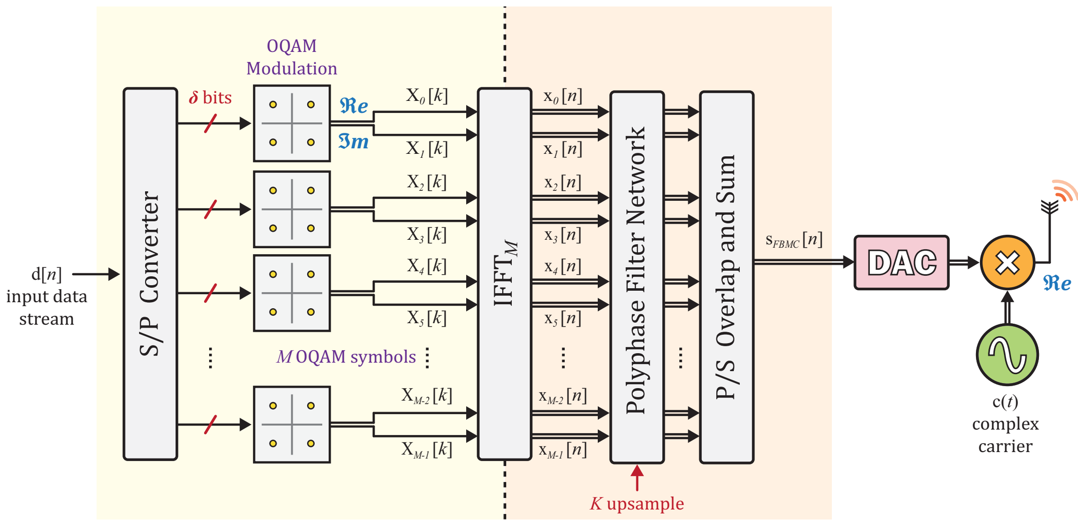

Figure 3.8: PPN-FBMC/OQAM modulator and transmitter architecture

The main advantage of this design is that the size of the IFFT (in which the bulk of the multiply-accumulate operations are carried out) is limited to M (rather than MK, as with FS-FBMC). There are drawbacks, however, with the PPN- receiver. As shown in Figure 3.9, equalisation must be carried out as a complex multi-tap process in the time-domain, prior to the receiver's FFT (unlike the single tap process required for OFDM), which adds a processing overhead and a time delay [9]. Carrier Frequency Offset (CFO) and timing synchronisation must also be performed in the time-domain. Time-domain misalignment significantly reduces the amount of channel delay spread the receiver can compensate for; hence this architecture does not perform well in multipath environments [11].

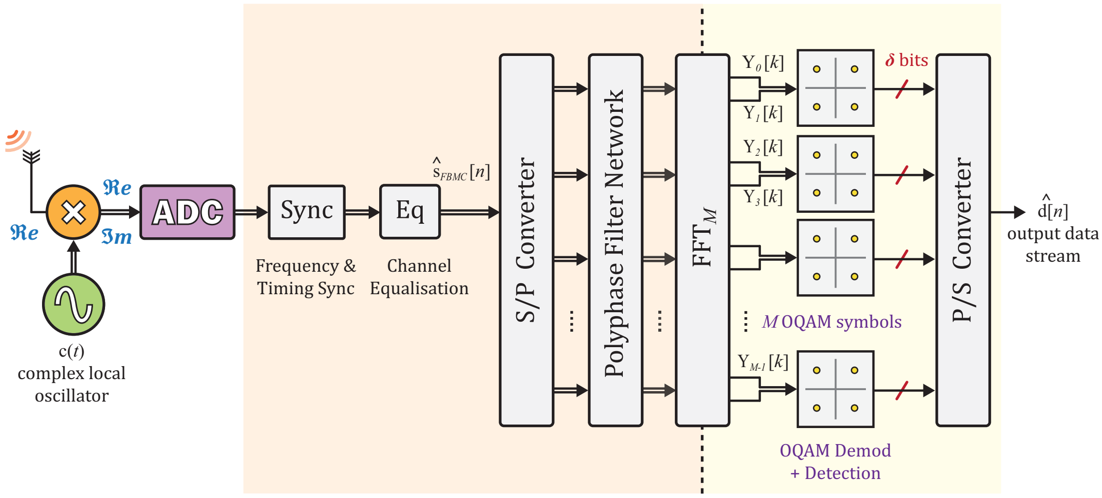

Figure 3.9: PPN-FBMC/OQAM receiver and demodulator architecture

3.3.2 FS-FBMC/OQAM Architecture

In comparison, the FS-FBMC/OQAM transmitter sees M modulated OQAM symbols upsampled by K in the frequency-domain ('frequency spread') and convolved with the frequency coefficients of the prototype filter. Next, the MK filtered samples are passed into the IFFT, and K of the time-domain outputs are 'overlapped and summed' together to create the FBMC symbol, as shown in Figure 3.10 [8].

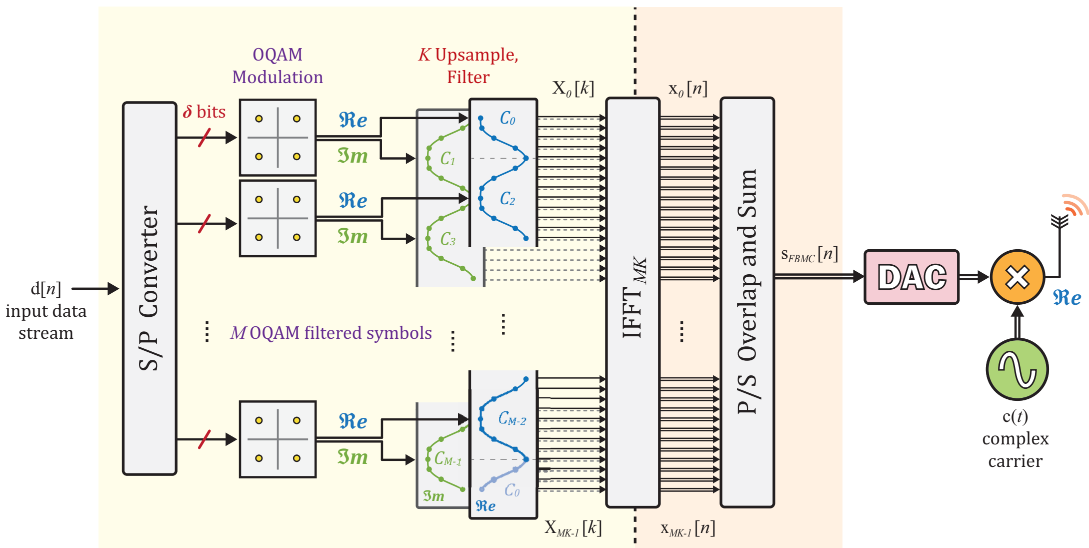

Figure 3.10: FS-FBMC/OQAM modulator and transmitter architecture

While there is a significant amount of redundant processing in this transmitter, the gains are made in the FS- receiver. This is shown in Figure 3.11. Here, CFO and Timing synchronisation systems can be positioned after the receiver's FFT, and similarly, equalisation can be performed as a single tap operation in the frequency-domain (in the same way as with OFDM) [9]. This means that it is better able to compensate for the effects of multipath. Additionally, the FFT operation can be carried out asynchronously (i.e. without prior knowledge of the time domain alignment) [28]. Another benefit to this receiver architecture is that the higher frequency domain resolution of the FFT (MK rather than M bins) will lead to more accurate sensing results, should spectrum sensing be being carried out in the radio. The greater number of FFT bins will mean, however, that this architecture requires a greater number of computational resources during implementation than an equivalent PPN-FBMC transmitter/ receiver pair [52].

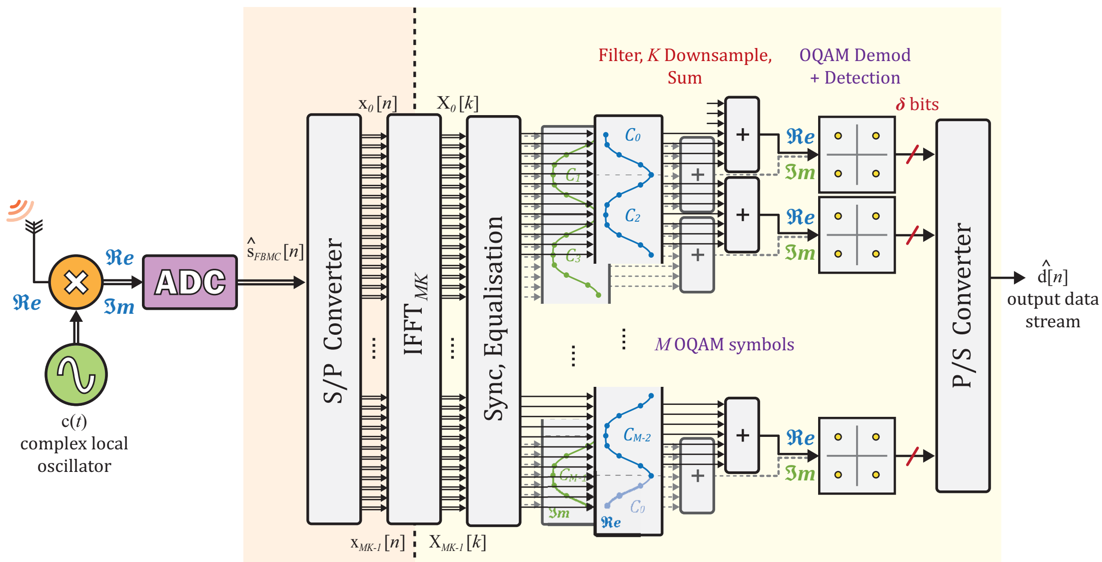

Figure 3.11: FS-FBMC/OQAM receiver and demodulator architecture

While PPN-FBMC often regarded as the 'standard' FBMC architecture because of its efficient implementation [10], the synchronisation benefits of the FS-FBMC receiver mean that the frequency spreading technique is the architecture of choice when designing radios for use in a DSA environment [11]. As the designs are essentially equivalent, and result in the same output waveform, in theory it is possible to have a mixed architecture radio; i.e. using a PPN-FBMC transmitter and an FS-FBMC receiver [85]. This is an attractive concept, as it results in the 'best of both worlds'.

3.3.3 FBMC Prototype Filters

Prototype filters are designed in the frequency- domain using the frequency sampling method [83], regardless of which architecture is latterly used. The filter is a symmetric half nyquist filter, and the number of non-zero coefficients is given by $P = 2K - 1$ [9]. The higher the K value, the better the ACLR; but a trade-off is made to keep K small, to keep the computational requirements of the radio low. This has led to $K = 4$ becoming a common value, as used in the PHYDYAS[13] project. The coefficients are calculated such that Eq. (3.1) is satisfied:

$$\frac{1}{K}\sum_{k=-K+1}^{K-1}|H_k|^2 = 1 \qquad [8]. \tag{3.1}$$

With $K = 4$, this gives frequency coefficients of

$$H_0 = 1 \qquad H_1 = H_{-1} = 0.97196$$
$$H_2 = H_{-2} = \sqrt{2}/2 \qquad H_3 = H_{-3} = 0.235147\ ,$$

resulting in the filterbank shown in Figure 3.12.

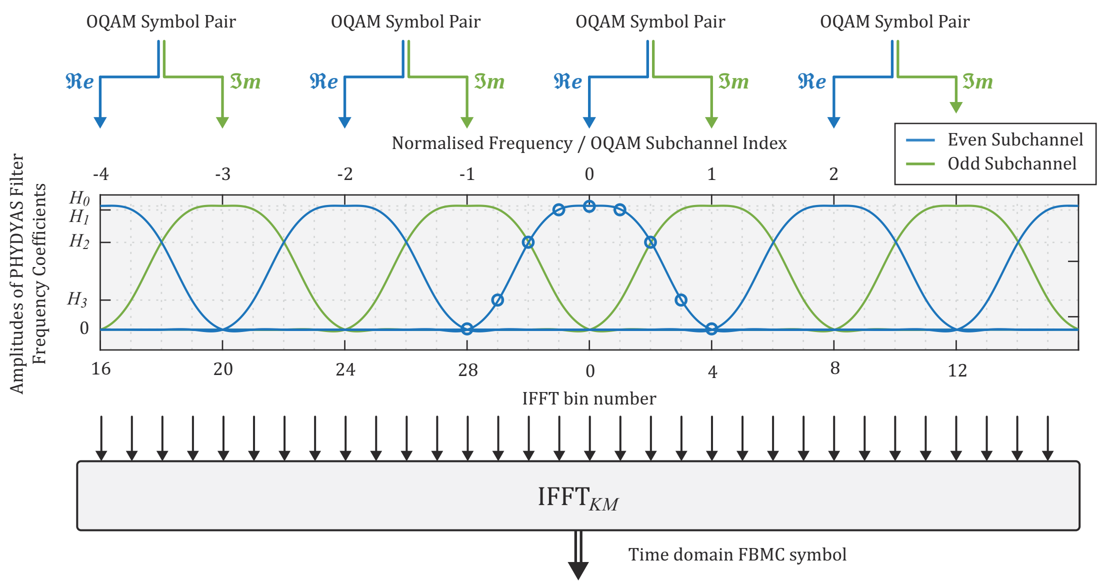

Figure 3.12: Part of a FS-FBMC/OQAM transmitter with $M = 8$ / $K = 4$ PHYDYAS filter, highlighting the OQAM subchannel overlap

13. PHYDYAS, the PHYsical layer for DYnamic AccesS, was an EU FP7 funded project that ran from the start of 2008 until mid 2010. The aim of this project was to create a new FBMC based PHY layer that was well suited to DSA applications [8].

It is key to note here that only subchannels that are direct neighbours overlap. Disabling a single subchannel (which can be achieved by simply inputting a zero-valued OQAM symbol to the transmitter) creates spectral separation between the remaining subchannels, removing the requirement of orthogonality between them [9]. Disabling a number of neighbouring subchannels will create a 'hole' in the generated FBMC/OQAM signal (essentially making it NC).

3.3.4 Non Contiguous FBMC (NC FBMC)

As with NC OFDM, NC FBMC symbols can be created by modulating complex symbols with a value of (0+0j) into the subchannels which are not being used. Because FBMC symbols have special pulse shaping filters for each channel, there is minimal OOB leakage between channels. An FBMC subchannel is shown in Figure 3.13.

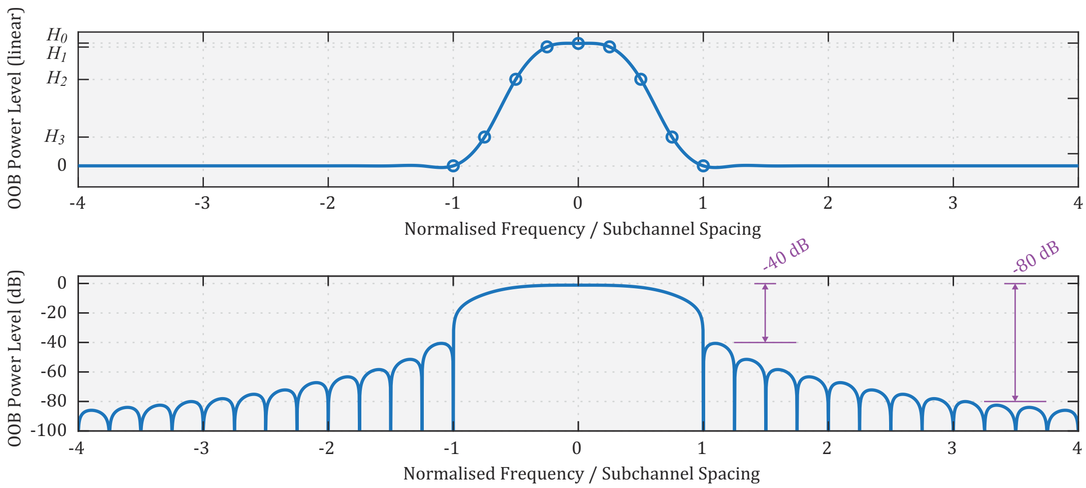

Figure 3.13: Power spectrum of a PHYDYAS FBMC/OQAM subchannel, highlighting OOB leakage

With the $K=4$ PHYDYAS filter, the power in the first disabled OQAM subchannel is around 40 dB lower than in-band levels, and within 3 subchannel spacings, the OOB attenuation is >80 dB [212]. The OOB leakage power is 60 dB lower than that of NC OFDM; i.e. the leakage is *>1 million times less powerful.*

Unlike the OFDM based techniques, this signal can be dynamically molded to fit around existing PUs on a subchannel-by-subchannel basis, and transmitted while causing minimal interference to them.

3.4 A Comparison of the Candidate MultiCarrier Schemes

The previous Sections have discussed OFDM and FBMC based NC-MCM schemes, reviewing the designs of transmitters and receivers from a system level implementation. Each of these schemes have different transmitter and receiver complexities; but also, spectral characteristics. Power spectrum plots have been displayed that highlight the frequency localisation of the subcarriers/ subchannels, and the OOB leakage the schemes suffer from.

In general, MCM schemes are designed to have a high symbol density, high levels of time and frequency localisation, and to be orthogonal. This leads to schemes that have a high spectral efficiency (i.e. high number of bits/Hz), that suffer from lower levels of spectral leakage, and have minimal ICI and ISI [79]. According to the fundamental limitations of the Balian-Low Theorem however, it is mathematically impossible for a scheme to meet all of these properties simultaneously [24][92].

Plain OFDM (with no CP/windowing) is orthogonal, has excellent time localisation, and transmits with the maximum symbol density at the Nyquist rate. However, it suffers from poor frequency localisation and has very high spectral and OOB leakage as a result of discontinuities between OFDM symbols (meaning it is ultimately not suitable for RF broadcast). The frequency localisation issue can be combatted by performing windowing, but this in turn requires the addition of a CP in order to protect the orthogonality in the subcarriers. The CP reduces the symbol density and throughput rate of the OFDM + CP/windowing transmitter. F-OFDM schemes feature the CP/windowing, and therefore have a reduced symbol density too. They can achieve improved frequency localisation due to the addition of the filter, however, the filter lengthens the F-OFDM symbol duration, meaning it has poorer time localisation.

FBMC/QAM schemes (which have not been discussed in depth) are very similar to OFDM + CP/windowing, so also suffer from reduced symbol density. In contrast, FBMC/OQAM schemes do not require a CP, and are able to transmit with the maximum symbol density at the Nyquist rate. The Balian-Low Theorem dictates something must 'give', and with FBMC/OQAM, this is the (complex) orthogonality. FBMC/OQAM subchannels are orthogonal in the real domain only [38]. The larger the overlapping factor in an FBMC/OQAM scheme, the greater the frequency localisation; but high values mean it will suffer from a long FBMC symbol duration, and poorer time localisation. All of these trade-offs must be balanced when selecting an NC-MCM scheme to use in a communications system.

To operate in a DSA environment, dynamic reconfigurability and low OOB leakage can be considered as the most important requirements for SU radios. Taking the example scenario where four spectral fragments are available in a particular frequency band, as shown in the top plot of Figure 3.14, it is possible to compare how suitable the different schemes are for the task.

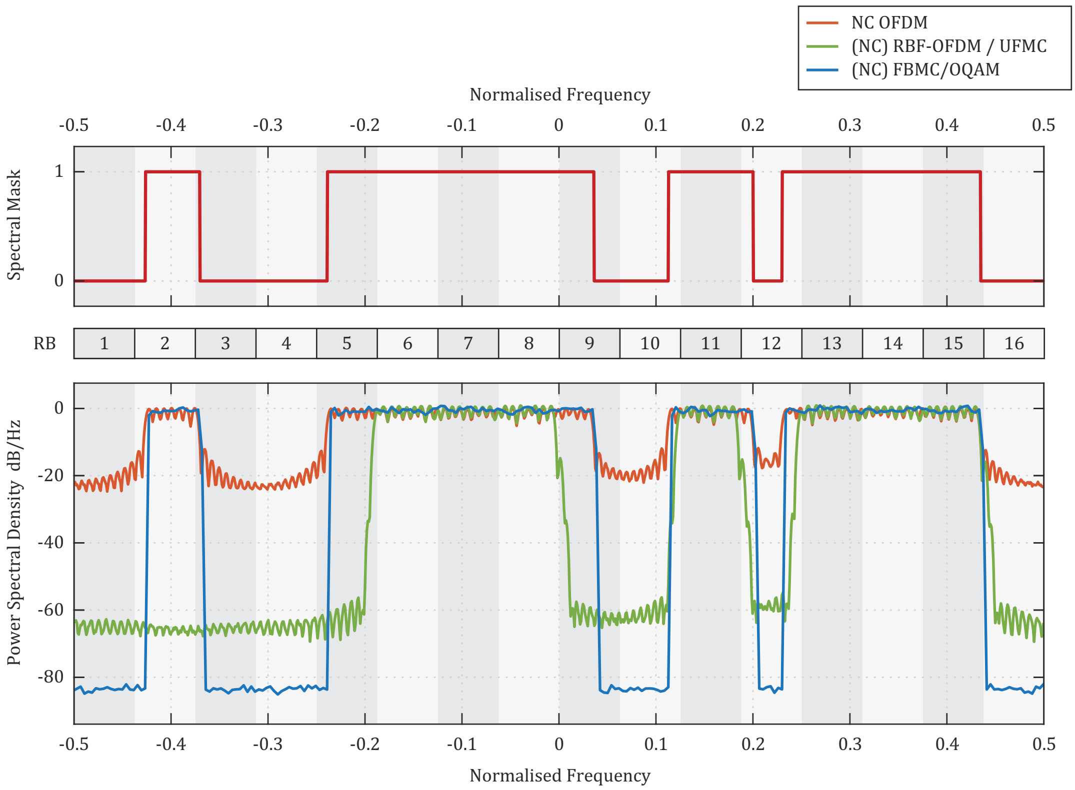

Figure 3.14: An example spectral mask (top); and (bottom) comparison NC power spectra of signals generated with OFDM, RBF-OFDM/ UFMC and FBMC/OQAM transmitters

The OFDM based systems have been configured with 128-point IFFTs. With the defined spectral mask, a maximum of 79 QAM subcarriers are available for use. (The remaining 49 subcarriers must be switched 'off').

It is clear from the plot that the NC OFDM transmitter has the highest OOB leakage levels. The power leaked into 'off' subcarriers is only around 20dB lower than the in-band power level. This scheme, it can be argued, is not suitable for DSA.

Pulse shaping bandpass Finite Impulse Response (FIR) filters with rolloffs spanning 4 subcarriers are used for the RBF-OFDM transmitter, providing an attenuation of around 65dB. Here, the spectrum has been divided up into 16 RBs, each containing 8 subcarriers. This means that 16 NC OFDM modulator branches are in use; totalling 16 128-point IFFTs and 16 pulse shaping filters. The OOB leakage is significantly lower than the NC OFDM transmitter (in this case 40dB lower), and the level of attenuation can easily be customised by modifying the length of the pulse shaping bandpass FIR filters. The drawback to this scheme is that not all of the 'available' subcarriers can be used, because the RBs do not line up exactly with the spectral mask. In this example, only 7 of the 16 RBs are utilised, despite there being subcarriers 'available' throughout 12 of them. This essentially means that, with this example, the transmitter is only making use of 71% of the available spectral resources, therefore limiting its total throughput and spectral efficiency. In terms of the transmitter's physical resources (i.e. RB branches), only 44% are used with the given spectral mask.

The FBMC/OQAM transmitter has been configured to use the $K=4$ PHYDYAS filter, and 256 OQAM subchannels (matching the QAM headline throughput rate, for fair comparison). This means that the transmitter uses a $K \times M=1024$-point IFFT. 156 of the 256 OQAM subchannels are available for use with the defined spectral mask. As each subchannel has its own filter, and each subchannel can be controlled independently, 100% of the available spectral resources can be used. The OOB leakage here is significantly less than NC OFDM, with OOB power 80 dB lower than the in-band level. The OOB leakage power with FBMC/OQAM is >60dB less than NC-OFDM, and >20dB less than RBF-OFDM with the pulse shaping bandpass FIR filter used in this example. While there is an increase in overall system complexity, in terms of the number of operations per second that must be carried out [47][52], and it has a longer PHY latency than OFDM based schemes [15], the FBMC/OQAM transmitter achieves a greater data throughput rate and a greater spectral efficiency [41].

For the scenario where a DSA SU radio was being designed to target very fragmented spectrum, the number of RBs required by the RBF-OFDM modulator would need to be drastically increased in order to make it more spectrally agile and achieve a comparable throughput rate. In turn, this would negating the complexity gains it displays over FBMC/OQAM. In this situation, the FBMC/OQAM modulator stands out as the strongest contender. This is in line with the findings of Farhang-Boroujeny [41], Gerzaguet [52], Mahmoud [84], Ravindran [123] and Weiss [150].

As discussed in Section 1.4 (page 6), much of the SU literature is concentrated on NC OFDM. While some researchers have identified the spectral benefits FBMC/OQAM schemes offer over OFDM, very few have reported on implementations of SU FBMC radios on real-time SDR hardware. There is a research opportunity, therefore, in exploring an FBMC PHY for the SU use case featured in this thesis. While this work is focused on exploring the viability of SU access to vacant spectrum in the FM Radio band, the general challenge of accessing fragmented vacant spectrum should not be considered a mature research topic. Controlled shared access to vacant TVWS and cellular channels is only just beginning; no 'best practices' or recommendations in terms of modulation schemes and implementation algorithms have yet been developed to enable fully dynamic access to (fragmented) vacant spectrum. The learnings from developing, implementing and experimenting with an FBMC based SDR solution (as presented in this thesis) should therefore be considered a contribution to the DSA research field.

3.5 Chapter Conclusions

This chapter has provided a brief overview of the popular NC-MCM schemes OFDM, RBF-OFDM/ UFMC and FBMC/OQAM (also known as OFDM/OQAM), with a focus on system level design and the waveforms that they produce. OOB leakage power levels for the different schemes have been discussed, and spectral comparisons made for an example SU spectral mask.

RBF-OFDM and UFMC result in a reduced system complexity than FBMC when few RBs are used. When available NC spectrum is very fragmented, radios using these schemes will be unable to make use of all spectral resources, due to the coarse frequency resolution of RBs. This will result in the radio having a lower spectral efficiency and lower data throughput rates than an equivalent design using FBMC/ OQAM. In the fragmented spectrum situation, FBMC/OQAM is the most suitable scheme for DSA-enabled SUs.

Chapter 4

FM Radio

Frequency Modulation (FM) is an analogue scheme which sees a carrier wave modulated with an information signal in a way that causes the carrier's frequency to fluctuate as the amplitude of the information signal changes. This modulation standard is commonly used for commercial radio stations due to its high resilience to additive noise, and is used by millions of people from all around the world to listen to music, sport and talk shows every day.

As will be discussed in this chapter, the FM band is often poorly utilised, and a significant amount of the allocated spectrum can be considered 'vacant' (from the perspective of a SU). This band is a potential candidate for SU DSA.

4.1 Chapter Overview and Contributions

In this chapter a case study is presented that investigates the FM Radio band under-utilisation in Central Scotland, allowing a comparison to the work by Otermat *et al.* [116] in North America. To the best of the author's knowledge, this is the first such field test study carried out in the UK. As expected, a significant amount of vacant spectrum was found. Full results of this study are presented in Appendix A.

A novel energy grid DSM and load balancing solution is proposed. Leveraging the Thread protocol (Section 4.5.2), vacant FM Radio spectrum and DSA-enabled radio, the new wide area broadcast solution would allow energy and grid operators to communicate DSM messages, in gaps of the FM band, to smart home consumer devices.

4.2 Commercial FM Radio Overview

Due to an initial lack of regulation, spectrum allocated to FM Radio (and even the form of the signals transmitted) is inconsistent around the world. When the first FM stations were established using Edwin Armstrong's FM Radio technology in the USA, they operated between 42–50 MHz. Lobbying by disgruntled 'interested parties' (AM Radio broadcasters NBC and ABC) led to the FCC shifting the band to 87.9–107.9 MHz in 1945 [81]. This rendered all existing transmitting and receiving equipment obsolete, and stifled uptake of the technology. Years went by before FM really took off, and it was not until the 1960s that regulators and standards bodies began laying the ground rules [137].

The 'de-facto' band later designated by the ITU-R spans from 87.5–108 MHz [72]. Other standard recommendations include a frequency deviation of 75 kHz, a signal bandwidth of 200 kHz (±100 kHz either side of carrier), and a co-channel interference limit of 45 dB [70]. Permitted centre frequencies are spaced 100 kHz apart, leading to a total of 206 potential centre frequencies (e.g. 87.5, 87.6, 87.7 MHz etc.). The ITU-R also oversaw the design of the stereo FM Multiplex, which sees 'left' and 'right' audio signals multiplexed together to allow transmission of both mono and stereo audio signals, and the RDS (Radio Data Service) add-on which is used to transmit digital information such as the station name and flags for traffic reports. The spectrum of a standard FM Radio signal is shown in Figure 4.1.

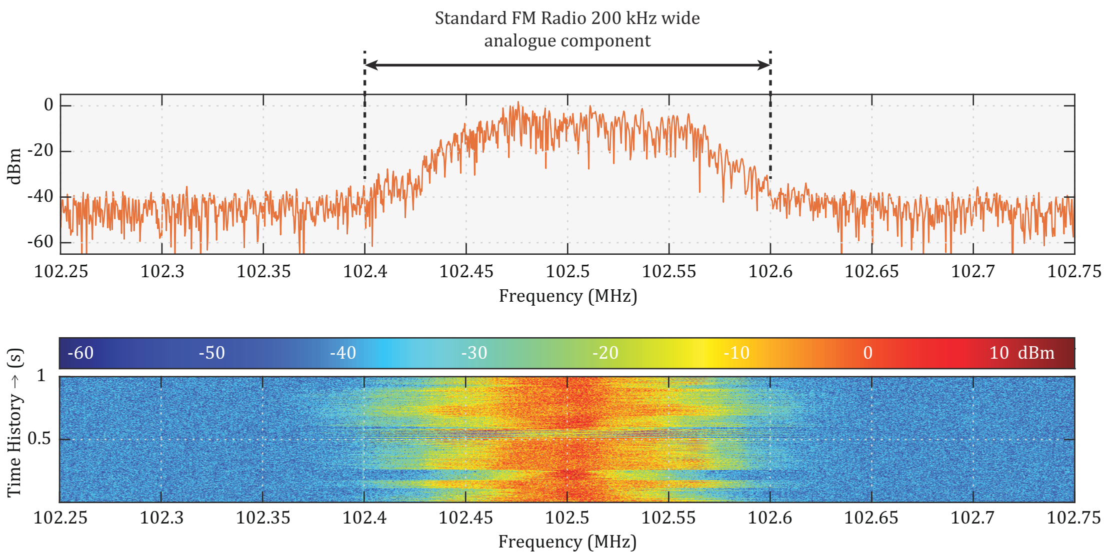

Figure 4.1: The power spectrum and spectrogram of a standard FM Radio station ('Clyde 1' FM signal captured with a USRP B210 in Glasgow, Scotland, UK)

4.2.1 Worldwide Variations

Nearly all countries have adopted these guidelines (most allocating 88–108 MHz to FM Radio), however there are some anomalies. Some former Soviet-bloc countries (including Russia, Lithuania and Ukraine) still use the ORIT FM band (*Organisation Internationale de Radiodiffusion et de Télévision* — a now defunct standards body), which spans from 65.8–75 MHz [72]. ORIT FM signals have a bandwidth of 10 kHz, and use a different process to generate stereo signals. Japan broadcasts FM Radio from 76–95 MHz, because the 'standard' FM band is used for analogue 'NTSC' TV. Japanese FM signals are still 200 kHz wide, however their stereo FM multiplex does not contain an RDS component.

In North America, a technology named 'HD Radio' (Hybrid Digital) is used to transmit digital signals alongside analogue FM (and AM) stations, in the form of OFDM sidelobes. With HD Radio it becomes possible to transmit up to 4 stations on each centre frequency—one analogue station and three digital (e.g. 92.3 FM, HD1, HD2 and HD3)—allowing multiple languages of a talk show or different musical genres to be broadcast on the same FM carrier simultaneously [186]. This hybrid signal has a bandwidth of 400 kHz, as the digital sidelobes are transmitted from ±(101.7/129.3 to 198.4) kHz either side of the main carrier [174]. The spectrum of an FM HD Radio signal is shown in Figure 4.2.

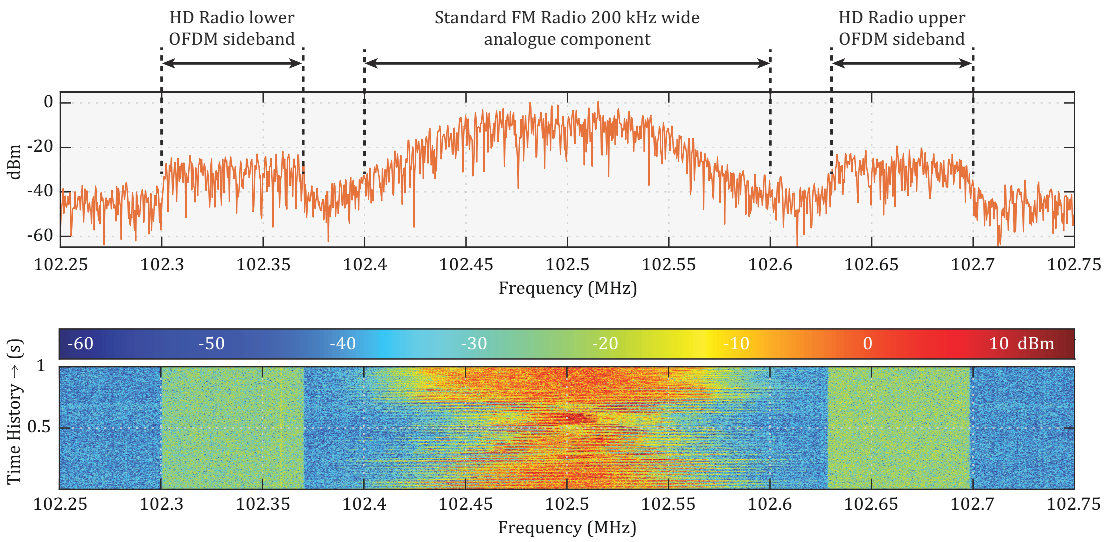

Figure 4.2: The power spectrum and spectrogram of an FM HD Radio station ('KSJO - Bolly 92.3' FM signal captured with a USRP B210 in Santa Clara, California, USA)

4.2.2 Digital Switchover

As of 2017, Norway ended national[14] broadcasting of FM Radio altogether, in favour of a DAB solution. The reported motive for this is that existing transmitter equipment was reaching end of life, and it was going to be more economical (and latterly energy saving) to install and operate digital transmitters instead [198]. One region of northern Italy, South Tyrol, has also begun turning off its FM transmitters. This is a mountainous alpine region, where a network of 212 transmitters was only able to provide 3 FM stations due to frequency channel reuse. In recent years, 84 DAB+ transmitters have been installed, which provide >99.5% coverage of the territory, and are able to broadcast 22 stations thanks to digital multiplexing [202]. The only other country with a set date to transition away from FM is Switzerland, and they intend to switch to digital between 2020/ 2024 [213].

In contrast, Sweden and Denmark have both cancelled their plans to switch to digital services, stating that FM currently provides a better service to the consumer [205][211]. Closer to home, the digital strategy in the UK had originally been that when digital radio accounted for >50% of listeners a switch off would begin. Despite this milestone having already passed, no commitments have yet been made. A recent statement by the BBC said that it would be "premature to shut down analogue", and that "radio is better served by a mixed economy" [167]. In many nations the reliance on, and investment in, 'trusty' FM Radio will likely mean that the near 100 year old technology's existence is assured for many years to come.

4.3 FM Band Utilisation

A recent study conducted across the whole of the USA has found that a large amount of the FM Radio spectrum is expected to be unallocated at any given location [117]. While only an initial investigation, the findings show a strong correlation between the population of an area and FM spectrum utilisation [116][118]. The authors show that often a significant amount of the band is unallocated, and propose that this spectrum could be targeted by opportunistic SUs for IoT applications. The findings of Otermat *et al.* are presented in Table 4.1.

14. Community run FM stations in Norway will continue to transmit until 2022

Table 4.1: FM Occupancy findings of Otermat *et al.* [118]

Population		Expected average 'unallocated' spectrum	Expected average 'vacant' spectrum (subset of 'unallocated')
Rural	< 100,000	16.2 MHz	13.2 MHz
Urban	100,000 – 1 million	15 MHz	6 MHz
Dense Urban	> 1 million	10.6 MHz	2.7 MHz

The correlation between population and unallocated spectrum is intuitive; where there are more people, more FM stations are broadcast, because there is more of a market. Many stations are funded via advertising, and there is little point broadcasting adverts where few will hear them! It is striking to see just how much of the band is expected to be unallocated—taking the 'urban' environment for example, only 25% of the channels are in use on average.

The authors note that 'unallocated' spectrum does not equate to 'vacant' spectrum however, as the FCC rules on minimum distance separation (protected radii around transmitters; essentially geographical frequency guard bands around active stations) must be considered. They make additional calculations to estimate the amount of 'vacant' spectrum (a subset of the 'unallocated' spectrum) that could potentially be available for SUs, and these results are presented in Table 4.1 also. While the amount of 'vacant' spectrum is found to be much lower (i.e. only 40% of the 'unallocated' 'urban' spectrum could be considered vacant when guards are considered), there is still a significant bandwidth available. 6 MHz would theoretically be sufficient to broadcast an entire Region II DTT multiplex channel, for example.

4.3.1 Case Study: FM Occupancy in Central Scotland

There have been no comparable studies carried out to analyse the occupancy of the FM band in Scotland, or the UK as a whole. It was decided, therefore, that a field test study would be carried out to investigate FM channel occupancy in Central Scotland, allowing for a comparison to be made with the findings from America.

A portable radio spectrum harvesting solution was developed, which featured an omni directional 'VHF' antenna, a USRP B210 and a laptop running MATLAB; with power provided by a car battery and inverter. Figure 4.3 shows a photo of the equipment.

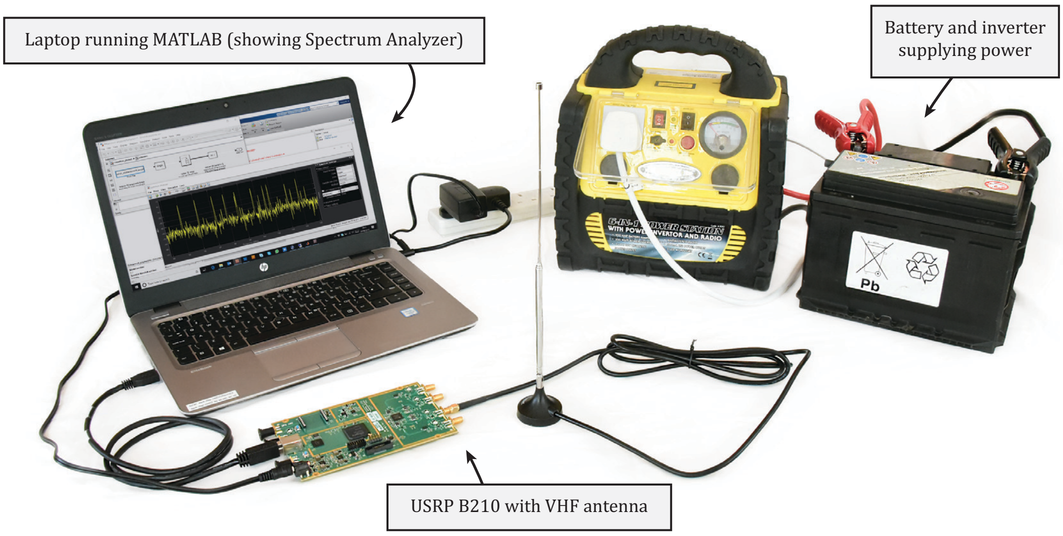

Figure 4.3: Experimental setup for FM spectrum harvesting

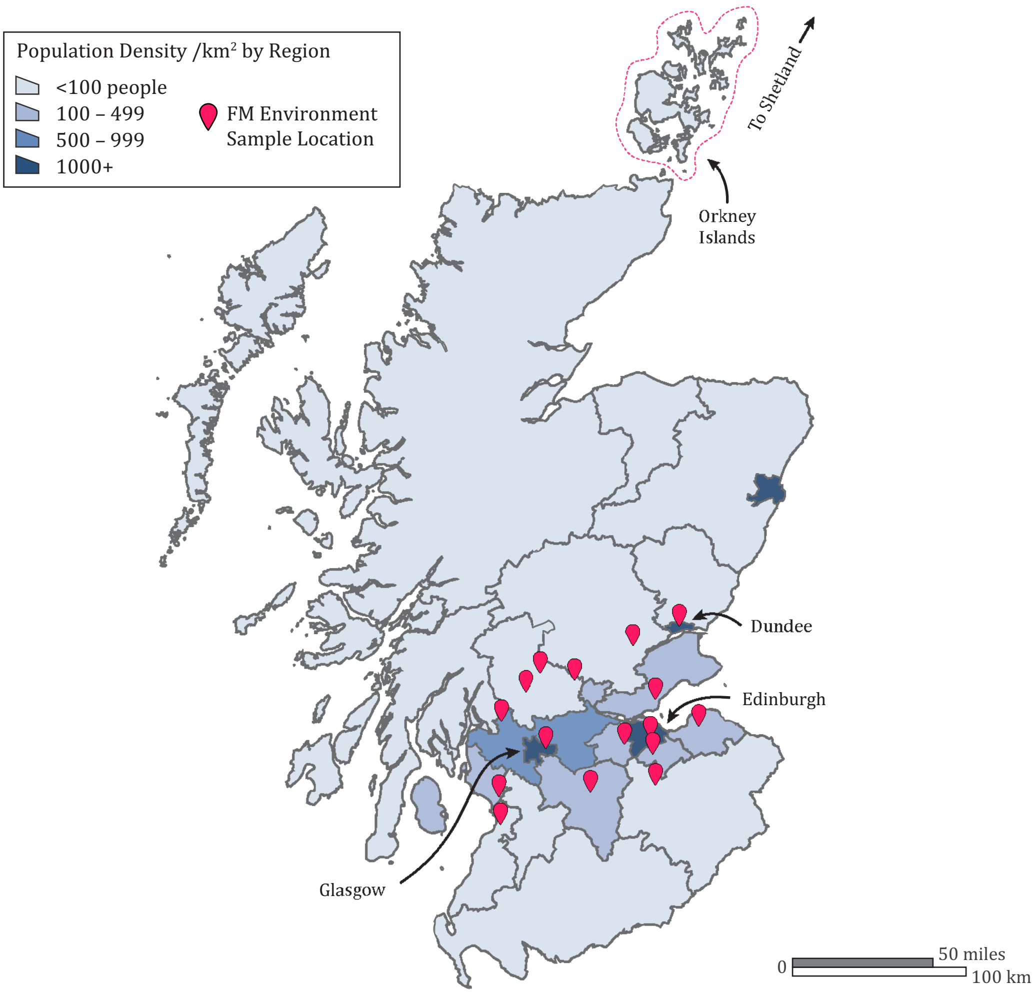

Figure 4.4: Population density map showing the main landmass of Scotland [197], with highlighted FM environment sample locations

The USRP was tuned to 98 MHz (the centre of the FM band), and the sampling rate was configured to 20.48 MHz. With these settings, the SDR received all ambient signals broadcast between 87.76 and 108.24 MHz. Contiguous samples of the entire FM Band were received and recorded to the laptop, to allow for offline analysis.

Measurements were taken in three of the largest cities, in smaller commuter towns, and in rural villages across Central Scotland. The FM environment sample locations are shown overlain on a population density map in Figure 4.4, and the findings from this investigation are presented in Table 4.2 (over break).

Table 4.2: Measured FM band utilisation in Central Scotland

Location (latitude, longitude)	Area Pop.	Number of FM stations received	Unallocated FM spectrum
Glasgow (City Centre) (55.860837, -4.243749)	1.2 million	22 (16 unique)	15.6 MHz
Edinburgh (South) (55.911816, -3.212972)	510,000	35 (15 unique)	13.0 MHz
Dundee (City Centre) (56.454091, -2.97862)	150,000	19 (11 unique)	16.2 MHz
Livingston, W Lothian (55.914130, -3.514740)	66,000	31 (14 unique)	13.8 MHz
Cumbernauld, N Lanarkshire (55.950273, -3.984263)	53,000	12 (11 unique)	17.6 MHz
Kirkcaldy, Fife (56.119926, -3.166247)	50,000	27 (14 unique)	14.6 MHz
Perth (City Centre) (56.389336, -3.444147)	47,500	19 (9 unique)	16.2 MHz
Kilmarnock, Ayrshire (55.609514, -4.486059)	47,000	14 (8 unique)	17.2 MHz
Ayr, Ayrshire (55.461264, -4.630632)	47,000	23 (9 unique)	15.4 MHz
Alexandria, Dunbartonshire (56.002065, -4.589235)	24,000	20 (10 unique)	16 MHz
Penicuik, Midlothian (55.837350, -3.224719)	16,000	15 (12 unique)	17.0 MHz
Haddington, E Lothian (55.955352, -2.782968)	9,200	19 (12 unique)	16.2 MHz

Table 4.2: Measured FM band utilisation in Central Scotland

Location (latitude, longitude)	Area Pop.	Number of FM stations received	Unallocated FM spectrum
Dunblane, Perthshire (56.186605, -3.9657505)	9,000	18 (12 unique)	16.4 MHz
Peebles, E Lothian (55.651366, -3.189633)	8,900	14 (8 unique)	17.2 MHz
Callander, Stirlingshire (56.24347, -4.215989)	3,200	20 (12 unique)	16.0 MHz
Aberfoyle, Stirlingshire (56.178748, -4.383894)	900	16 (10 unique)	16.8 MHz

The Greater Glasgow area is the only region in Scotland with a population over a million, and here, only 22 stations are broadcast. Based on the measurements, the average amount of unallocated spectrum at sample locations with a population <100,000 was found to be 16.1 MHz. It should also be noted that at many of the test sites, duplicate copies of stations were received on multiple different carriers, because signals from multiple neighbouring transmitters were present. In Alexandria for example, there were four copies of 'BBC Radio 1', three each of 'BBC Radio 2' and 'BBC Radio 3', and duplicates of some others too. (A full list of the results is presented in Appendix A). If these duplicates were discounted, even more spectrum could potentially be available for SUs. These results are largely in line with the findings of [118] (Table 4.1), which predicted the amount of unallocated spectrum to be in excess of 15MHz for areas with these population densities. These valuable spectral resources could be accessed and used by a new SU radio, designed specifically to coexist with the FM Radio PUs.

4.4 Motivation to Target FM Band for SU Access

In general terms, signals broadcast at lower frequencies are able to propagate further with the same transmit power than those at higher frequencies, due to channel effects and signal path loss [54]. Fundamental issues such as free space path loss, absorption loss, reflection, diffraction, scattering and even problems with the physical terrain, cause greater amounts of attenuation to signals transmitted at higher frequencies [71]. This is why a significant portion of services have traditionally operated in the lower part of the radio spectrum, and few consumer services have traditionally been broadcast above 6 GHz.

With the introduction of 'mmWave' in the 5G New Radio (NR) ecosystem, however, change is on the horizon [1]. The key motive for using these higher frequencies (between 24 and 60 GHz) is that greater bandwidths are available, meaning that cells can have a far higher capacity, and be able to support more devices with even higher data rates. The trade-off for these higher data rates is poorer propagation characteristics [53]. A recent 5G waveform propagation mapping study by the UK's Ordinance Survey found that heavy rainfall, sleet, vegetation (especially leaves) and street furniture such as road signs, traffic lights, lamp posts and bus shelters all cause "*substantial propagation problems*" for 5G mmWave signals [115]. With 5G mmWave, there is clearly a tradeoff being made between the propagation characteristics and overall communication channel throughput.

In the world of IoT, high data rates are less of a concern. Sensor and electrical switching nodes are likely to generate minimal amounts of traffic, and may wish to sleep when not in use; so factors such as transmit range and power efficiency become important instead. These requirements point to lower frequency and lower bandwidth solutions. With the advent of DSA, and regulators opening their minds to spectrum sharing, any lower frequency band that is not used to its full potential by the PU could be viewed as a potential SU target.

Consider the FM Radio spectrum. This band is largely consistent worldwide, and while it is used primarily to transmit analogue signals, it seems likely that FM will continue being broadcast for the forseeable future (as discussed in Section 4.2.2, digital switchovers are being delayed and cancelled). Otermat *et al.* showed that a significant amount of the band was unallocated across the whole of the USA [118]; and following the field tests in Section 4.3.1, very similar results have now been obtained for sites across Central Scotland. With a dramatic increase in the number of broadcast FM stations unlikely, it is almost certain that a few MHz of 'vacant' FM spectrum will remain available in all towns, cities and rural areas across the country for years to come, as shown in the spectrum captures for Central Glasgow and Dunblane in Figure 4.5.

Signals at FM frequencies have relatively long wavelengths (~3m), with excellent propagation characteristics. They are able to diffract around objects such as hills and

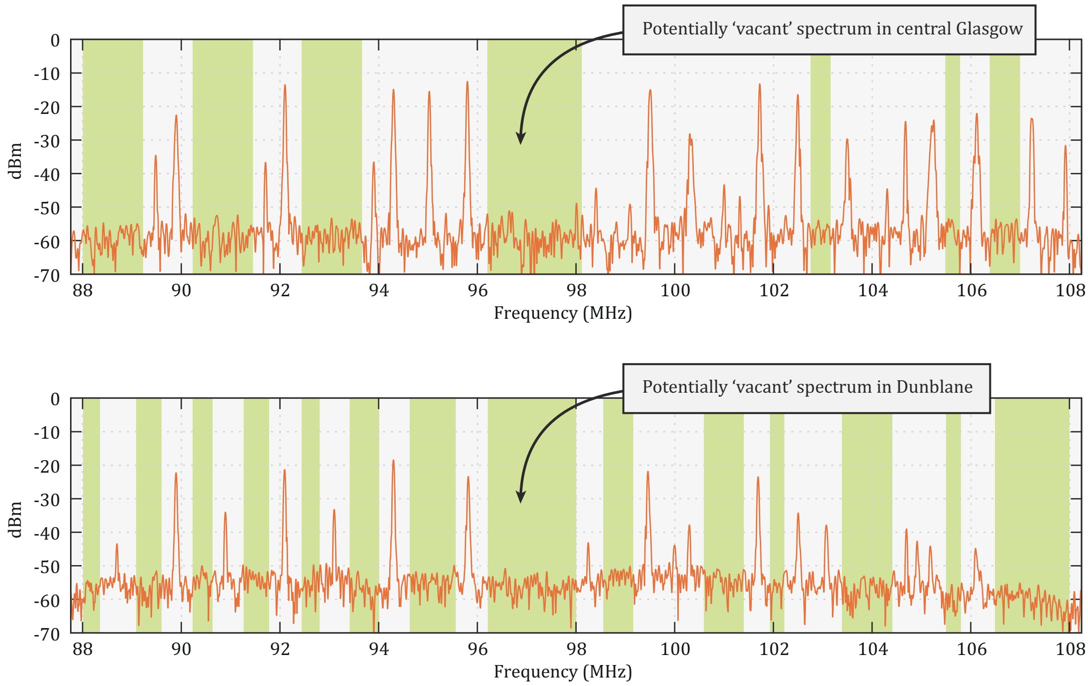

Figure 4.5: Snapshots of the FM spectrum in the centres of Glasgow (top) and Dunblane (bottom), highlighting potentially 'vacant' spectrum fragments in both cities

human-made structures, and have high levels of penetration through buildings—something that higher frequency signals, such those used for Wi-Fi and cellular, often struggle to do. The NC nature of unallocated and 'vacant' spectrum in the FM band should be considered one of the biggest design constraints, when designing a SU radio to operate in it. As is evident in Figure 4.5, not all of the 'vacant' spectrum will be found in one contiguous subband—it will be fragmented sporadically between broadcast FM Radio stations. To fully utilise the available resources, the radio would have to aggregate all of these fragments together.

Aggregation is achievable with a NC-MCM scheme that uses a variable spectral mask. Knowing which PU FM Radio channels were in use, SU subchannels in the transmitter could be disabled and spectrally 'knocked-out' in order to ensure that the PU signals were always protected. The set of subchannels to disable would be determined either by consulting a (new) FM Radio geolocation database, or locally by the SU, using a (regulator-approved) spectral sensing technique. No SU ACLR limits have been set by regulators for the FM Radio band, because DSA is currently not implemented within it; however a figure can be estimated based on a review of the published ITU-R FM Radio regulations.

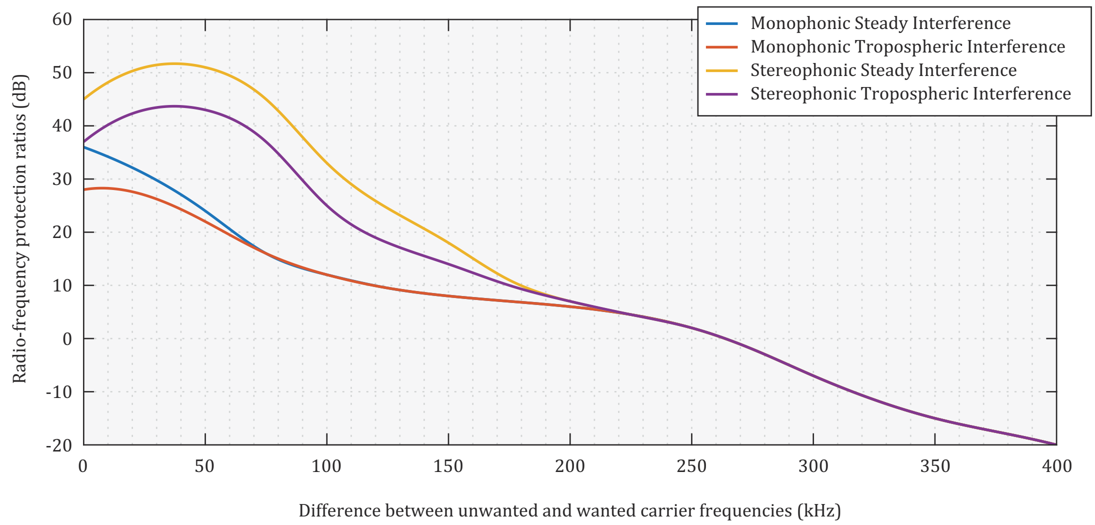

Figure 4.6: ITU-R BS.412-9 RF protection ratio (dB) for FM signals using a maximum frequency deviation of ± 75 kHz [70]

ITU-R BS.412-9 presents information about the protection ratios required for FM Radio signals [69][70]. These values can be thought of as the worst permittable Signal to Interference Ratio (SIR) from the perspective of the FM signal, before interference is audible at the output of the receiver. They vary depending on:

- whether the signal to be protected is mono or stereo FM
- the frequency deviation of the FM signal
- whether the interference is steady or tropospheric
- the carrier frequency spacing between the FM and interfering signals

A graph of the ratios is presented in Figure 4.6. Taking the example of a stereo FM signal subjected to a steady interference signal spaced 100 kHz away (i.e. the yellow line of Figure 4.6), the protection ratio is shown to be 33 dB. Therefore, the power of the interferer (at the time it reaches the FM receiver) under these conditions must be at least 33 dB less than the power of the in-band FM signal in order not to cause noticeable interference. From this, it is possible to estimate the maximum permitted OOB leakage and transmit powers for an NC-MCM SU signal operating in the FM Radio band [120]. Taking the yellow line from Figure 4.6 and inverting it, the protection ratio can be plotted alongside an FM carrier, as illustrated in Figure 4.7. From this, it can be seen that the OOB leakage must always be at least 52 dB lower than the power of the PU FM Radio signal (again, at the time it reaches the FM receiver),

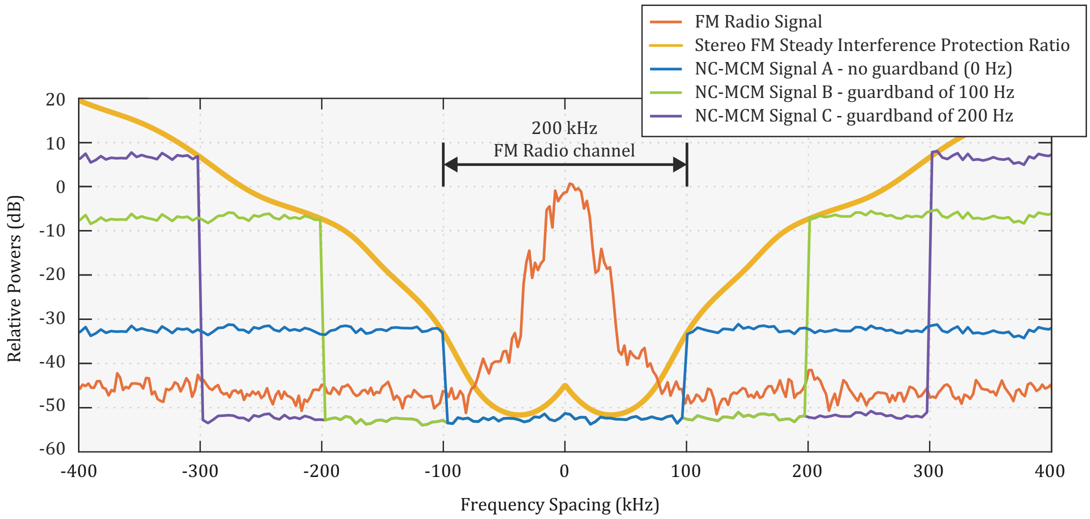

Figure 4.7: Illustration of NC-MCM signals with various guardbands and their predicted maximum relative powers in order to meet FM protection ratios

while the permitted transmit power of the in-band part of the SU will relate to the frequency guardband in use. When no guardband is used, and the SU signal uses immediately adjacent spectrum, the maximum SU power at the receiver must be 33 dB less than the PU (to meet the interference threshold presented in yellow, extracted from Figure 4.6). If a 100 kHz guard is used, the transmit power can increase to 7 dB less than the PU, etc. If a SU that meets this criterion can be developed, it should be possible for it to coexist with the PUs of the FM Radio band.

4.5 FM Band for the Smart Grid

This section presents a novel SU re- use case for vacant spectrum in the FM Radio band. It is proposed that this spectrum could be (secondary re-)used by Distribution Network Operators to broadcast Demand Side Management messages to consumer smart home equipment, and in doing so, provide a communications solution for load balancing in future smart grids.

4.5.1 Demand Side Management and the Smart Grid

A vision of the future smart city frequently discussed by electrical engineers is the 'smart grid' [42]. While much research is ongoing [39][43][56][57], currently there seems to be little traction in actually developing a system where DNOs are able to remotely perform DSM by controlling consumer devices (such as washing machines, freezers and Electric Vehicle (EV) charging stations) in customers' homes. (Note—this might be partly due to consumer resistance to the idea!)

The EU mandated over a decade ago that, by 2020, at least 80% of consumer premises should have access to 'smart meter' technology [37]. Smart meters are currently being offered to all premises in the UK, and these are designed to inform consumers about their usage and facilitate automated energy meter readings. The 'SMETS2' smart meters communicate with the customer's energy supplier, and send usage information so that the customers are only charged for the energy they use. In England they operate on a newly created 'flagship' 2G cellular network operated by Telefonica/O2, and in Scotland, an Arqiva-run 420 MHz Land Mobile service [171]. While these devices provide the facility to automatically disconnect and reconnect electricity and gas supplies for safety reasons, they cannot perform DSM, as they cannot control or individually switch end user devices.

The closest the UK currently has to the smart grid DSM dream is a service called the Radio Tele-switching System (RTS), which ironically has existed for nearly 40 years [151]. RTS is a service which controls 'tele-switched' electricity meters for the remote switching of electric storage heater radiators, many of which are located in rural Scottish Highlands & Islands [80]. (A tele-switched supply is shown in Figure 4.8, courtesy of [172]). It was introduced to enable the Central Electricity Generating Board (now defunct) to spread the charging load of storage heaters throughout the day at times when there was a lower overall demand on the grid. This basic form of load balancing sees digital information (with a data rate of 1.5 kb/s) encoded alongside the BBC Radio 4 long wave AM Radio carrier, 198 kHz, and broadcast simultaneously from the UK's three long wave transmitters: Droitwich, Westerglen and Burghead. With RTS, a single 50 bit message (18 bits of which comprise a header and redundancy code) is capable of switching 200 MW or more of load in pseudo-real-time [175].

The archaic transmitting equipment used for long wave in the UK relies on thermionic glass valves. In 2011, the BBC announced that they would no longer have replacement valves manufactured [209]. With fewer than 10 spares remaining in the world, the days of long wave AM Radio are numbered. When one of the final remaining two valves breaks, it will be impossible to continue broadcasting. In light of this, Ofgem (the Office of Gas and Electricity Markets regulator) had planned for RTS to be

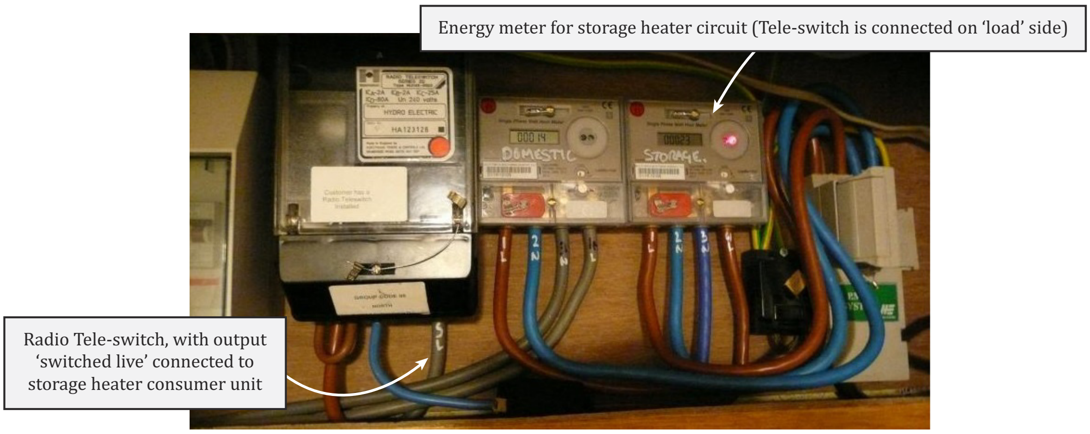

Figure 4.8: Photograph of a Scottish Hydro Electric Radio Tele-switch, used to control the electricity supply to a storage heater consumer unit, from[172]

discontinued nationwide in 2019 [80]. However, the Energy Networks Association arranged an extension of the service with the BBC until 2021 (if the valves last that long!), due to the lack of suitable alternative smart metering and DSM load balancing equipment [181]. Scottish Hydro Electric industry experts presented a paper in 2013 that stated an equivalent load control system must be considered the minimum required level of functionality in smart meters [151], and without it, they estimated that an additional £160m of new generation assets would be needed.

At some point in the very near future, DNOs will lose the ability to control storage heaters over RTS. This should be the least of their concerns though, as the UK enters the EV age. At a time when the electricity grid is becoming increasingly reliant on volatile renewable generation sources, and baseline fossil fuel power plants are being phased out, the concept of millions of EVs plugging in to charge each night, with no way to remotely control charging cycles, is a concern [94]. It has even led to Ofgem issuing guidance to only charge EVs outside of peak hours [200].

Looking forward, the National Grid say there will be sufficient capacity in the grid, but only if smart, remotely controlled chargers are used [207]. The issue with this statement is that, to date, there has been little in the way of standardisation of normal EV chargers; let alone smart chargers. Other than the small number that are being upgraded for a smart charging trial in London [208], none of the existing chargers in the UK can be remotely controlled by the grid operators. While EVs draw energy out of the grid, they could also be used as an energy source when connected, and feed back into the grid—Vehicle to Grid (V2G)—to help balance it [154]. EVs are the perfect candidate for DSM; but enabling this technology will require standardisation, of both the EV + charger technology and the communications protocol used [90]. There are currently various communications protocols being considered for last-mile DSM worldwide, several of which are based on meshing networks and IEEE 802.15.4 [57].

4.5.2 Thread Protocol

Often new technologies take many years to become widely adopted, because equipment manufacturers do not invest time and money in adopting something that could become a market failure; and consumers are slow to buy new technology.

Thread is an open source and industry-led smart home and IoT communication standard that has been developed in recent years [201][210]. It is based on the low power 6LoWPAN, built on top of the IEEE 802.15.4 MAC and PHY [76][139], and is fully compatible with DotDot ":||", the Application Layer IoT device inter-operability language [217]. It has gained the support of many leading technology companies, and silicon/appliance manufacturers. Arm, Qualcomm, Nordic Semiconductor, NXP, Texas Instruments, Nest (Google), Apple, OSRAM, Philips, Samsung, Siemens and Yale are developing 'smart' products that support Thread; and Thread-enabled smart cameras, thermostats, door locks and LED lights are already being installed in consumer homes [168]. It is fast becoming the de facto IoT standard for the smart home [196], and therefore, it would be logical for this well established, IP-based, wireless mesh standard to be the frontrunner for Home Area Network (HAN) DSM. Likewise, an argument could be made that smart EV charger manufacturers should adopt it too.

4.5.3 A New Future for FM?

Theoretically, it is possible to transmit multicast messages over Thread (i.e. single transmitter to many receivers), as it is IPv6 based. This would be ideal for last-mile HAN DSM, as the grid operator would be able to address many devices with a single message. These devices (e.g. washing machines) could be programmed for remote switch-on when the demand on the grid is lower, and energy is cheaper. Thread is designed to use gateways called Border Routers to connect to Wide Area Networks (WAN) for backhaul (often the Internet), as shown in Figure 4.9. These tend to be

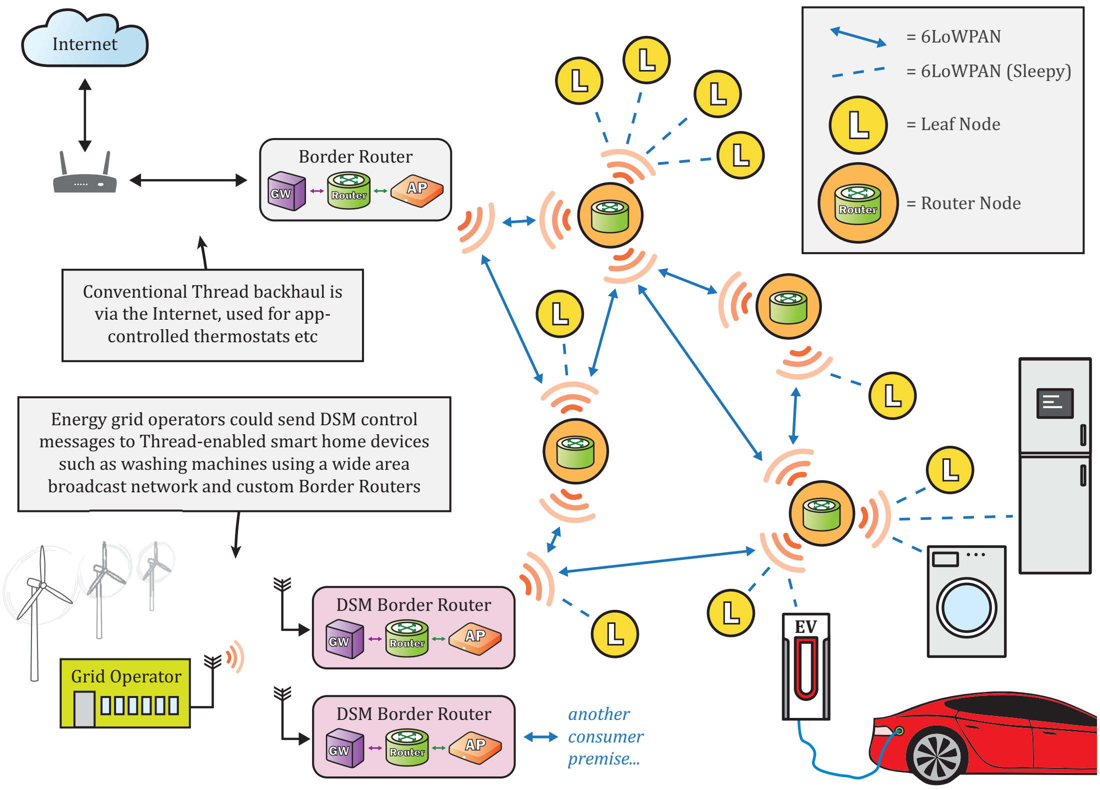

Figure 4.9: Example Thread network with a series of Router and Leaf nodes, with Border Routers facilitating Internet access and DSM facilities

connected via Ethernet to household broadband routers to allow remote access to smart devices; however, an alternative backhaul technique could be used as long as a new Border Router was created to support it.

As has been described in depth throughout this Chapter, the FM Radio band is not fully utilised, and presents an excellent opportunity for SU reuse for IoT applications. This band could be targeted by a bespoke DSA-enabled radio, designed to enable DNOs to broadcast WAN DSM load balancing messages to consumer equipment as part of a future energy smart grid.

A new national broadcast–only WAN could be developed that operates as a SU in vacant channels of the FM Radio band, that sees DSM messages transmitted alongside analogue FM Radio stations. This could leverage the existing infrastructure (radio masts, multiplexers, antennas etc) that is currently in place for FM Radio broadcasting. An additional SU radio would need to be installed at each site, which would latterly be operated by DNOs in a similar manner to the RTS service. This radio could either be truly DSA-enabled and cognitively identify vacant FM Radio channels and develop its own NC-MCM mask, or (more likely), be controlled by a SU database, such as the one described in the tiered access model suggested by Ofcom for future spectrum management (Section 2.4.3 (page 28)).

For the smart home, a new SU Thread Border Router could be developed specifically to receive signals from the FM band SU WAN, translate the received data payloads to IPv6 packets, and rebroadcast the received DSM messages into the HAN environment using the Thread protocol. This would have the potential to enable the remote switching of many DotDot compatible home appliances, and potentially enable smart EV charging and V2G solutions; providing DNOs a method to balance the grid in pseudo real time. One of the issues installers of SMETS2 smart meters are facing is that the ambient signal strength of the backhaul 2G and 420 MHz networks is often very weak deep inside consumer premises, and this is leading to increased costs and the installation of additional antennas on external walls [26]. As discussed in Section 4.4, the physical properties of signals broadcast in the lower frequency FM Radio band will result in higher levels of penetration through buildings, and therefore broadcasting WAN messages in the FM band will likely result in increased performance of SU Thread Border Router receivers installed in the home.

Implementing this would obviously require extensive resources and development time, alongside support from DNOs; but the same would be true for any other proposed DSM solution. The primary advantage this proposal offers is that would see SU reuse of vacant FM Radio band spectral resources that would be otherwise wasted.

4.6 Chapter Conclusions

This chapter has reviewed the common analogue radio standard known as FM, its worldwide broadcast variations and the (non-impending) digital switchover. Underutilisation of the band has been discussed, and a case study presented that explores FM band occupancy in Central Scotland, highlighting the significant amount of vacant spectrum. The results were found to be very similar to a case study from the USA, which predicted around only 25% of the spectral resources to be in use in an urban environment. The favourable propagation characteristics of signals broadcast in the FM Radio band were discussed, and a motive for SU reuse presented. ITU-R FM Radio protection ratios have been analysed, and an argument made that, subject to in-band and OOB power levels, it should be possible for SUs to coexist in the FM Radio band without causing audible interference to PU signals.

A novel use case for SU reuse of vacant FM spectrum was proposed, and a SU radio solution described that would enable DNOs to broadcast DSM load balancing messages to consumer smart home equipment and EVs as part of a future energy smart grid. This would provide an improved replacement to the ageing RTS, which will soon be discontinued when the remaining AM Radio broadcast equipment fails.

Chapter 5

PHYDYAS FBMC Transmitter

This chapter provides a review of the practical DSP work that was carried out during the development of the DSA-enabled SU radio PHY for operation in the FM Radio band. The radio uses the NC-MCM scheme FBMC, and the PHYDYAS prototype filter was chosen because of its favourable spectral characteristics and suitability for dynamic spectrum applications. The radio transmitter and receiver PHY layers were developed in Simulink, using low level HDL-compatible components from the MathWorks HDL Coder library. This would later speed up the targeting process, as the design was already optimised for FPGA/ SDR implementation.

5.1 Chapter Overview and Contributions

A novel DSA-enabled PHYDYAS FS-FBMC/OQAM radio transmitter is presented, designed to operate as a SU in the band traditionally used for FM Radio broadcasting (88-108 MHz). The transmitter leverages cognitive radio techniques to automatically adjust its channel mask, and mold its spectral output around PU signals. To the best of the author's knowledge, this is the first radio design proposed to address the opportunity (and challenge) of enabling DSA in the FM band; which, as discussed in Chapter 4, is not being used to its full potential.

System parameters optimised for the task were chosen, and a custom FS-FBMC modulator architecture was developed that met the design constraints for ZynqSDR targeting (Section 2.5.1 page 37). A transmitter protocol is proposed, and basic receiver is implemented to facilitate system simulation. Finally, investigations are carried out to explore the effects this SU radio has on the quality of PU FM Radio signals, and vice versa, the effects that PU signals have on the SU under various SU transmit powers, in a simulation environment.

5.2 SU Access to FM Band with FS-FBMC/OQAM

As discussed in Chapter 4, the FM Radio band spans 20 MHz[15], and each 'FM channel' is 200 kHz wide. Designing the radio such that meant there was an integer number of SU OQAM subchannels inside each FM Radio channel would result in the most efficient solution.

The IFFT is the core feature of an FS-FBMC transmitter; it is the component which converts filtered OQAM samples from the frequency domain into time domain FBMC symbols. Due to the nature of its implementation, the IFFT works most optimally when a power-of-2 number of samples (N) are input to it. With a sampling rate of f_s, the frequency domain spacing of the input samples is f_s/N. In FS-FBMC of course, $N=MK$, and with the PHYDYAS filter, $K=4$; so it was important that the number of subchannels chosen for the radio was a power-of-2 number.

Therefore, a system sampling rate of $f_s=20.48$ MHz was chosen, along with $M=1024$ OQAM subchannels. With these parameters, the (overlapping) subchannels would each have a bandwidth of 40 kHz and be spaced 20 kHz apart, meaning that 10 subchannels would fit inside each standard 'FM channel', as illustrated in Figure 5.1.

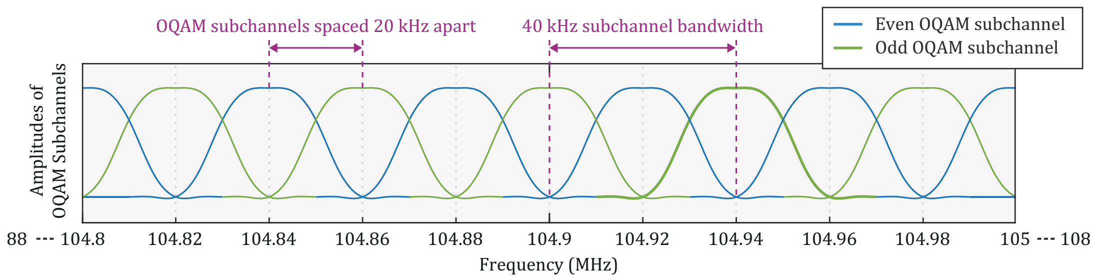

Figure 5.1: FBMC/OQAM subchannels, configured to operate inside the FM Radio band

One of the most important requirements of the radio is that it must cause minimal interference to FM Radio PU signals. Therefore, the transmitter must have the ability to disable and spectrally 'knock-out' certain subchannels. The most logical way to implement this was with a binary (on/off) spectral mask, as shown in Figure 5.2. As (at the time of writing) no geolocation database exists for SUs operating in the FM Radio band, an automated spectral sensing technique had to be developed in order to create and update the mask at runtime.

15. (88–108 MHz)

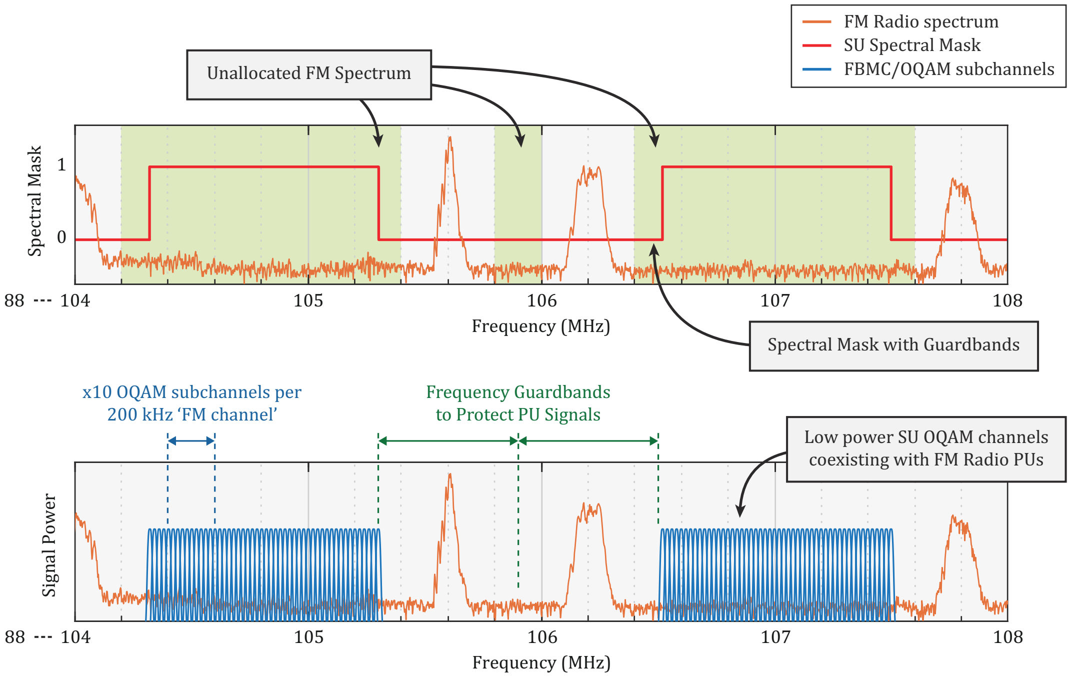

Figure 5.2: An example channel mask (top), applied to FBMC/OQAM subchannels (bottom)

5.3 Transmitter High Level Overview

When the transmitter is activated, a channel mask (complete with guardbands to protect detected FM Radio stations) is automatically generated by the 'maskGen' module, shown in Figure 5.3. This mask will contain x active, and $M-x$ disabled subchannels. Next, x bits of binary data (and $M-x$ null bits) are acquired from a data buffer, and are fed (according to the channel mask) into a Gray coding and OQAM modulation stage, shown in blue in Figure 5.3. This creates complex OQAM symbols. The mask is applied to the symbols, which then enter the FS-FBMC modulator. Here they are upsampled by a factor of $K=4$, and convolved with the frequency domain coefficients of the PHYDYAS prototype filter. The MK filtered samples pass through an IFFT to generate time domain FBMC symbols, and K of these are then 'overlapped and summed' together in the time domain prior to being output to the radio front end. The roll-off of the PHYDYAS filter means that the power of the OOB leakage in spectrum holes (i.e. in disabled parts of the mask) will be 80 dB below the in-band level [145].

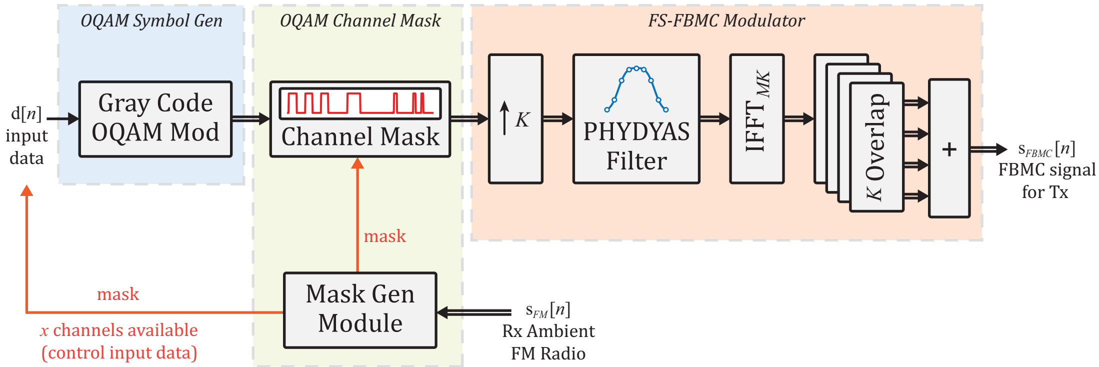

Figure 5.3: High level block diagram of the processes carried out inside the PHYDAYS FS-FBMC/OQAM transmitter

If every subchannel was found to be available for use, the PHY throughput rate of the transmitter would be just under 20 Mb/s (a function of the 4-OQAM scheme used). This is never likely to occur however, as the transmitter would require the full 20 MHz of spectrum to achieve this rate. The throughput of this radio is a function of the number of FM stations being broadcast in the local area, the frequencies they are using, and the size of the frequency guardband used in the SU transmitter's mask. To give an example, even if the same number of FM stations were being broadcast in locations 'A' and 'B', it is unlikely that the amount of 'vacant' spectrum in A and B would be the same (as the FM stations are likely to use different centre frequencies); therefore, the SU radio would almost certainly achieve a different throughput rate in location A to location B.

Based on the findings from the USA [118], in regions with a population between 100,000 and 1 million, there is on average around 6 MHz of available spectrum; meaning that a PHY throughput rate of 6 Mb/s could be possible with this radio. While such a throughput would not be suitable for streaming 4K video, it would be more than sufficient for an IoT application.

5.4 Fixed Point Synthesisable FS-FBMC PHY

The transmitter was developed within Simulink, using low level components from the *HDL Coder* toolbox. During initial development and module testing, floating point arithmetic was used throughout to ensure data integrity. Latterly the design was converted to fixed point, prior to the ZynqSDR targeting process discussed in Chapter

6. The system was developed with 'valid lines' (which can be thought of as digital enable signals), in such a way that every system clock 'tick' would see individual samples progressing to their next clocked element in the design, as would be seen later on the FPGA. This 'hardware first' approach was taken to prevent a system redesign prior to targeting. (The alternative option would have been to start with simulation-only blocks which were not suited to hardware targeting, and did not feature valid lines).

5.4.1 OQAM Modulation

The first component of the transmitter design is a module that converts a stream of binary data into Gray coded OQAM symbols. Conventionally in FBMC transmitters, OQAM 'preprocessing' is shown as a process wherein Gray coded complex QAM symbols are separated into their I and Q components, upsampled by a factor of 2, and staggered to create I and Q OQAM symbols. It is more efficient to map Gray coded binary directly to the subchannels, however, which was the method adopted.

The Gray coding is performed in a fixed manner. The coded bits are passed into the modulator, where either an odd or even OQAM symbol is created. The first bit to arrive is mapped to an odd symbol, the second to an even, and so on, until M bits have been mapped to subchannels. At this stage the modulator toggles, and OQAM symbols generated for the next FBMC symbol are created in the reverse order, i.e. even then odd, etc.

5.4.2 PHYDYAS FS-FBMC Filterbank PHY Implementation

After OQAM modulation, symbols are upsampled by a factor of K, and convolved with the PHYDYAS filter coefficients using a simple FIR filter. This increases the system sampling rate to Kf_s. Next, the samples are passed through a 4096-point (MK) IFFT to generate time domain FBMC symbols. As shown in Figure 3.10 (page 49), these FBMC symbols must be overlapped and summed together, and the system sampling rate must be reduced back to f_s to complete the modulation process. The solution was to use a bank of K FIFOs (First-In First-Out memory units). These stored the generated symbols at Kf_s and performed a rate transition to the lower sampling rate, f_s. The FIFOs were arranged to be overlapping in time, such that their outputs could simply be summed together. While this solution worked, and produced the correct output, an implementation issue would have been encountered later when it came to targeting the ZynqSDR. (Essentially, no components in the design may have a sampling rate higher than the overarching system sample rate f_s—the sampling rate inside the design may be *lower* than f_s, but not greater).

The system sampling rate in this design is f_s = 20.48 MHz; and after the K upsampling, the rate increases to Kf_s, i.e. 81.92 MHz, as shown in the top part of Figure 5.4. This sampling rate could not be supported by the hardware, so the modulator was redesigned, and split into K parallel processing branches using a series of FIFOs, as shown in the bottom part of Figure 5.4. Each branch was fed a contiguous burst of M OQAM symbols at a rate of f_s / K. When these parallel modulators upsample by K, FIR filtered and generated FBMC time domain symbols using IFFT blocks, they each output at the original rate, f_s. By their parallel nature, these modulators were already 'overlapping' in time, so a final summation was all that was required to combine them and generate the FBMC time domain signal. This FS-FBMC PHY, developed in Simulink, is presented in Figure 5.5.

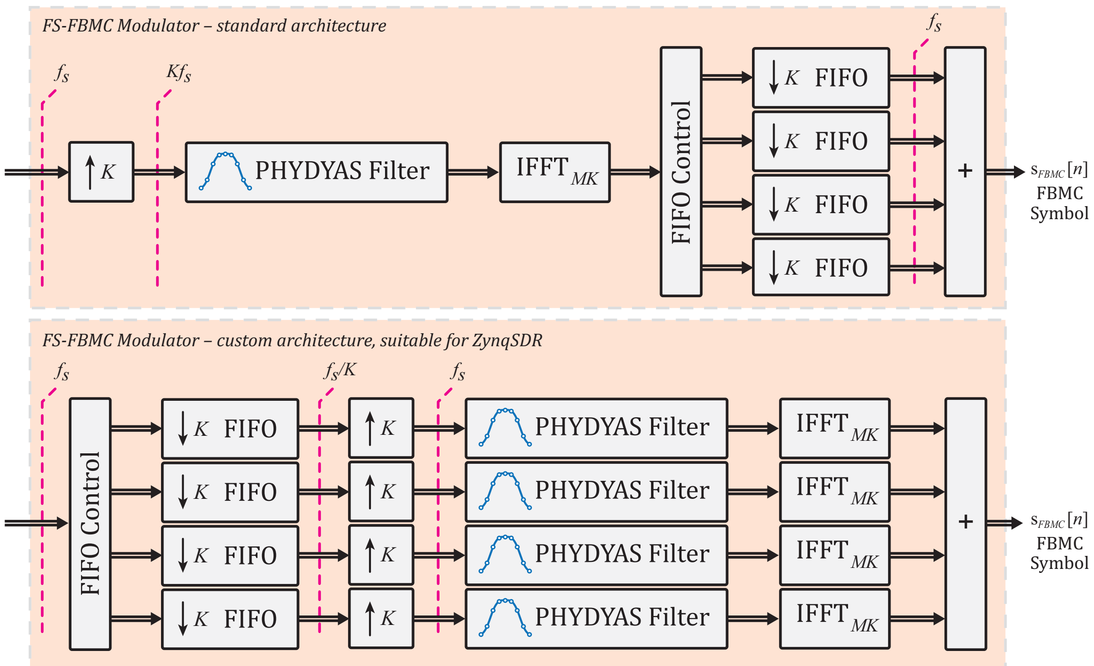

Figure 5.4: Comparison of the standard FS-FBMC modulator architecture and the custom configuration developed for compatibility with ZynqSDR

It was confirmed via simulation that this alternate architecture generated exactly the same signal. While the physical resource requirements of the modulator component

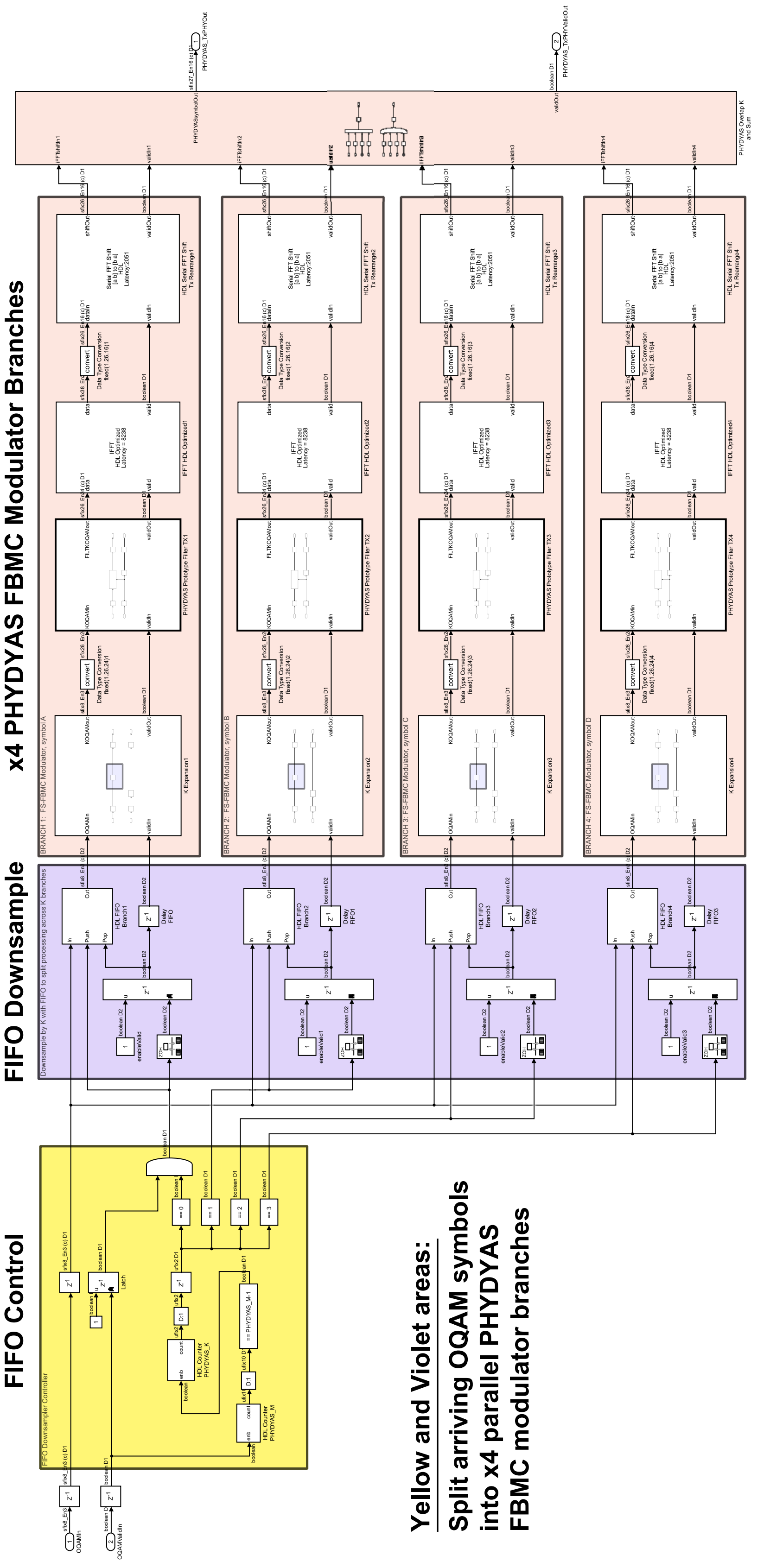

Figure 5.5: Simulink Model: PHYDYAS FS-FBMC modulator $K = 4$ parallel implementation (zoom into high resolution PDF to see greater detail)

increased by a factor of K, the design performs almost the same number of operations per second; and hence the designs are essentially computationally equivalent [85].

5.4.3 Output Gain Control

It was noted when performing initial simulations of the FBMC modulator that there was a relationship between the number of active subchannels and the average amplitude of the output FBMC symbols. As the design would eventually be targeted to SDR hardware, where it would be important to maintain full use of fixed point wordlengths, an 'autoGain' module was developed to perform gain correction. Samples were taken to find output symbol amplitudes, and this information was used to calculate gain correction values required to maximise the dynamic range. The module used a LUT to apply the appropriate gain, based on x, the number of subchannels in use. The LUT output is shown in Figure 5.6. With x=128 subchannels, for example, the autoGain module would apply a gain correction of 163 (i.e. multiply the samples by 163 to increase their amplitude); while for x=768 subchannels, a correction of 68.

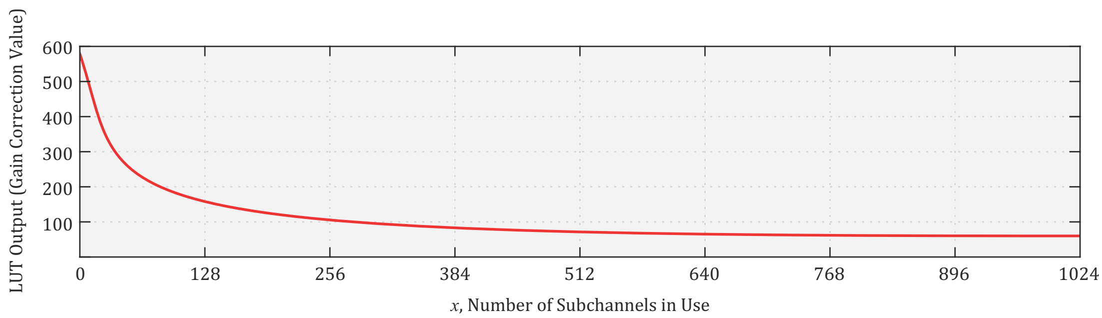

Figure 5.6: Plot showing the correction gain required vs the number of active subchannels

5.5 Near Real-Time FBMC Mask Control

In order to control the FBMC modulator, and ensure that information was only modulated into subchannels which were available for the SU, a 'maskGen' module was developed. This module, in terms of the number of components, is far more complex than the rest of the FBMC modulator. The maskGen module was designed to scan through the FM band, perform FM demodulation at each permitted FM centre frequency, classify whether a PU is present or not, and then generate a spectral mask of length MK with guardbands to protect the PU. The top level diagram of this module is presented in Figure 5.7. Samples of the FM spectrum, centred at 98 MHz, are input to the module with an int16 (i.e. 16-bit signed integer format) datatype; along with boolean (1-bit binary) control signals to manage the mask making process. The full design can be viewed in Figure 5.8.

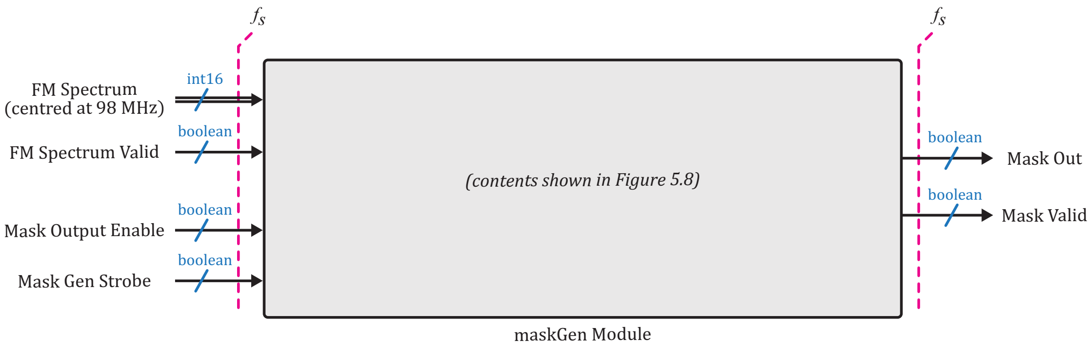

Figure 5.7: Top level diagram of maskGen module

5.5.1 Synthesisable FM Matched Receiver

Samples of the full FM Radio spectrum are input to the matched receiver. The complex samples are mixed with a complex sine wave, to shift the spectrum so that the FM Radio channel of interest is centred at 0 Hz. Next, decimation by a factor of 64 is performed, to reduce the sample rate from f_s to 320 kHz. The lowpass filters in the decimators filter the samples, isolating single FM Radio channels. (Serial filter architectures were leveraged to achieve efficient HDL implementations). The tuner and decimators are contained within the orange and beige blocks of Figure 5.8.

Next, FM demodulation is performed using a *Complex Delay Line Frequency Discriminator*, as developed in [137] (pp. 355-358). This is a series of DSP blocks that efficiently approximate a differentiator, converting FM phase changes to amplitude changes. This non-coherent demodulator is described in Eq. (5.1).

$$s_{demod}[n] = \angle\left\{\left(s_i[n] - s_q[n]\right) \times \left(s_i[n-1] + s_q[n-1]\right)\right\}, \qquad (5.1)$$

where s_i is the In Phase, and s_q the Quadrature Phase component of the modulated FM signal, in the discrete time domain

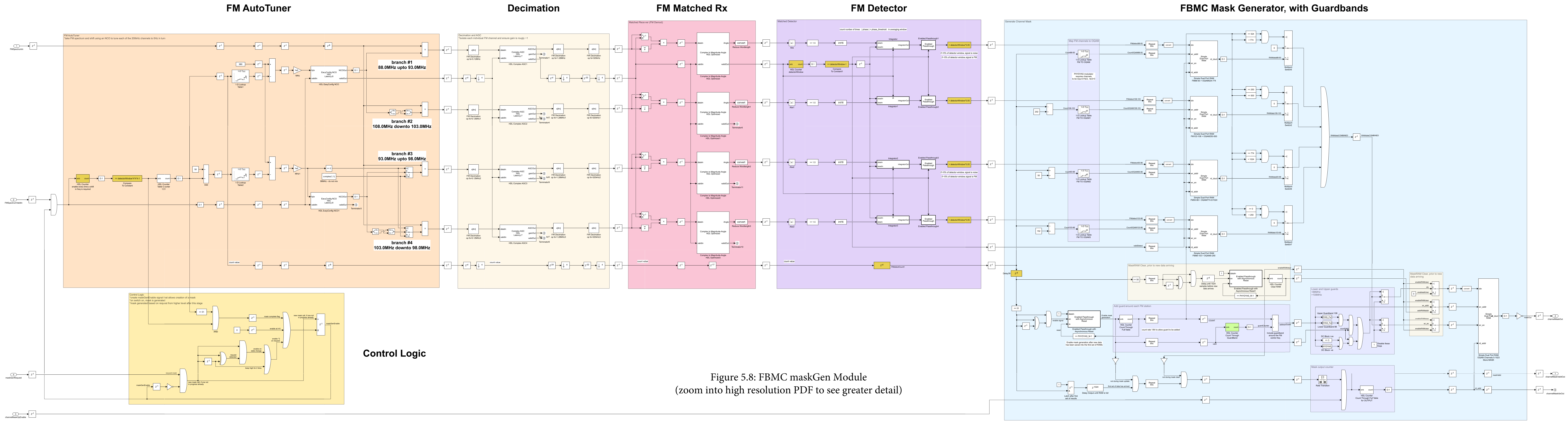

Figure 5.8: FBMC maskGen Module
(zoom into high resolution PDF to see greater detail)

The ‘argument’ operation is carried out with a CORDIC processor, as this technique is suited to FPGA targeting. The demodulator is presented in the red block of Figure 5.8.

5.5.2 Fixed Point maskGen Implementation

The demodulated output samples (i.e. the phase of the FM signal, which contains the modulated information) are integrated over a short time window, which can be referred to as τ. When an active FM Radio channel is demodulated, there are minimal phase changes in the output audio signal over this short time window. When noise is demodulated however, there are large phase changes, with the output fluctuating randomly in the range $\pm\pi/2$. It is therefore possible to distinguish between an active FM Radio channel and a noise channel with a simple threshold operation.

Simulations were carried out to investigate the optimal length of this time window, using the various FM Radio environment recordings from Central Scotland and the one from Santa Clara, USA. While a longer time window may result in more accurate detection in noisy channels, the longer the time window is, the longer the transmitter as a whole would take to adapt to any changes in the received FM environment. A window of 2048 samples (equating to τ=6.4 ms) was chosen based on the results of a simulation study. The detector was found to be 100% accurate when identifying active channels in the data sets available during simulation; even those that were on the cusp of being overpowered with noise. It also ignored the FM HD Radio sidelobes, as these were classified as noise. (If the radio was being designed for use in the USA, additional guardbands may be required to protect these digital channels).

With a single demodulator/ detector path, the full FM Radio band (of 20 MHz) would be scanned and classified in 1.28 seconds. This is (relatively) slow, and would mean a considerable delay between channel mask updates (and therefore, spectral changes to the output FBMC signal; as $T_{update} = T_{maskGen} + T_{FBMCdelay}$). In order to speed up the mask building process, four parallel branches of demodulators and detectors were developed. This did not result in x4 the component cost as there could be some reuse, as can be seen in Figure 5.8, and it reduced the time to process the full band to 320 ms. (If a single demodulation branch were used, the band would be scanned and a mask created in a period of 1.28 seconds).

After demodulating and classifying the state of each FM Radio channel, a series of memory blocks, look up tables, counters and low level logic blocks were used to automatically construct a channel mask. Outputs from the detector stage were synchronously saved in memory (i.e. as each FM channel was scanned and classified). The system was designed to process this data asynchronously, and create guardbands around each detected FM Radio channel by disabling a number of channels either side of an active FM channel. The size of this could be varied by changing a setting in one of the counters. The FM channel classifier and FBMC mask generator are contained within the purple and blue blocks of Figure 5.8.

5.6 Transmitter PHY Protocol

A simple protocol was developed to control the transmitter PHY layer. A flowchart highlighting the various processes is presented in Figure 5.8. On switch-on, the transmitter is configured to sleep. If data is presented for transmission from a higher level of the stack, the process to generate a new FBMC channel mask is started. Once a mask is ready, the transmitter outputs an FBMC modulated preamble (according to the mask), followed by multiple FBMC modulated payload symbols (again according to the mask), in a burst. Conventionally the preamble would not pass through the modulator; however in this design it is important that the radio always adheres to the channel mask, and FBMC modulation is the only way to guarantee this.

When the burst reaches its maximum permitted length, a new burst is initiated. When no more data is queued to send, the transmitter goes back to its sleep state. In parallel to the transmitting process, the transmitter is also configured to automatically update its channel mask; and updates are forced using a timed strobe. The mask can be changed multiple times a second if required (a full update taking 320.15 ms to propagate when the FBMC latency is accounted for), in an effort to protect ambient PU signals.

5.6.1 FBMC Burst Structure and Preamble

An example PHYDYAS FBMC symbol is shown in the frequency domain (prior to the IFFT operation) and in the time domain (after the IFFT) in Figure 5.9. From the frequency domain plot, it is clear that a NC FBMC channel mask is in use – this particular mask is suited to the FM band in Glasgow City Centre. K of these FBMC

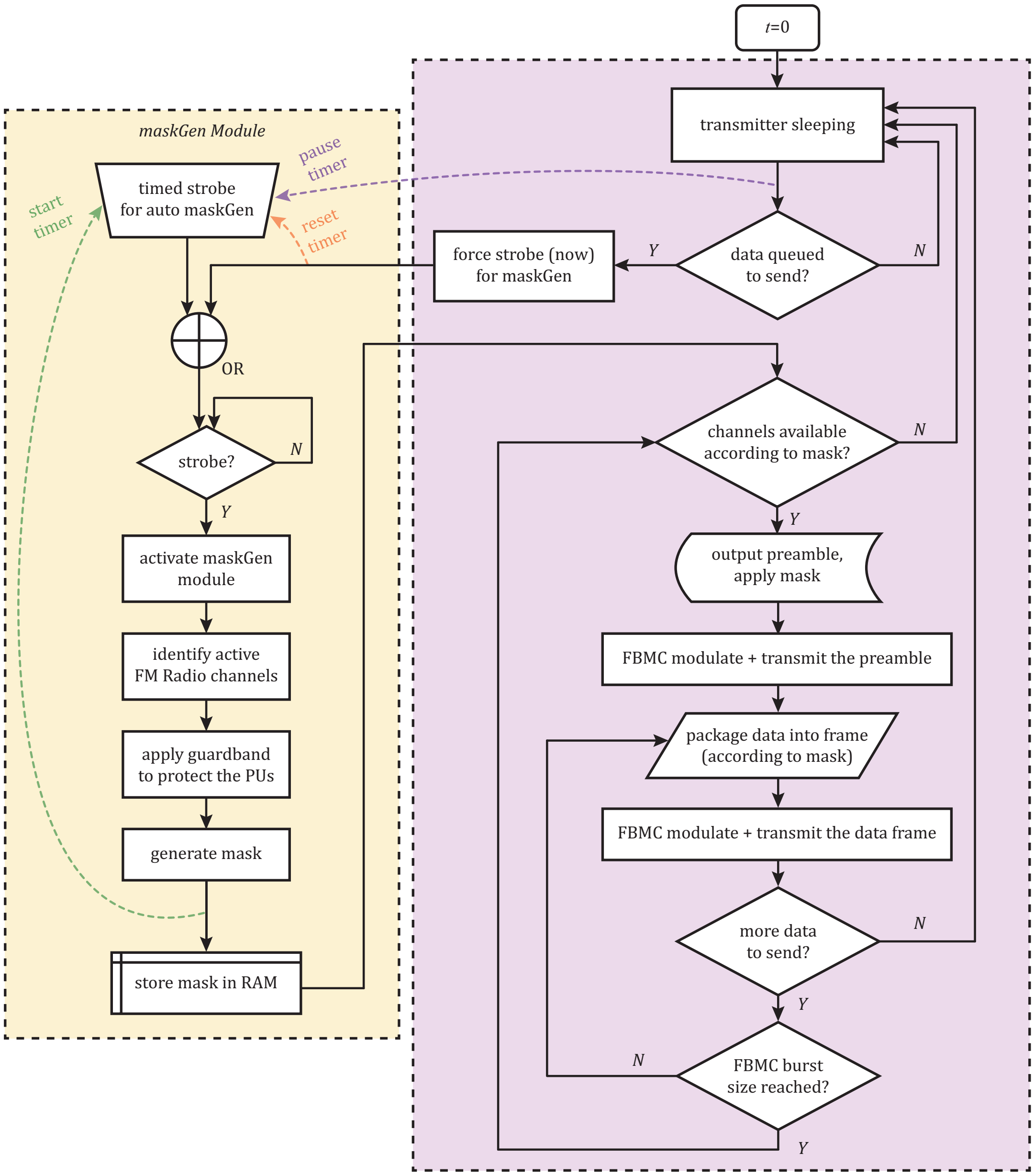

Figure 5.8: Flow chart showing transmitter PHY protocol

symbols are overlapped and summed together in the transmitter, producing an FBMC output signal similar to that shown in Figure 5.10.

In this example, a short burst of 4 FBMC payload symbols is used. Notice that the total number of samples in the output signal is not $4KM$, but rather $KM + 3M$. In general, the payload burst length can be represented as $KM + (\eta - 1)M$ samples, or $\left(KM + (\eta - 1)M\right)/f_s$ seconds, where η is the total number of FBMC symbols in the burst.

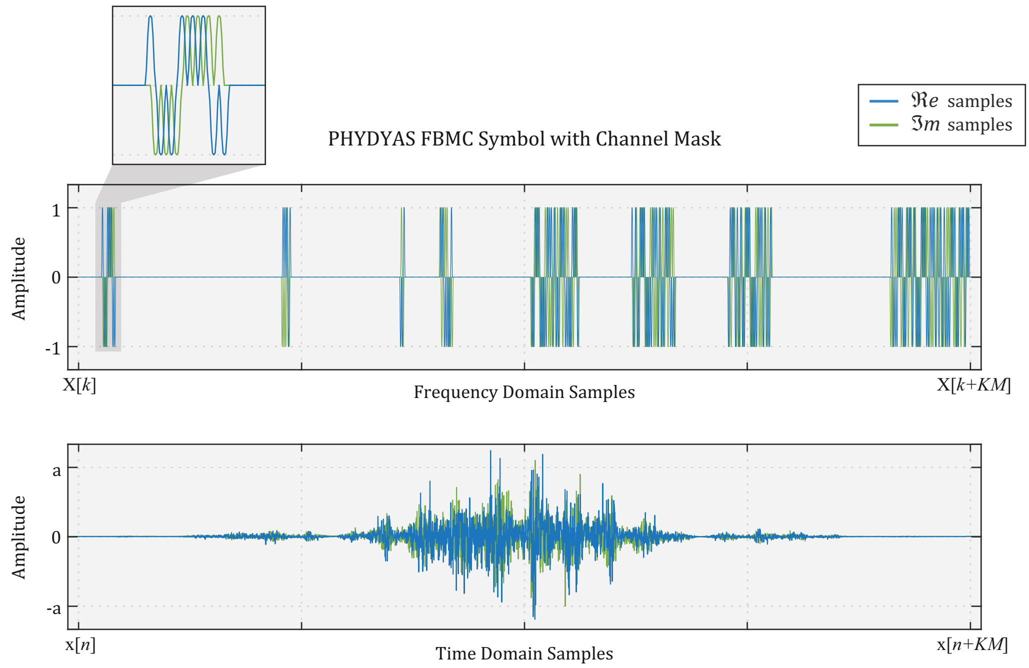

Figure 5.9: PHYDYAS FBMC symbol in the frequency and time domains, with FBMC channel mask for the Glasgow FM Radio band

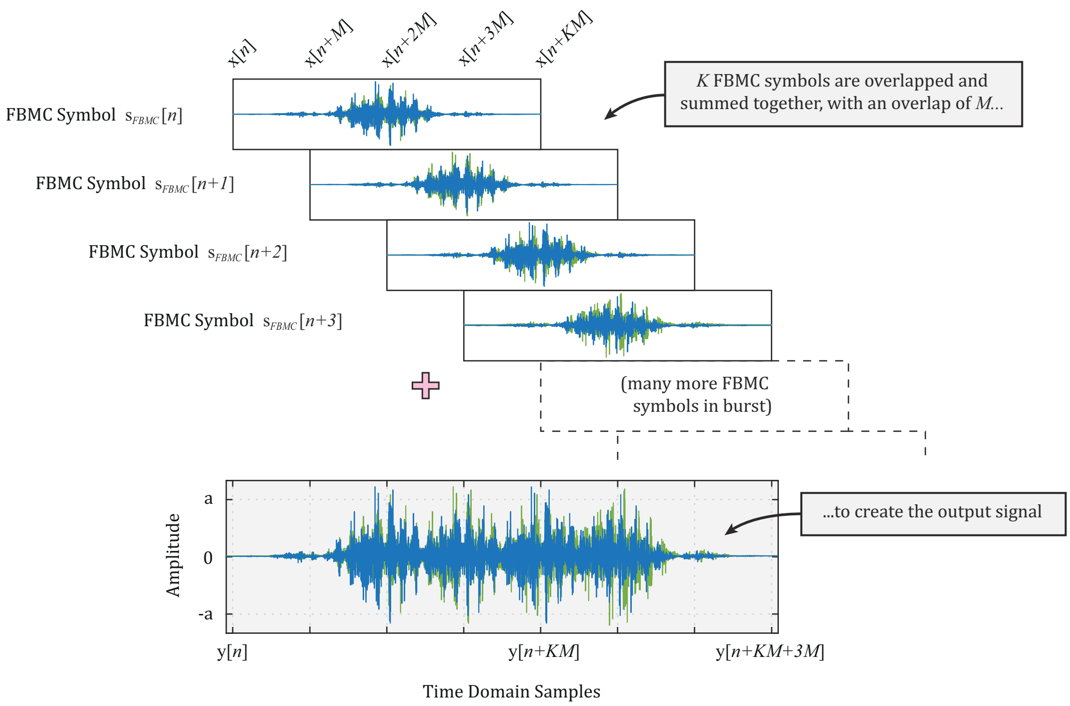

Figure 5.10: FBMC symbols overlapped and summed to create the output signal

In the PHYDYAS Primer document [8], an FBMC burst is proposed which features two preamble symbols back-to-back, followed by a gap, and then the payload data. With this configuration, the preamble and data payload symbols do not overlap in time; and therefore do not interfere with each other. This burst structure is illustrated in Figure 5.11.

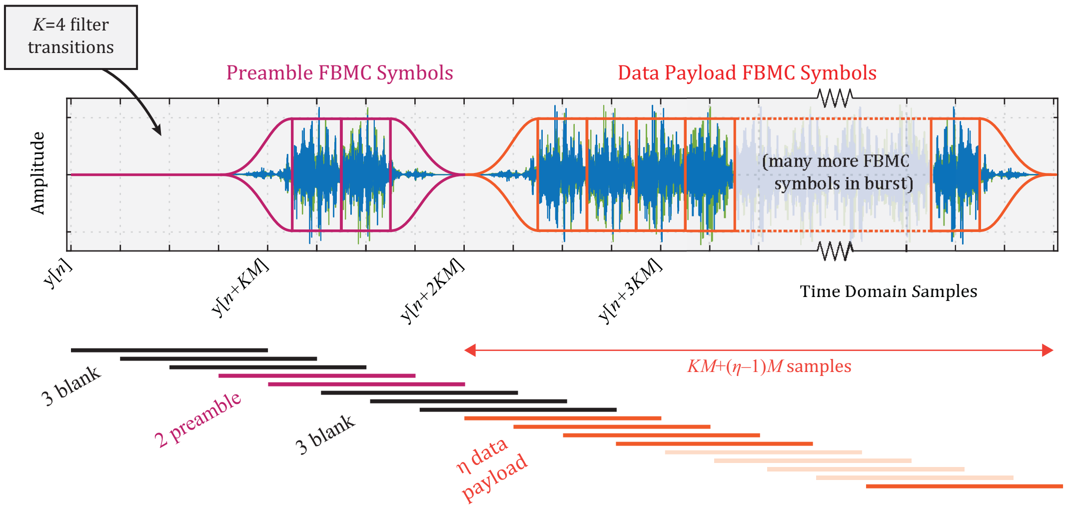

Figure 5.11: FBMC burst structure presented in [8]

In order to maintain the NC spectral output, the preamble symbols must pass through the FBMC/OQAM modulator and have the transmitter mask applied. A preamble was developed for the FM Radio SU based on a Zadoff-Chu sequence [21], manipulated to be suitable for OQAM modulation. When these preamble symbols were FBMC modulated and output, they could be used by a receiver for initial timing synchronisation.

With the chosen parameters of the FM Radio SU transmitter, each time domain FBMC symbol has a period of 200 μs and can convey up to 1000 bits of information; although the figure is more likely to be in the range of ~250 bits depending on the ambient FM Radio environment, and the amount of vacant FM spectrum (i.e. if, in a particular location, 5 MHz of vacant spectrum was available to the SU, 250 bits of information could be conveyed in each FBMC symbol). An arbitrary number of $\eta = 992$ payload symbols was selected. Including the 8 symbols for the non overlapping preamble, this resulted in a total burst length of 1000 FBMC symbols. With these values, and the 5 MHz of spectrum, each burst would convey 248 kb of data, and have a period of 50.15 ms; leading to a data rate of 4.945 Mb/s.

5.7 Basic Receiver Design

In order to test that the transmitter was modulating information correctly, a basic receiver was developed in Simulink. This receiver did not feature a frequency synchronisation system (which would be required in order to operate in the real world, where there would be a physical disconnect between the transmitter and receiver, and transmitted signals would be subject to channel effects, timing and frequency offsets). However, as it could be connected back-to-back with the transmitter in a simulation model, a synchronisation system was not required at this stage in the development process[16].

After an AGC stage in the receiver that simulated the ZynqSDR front end (wordlengths, signal amplitudes etc), samples of the FBMC signal enter a preamble detector/ timing synchronisation stage, as shown in Figure 5.12. A combination of autocorrelation and matched filtering were used for coarse and fine timing

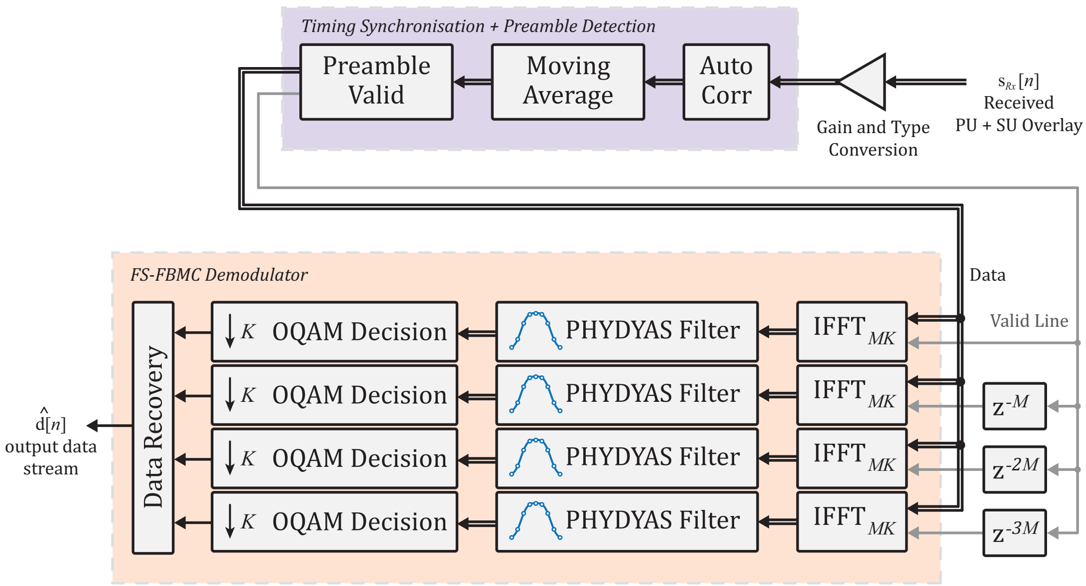

Figure 5.12: High level block diagram of the processes carried out by the simulation-based FBMC receiver

16. A more complete FS-FBMC receiver architecture capable of performing asynchronous frequency and time synchronisation is presented in [28]. In this paper the authors propose a longer preamble containing pilot carriers in known subchanels (similar to LTE). The FFT blocks in [28] are able to run asynchronously, with channel equalisation, frequency and timing synchronisation performed after the FFT. This approach would not be sufficient for the FM Radio SU design, as the subchannels required for the pilots may need to be disabled to protect PU signals. Further work is required to identify an optimal frequency synchronisation technique for this SU design.

synchronisation, allowing the receiver to accurately identify the first sample of the payload data symbols. This ‘valid line’ would then control a bank of synchronous FFTs, matched PHYDYAS filters, and K downsamplers, recovering the transmitted OQAM symbols. Plots captured from these processes are displayed in Figure 5.13.

5.7.1 Inferring the Transmitter Mask

The transmitter mask is unknown to the receiver, and therefore has to be inferred from the received signal. When a recording of the FM Radio band was passed through the receiver, it was noted that the demodulation and filtering processes resulted in output samples with negligible energy in all frequency bins except those related to the centre frequencies of the FM stations. In contrast, when an FBMC signal passed through these stages, the output amplitude in active subchannels was always found to be significantly greater.

Conventionally in a QAM-based modulation scheme, constellation diagrams would be used to display the signal at the output of the receiver. In that case, it is easy to visually inspect the signal quality, and to classify QAM samples as having a certain digital values. As OQAM was in use here however, there were no IQ symbols; only I or Q (or indeed, neither, when a subchannel is disabled).

The constellation of the received OQAM signal after downsampling (i.e. a redraw of the bottom plot of Figure 5.13) is presented in Figure 5.14. This appears a little unusual, due to the fact there are no IQ symbols. Grouping the I and Q OQAM symbols into “QAM” pairs, a more normal constellation diagram can be drawn. Note however, that not every “QAM” pair features both I and Q symbols, hence there are still clusters located on the real and imaginary axes. The central cluster, located around (0,0), relates to subchannels containing no OQAM symbols where the channel mask is “off”.

A simple thresholding operation was incorporated into an OQAM symbol decision module that was able to categorise received samples, and infer the channel mask. After a Gray decoding stage, the decision module output demodulated ‘OQAM symbol value’ and ‘valid’ signals that could be used to extract valid binary samples in the final stages of the receiver.

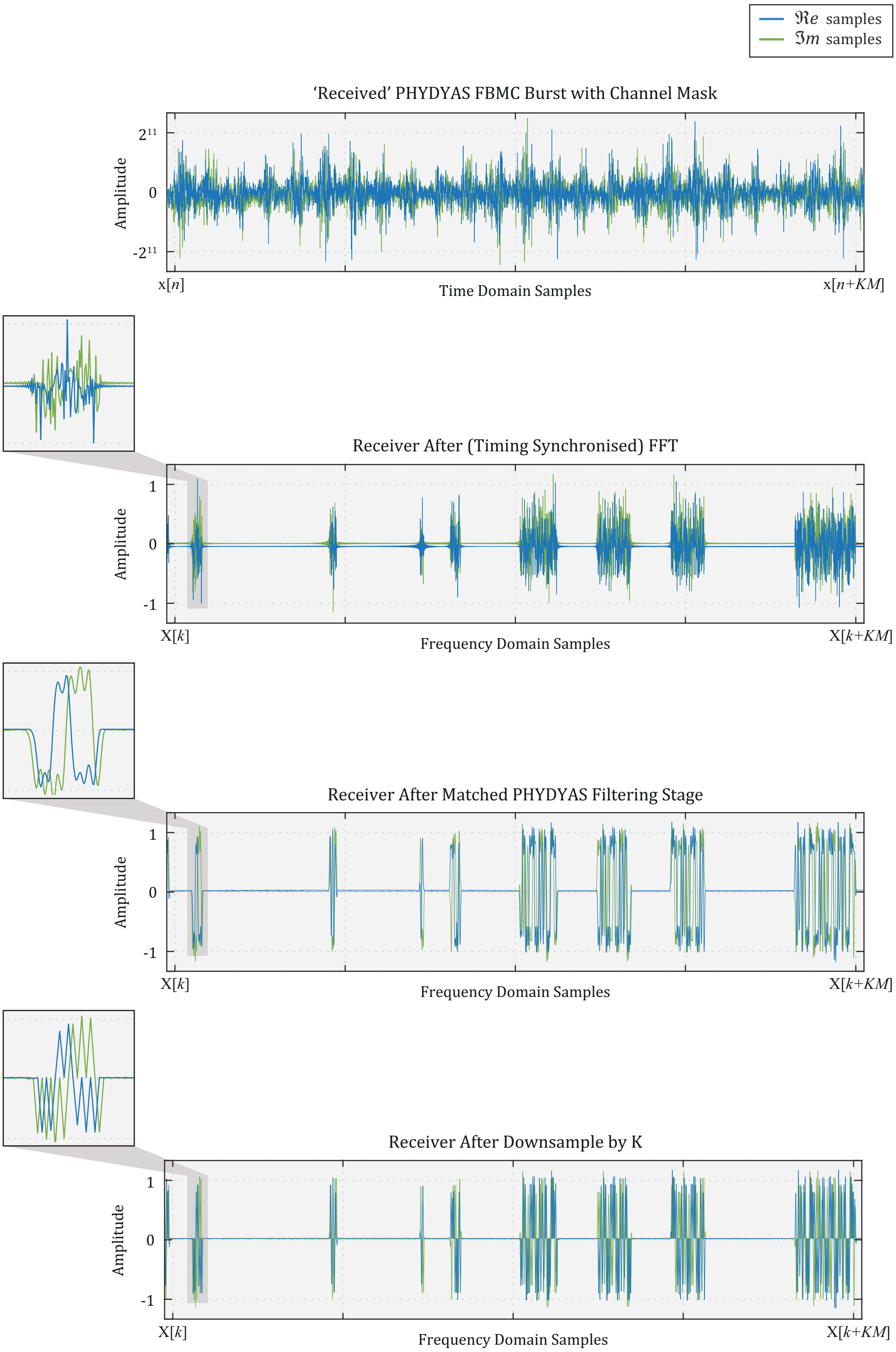

Figure 5.13: Plots showing a 'received' FBMC burst signal passing through the first stages of the receiver

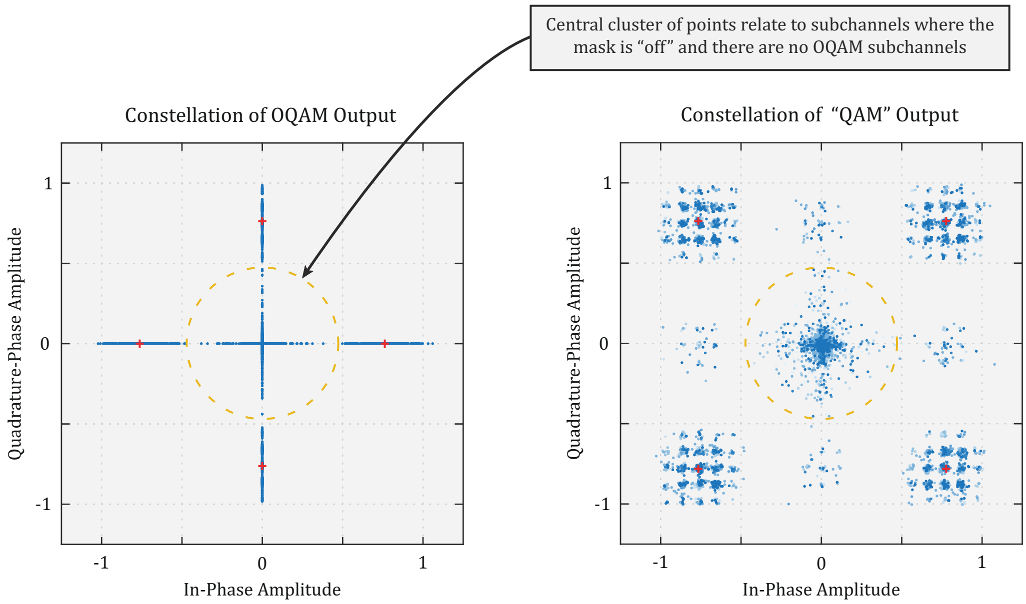

Figure 5.14: Constellation diagrams showing (left) OQAM output, (right) emulated "QAM" output

5.8 Design Validation by Simulink Simulation

Initial simulations were carried out to confirm that binary data input to the transmitter could be received correctly under perfect channel conditions. Next, 'field test' simulations were performed in a realistic channel by adding the SU FBMC signal to the PU FM spectrum capture for Glasgow, recorded using the USRP (Chapter 4). The 'transmit power' of the SU signal was varied, and the PU signal power was kept constant. This allowed for interference investigations from two perspectives, i.e.

- Interference caused by the PU FM Radio stations (+ channel noise) to the SU FBMC signal, and
- Interference caused by the SU FBMC signal to the PU FM Radio stations

5.8.1 Calibration of PU FM Spectrum Capture

The USRP was un-calibrated, which meant that the recorded FM band samples all had relative power levels; hence appropriate scaling was required in software. Technical parameters of the UK's FM transmitters were downloaded from the Ofcom website

[112], and calculations were performed to estimate the average expected receive power of the BBC national stations transmitted from the Blackhill transmitter, at the location of the Glasgow FM spectrum recording. The Perez-Vega Zamanillo / FCC F(50,50)[17] free space VHF channel model, Eq. (5.2), was used for this [119].

$$P_{Rx\_dBw} = P_{TxERP\_dBw} - 10\, n \log_{10}(d) + 20\log_{10}\left(\frac{4\pi}{\lambda_m}\right) \quad (5.2)$$

$$\textit{Isotropic Receive Power,} \quad P_{Rx} = 10^{\left(\frac{P_{Rx\_dBw}}{10}\right)} \text{ W}$$

$$\textit{where} \quad n = \sum_{i=0}^{4} \sum_{j=0}^{4} b_{ij}\, h^i\, d^j$$

according to the Perez-Vega Zamanillo 4th degree Path Loss Coefficients

A MATLAB implementation of this model was developed based on [119], and the model showed an expected receive power of 24 W/ -16.2 dBm. While the F(50,50) model is an accurate VHF model, it does not take into account the geography of the transmit channel; so some further attenuation should be expected. In light of this, the power of the recorded FM signal was adjusted, such that the average Blackhill BBC station power was around -16.5 dBm; resulting in the recorded noise floor at -55dBm.

5.8.2 SU FBMC Transmit Power Levels

With no existing regulations for SUs transmitting in the FM Radio band, there were no rules for SU transmit power levels. Reasonable power levels therefore had to be estimated. In the EU, the maximum Wi-Fi transmit power is 0.1 W/ 20 dBm. The FCC has a higher limit of 4 W/ 36 dBm for the USA, which is the same power agreed upon for TVWS broadcasts by the FCC and Ofcom [104]. With these figures in mind, the SU transmit power values shown in Table 5.1 were proposed and used hereafter. The approximate Signal to Interference Noise Ratio (SINR) (i.e. the power of the SU signal vs the power of the interfering PU signal) in each scenario is also presented.

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17. The FCC F(50,50) model is an analogue graph-based RF propagation model that was used for many years by the FCC when planning VHF and UHF spectrum allocations.

Table 5.1: SU radio transmit powers for simulations

SU Tx Power (W)	SU Tx Power (dBm)	Approximate SU SINR (dB)	SU OOB Power (dBm)
4	36	52.5	-44
3	34	50.5	-46
2	33	49.5	-47
1	30	46.5	-50
0.5	27	43.5	-53
0.1	20	36.5	-60
0.01	10	26.5	-70
0.001	0	16.5	-80
0.0001	-10	6.5	-90
0.00001	-20	-3.5	-100
0.000001	-30	-13.5	-110
0.0000001	-40	-23.5	-120
0.00000001	-50	-33.5	-130

In Section 4.4 (page 67), where ITU-R protection ratios were discussed, it was noted that the expected OOB power limit for an SU operating in the FM Radio band would be a minimum of 52 dB lower than the power of the FM signal. In this scenario (assuming all FM signals had the same power), that would set an OOB power threshold of -68.5 dBm. Maximum in-band transmit power levels would be determined by the frequency guardband in use. With a guard of 300 kHz, the SU could transmit at a power 20 dB greater than the power of the FM signal, implying an overall SU transmit power limit of 3.5 dBm. It would be interesting, therefore, to perform interference simulations with powers above this level, to analyse how seriously the SU FBMC signal interferes with PU FM Radio signals. It should be noted though, that the USRP-recorded noise floor in the FM spectrum for Glasgow is itself 13.5 dB higher than the interference threshold limit; meaning that the PU signals are likely to already be suffering from noise interference.

The FBMC signal was configured with the various powers, and added to the power-adjusted recording of the FM band. This resulted in spectra similar to the one shown in Figure 5.15. In this particular case, the power of the SU has been set to 0 dBm, and the mask was configured with a PU guardband of 300 kHz. For reference, an NC OFDM signal is also shown here with the same transmitter mask. It is evident from the plot (even without the need for further calculation) that, at this low transmit power, the NC OFDM signal's OOB leakage would interfere with, and completely 'drown out', many of the PU FM channels. The FBMC signal, however, fits well around them.

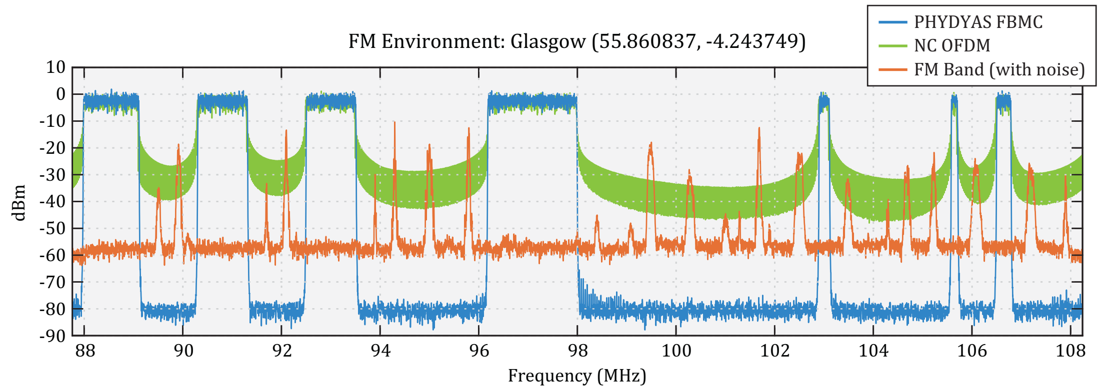


Figure 5.15: Spectrum Analyzer window showing the PHYDYAS FBMC, NC-OFDM and recorded FM radio signals — SU transmit power = 0 dBm

The combined signal, i.e. the SU FBMC added to the noisy PU FM Radio spectrum capture is hereinafter referred to as the 'PU+SU Overlay' signal.

5.8.3 Measuring PU to SU Interference: SU Bit Error Rates

A series of long simulations were carried out, wherein millions of bits of binary payload data were input to the transmitter, FBMC modulated and added to the Glasgow FM Radio environment recording, demodulated using the receiver, and then compared to inspect data integrity. The results of the simulations are shown in Figure 5.16. As the SU transmit power is decreased, the Bit Error Rate (BER) increases, as expected. This is largely due to the number of false 'bits' detected that are actually high power interference from FM Radio channels, during the 'mask inference' stage in the receiver. These false detections are located in 'off' parts of the FBMC channel mask, and therefore do not actually cause interference to the active FBMC data subcarriers; they just cause the receiver to think that more subchannels are in use than there actually are.

If a header was added to the burst protocol, which was able to signal the channel mask used in a resilient manner, the receiver should be able to ignore these false detections.

When the channel mask is known to the receiver, the BER is significantly reduced, as channel noise becomes the main source of interference. The simulation results showed that, even with an SINR of -13.5 dB, every transmitted bit could be recovered correctly in the receiver when the mask was known.

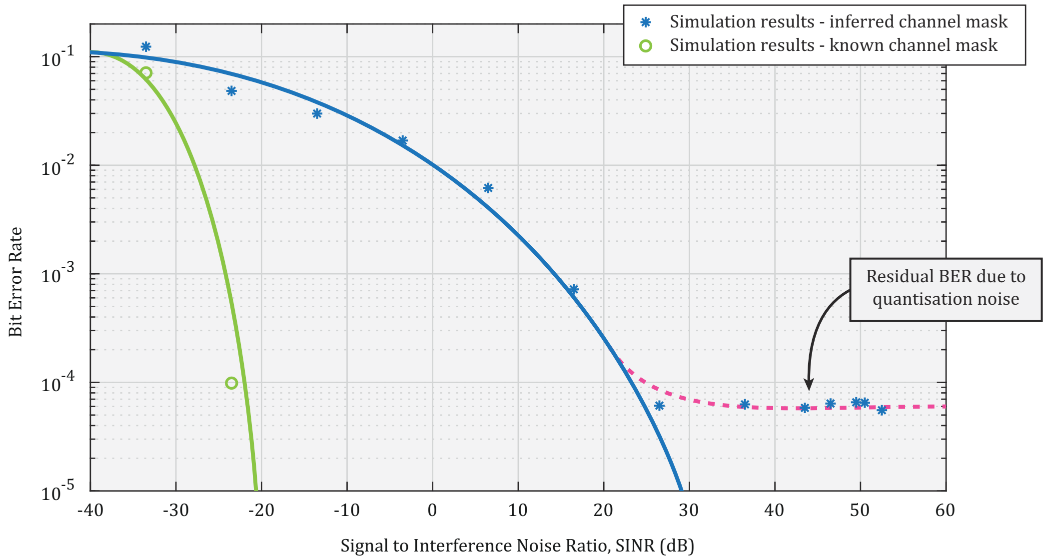


Figure 5.16: Plot of simulated SU BER in PU FM Radio + noise channel for various SU transmit powers

Due to the fact that the receiver captures the whole of the FM Radio band, saturation of the front end is a concern when there is a low SU transmit power. The SDR's ADC has a fixed resolution, and after AGC, captured samples of the PU+SU Overlay will always have the same limited wordlength. When the SU signal has a low enough signal power for the SINR to be negative, the relative amplitude of the demodulated FBMC signal will be lower than the amplitude of the PU components, as illustrated in Figure 5.17. This creates a challenge for the decision module, as thresholding levels need to dynamically adapt to recover the transmitted data.

The system BER could be improved using Error Correction Code (ECC) techniques. Adding redundancy would lower the overall data throughput of the radio, however that may not be a concern depending on its ultimate application.

With only a basic receiver and interference/ noise channel, these tests cannot fully explore the behaviour and BER of the radio pair. Additional channel effects such as fading, Doppler, frequency and phase offsets should be applied, and SDR front end sampling jitter should be simulated. However, this would require a more complex

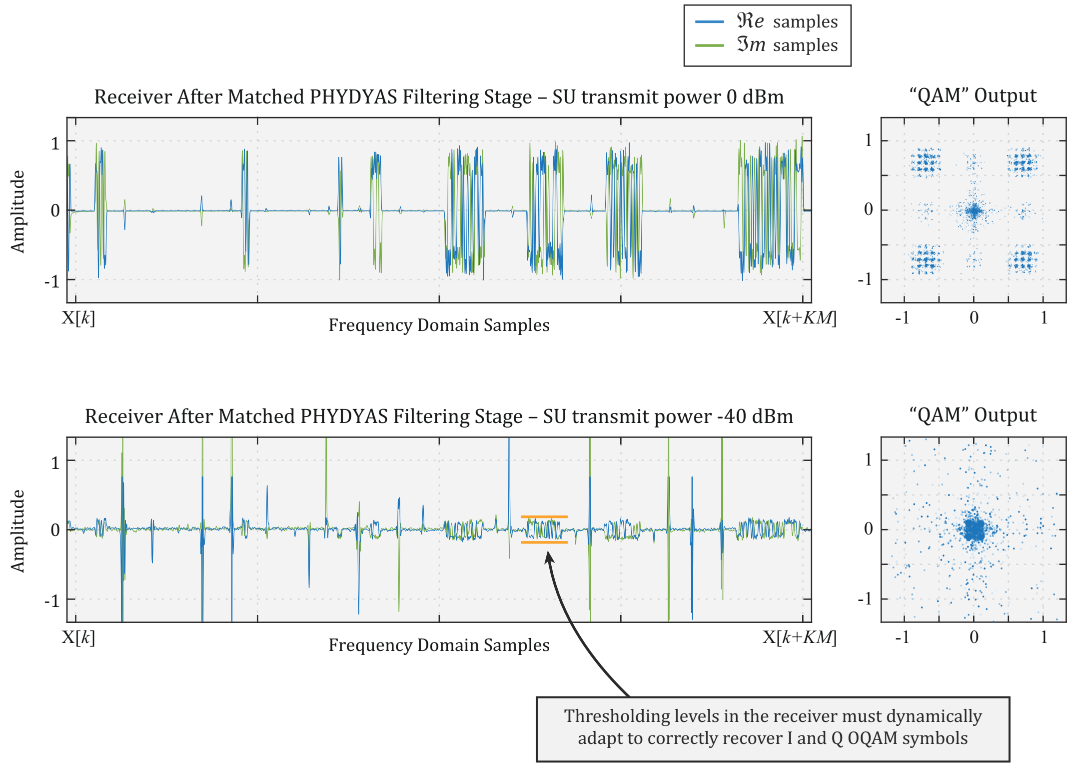


Figure 5.17: Plots showing 'received' FBMC burst signals with different SU transmit powers, after FFT demodulation and PHYDYAS filtering:
(top) transmit power 0 dBm / SINR 16.5 dB
(bottom) transmit power 40 dBm / SINR -25.5 dB

receiver architecture, complete with further synchronisation systems; and is therefore outwith the scope of the work presented in this thesis. What these proof of concept simulations have confirmed is that the SU FBMC transmitter is capable of modulating digital information into gaps in active FM Radio spectrum.

5.8.4 Measuring SU to PU Interference: PU FM Station Quality

One of the primary aims of the transmitter design is for the SU to be capable of coexisting with PU FM Radio signals. Fundamentally, this means that the SU must avoid interfering with the PU in any way that degrades the received PU signal quality. In order to explore the interference levels experienced by individual PU FM Radio stations, each of the active FM Radio channels (from the PU+SU Overlay signal) had to be isolated. The PU+SU Overlay signal was mixed with a complex exponential to shift each active FM channel to baseband in turn, and decimation by a factor of 100 was performed to reduce the bandwidth to 204.8 kHz.

Quantitative Measurement of Interference

The average power for each of the PU (+ noise) and SU signals (P_{PU} and P_{SU}) in active FM Radio channels (for the signals shown in Figure 5.15) under various transmit power levels were found using Eqs. (5.3) and (5.4), respectively.

$$P_{PU} = \frac{1}{N}\sum_{n=1}^{N} |s_{PU}(n)|^2 \quad (5.3)$$

$$P_{SU} = \frac{1}{N}\sum_{n=1}^{N} |s_{PU+SU}(n)|^2 - P_{PU} \quad (5.4)$$

(where s_{PU} is the power-adjusted FM signal with noise, and s_{PU+SU} is the PU+SU Overlay with noise), allowing the Signal to Interference Ratio (SIR) to be calculated. Figure 5.18 shows the average SIR experienced across all active PU FM Radio channels, against SU transmit power.

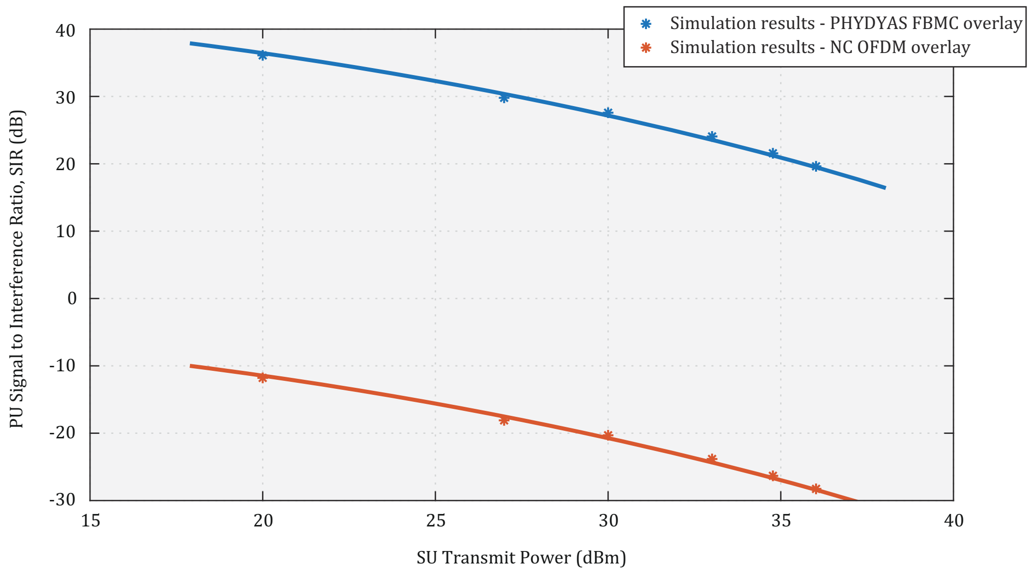


Figure 5.18: Plot of average SIR (SU to PU) for various SU transmit powers

With a SU transmit power of 20 dBm (as demonstrated in Figure 5.15), simulations show the interference of the FBMC SU signal to be negligible; its OOB leakage is on average over 4200 times less powerful than the PU FM Radio stations. Even with a transmit power of 36 dBm, from a numerical point of view, the SIR results indicate that the FBMC signal causes minimal interference. For comparison, simulation results for the NC OFDM SU signal are also presented. The plot shows that overlaying the FBMC signal on the FM spectrum results in ~47 dB improvement in PU SIR when compared with overlaying an NC-OFDM signal.

Qualitative Measurement of Audio Interference

As the FM signals fundamentally contain audio, and the human ear is an excellent detector for audio [77], qualitative listening tests were also performed. Each of the 22 active FM Radio channels from the original USRP-captured recording of the Glasgow FM band were demodulated in Simulink, in order to extract the audio signal contained within. These outputs were saved, creating a 'golden reference' set of demodulated FM audio signals for later comparison. Next, the PU+SU Overlay signals for each of the different SU transmit powers were demodulated, so that the audio quality of each FM channel could be rated in the presence of the SU signals.

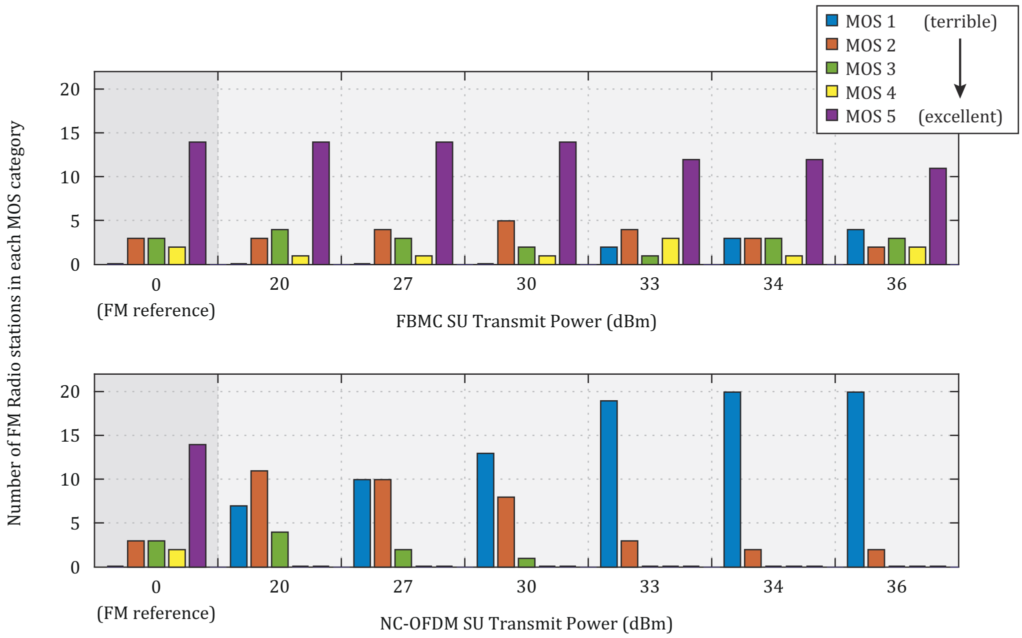


Figure 5.19: Plots of station audio quality MOS for PHYDYAS FBMC and NC-OFDM overlay signals

The simple Mean Opinion Score (MOS) method [77] was adopted for qualitative listening comparison, which saw a score between 1-5 awarded by 8 listeners depending on perceived quality (1=terrible, 5=excellent). The results of this exercise are shown in Figure 5.19. While these are inherently subjective, the trend is consistent with the quantitative results obtained.

With reference to Figure 5.19, as the NC OFDM SU transmit power is increased, the quality of the received PU signals rapidly decreases (MOS-2 and MOS-1 quickly start to dominate); whereas with the FBMC SU signal, the quality remains high (MOS-5 stations persist). At the maximum transmit power tested, 11 stations (of the 14 originally rated at MOS-5) could still be received perfectly, without any noticeable interference. The 4 stations that did become overpowered by PHYDYAS OOB interference at 36 dBm transmit power were all duplicate stations from a secondary transmitter; which were not even intended to serve Glasgow[18]. While further testing is of course necessary with real FM Radio receiver hardware, these initial results indicate that, at low transmit powers, it should be possible for this SU transmitter to coexist with the PU in the FM band without causing noticeable interference.

All of the demodulated signals have been catalogued to allow the reader to make their own judgements of audio quality. This dataset was published as part of [6], and is available for direct download at [5].

5.9 Chapter Conclusions

This chapter has presented the design and implementation of a novel DSA-enabled radio transmitter PHY that enables SU operation inside the FM Radio band. The radio uses the FS-FBMC/OQAM NC-MCM scheme with the PHYDYAS filter, and was developed in Simulink using low-level HDL components from the HDL Coder library. The transmitter leverages cognitive radio techniques to automatically adjust its channel mask, and mold its spectral output around PU signals.

A transmitter protocol was proposed, and basic receiver was implemented to facilitate system simulation. BERs were presented for the SU radio under various SINRs, and investigations were carried out to explore the effects that the SU radio has on the quality of PU FM Radio signals under various SU transmit powers. These initial ‘field test’ simulations provided promising evidence that the SU radio could coexist with the PUs of the FM Radio band.

18. This is an issue related to the definition of the “service area” for PU transmitters. If their signals can be received outside of their defined service area, should they still be viewed as PUs at these locations? Take the example of Clyde 1—this is intended to serve Glasgow. Should it be viewed as a PU in Edinburgh if it can be received there? This is very much a matter for Ofcom to decide.

Chapter 6

ZynqSDR Hardware Implementation

Chapter 5 described the design and implementation of the SU transmitter, and the proof of concept 'field test' simulations that were carried out on a workstation. The next phase of testing would see the transmitter targeted to programmable SDR hardware, to allow a series of experiments to be carried out to investigate practical RF coexistence issues, and to validate the design's DSA capabilities.

6.1 Chapter Overview and Contributions

In this chapter, steps taken to modify the transmitter design to prepare for hardware implementation are presented, and then the process of targeting the design to a ZynqSDR is discussed. Once implemented on the hardware, the transmitter is subjected to the various FM Radio environments sampled from around Central Scotland in a closed loop simulation. An investigation into SU guardband sizes is carried out, and interference effects are explored. Finally, the design is configured into full 'cognitive' mode, and is shown to be capable of adapting its NC transmitter mask in real time to protect FM Radio signals that it detects off the air.

As mentioned previously, a video presentation has been developed as a graphical abstract to this work. It acts as a companion to this chapter, and allows the reader to better visualise how experiments were carried out, and view 'live' spectrum analyser windows that show the real time operation of the radio. The video has been published and issued a DOI, and is available to download and watch at:
https://doi.org/10.15129/607b5dd7-1ab6-4efb-8a55-18876919714c
https://youtu.be/AZoS_-n-SsY (also available to watch on YouTube)

6.2 Real Time Simulation on ZynqSDR Hardware

Due of the sheer volume of simultaneous computation, the Simulink simulations carried out in Section 5.8 could not be performed in real time. FPGAs are better suited to the parallel processing requirements of communications systems, and as such, targeting the transmitter to a ZynqSDR would allow for real time simulations to be performed out in a 'closed' environment. To do this, the transmit user logic area would be targeted, and the loopback functionality activated to feed samples of the generated FBMC signal back to the receiver and host computer, for examination in Simulink scopes.

The transmitter design in Figure 5.3 (page 78) requires complex samples of the FM band to be input to the maskGen module. These were provided using the ZynqSDR `transmitRepeat()` function. A recording of FM samples was loaded into the transmit register, and the function activated; meaning that samples are passed into the user logic area at the appropriate sampling rate. A mask was created, and the transmitter activated. Samples of the FBMC signal were then output to the SDR front end, looped back, and passed through the (untargeted) receiver user logic area. These were then fetched by the driver, and are passed back to the host computer over Ethernet, as shown in Figure 6.1.

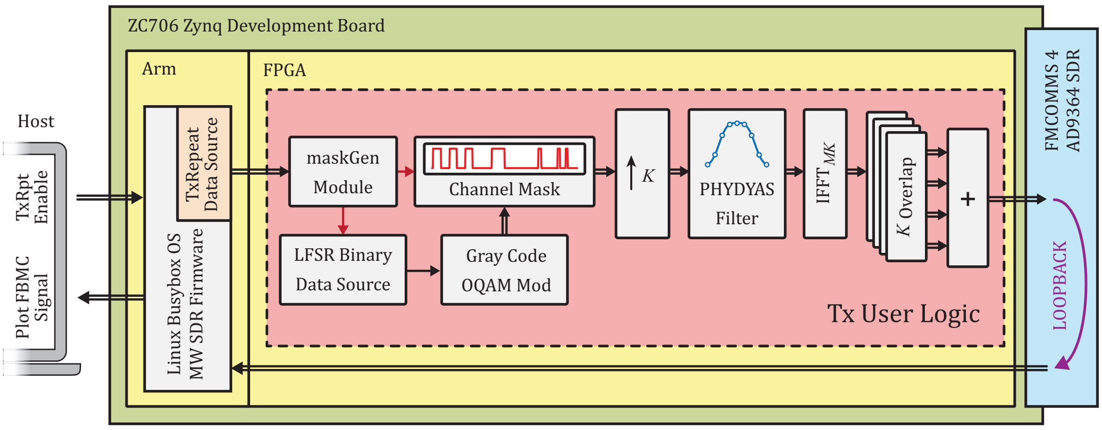


Figure 6.1: Transmitter design configuration for real time simulation on ZynqSDR

Once the design was deployed and the `transmitRepeat()` function enabled, the host computer could run a simple model with ZynqSDR Receiver and Spectrum Analyzer blocks. This would allow for visualization of the 'transmitted' FBMC signal.

6.2.1 Transmitter User Logic Design

The top level block of the Tx user logic design is shown in Figure 6.2. Here there are *I*, *Q* and *Valid* input and output ports. The *I* and *Q* ports have a datatype of int16 (i.e. 16-bit signed integer format), and the *Valid* is boolean (1-bit binary). The sampling frequency of all of these ports is f_s = 20.48 MHz. This Simulink block is essentially substituted directly into the transmit user logic area.

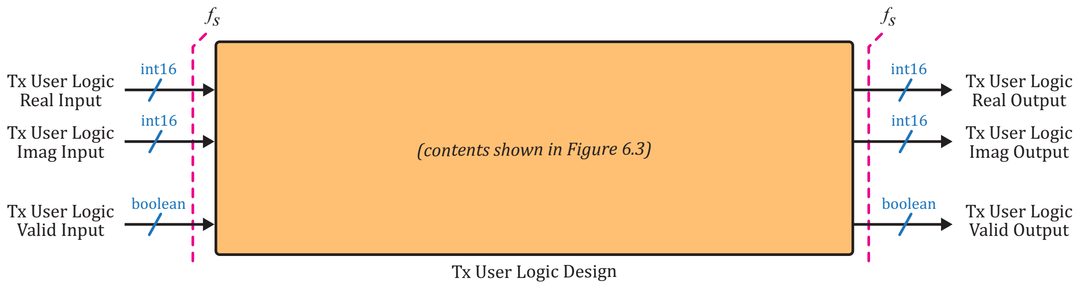


Figure 6.2: Top level diagram for transmitter user logic area

Figure 6.3 presents the next level in the hierarchy. FM samples input to the Tx user logic enter the 'maskGen' module. This contains a matched detector, and is able to scan the entire (baseband) FM spectrum and generate a channel mask complete with guardbands in 0.33 seconds. The output mask is used to control a Tx data buffer, ensuring that none of the random binary data generated by the LFSR (Linear Feedback Shift Register), which models the FBMC data signal, is lost. Next, the binary stream undergoes Gray coding, and OQAM preprocessing, creating OQAM symbols. The mask is reapplied in a binary fashion (on/off), to ensure that no data has been mapped into a subchannel that should be disabled, and the symbols enter the FBMC modulator of Figure 5.5 (page 81).

In order to ensure that the FBMC symbols are generated to the highest accuracy (i.e. do not suffer from quantisation noise), the wordlength of the modulator stage is allowed to grow to 27 bits with 16 fractional bits. Scaling was therefore required to reduce the wordlength back to 16-bits prior to the output, in order to utilise the full dynamic range of the 12-bit DAC. As discussed in Section 5.4.3 (page 82), an 'autoGain' module was developed for this purpose. The output gain was modified such that the average value of the samples was always around ±26000 (FBMC has a high peak to average power ratio; so this allows for some large peaks with amplitudes up to ±32767 before saturation will occur).

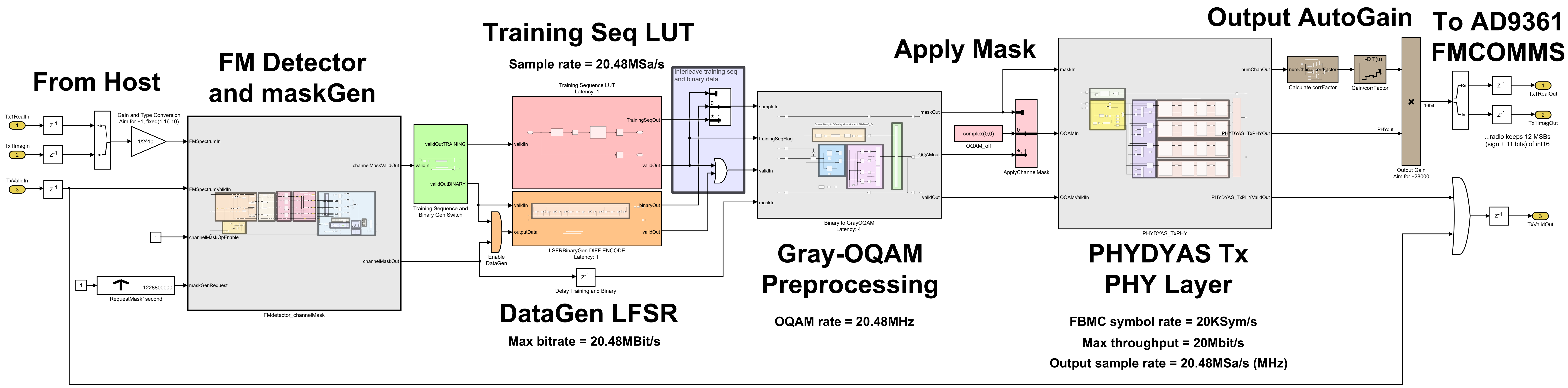


Figure 6.3: Simulink Model: components inside the transmitter user logic top level block
(zoom into high resolution PDF to see greater detail)

6.2.2 Targeting Process

Once the design was ready to be targeted, the HDL Workflow Advisor tool was initiated. This tool compiled the model and generated HDL code, which was then packaged as an IP (Intellectual Property) core, and passed to a Xilinx Vivado shell to build the project. Once the build was complete, a Xilinx bitstream was created.

Using MATLAB commands from the Zynq-Based Radio support package, the ZynqSDR's FPGA was programmed with the full design. This comprised the base MathWorks project (complete with various data movers, clock generators and Analog Devices IP cores to control the AD9364), and the targeted Tx user logic area, containing the PHYDYAS radio transmitter.

6.2.3 Real Time Simulation Results

Prerecorded samples of the FM Radio spectrum were loaded into the transmit register using `transmitRepeat()`, and a simple receiver design was developed that contained ZynqSDR Receiver and Spectrum Analyzer blocks. `transmitRepeat()` was enabled, and the receiver was run. The targeted design began generating FBMC signals, which were looped back to the receiver, and passed to the host computer. The spectrum of the generated FBMC signals could then be examined in Simulink, all in real time.

The transmitter design was further validated by running real time simulations with all of the FM Radio environments harvested from the 16 different locations around Central Scotland (the mixture of cities, towns and villages, listed in Table 4.2 (page 63)). From reprogramming the `transmitRepeat()` register to seeing signals arriving in the Spectrum Analyzer windows, each of these real time simulations took around 10 seconds to complete. In comparison, they would have taken around 30 minutes each if the full design was running in a compiled Simulink model on a computer. This significant time saving is one of the main benefits that ZynqSDR targeting brings when prototyping communications system designs.

Figure 6.4 presents a screenshot from the chapter companion video *(t=6:08)*. Here, a demonstration is made showing how rapidly the FM Radio environment can be changed, and a real-time simulation run. In the top left, there is a MATLAB live script.

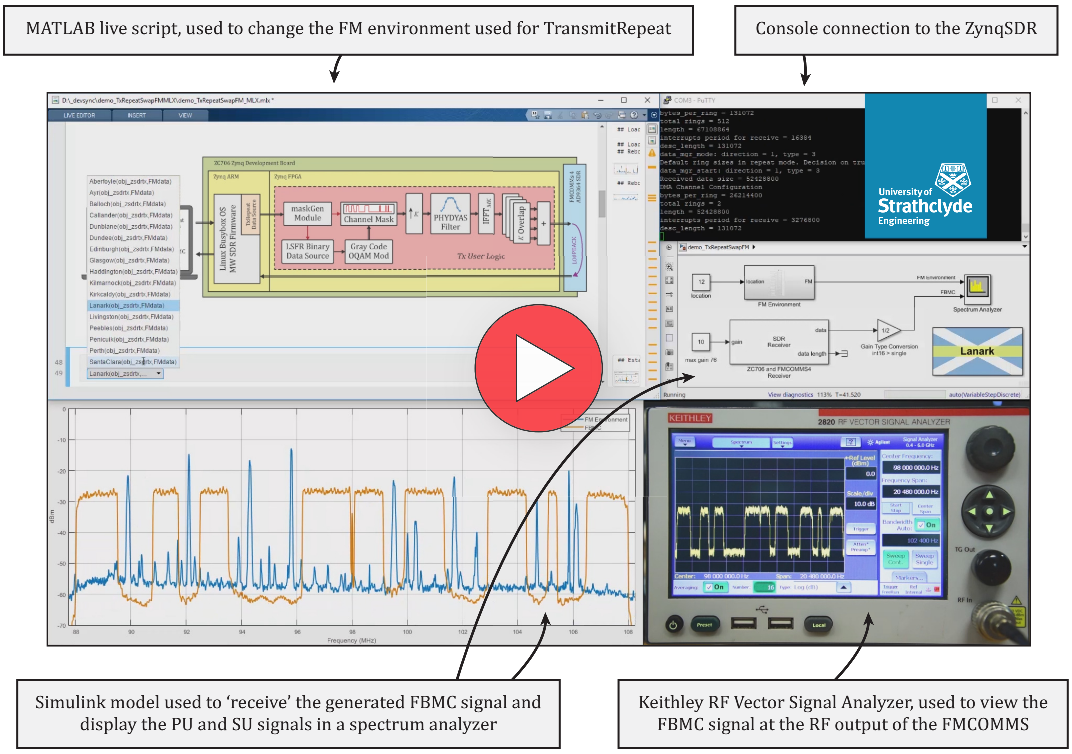


Figure 6.4: Screenshot from the companion video, demonstrating real-time simulation of the SU radio with assorted FM Radio environments

Different FM environments can be programmed onto the ZynqSDR with the `transmitRepeat()` function, by selecting them from the dropdown menu. The Simulink model used to interface with the ZynqSDR and 'receive' the generated FBMC signal is shown, along with a Spectrum Analyzer window presenting the spectrum of the generated signal, and the selected FM environment. For demonstrations purposes, a video recording of a Keithley RF Vector Signal Analyzer is also presented. This was connected to the FMCOMMS, and used to verify that the RF output of the SDR matched what was presented in the Simulink scope.

The resulting spectra for four different FM Radio environments are shown in greater detail in Figure 6.5 (note, the power levels used here are arbitrary, as the SU signal is not output to calibrated amplifier components, and simply looped back inside the SDR). As can be seen, the transmitter design has successfully adapted its mask in each instance to prevent PU interference. The eagle-eyed reader may notice that, in the Aberfoyle environment for example, some seemingly high-energy peaks in the FM spectrum (e.g. 100.1, 100.3 MHz) have not been classified as FM Radio stations by the

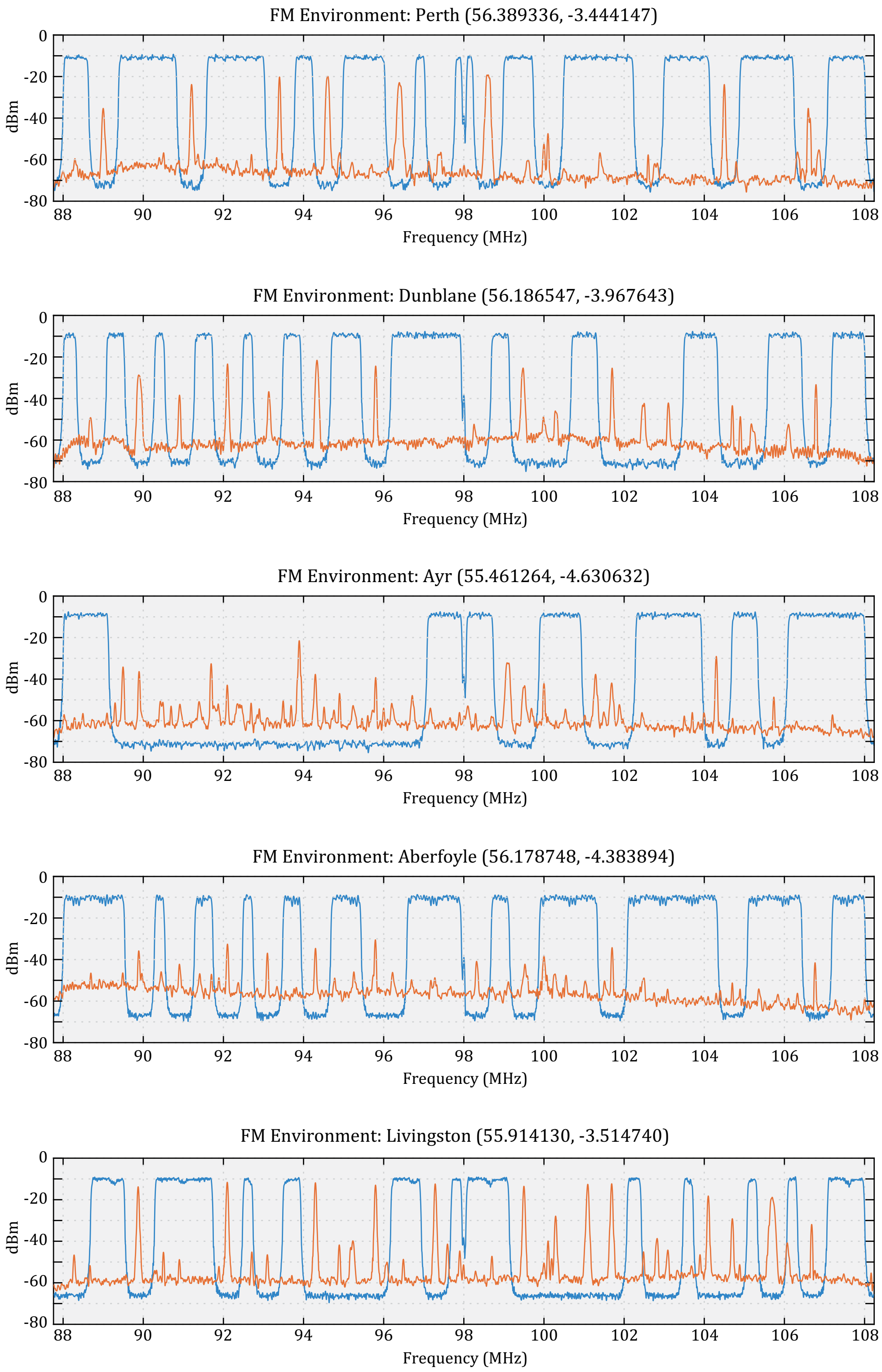


Figure 6.5: Real time simulation results using ZynqSDR hardware: results from five different FM Radio environments from Central Scotland (*note, power levels used here are arbitrary*)

maskGen module. This is because the Signal to Noise Ratio (SNR) of the signals is so poor that there is no audible audio signal present on these carriers; just high energy noise. These were identified as duplicate stations, which are not intended to serve the location in question.

The guardband used in the FBMC mask for these initial simulations spanned 300 kHz either side of an active FM Radio centre frequency. This is an estimated value, as it was not known what would ultimately be required in order to prevent interference with commercial off-the-shelf FM Radio receivers. With this setting, the throughputs presented in Table 6.1 were achieved for each of the 16 Central Scotland FM Radio environments tested.

Table 6.1: 4-OQAM PHYDYAS FS-FBMC Throughput Rates

Location	Number of FM Stations (number unique)	Unallocated Spectrum (MHz)	Throughput with 300 kHz Guard (Mb/s)
Edinburgh	35 (15)	13.0	4.78
Livingston	31 (14)	13.8	6.70
Kirkcaldy	27 (14)	14.6	5.42
Ayr	23 (9)	15.4	7.38
Glasgow	22 (16)	15.6	5.50
Callander	20 (12)	16.0	8.98
Balloch	20 (10)	16.0	11.1
Haddington	19 (12)	16.2	9.90
Perth	19 (9)	16.2	9.60
Dunblane	18 (12)	16.4	8.30
Dundee	18 (12)	16.4	6.92
Lanark	16 (12)	16.8	11.90
Aberfoyle	16 (10)	16.8	9.68
Penicuik	15 (12)	17.0	11.38
Kilmarnock	14 (8)	17.2	11.40
Peebles	14 (8)	17.2	11.22

(Note – the number of unique FM stations in each location is presented along with the total number received. If these duplicate stations were discounted, higher SU throughput rates would be possible.)

From the results of Table 6.1, it is clear that the throughput is not directly proportional to the number of FM stations received at a particular location. (Take the examples of Callandar/Balloch, Haddington/Perth, Dunblane/Dundee, Lanark/Aberfolye. Each of these pairs feature the same number of FM stations, however, the stations broadcast on different frequencies. This leads to different guardband arrangements in the SU subcannel masks, and different overall throughput rates). There is a general trend however, that the throughput increases as the number of stations decreases.

It is interesting that throughput rates of around 5 Mb/s are possible, even in Glasgow, Edinburgh and Dundee, three of the four largest cities in the country. In line with the findings of [118], in rural areas (such as Balloch, Lanark and Peebles), the amount of usable vacant spectrum—and therefore throughput rate—increases dramatically.

6.3 Transmitter Guardband Optimisation

The throughput achievable with the radio is linked to the number of active channels; and therefore, the size of the frequency guardband used to protect the PU signals. A narrower guardband will lead to higher data rates; however, it could also result in interference being caused to commercial off-the-shelf FM Radio receivers.

By design, the superheterodyne demodulators in FM receivers contain a bandpass filter which passes a narrow band of frequencies, centered around the FM carrier. This is highlighted by the red band sketched in the plot of Figure 6.6. The passband of the filter could be very narrow (e.g. ±100 kHz either side of the carrier frequency), or it could be much wider; the characteristic of the analogue filter is an unknown design choice made by the radio manufacturer. It is likely that the filter characteristic will also vary between different FM Radio receivers, and could be impacted by aging.

Normally, FM Radio stations are spaced a minimum of 200 kHz apart; so it was expected that the filter would begin to attenuate frequencies past ±100 kHz, in order to prevent co-channel intermodulation. This is in line with the FM Radio protection ratios presented in BS.412-9 [70]. The wider the passband is, the larger the FBMC transmitter's guardbands will have to be. An interesting research question, then, is what size of guardband would be required in order to prevent noticeable interference?

6.3.1 Hardware Configuration

Due to RF spectrum emission regulations (at the time of writing), it would be illegal to transmit RF signals in the FM Radio band for these tests using the prototype SU radio. (Details on the UK's Wireless Telegraphy Act and other radio spectrum emission laws can be viewed on the Ofcom website [107]). The ZynqSDR also lacks a suitable 'RF front end' (containing power amplifiers, analogue filters and duplexers) that would ensure unwanted harmonics and OOB spectral images do not cause interference to neighboring bands–i.e. ensuring the device would not be an "RF Jammer" as classified by Ofcom, use of which would also be illegal. (Developing such a front end would require extensive analogue engineering and expense). The solution, therefore, was to perform tests in a controlled and legal environment by transmitting through RF coaxial cables. The hardware implementation from Figure 6.6 was used for these tests.

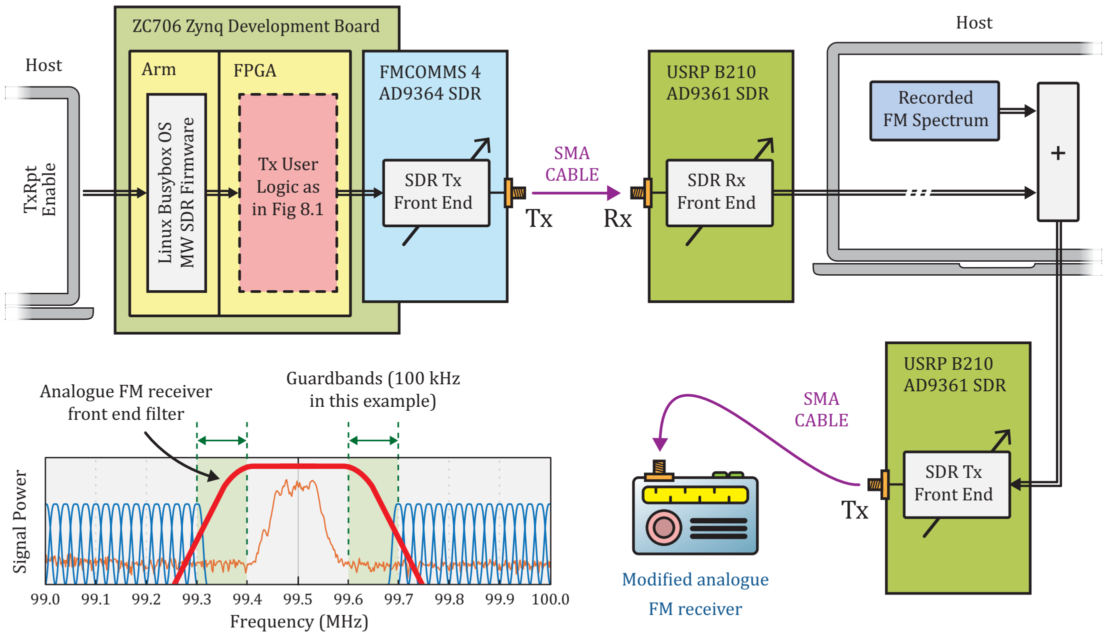


Figure 6.6: Hardware configuration used to investigate SU to PU interference for various FBMC frequency guardbands, and a plot demonstrating the speculated frequency response of the analogue FM Radio receiver's front end filter

The ZynqSDR internal loopback was disabled, and a USRP was connected directly to the Tx output port of the FMCOMMS 4. The transmitter was enabled as before (with recorded FM data passed to the ZynqSDR to allow the transmitter to generate the mask). The modulated FBMC signal was output, received by the USRP, and then saved to the computer. In a second Simulink model, the FBMC recording was added to the power-adjusted recordings of the FM spectrum, with the SU power set to around 0 dBm. This was in line with the predicted SU transmit power limit for a signal with a 300 kHz guardband (Section 5.8.2 (page 94)).

An old analogue FM Radio receiver was sourced, and its antenna (and internal wiring) was removed and replaced with an SMA port and shielded RF cable. The USRP was cabled directly to the FM Radio, and the combined PU+SU Overlay signal was re-transmitted directly into the FM Radio receiver. The receiver was tuned to the centre frequencies of the locally re-transmitted FM stations, and the signals were demodulated and output to the device's speaker.

6.3.2 Experimental Results

With the 300 kHz guardbands, no perceptible interference was detected in the audio outputs of the demodulated FM Radio signals, for any of the FM environments tested. This was expected, as the 400 kHz 'gap' between the FM centre frequency and the edge of the FBMC signal was greater than the expected passband of the FM receiver's front end filter. Tuning to parts of the band where the FBMC signal was transmitting, a buzzing noise was heard from the speaker of the FM receiver. *(The reader can listen to this in the companion video, at t=9:00)*. Because the energy at these frequencies was considerably greater than the standard 'white noise' floor normally found between FM Radio stations, the buzzing audio output was quite loud.

Parameters of the transmitter design were adjusted to change the width of the guardbands from 300 kHz to 200 kHz, then 100 kHz and finally 0 kHz, as shown in Figure 6.7, and new FPGA bitstreams were created for each configuration. (As introduced in Section 4.5.3 (page 71), Figure 6.7 presents the ITU-R designated protection ratio of a stereo FM signal). Repeating the previous steps, the signals with the narrower guardbands were generated and transmitted to the FM receiver.

The results are presented in Table 6.2. No noticeable interference was caused from the FBMC signal with the guardband configured at 200 kHz. This was interesting, as the SU was transmitting at a power 13 dB greater than the predicted SU power limit for this

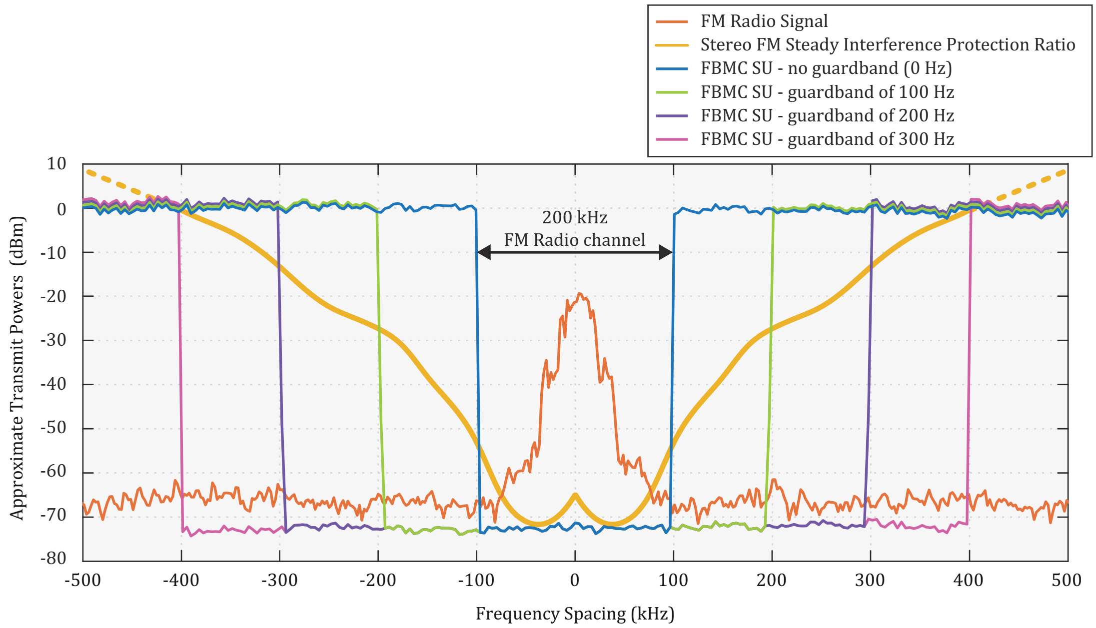


Figure 6.7: SU FBMC signals generated with different guardband sizes, indicating simulated transmit power level vs predicted SU transmit power limits

Table 6.2: Qualitative Results from Guardband Size Investigation

Guardband Size	SU 'Tx Power' (above anticipated limit)	Observations	Comment
300 kHz	0 dB	All stations can be received with no degradation in quality.	Potentially too conservative, SU could use more spectrum.
200 kHz	13 dB	All stations can be received with no degradation in quality.	Indicates that a 200 kHz guardband might be sufficient. Note high Tx power.
100 kHz	27 dB	Stations that sounded noisy originally (i.e. prior to overlaying the SU) deteriorated further.	Noise could be linked to higher Tx power.
0 kHz	52 dB	The strongest (BBC) signals could still be received perfectly. Weaker signals overcome by SU interference.	Interesting that some stations were unaffected by the very high power SU.

guardband. With the 100 kHz guardbands, a slight degradation in audio quality was noted for some of the FM stations that were originally received with a lower power. Very surprisingly, around half of the FM Radio signals could still be demodulated successfully with a good quality audio output when there was no guardband in place at all (0 kHz). Here the SU transmit power was over 50 dB greater than the predicted power limit. A strong crackling noise could be heard on the weaker stations, likely to be the result of some of the FBMC subcarriers passing through the FM receiver's front end filter and being demodulated, as highlighted by the plot in Figure 6.6.

From these initial results, it would appear that the front end analogue filter in the FM receiver used in these tests passes frequencies past ±200 kHz. An FBMC guardband of 200 kHz (i.e. ±300 kHz from the FM centre frequency) would therefore be a safe choice—as long as every FM receiver in the world met this minimum filter requirement. Reducing the guardband to 200 kHz would result in an increase to the FBMC throughput rates, as presented in Table 6.3:

Table 6.3: 4-OQAM PHYDYAS FS-FBMC Throughput Rates with 200 kHz Guardband

Location	*Throughput with 300 kHz Guard (Mb/s) [Table 6.1]*	Throughput with 200 kHz Guard (Mb/s)
Edinburgh	*4.78*	7.32
Livingston	*6.70*	8.72
Kirkcaldy	*5.42*	7.82
Ayr	*7.38*	8.88
Glasgow	*5.50*	8.30
Callander	*8.98*	11.48
Balloch	*11.1*	13.10
Haddington	*9.90*	12.10
Perth	*9.60*	12.0
Dunblane	*8.30*	10.90
Dundee	*6.92*	8.92

Table 6.3: 4-OQAM PHYDYAS FS-FBMC Throughput Rates with 200 kHz Guardband

Location	*Throughput with 300 kHz Guard (Mb/s) [Table 6.1]*	Throughput with 200 kHz Guard (Mb/s)
Lanark	*11.90*	13.70
Aberfoyle	*9.68*	11.88
Penicuik	*11.38*	13.48
Kilmarnock	*11.40*	13.20
Peebles	*11.22*	13.10

It is unlikely, however, that all FM receivers will have the same front end bandpass filter characteristic. Further research with a series of different FM Radio receivers (a mixture of analogue and digital devices) would be required in order to generate an informed recommendation for the minimum guardband that must be set to prevent interference to the existing FM Radio equipment in use across the country, some of which may be several decades old. In order to perform these tests, it is likely that the PU + SU Overlay signals would need to be broadcast through the air to a range of devices inside an RF-shielded anechoic chamber.

6.4 Real Time 'Cognitive' Radio

The ultimate aim of this work was to develop a 'cognitive' DSA radio that was able to automatically reconfigure its channel mask (without the need for a SU geolocation database), and transmit in empty channels of the FM Radio band whilst ensuring the protection of PUs. To achieve this goal, the radio must regularly receive and process the ambient FM Radio environment, and update the mask as soon as changes are detected in the PU spectrum.

Transmitting and receiving in the same frequency band at the same time is an engineering challenge, as the receiver will detect signals being output from the transmitter. Additional RF hardware such as a circulator would have to be used to help prevent the receiver's SDR front end from becoming saturated. For the reasons discussed in Section 6.3, however, all transmit tests at this time must be cabled; so this removes the cross-talk issue from the equation.

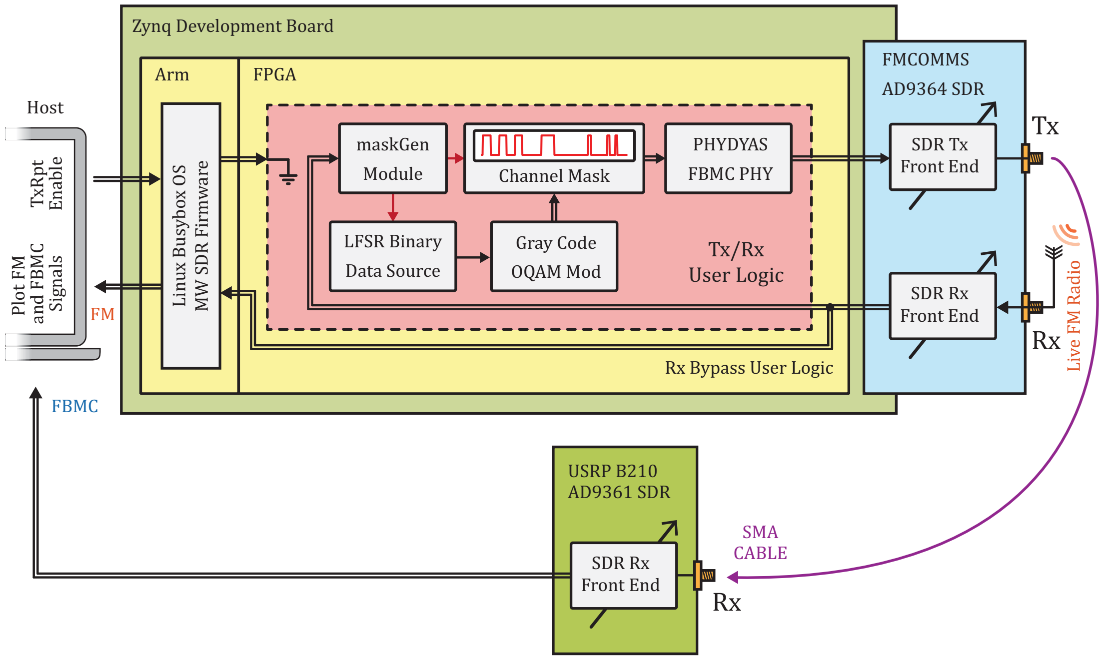


Figure 6.8: Hardware configuration for 'cognitive' DSA radio tests

After some modifications to the user logic design, it was possible to use the hardware configuration of Figure 6.8 to test the radio's cognitive capabilities. Live FM Radio signals would be acquired from an antenna, and fed into the maskGen module to allow for real time reconfiguration. The remainder of this section describes the modifications and hardware setup required to complete this last set of tests, and reviews the results obtained.

6.4.1 User Logic Design Modifications

Additional ports were added to the Tx user logic design in Simulink to enable simultaneous transmit and receive (thus making it into a TxRx user logic design). The existing transmitter input ports were grounded, as these were no longer required; and the receiver input ports were looped round and connected to the input of the maskGen module, as shown in Figure 6.8. This meant that live FM Radio signals received by the ZynqSDR front end would be used when the mask was being generated.

A 'maskUpdate' strobe (a feature of the maskGen module) was configured to force the radio to automatically perform a new scan and generate a new mask once every second.

This permitted near-real-time reconfiguration of the FBMC signal's mask, and allowed for a more interactive test to be carried out.

6.4.2 Hardware Configuration

A USRP was connected via an SMA cable to the ZynqSDR Tx output port, and a VHF antenna was attached to the Rx input port. A Simulink model was created, and a ZynqSDR Receiver block was placed in it with 'Bypass user logic' mode enabled. This block output the received FM Radio spectrum, as presented to the maskGen module in the targeted TxRx user logic design (as shown in Figure 6.8). A USRP Receiver block was also added, and this, along with the ZynqSDR block, was connected to a Spectrum Analyzer to enable simultaneous viewing of both the received FM Radio spectrum, and the generated/transmitted/received FBMC signal.

6.4.3 Experimental Results

The radio equipment was tested in a room where it was possible to receive strong ambient FM Radio signals. `transmitRepeat()` was enabled (to activate the transmit path of the FMCOMMS), and the receiver model was run. When the first frames of data arrived in Simulink, a plot that was almost identical the one in Figure 5.15 (page 96) was displayed in the Spectrum Analyzer window; meaning that the design was working.

Some handheld FM Transmitters were activated (the type one would use to broadcast music from a phone via a 3.5mm headphone jack to an older car radio) in order to add more FM signals to the spectrum. Within a second, the FBMC signal adapted and new spectral holes appeared to protect these newly detected FM signals.

Next, the centre frequencies of the handheld transmitters were varied. Shifting the carriers up and down through the FM band, the FBMC signal kept adapting, with the spectral holes following the FM carriers as they moved. As mentioned previously, a video demonstrating the responsiveness of the design was made. In the video it is possible to see how the FBMC channel mask adapts in real time to suit the ambient environment. Screenshots from the video *(t=10:28)* are presented in Figure 6.9.

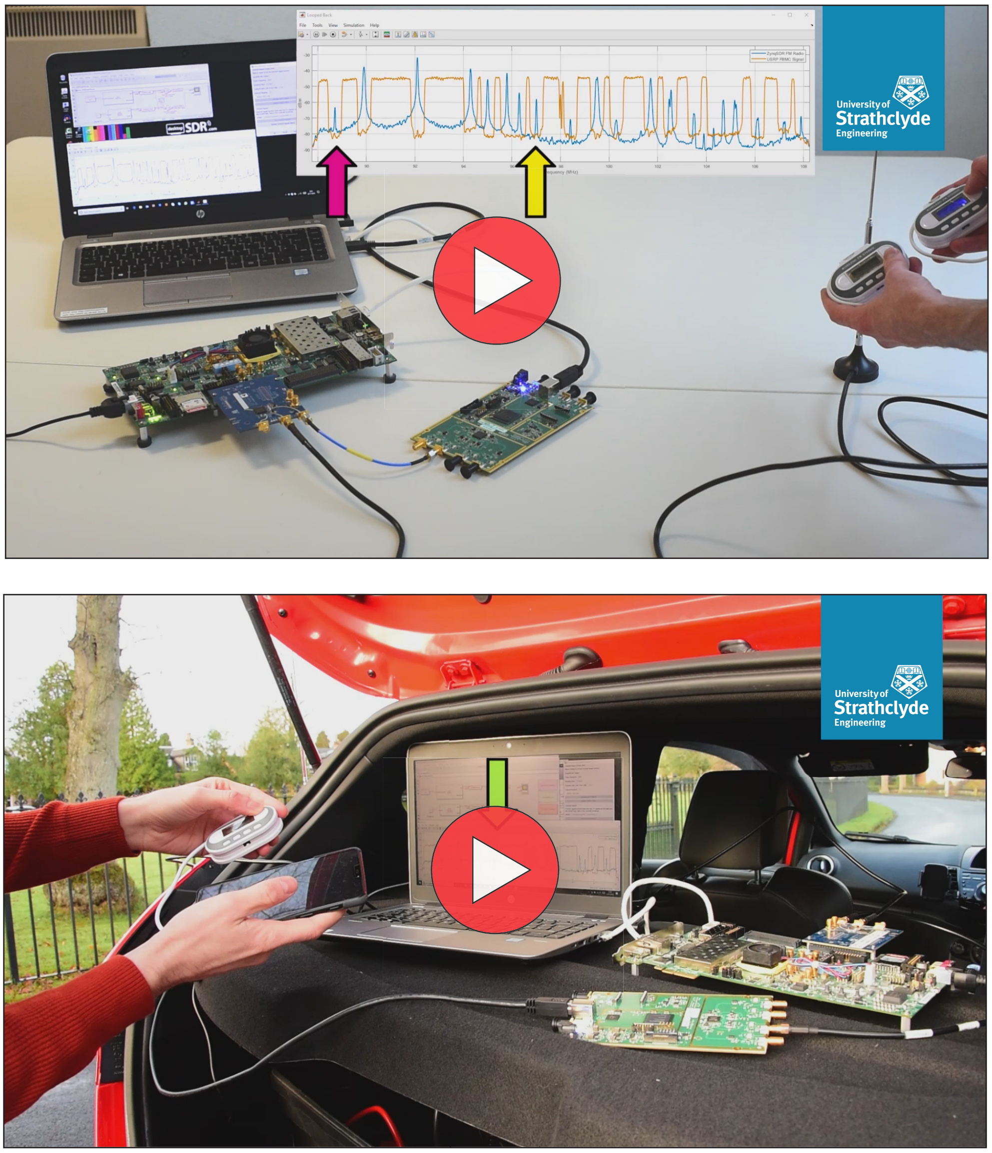


Figure 6.9: Screenshots from the companion video, demonstrating the FBMC signal dynamically adapting to the changing FM Radio environment in real time on the ZynqSDR (top) at the University of Strathclyde in Glasgow city centre, and (bottom) from the back of a car in Uddingston

Further tests were carried out for alternative FM Radio environments. These tests were conducted in two ways: firstly, by connecting a second USRP to the Rx input port of the FMCOMMs, and re-transmitting recorded FM data into the ZynqSDR receiver (to allow for subsequent mask generation); and secondly, by moving the equipment to different locations (Uddingston, Lanark, Falkirk and Edinburgh were used) and performing live off-the-air tests out the back of a car. In all cases, the radio was found to be capable of adapting autonomously to keep PU signals protected, whilst maintaining its SU FBMC broadcast.

6.5 Chapter Conclusions

This chapter has presented the practical work carried out in targeting the SU FBMC transmitter to programmable ZynqSDR hardware, using various (software) tools provided by MathWorks and Xilinx. Real time on-hardware simulations were performed to confirm that the radio design developed via this research was able to adapt to the different prerecorded FM Radio environments presented to it. The results provide more evidence that this PHYDYAS FBMC based SU radio would be capable of coexisting with the FM Radio PUs. Achievable SU throughput rates for 16 locations across central Scotland were presented, highlighting that a significant portion of the band is suitable for SU access.

Further, an investigation into the necessary FBMC SU guardband size was carried out. Initial results suggest that a 200 kHz guardband would prevent the radio interfering with FM Radio PUs; however, this needs to be confirmed by further research with additional radio hardware. Finally, tests were carried out to prove that the SU radio was capable of automatically reconfiguring its channel mask in a ‘cognitive’ manner. It was shown to be capable of dynamically adapting its NC transmitter mask in real time to protect FM Radio signals that it detects off the air, and a video demonstrating this behaviour has been made available.

Chapter 7

Conclusions

This thesis has presented the work carried out in designing, implementing and targeting a novel real-time DSA-enabled radio transmitter PHY to programmable SDR hardware. This transmitter enables SUs to access the band traditionally used for FM Radio broadcasting (88-108 MHz), and establish data communication channels in vacant parts of the FM Radio PU spectrum using a MCM scheme with an NC channel mask. This radio was designed to enable the transmission of signals for IoT/ smart grid applications, making use of underutilised spectral resources, whilst ensuring the protection of incumbent PU signals.

7.1 Resume

Traditional spectrum policies have seen spectral regulators categorise bands of the electromagnetic spectrum for specific applications, and exclusively license these bands to particular PUs. The RF spectrum is a valuable commodity, and therefore licences often cost a significant amount of money. Despite this, for various reasons PUs often do not use all of their licensed spectrum, and this results in valuable spectral resources lying fallow. The FM Radio band is a prime example of this. The full 20 MHz band is categorised for transmission of these analogue (modulated audio) signals, yet not all of the band is used. This was demonstrated through the work of Otermat *et al.* in the USA [118], and by the FM occupancy for Central Scotland case study presented in Chapter 4.

New shared spectrum initiatives are seeing spectral models change. The various regulator-approved trials that have taken place around the world have demonstrated that SUs can peacefully coexist with PUs in a number of different real RF environments. As discussed in Chapter 2, the UK regulator Ofcom is now allowing unlicensed (free) shared access to TVWS, and light-licensed shared access to a range of 4G and 5G cellular bands. While this can be considered a great regulatory leap forward, Ofcom is still some way from permitting DSA. DSA is a method of spectrum sharing whereby SUs use dynamic modulation techniques in order to opportunistically establish communication channels in vacant parts of the spectrum. Many bands across the RF spectrum are underutilised, and permitting unlicensed or light-licensed shared access to them could bring a raft of benefits to the economy, rural communities and emerging smart city, and smart grid, technologies.

NC-MCM schemes can be used by SUs to generate signals that contain spectral ‘holes’, allowing SU signals to mold around PUs, and fill up all available spectral fragments. One of the main defining factors of NC-MCM schemes are their ACLR; the ratio between the power in active (‘on’) parts of the signal’s spectra, and the power that leaks into disabled (‘off’) parts; i.e. the OOB leakage. As discussed in Chapter 3, in a situation where SUs need to target very fragmented spectrum, FBMC/OQAM modulators can achieve a higher spectral efficiency and greater data throughput rates than other popular NC schemes. Despite the comparative increase in system complexity, FBMC/OQAM looks at this time to be the most suitable scheme for DSA-enabled SUs.

The analogue modulation technique ‘FM’ was introduced in Chapter 4. Worldwide broadcast variations and the status of the ‘digital switchover’ were reviewed. FM band utilisation was discussed, and the work of Otermat et al. was introduced [118], and a comparable case study was presented that reported on the utilisation of the FM band in Central Scotland. This highlighted the significant amount of vacant spectrum that exists, even in the centres of Scotland's largest cities. The motive for secondary reuse of this valuable vacant spectrum was presented. Finally, a novel energy grid DSM load balancing solution was proposed as an application that could be supported by a new DSA-enabled SU radio that operated in vacant spectrum of the FM Radio band.

In Chapter 5, the design and implementation of a novel DSA-enabled radio transmitter PHY that enables SU operation inside the FM Radio band was presented. This could be used by DNOs as part of a new DSM service, that would able to broadcast load balancing messages to consumer smart home equipment, providing an improved replacement to the ageing RTS. The radio uses the FS-FBMC/OQAM NC-MCM scheme with the PHYDYAS filter, and was developed in Simulink using low level HDL components from the HDL Coder library. The transmitter leverages cognitive radio techniques to automatically adjust its channel mask, and mould its spectral output around detected PU signals. A basic receiver was implemented to facilitate system simulation, and investigations were carried out to explore the effects this SU radio had on the quality of PU FM Radio signals, and the effects that PU signals had on the SU under various SU transmit powers.

The transmitter was targeted to programmable SDR hardware to allow a series of experiments to be carried out in Chapter 6. These enabled a practical RF coexistence investigation to take place, to validate the design's DSA capabilities. Real time on-hardware simulations were performed to confirm that the radio was able to adapt to the different pre-recorded FM Radio environments presented to it. Further, an investigation into the required FBMC SU guardband size was carried out. Finally, the design was modified to enable a 'cognitive' mode, where it would automatically reconfigure its channel mask in real time to prevent interference with PU FM Radio stations detected live off the air.

7.2 Key Conclusions

The primary goal of this research was to investigate whether it would be possible for a SU to operate inside the FM Radio band and transmit data for IoT/ smart grid type applications without causing interference to PU signals.

The findings presented in this thesis indicate that, yes, this would be possible, provided that spectrum regulations were modified to permit such use.

The proposed SU radio was designed specifically to operate in the FM Radio band. A modulation scheme featuring a low level of OOB leakage was chosen. With FS-FBMC/OQAM, the radio would be able to meet the predicted ACLR limits for an SU operating in the FM band, based on the (re)interpretation of the ITU-R BS.412-9 FM Radio regulations. System parameters of the radio were designed such that 10 (overlapping) OQAM subchannels would fit inside each standard 'FM channel', leading to a total of 1000 possible OQAM subchannels throughout the band.

Due to the lack of an existing spectrum sharing geolocation database for the FM Radio band, a spectrum sensing 'autoMask' module was incorporated into the design that was capable of automatically generating a spectrum mask to control the transmitter, and ensure that no data was modulated into OQAM subchannels relating to frequencies that were being used by a PU FM Radio station. The autoMask module tuned a series of matched detectors to the centre frequencies of each potential FM Radio carrier for classification, and was shown to be capable of automatically constructing a subchannel mask complete with guardbands, based on detected PU activity. The full detection and mask building process took just 320 ms, meaning that the mask could be updated multiple times a second, if required. (Note, this time could be reduced further by modifying the radio implementation).

The 'field test' simulations reported in Chapter 5 explored the effects the proposed SU radio had on the quality of PU FM Radio signals; and also the effects that PU signals had on the SU under various SU transmit powers. Interference caused to PU signals was gauged both quantitatively and qualitatively for SU signal broadcast powers far exceeding speculated permitted SU power limits. While some degradation of the demodulated FM signal audio output was noted for a broadcast power of 36 dBm (more than 30 dB greater than anticipated limits), at lower powers, e.g. 20 dBm, the effects were minimal. BER simulations carried out for a SU transmitter-receiver pair showed that, even with a SU SINR of -13.5 dB (i.e. broadcast power of -30 dBm), every transmitted bit could be recovered correctly by the receiver when the spectral mask was known.

When the SU was targeted to the ZynqSDR in Chapter 6, real time on-hardware simulations were carried out using a variety of FM Radio spectrum environments harvested from locations around Central Scotland. Results showed that the SU was always capable of detecting and protecting PU broadcasts, and also highlighted the significant amount of vacant and 'usable' spectrum in the band around the country.

An investigation into the required FBMC SU guardband size was carried out, where SU signals were transmitted (via cable) into a commercial off-the-shelf FM Radio receiver. By design, FM Radio receivers contain a filter to pass a narrow band of frequencies centered around the FM carrier; however the analogue filter characteristic is unknown, and is likely to vary between different FM Radio sets. Initial results indicate that a FBMC guardband of 200 kHz (i.e. ±300 kHz from the FM centre frequency) would prevent interference; however, further research with a series of different FM Radio receivers (analogue and digital) would be required to state conclusively the guardband size required.

The design was modified to operate in ‘cognitive’ mode, and was shown to be capable of automatically reconfiguring its channel mask in real time to prevent interference with PU FM Radio stations detected live off-the-air. Low power handheld FM transmitters were activated to add additional PU signals to the spectrum, and their centre frequencies were varied to confirm that the SU subchannel mask dynamically reconfigured itself. A video was presented that demonstrates this real time reconfiguration, highlighting the flexibility and suitability of the FBMC scheme for DSA applications.

This work has provided a strong argument for secondary reuse of vacant parts of the FM Radio band. With impending FM digital switchovers around the world being cancelled and delayed, it seems likely that FM will continue being broadcast for the forseeable future. It was shown in the Chapter 4 case study that this band, like many others, is not fully utilised. It is largely uniform worldwide, and signals at these frequencies have relatively long wavelengths with excellent propagation characteristics. This band would be ideal for a SU WAN broadcast channel, as signals transmitted at these frequencies (88–108 MHz) would able to diffract around objects such as hills and human-made structures, and benefit from high levels of penetration through buildings.

With the proposed 4-OQAM FS-FBMC radio design, SU data rates around 5.5 Mb/s would be achievable in Glasgow, the largest city in the country. In line with the findings of [118], in smaller towns and rural areas (such as Kilmarnock, Lanark and Peebles), the amount of usable vacant spectrum—and therefore achievable throughput rate—was shown to increase dramatically. These data rates may be in excess of what would be required for the proposed DSM/ smart grid load balancing application, as the current RTS solution is capable of switching 200 MW of electric storage heater load with a data rate of 1.5 kb/s; but this would allow for innovative, new, higher rate use cases to be developed and supported over time, without having to replace SU broadcast equipment.

7.3 Further Work

To date, the prototype SU FBMC radio PHY described in this paper has been targeted to ZynqSDR hardware, and tests have been carried out to explore whether it causes interference to PU FM Radio channels. A Simulink based receiver and a corresponding low level PHY layer protocol (with preamble/ data symbols and an FBMC burst structure) have also been developed; and used to explore interference caused by the PUs to the SU radio. The transmitter and receiver currently do not incorporate a communications stack; meaning that further work would be required to realize a fully functional communications link between A and B. As discussed in Section 6.2.1 (page 104), a LFSR is currently used to generate random 'data' for broadcast. Future upgrades would see an appropriate stack developed at each end.

The ZynqSDR is an excellent prototyping device for the lab environment, however it is not suitable for real world broadcast tests with a high RF output power. When the FBMC signal is generated in fixed point on the ZC706 FPGA (and limited to a 12-bit range in preparation for broadcast), its dynamic range is around 65 dB; i.e. the difference between the power in the 'on' and 'off' subchannels. After passing through the DAC and analogue stages on the FMCOMMs however, this is significantly reduced, to around 40 dB. This is likely to be due to the high PAPR of the output FBMC signal. An alternative SDR solution that features an appropriate analogue RF front end (containing power amplifiers, analogue filters and duplexers) would be required for the next stages. This would ensure the radio did not broadcast unwanted harmonics and aliased spectral images, which are a feature of all SDR front ends.

One potential solution is to target the design to alternative SDR hardware, such as a Xilinx RFSoC, which features a 14-bit DAC; or an USRP N210 with its 16-bit DAC. It is expected that a higher resolution DAC would combat the issue, leading to a lower noise floor, and greater dynamic range in the output signal. In Section 2.5 (page 32) the Xilinx RFSoC and its applicability for DSA applications was mentioned. One of the primary benefits this device offers is its ultra-wide sampling rates. It is possible to massively oversample at the RF front end, which in turn means aliased spectral images output from the SDR could be positioned 10s, 100s or 1000s of MHz away from the band of interest by design. In turn, lower cost analogue RF filters and wideband amplifiers could then be used, massively reducing the cost and complexity of the analogue RF front end. The RFSoC is therefore a highly attractive platform for future stages of implementation. Another potential avenue of research would be to explore digital predistortion, and aim to counter the effects of the conversion and analogue stages with real-time feedback and a distortion filter.

Further work is required to develop a receiver with full frequency and timing synchronisation systems. Best practise FS-FBMC synchronisation is still an ongoing research discussion. It is likely that a system similar to that proposed in [28] would perform well. As discussed, signalling the channel mask in a header at the beginning of every burst would result in lower BERs for the receiver. For the DSM use case, a system protocol would be required where coded messages broadcast across the FM Radio band SU FBMC WAN were received by the new DSM Border Router, interpreted, converted to IPv6 multicast messages, and then retransmitted in the HAN to smart home devices using the Thread protocol.

Due to UK radio spectrum laws, any real world broadcast trial (i.e. not transmitting through cables) would require regulatory consent and stakeholder consultation. Proof would need to be provided that the radio design would not cause unwanted interference to neighbouring bands, and in all likelihood (considering the way in which TVWS trials were approached), channel masks and guardbands would initially be set by the regulator. An intermediate step might be to explore transmission inside an RF shielded anechoic chamber. This would allow an initial chance to experiment with the simultaneous broadcast of FM Radio and FBMC signals without the chance of legal repercussions, to explore interference effects and receiver synchronization systems further. This would, at the same time, enable further research with a series of different FM Radio receivers (a mixture of analogue and digital devices). As discussed in Section 6.3.2 (page 112), this is required in order to generate an informed recommendation for the minimum guardband required.

7.4 Final Remarks

The demand for wireless connectivity is exponentially increasing. Innovative new shared and dynamic spectrum access techniques will be required in order to use the finite resources of the radio spectrum in more efficient ways. In light of this, regulators are beginning to adopt new shared spectrum strategies. Ofcom was one of the first to implement sharing for TVWS, and has recently permitted third parties shared access to all vacant licensed cellular spectrum; meaning SUs can build shared spectrum mobile networks and provide services in areas where PU licence holders do not want to.

This thesis has presented a disruptive new spectrum sharing technique that facilitates access to vacant spectrum in the FM Radio band. A novel, real-time FS-FBMC/OQAM DSA-enabled radio transmitter was designed, implemented, and targeted to ZynqSDR hardware, and it was shown through a series of investigations that it was capable of coexisting with incumbent FM Radio signals without causing noticeable levels of interference.

The FM Radio band is only one of many that are under-utilised. There are white and grey spaces all throughout the RF spectrum; all waiting to be accessed. Developing DSA-enabled radios to make use of them may be challenging, but it can be done.

It is hoped that the learnings from developing, implementing and experimenting with the FBMC based SDR solution presented in this thesis will help drive the DSA research field forwards, and maybe even help to influence future dynamic spectrum regulations.

Appendix A

FM Occupancy in Central Scotland: Results

Complete results from the FM occupancy study in Central Scotland are listed over the next few pages. Test locations are presented in the same order as in Table 4.2 (page 63).

Stations are identified and named where possible. The Frequency Finder website proved an invaluable resource for this task [183][184].

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
Glasgow (City Centre) (55.860837, -4.243749) Sample Date: 09/10/2017 Sample Time: 17:50	22 (16 unique)	89.5		BBC R2	Darvel	(55.579440, -4.291934)
		89.9		BBC R2	Black Hill	(55.862009, -3.873135)
		91.7		BBC R3	Darvel	(55.579440, -4.291934)
		92.1		BBC R3	Black Hill	(55.862009, -3.873135)
		93.9		BBC RScot	Darvel	(55.579440, -4.291934)
		94.3		BBC RScot	Black Hill	(55.862009, -3.873135)
		95.0		Celtic Music	Glasgow-Grafton Place	(55.863334, -4.246347)
		95.8		BBC R4	Black Hill	(55.862009, -3.873135)
		98.4		Pulse FM	Glasgow-Barrhead	(55.788847, -4.38401)
		99.1		BBC R1	Darvel	(55.579440, -4.291934)
		99.5		BBC R1	Black Hill	(55.862009, -3.873135)
		100.3		Heart Scot	Black Hill	(55.862009, -3.873135)
		101.0		RNIB Connect	Glasgow-West	(55.889738, -4.324631)
		101.7		Classic FM	Black Hill	(55.862009, -3.873135)
		102.5		Clyde 1	Black Hill	(55.862009, -3.873135)
		103.5		Sunny Govan	Govan	(55.845450, -4.3379580)
		104.3		BBC R4	Darvel	(55.579440, -4.291934)
		104.7		BBC RGaelic	Black Hill	(55.862009, -3.873135)
		105.2		Smooth Scot	Black Hill	(55.862009, -3.873135)
		106.1		Capital Scot	Black Hill	(55.862009, -3.873135)
		107.2		Awaz	Glasgow-Darnley Street	(55.842217, -4.270683)
		107.9		Camglen	Rutherglen	(55.827134, -4.210733)

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
Edinburgh (South) (55.911816, -3.212972) Sample Date: 11/08/2018 Sample Time: 16:55	35 (15 unique)	88.3		BBC R2	Forfar	(56.556543, -2.842590)
		88.7		BBC R2	Ben Gullipen	(56.211723, -4.261851)
		89.9		BBC R2	Black Hill	(55.862009, -3.873135)
		90.5	bad	BBC R3	Forfar	(56.556543, -2.842590)
		90.9	bad	BBC R3	Ben Gullipen	(56.211723, -4.261851)
		92.1		BBC R3	Black Hill	(55.862009, -3.873135)
		92.7	bad	BBC RScot	Forfar	(56.556543, -2.842590)
		93.1		BBC RScot	Ben Gullipen	(56.211723, -4.261851)
		94.3		BBC RScot	Black Hill	(55.862009, -3.873135)
		94.9		BBC R4	Forfar	(56.556543, -2.842590)
		95.2		Kingdom FM	Knock Hill	(56.125992, -3.523221)
		94.9		BBC R4	Black Hill	(55.862009, -3.873135)
		95.2		Kingdom FM	Purin Hill	(56.239084, -3.208267)
		96.6		Kingdom FM	Kirkcaldy	(56.120195, -3.145030)
		97.3		Forth 1	Craigkelly	(56.070826, -3.233516)
		97.6		Forth 1	Black Hill	(55.862009, -3.873135)
		97.9		BBC R1	Forfar	(56.556543, -2.842590)
		98.3		BBC R1	Ben Gullipen	(56.211723, -4.261851)
		98.5		BFBS	Dreghorn Barracks	(55.900974, -3.237714)
		99.5		BBC R1	Black Hill	(55.862009, -3.873135)
		100.1		Classic FM	Angus	(56.553681, -2.987294)
		100.3		Heart Scot	Black Hill	(55.862009, -3.873135)
		101.1		Heart Scot	Craigkelly	(56.070826, -3.233516)

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
		101.7		Classic FM	Black Hill	(55.862009, -3.873135)
		102.2	bad	Forth 1	Penicuik	(55.817836, -3.195177)
		102.5		Clyde 1	Black Hill	(55.862009, -3.873135)
		102.8		Tay FM	Angus	(56.553681, -2.987294)
		103.1		Central FM	Earls Hill	(56.070560, -4.060787)
		103.3	bad	Heart Scot	Penicuik	(55.817836, -3.195177)
		103.7	bad	BBC RGaelic	Forfar	(56.556543, -2.842590)
		104.1		BBC RGaelic	Craigkelly	(56.070826, -3.233516)
		104.7		BBC RGaelic	Black Hill	(55.862009, -3.873135)
		104.9		BBC R4	Ben Gullipen	(56.211723, -4.261851)
		105.7		Capital Scot	Craigkelly	(56.070826, -3.233516)
		106.1		Capital Scot	Black Hill	(55.862009, -3.873135)
Dundee (City Centre) (56.454091, -2.97862) Sample Date: 21/08/2018 Sample Time: 15:10	19 (11 unique)	88.3		BBC R2	Forfar	(56.556543, -2.842590)
		89.9		BBC R2	Black Hill	(55.862009, -3.873135)
		90.5		BBC R3	Forfar	(56.556543, -2.842590)
		92.1		BBC R3	Black Hill	(55.862009, -3.873135)
		92.7		BBC RScot	Forfar	(56.556543, -2.842590)
		94.3		BBC RScot	Black Hill	(55.862009, -3.873135)
		94.9		BBC R4	Forfar	(56.556543, -2.842590)
		95.8		BBC R4	Black Hill	(55.862009, -3.873135)
		96.1		Kingdom FM	Purin Hill	(56.239084, -3.208267)
		96.4		Tay FM	Tay Bridge	(56.444680, -2.924991)

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
		97.3		Forth 1	Craigkelly	(56.070826, -3.233516)
		97.9		BBC R1	Forfar	(56.556543, -2.842590)
		99.5		BBC R1	Black Hill	(55.862009, -3.873135)
		100.1		Classic FM	Angus	(56.553681, -2.987294)
		101.7		Classic FM	Black Hill	(55.862009, -3.873135)
		102.0		Wave FM	Law	(56.470265, -2.989476)
		102.8		Tay FM	Angus	(56.553681, -2.987294)
		103.7		BBC RGaelic	Forfar	(56.556543, -2.842590)
		105.4		Kingdom FM	Allanhill Farm	(56.316853, -2.777534)
Livingston, W Lothian (55.914130, -3.514740) Sample Date: 04/08/2018 Sample Time: 14:11	31 (14 unique)	88.3		BBC R2	Forfar	(56.556543, -2.842590)
		88.7	bad	BBC R2	Ben Gullipen	(56.211723, -4.261851)
		89.9		BBC R2	Black Hill	(55.862009, -3.873135)
		90.3	bad	BBC R3	Bowmore	(55.749246, -6.275147)
		90.5		BBC R3	Forfar	(56.556543, -2.842590)
		90.9	bad	BBC R3	Ben Gullipen	(56.211723, -4.261851)
		92.1		BBC R3	Black Hill	(55.862009, -3.873135)
		92.7	bad	BBC RScot	Lethanhill	(55.363027, -4.465627)
		93.1		BBC RScot	Ben Gullipen	(56.211723, -4.261851)
		94.3		BBC RScot	Black Hill	(55.862009, -3.873135)
		94.9	bad	BBC R4	Forfar	(56.556543, -2.842590)
		95.2		Kingdom FM	Knock Hill	(56.125992, -3.523221)
		95.8		BBC R4	Black Hill	(55.862009, -3.873135)

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
		96.1	bad	Kingdom FM	Purin Hill	(56.239084, -3.208267)
		96.5	bad	BBC R1	could not be identified...	
		97.3		Forth 1	Craigkelly	(56.070826, -3.233516)
		97.6		Forth 1	Black Hill	(55.862009, -3.873135)
		97.9		BBC R1	Forfar	(56.556543, -2.842590)
		98.7	bad	Forth 1	could not be identified...	
		99.5		BBC R1	Black Hill	(55.862009, -3.873135)
		100.3		Heart Scot	Black Hill	(55.862009, -3.873135)
		101.1		Heart Scot	Craigkelly	(56.070826, -3.233516)
		101.7		Classic FM	Black Hill	(55.862009, -3.873135)
		102.5		Clyde 1	Black Hill	(55.862009, -3.873135)
		102.8		Tay FM	Angus	(56.553681, -2.987294)
		103.1		Central FM	Earls Hill	(56.070560, -4.060787)
		103.9	bad	BBC R3	could not be identified...	
		104.1		BBC RGaelic	Craigkelly	(56.070826, -3.233516)
		104.7		BBC RGaelic	Black Hill	(55.862009, -3.873135)
		105.7		Capital Scot	Craigkelly	(56.070826, -3.233516)
		106.1		Capital Scot	Black Hill	(55.862009, -3.873135)
Cumbernauld, N Lanarkshire (55.950273, -3.984263) Sample Date: 22/07/2018 Sample Time: 12:56	12 (11 unique)	89.9		BBC R2	Black Hill	(55.862009, -3.873135)
		92.1	bad	BBC R3	Black Hill	(55.862009, -3.873135)
		94.3		BBC RScot	Black Hill	(55.862009, -3.873135)
		95.8		BBC R4	Black Hill	(55.862009, -3.873135)

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
		97.6		Forth 1	Black Hill	(55.862009, -3.873135)
		99.5		BBC R1	Black Hill	(55.862009, -3.873135)
		100.3		Heart Scot	Black Hill	(55.862009, -3.873135)
		101.7		Classic FM	Black Hill	(55.862009, -3.873135)
		102.5		Clyde 1	Black Hill	(55.862009, -3.873135)
		104.7		BBC RGaelic	Black Hill	(55.862009, -3.873135)
		105.2		Smooth Scot	Black Hill	(55.862009, -3.873135)
		106.1		Capital Scot	Black Hill	(55.862009, -3.873135)
Kirkcaldy, Fife (56.119926, -3.166247) Sample Date: 21/08/2018 Sample Time: 16:10	27 (14 unique)	88.3		BBC R2	Forfar	(56.556543, -2.842590)
		89.1	bad	BBC R2	Ashkirk	(55.509899, -2.840668)
		89.9		BBC R2	Black Hill	(55.862009, -3.873135)
		90.5	bad	BBC R3	Forfar	(56.556543, -2.842590)
		90.9	bad	BBC R3	Ben Gullipen	(56.211723, -4.261851)
		91.3	bad	BBC R3	Ashkirk	(55.509899, -2.840668)
		92.1		BBC R3	Black Hill	(55.862009, -3.873135)
		93.1	bad	BBC RScot	Ben Gullipen	(56.211723, -4.261851)
		93.5	bad	BBC RScot	Ashkirk	(55.509899, -2.840668)
		94.3		BBC RScot	Black Hill	(55.862009, -3.873135)
		94.9	bad	BBC R4	Forfar	(56.556543, -2.842590)
		95.8		BBC R4	Black Hill	(55.862009, -3.873135)
		96.1		Kingdom FM	Purin Hill	(56.239084, -3.208267)
		96.6		Kingdom FM	Kirkcaldy	(56.120195, -3.145030)

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
		97.3		Forth 1	Craigkelly	(56.070826, -3.233516)
		97.9	bad	BBC R1	Forfar	(56.556543, -2.842590)
		98.3	bad	BBC R1	Ben Gullipen	(56.211723, -4.261851)
		99.5	bad	BBC R1	Black Hill	(55.862009, -3.873135)
		101.1		Heart Scot	Craigkelly	(56.070826, -3.233516)
		101.7		Classic FM	Black Hill	(55.862009, -3.873135)
		102.2		Forth 1	Penicuik	(55.817836, -3.195177)
		102.8	bad	Tay FM	Angus	(56.553681, -2.987294)
		103.3		Heart Scot	Penicuik	(55.817836, -3.195177)
		104.1		BBC RGaelic	Craigkelly	(56.070826, -3.233516)
		105.7		Capital Scot	Craigkelly	(56.070826, -3.233516)
		106.8	bad	Original 106	Durris	(56.998945, -2.390059)
		107.6		East Coast FM	Garleton Hills	(55.974406, -2.781814)
Perth (City Centre) (56.389336, -3.444147) Sample Date: 21/08/2018 Sample Time: 09:59	19 (9 unique)	88.3	bad	BBC R2	Forfar	(56.556543, -2.842590)
		89.0		BBC R2	Kirkton Mailer	(56.372815, -3.455317)
		91.2		BBC R3	Kirkton Mailer	(56.372815, -3.455317)
		92.7	bad	BBC RScot	Forfar	(56.556543, -2.842590)
		93.4		BBC RScot	Kirkton Mailer	(56.372815, -3.455317)
		94.6		BBC R4	Kirkton Mailer	(56.372815, -3.455317)
		94.9	bad	BBC R4	Forfar	(56.556543, -2.842590)
		96.4		Tay FM	Tay Bridge	(56.444680, -2.924991)
		97.4		BBC R1	could not be identified...	

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
		98.6		BBC R1	Kirkton Mailer	(56.372815, -3.455317)
		99.6	bad	Tay FM	could not be identified...	
		100.1		Classic FM	Angus	(56.553681, -2.987294)
		101.4	bad	BBC R4	could not be identified...	
		102.6	bad	BBC RScot	could not be identified...	
		102.8		Tay FM	Angus	(56.553681, -2.987294)
		104.5		BBC RGaelic	Kirkton Mailer	(56.372815, -3.455317)
		104.8	bad	BBC R3	could not be identified...	
		106.2	bad	unknown...	could not be identified...	
		106.6		Wave FM	Kinnoull Hill	(56.393037, -3.409280)
Kilmarnock, Ayrshire (55.609514, -4.486059) Sample Date: 19/08/2018 Sample Time: 10:44	14 (8 unique)	89.5		BBC R2	Darvel	(55.579440, -4.291934)
		89.9	bad	BBC R2	Black Hill	(55.862009, -3.873135)
		91.7		BBC R3	Darvel	(55.579440, -4.291934)
		92.1		BBC R3	Black Hill	(55.862009, -3.873135)
		93.9		BBC RScot	Darvel	(55.579440, -4.291934)
		94.3	bad	BBC RScot	Black Hill	(55.862009, -3.873135)
		95.8	bad	BBC R4	Black Hill	(55.862009, -3.873135)
		96.7		West FM	Darvel	(55.579440, -4.291934)
		99.1		BBC R1	Darvel	(55.579440, -4.291934)
		99.5	bad	BBC R1	Black Hill	(55.862009, -3.873135)
		101.3		Classic FM	Darvel	(55.579440, -4.291934)
		101.7		Classic FM	Black Hill	(55.862009, -3.873135)

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
		104.3		BBC R4	Darvel	(55.579440, -4.291934)
		106.1	bad	Capital Scot	Black Hill	(55.862009, -3.873135)
Ayr, Ayrshire (55.461264, -4.630632) Sample Date: 19/08/2018 Sample Time: 11:33	23 (9 unique)	89.5		BBC R2	Darvel	(55.579440, -4.291934)
		89.9		BBC R2	Black Hill	(55.862009, -3.873135)
		90.5	bad	BBC R3	Millburn Muir	(55.98127, -4.601023)
		91.7		BBC R3	Darvel	(55.579440, -4.291934)
		92.1		BBC R3	Black Hill	(55.862009, -3.873135)
		92.7	bad	BBC RScot	Millburn Muir	(55.98127, -4.601023)
		93.5	bad	BBC RScot	Ashkirk	(55.509899, -2.840668)
		93.9		BBC RScot	Darvel	(55.579440, -4.291934)
		94.3		BBC RScot	Black Hill	(55.862009, -3.873135)
		94.9	bad	BBC R4	Lethanhill	(55.363027, -4.465627)
		95.8		BBC R4	Black Hill	(55.862009, -3.873135)
		96.7		West FM	Darvel	(55.579440, -4.291934)
		97.9	bad	BBC R1	Millburn Muir	(55.98127, -4.601023)
		98.1	bad	BBC R1	Rothesay	(55.878187, -4.998879)
		98.7	bad	BBC R1	Ashkirk	(55.509899, -2.840668)
		99.1		BBC R1	Darvel	(55.579440, -4.291934)
		99.5		BBC R1	Black Hill	(55.862009, -3.873135)
		101.3		Classic FM	Darvel	(55.579440, -4.291934)
		101.7		Classic FM	Black Hill	(55.862009, -3.873135)
		104.0		BBC RGaelic	Rothesay	(55.878187, -4.998879)

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
		104.3		BBC R4	Darvel	(55.579440, -4.291934)
		104.7	bad	BBC RGaelic	Black Hill	(55.862009, -3.873135)
		107.2	bad	Awaz	Glasgow-Darnley Street	(55.842217, -4.270683)
Alexandria, Dunbartonshire (56.002065, -4.589235) Sample Date: 22/07/2018 Sample Time: 22:38	20 (10 unique)	88.3		BBC R2	Millburn Muir	(55.98127, -4.601023)
		88.9		BBC R2	Black Hill	(55.862009, -3.873135)
		90.5		BBC R3	Millburn Muir	(55.98127, -4.601023)
		90.9	bad	BBC R3	Ben Gullipen	(56.211723, -4.261851)
		91.6	bad	BBC R3	Durris	(56.998945, -2.390059)
		92.1	bad	BBC R3	Black Hill	(55.862009, -3.873135)
		92.7	bad	BBC RScot	Millburn Muir	(55.98127, -4.601023)
		94.3	bad	BBC RScot	Black Hill	(55.862009, -3.873135)
		95.9	bad	BBC R4	Durris	(56.998945, -2.390059)
		97.0		Clyde 1	Millburn Muir	(55.98127, -4.601023)
		97.9		BBC R1	Millburn Muir	(55.98127, -4.601023)
		98.3	bad	BBC R1	Ben Gullipen	(56.211723, -4.261851)
		99.1	bad	BBC R1	Darvel	(55.579440, -4.291934)
		99.5	bad	BBC R1	Black Hill	(55.862009, -3.873135)
		100.0		Heart Scot	Millburn Muir	(55.98127, -4.601023)
		101.7	bad	Classic FM	Black Hill	(55.862009, -3.873135)
		103.0		YOUR Radio	Dumbarton	(55.944013, -4.577704)
		104.1		BBC R4	Millburn Muir	(55.98127, -4.601023)
		105.5	bad	unknown...	could not be identified...	

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
		107.7	bad	Argyll FM	South Knapdale	(55.916906, -5.462630)
Penicuik, Midlothian (55.837350, -3.224719) Sample Date: 11/08/2018 Sample Time: 16:20	15 (12 unique)	88.6		BBC R2	Penicuik	(55.817836, -3.195177)
		90.8		BBC R3	Penicuik	(55.817836, -3.195177)
		93.0		BBC RScot	Penicuik	(55.817836, -3.195177)
		94.3	bad	BBC RScot	Black Hill	(55.862009, -3.873135)
		95.5		BBC R4	Penicuik	(55.817836, -3.195177)
		97.3		Forth 1	Craigkelly	(56.070826, -3.233516)
		98.2		BBC R1	Penicuik	(55.817836, -3.195177)
		101.1	bad	Heart Scot	Craigkelly	(56.070826, -3.233516)
		102.2		Forth 1	Penicuik	(55.817836, -3.195177)
		103.3		Heart Scot	Penicuik	(55.817836, -3.195177)
		104.4		BBC R4	Penicuik	(55.817836, -3.195177)
		105.7	bad	Capital Scot	Craigkelly	(56.070826, -3.233516)
		107.4		Crystal FM	Penicuik Cricket Club	(55.828379, -3.219445)
		107.6	bad	East Coast FM	Garleton Hills	(55.973892, -2.781813)
		107.8	bad	Black Diamond	Newtongrange	(55.862372, -3.039977)
Haddington, E Lothian (55.955352, -2.782968) Sample Date: 11/08/2018 Sample Time: 13:12	19 (12 unique)	89.9		BBC R2	Black Hill	(55.862009, -3.873135)
		91.3	bad	BBC R3	Ashkirk	(55.509899, -2.840668)
		92.1	bad	BBC R3	Black Hill	(55.862009, -3.873135)
		93.5	bad	BBC RScot	Ashkirk	(55.509899, -2.840668)
		94.3		BBC RScot	Black Hill	(55.862009, -3.873135)
		95.8		BBC R4	Black Hill	(55.862009, -3.873135)

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
		96.8		Radio Borders	Selkirk	(55.555135, -2.794081)
		97.3	bad	Forth 1	Craigkelly	(56.070826, -3.233516)
		98.7	bad	BBC R1	Ashkirk	(55.509899, -2.840668)
		99.5		BBC R1	Black Hill	(55.862009, -3.873135)
		100.3	bad	Heart Scot	Black Hill	(55.862009, -3.873135)
		101.1	bad	Heart Scot	Craigkelly	(56.070826, -3.233516)
		101.7		Classic FM	Black Hill	(55.862009, -3.873135)
		102.2	bad	Forth 1	Penicuik	(55.817836, -3.195177)
		103.3	bad	Heart Scot	Penicuik	(55.817836, -3.195177)
		103.9	bad	BBC R4	Ashkirk	(55.509899, -2.840668)
		104.1	bad	BBC RGaelic	Craigkelly	(56.070826, -3.233516)
		105.7	bad	Capital Scot	Craigkelly	(56.070826, -3.233516)
		107.6		East Coast FM	Garleton Hills	(55.973892, -2.781813)
Dunblane, Stirlingshire (56.186605, -3.967505) Sample Date: 22/07/2018 Sample Time: 19:32	18 (12 unique)	88.7		BBC R2	Ben Gullipen	(56.211723, -4.261851)
		89.9		BBC R2	Black Hill	(55.862009, -3.873135)
		90.9		BBC R3	Ben Gullipen	(56.211723, -4.261851)
		92.1		BBC R3	Black Hill	(55.862009, -3.873135)
		93.1		BBC RScot	Ben Gullipen	(56.211723, -4.261851)
		94.3		BBC RScot	Black Hill	(55.862009, -3.873135)
		95.8		BBC R4	Black Hill	(55.862009, -3.873135)
		98.3	bad	BBC R1	Ben Gullipen	(56.211723, -4.261851)
		99.5		BBC R1	Black Hill	(55.862009, -3.873135)

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
		100.3		Heart Scot	Black Hill	(55.862009, -3.873135)
		101.7		Classic FM	Black Hill	(55.862009, -3.873135)
		102.5		Clyde 1	Black Hill	(55.862009, -3.873135)
		103.1		Central FM	Earls Hill	(56.070566, -4.060787)
		104.7		BBC RGaelic	Black Hill	(55.862009, -3.873135)
		104.9		BBC R4	Ben Gullipen	(56.211723, -4.261851)
		105.2		Smooth Scot	Black Hill	(55.862009, -3.873135)
		106.1		Capital Scot	Black Hill	(55.862009, -3.873135)
		106.8		Original 106	Durris	(56.998945, -2.390059)
Peebles, E Lothian (55.651366, -3.189633) Sample Date: 11/08/2018 Sample Time: 15:30	14 (8 unique)	88.4		BBC R2	Peebles	(55.661168, -3.228544)
		89.1	bad	BBC R2	Ashkirk	(55.509899, -2.840668)
		90.6		BBC R3	Peebles	(55.661168, -3.228544)
		92.8		BBC RScot	Peebles	(55.661168, -3.228544)
		93.5	bad	BBC RScot	Ashkirk	(55.509899, -2.840668)
		94.3	bad	BBC RScot	Black Hill	(55.862009, -3.873135)
		95.0		BBC R4	Peebles	(55.661168, -3.228544)
		95.8	bad	BBC R4	Black Hill	(55.862009, -3.873135)
		96.8	bad	Radio Borders	Selkirk	(55.555135, -2.794081)
		98.0		BBC R1	Peebles	(55.661168, -3.228544)
		99.1	bad	BBC R1	Innerleithen	(55.619497, -3.073230)
		100.9	bad	Classic FM	Selkirk	(55.555135, -2.794081)
		101.7		Classic FM	Black Hill	(55.862009, -3.873135)

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
		103.1		Central FM	Earls Hill	(56.070566, -4.060787)
Callander, Stirlingshire (56.24347, -4.215989) Sample Date: 22/07/2018 Sample Time: 21:28	20 (12 unique)	88.7		BBC R2	Ben Gullipen	(56.211723, -4.261851)
		88.9		BBC R2	Oban	(56.403511, -5.485661)
		89.9		BBC R2	Black Hill	(55.862009, -3.873135)
		90.9		BBC R3	Ben Gullipen	(56.211723, -4.261851)
		91.1		BBC R3	Oban	(56.403511, -5.485661)
		92.1		BBC R3	Black Hill	(55.862009, -3.873135)
		93.1		BBC RScot	Ben Gullipen	(56.211723, -4.261851)
		94.3		BBC RScot	Black Hill	(55.862009, -3.873135)
		95.8		BBC R4	Black Hill	(55.862009, -3.873135)
		97.3		Forth 1	Craigkelly	(56.070826, -3.233516)
		98.3		BBC R1	Ben Gullipen	(56.211723, -4.261851)
		98.5		BBC R1	Oban	(56.403511, -5.485661)
		99.5		BBC R1	Black Hill	(55.862009, -3.873135)
		101.7		Classic FM	Black Hill	(55.862009, -3.873135)
		102.5		Clyde 1	Black Hill	(55.862009, -3.873135)
		103.1		Central FM	Earls Hill	(56.070566, -4.060787)
		104.6		unknown...	could not be identified...	
		104.9		BBC R4	Ben Gullipen	(56.211723, -4.261851)
		106.8		Original 106	Durris	(56.998945, -2.390059)
		107.3		unknown...	could not be identified...	

Location, Date & Time (latitude, longitude)	Number of FM stations received	Station Frequency	Perceived Quality	Station Callsign	Transmitter Name (Ofcom)	Transmitter Location (latitude, longitude)
Aberfolye, Stirlingshire (56.178748, -4.383894) Sample Date: 22/07/2018 Sample Time: 22:03	16 (10 unique)	88.7	bad	BBC R2	Ben Gullipen	(56.211723, -4.261851)
		89.9		BBC R2	Black Hill	(55.862009, -3.873135)
		90.9	bad	BBC R3	Ben Gullipen	(56.211723, -4.261851)
		91.7	bad	BBC R3	Darvel	(55.579440, -4.291934)
		92.1		BBC R3	Black Hill	(55.862009, -3.873135)
		93.1		BBC RScot	Ben Gullipen	(56.211723, -4.261851)
		94.3		BBC RScot	Black Hill	(55.862009, -3.873135)
		95.8		BBC R4	Black Hill	(55.862009, -3.873135)
		97.3		Forth 1	Craigkelly	(56.070826, -3.233516)
		98.3		BBC R1	Ben Gullipen	(56.211723, -4.261851)
		99.5		BBC R1	Black Hill	(55.862009, -3.873135)
		100.3		Heart Scot	Black Hill	(55.862009, -3.873135)
		101.7		Classic FM	Black Hill	(55.862009, -3.873135)
		102.5		Clyde 1	Black Hill	(55.862009, -3.873135)
		103.1	bad	Central FM	Earls Hill	(56.070560, -4.060787)
		104.9	bad	BBC4	Ben Gullipen	(56.211723, -4.261851)

Published Works

Below is a list of publications (and their abstracts, if applicable) resulting from work carried out during these studies. Publications [A]-[D] are focused specifically on this research, while the others can be grouped as publications on SDR. [I]-[K] are the result of research collaboration with the University of Huddersfield, where colleagues were working on Partial Discharge detection.

[A] K. W. Barlee *et al.*, "Rapid Prototyping and Validation of FS-FBMC Dynamic Spectrum Radio with Simulink and ZynqSDR" (journal), in IEEE Open Journal of the Comms. Soc. (OJ-COMS), Nov 2020.
Available: https://doi.org/10.1109/OJCOMS.2020.3039928

> *This paper presents the research carried out in developing and targeting a novel real-time Dynamic Spectrum Access (DSA) Frequency Spread Filter Bank Multicarrier (FS-FBMC) transmitter prototype to programmable 'ZynqSDR' Software Defined Radio (SDR) hardware, and introduces a series of experiments used to validate the design's 'cognitive' DSA capabilities. This transmitter is a proof of concept, that uses DSA techniques to enable Secondary Users (SUs) to access the band traditionally used for FM Radio broadcasting (88-108\,MHz), and establish data communication channels in vacant parts of the FM Radio Primary User (PU) spectrum using a multicarrier modulation scheme with a Non Contiguous (NC) channel mask. Once implemented on the hardware, the transmitter is subjected to various FM Radio environments sampled from around Central Scotland, and it is demonstrated that it can dynamically adapt its NC transmitter mask in real time to protect the FM Radio signals it detects. A video is presented of this dynamic on-hardware spectral reconfiguration, and the reader is encouraged to view the video to appreciate the responsiveness of the design. An investigation into potential FBMC guardband sizes is carried out, with initial findings indicating a guardband of 200\,kHz (either side of an FM Radio station) is required in order to prevent interference with the PUs. This paper also demonstrates the capabilities of the MATLAB®/ Simulink ZynqSDR workflow, and provides a case study and reference design that we feel other researchers working in this field can benefit from.*

[B] K. W. Barlee, R. W. Stewart and L. H. Crockett, "Secondary User Access for IoT Applications in the FM Radio Band using FS-FBMC" (conference paper + presentation), in IEEE 5G World Forum (5GWF), Silicon Valley, CA, USA, Jul 2018.
Available: https://doi.org/10.1109/5GWF.2018.8517058
Available: https://www.slideshare.net/slideshow/embed_code/key/HFNDdTPleQcXeW

> *In this paper a Dynamic Spectrum Access (DSA) Physical layer (PHY) technique is proposed that allows Secondary User (SU) access to the traditional FM Radio spectrum (88-108 MHz) for alternative data communication applications. FM radio waves have excellent propagation characteristics for long distance transmission, and have high levels of penetration through buildings. Using tools such as a structured geolocation database of licensed Primary User (PU)*

FM Radio transmitters, unlicensed SUs can access portions of the 20 MHz-wide band and transmit signals that place spectral 'holes' with suitable guard bands around all known PUs. Based on the PU protection ratios published by Ofcom and the FCC, the operation of a FBMC (Filter Bank Multi-Carrier) transmitter is demonstrated for an urban environment, and through 'field test' simulation it is shown that the Out Of Band (OOB) leakage of the proposed PHY (energy in the 'holes' that can interfere with the PU) is 47 dB lower than that of using an equivalent OFDM PHY. The results show that the proposed PHY is a suitable candidate for DSA-SU communication (e.g. in smart city IoT applications), whilst ensuring the integrity of incumbent PU signals.

[C] K. W. Barlee, R. W. Stewart and L. H. Crockett, "Dynamic Spectrum Access: Secondary User coexistence in the FM band" (poster), Presented at New England Workshop on Software Defined Radio, Worcester, USA, May 2018.
Available: https://pureportal.strath.ac.uk/en/publications/dynamic-spectrum-access-secondary-user-coexistence-in-the-fm-band

[D] K. W. Barlee, "Glad to be Grey: The Power of Shared Spectrum" (magazine), in UK Government Department for Digital, Culture, Media and Sport (DCMS) 5G Innovation Briefing, no. 3, pp. 53-56, Jun 2020.
Available: https://flickread.com/edition/html/5f15a4240e557#53

The colours of the spectrum are white, black and grey. That might not sound very dynamic, but Kenny Barlee from the University of Strathclyde shines a light on how, by making nice with the organisations that have the right to use frequencies nationally, small companies can play in the spaces that have been left in the dark.

[E] Joshua Goldsmith *et al.*, "Control and Visualisation of a Software Defined Radio System on the Xilinx RFSoC Platform Using the PYNQ Framework" (journal), in IEEE Access, vol 8, pp. 129012-129031, Jul 2020.
Available: https://doi.org/10.1109/ACCESS.2020.3008954

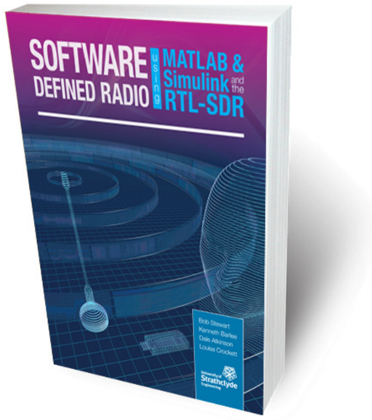
The availability of commercial Radio Frequency System on Chip (RFSoC) devices brings new possibilities for implementing Software Defined Radio (SDR) systems. Such systems are of increasing interest given the pace of innovation in wireless technology, and the pressure on RF spectrum resources, leading to a growing need to access the spectrum in more dynamic and innovative ways. In this paper, we present an SDR demonstration system based on the Xilinx RFSoC platform, which leverages the Python- based 'PYNQ' (Python Productivity for Zynq) software framework. In doing so, we highlight features that can be extremely useful for prototyping radio system design. Notably, our developed system features Python-based control of hardware processing blocks and Radio Frequency (RF) data converters, as well as direct visualisation of communications signals captured within the chip. The system architecture is reviewed, hardware and software components are discussed, functionality is demonstrated, and aspects of the system's performance are evaluated. Finally, it is noted that this combined RFSoC + PYNQ approach is readily extensible for other SDR systems; we highlight our online shared resources, and invite other engineers to investigate and build upon our work.

[F] R. W. Stewart *et al.*, "A low-cost desktop software defined radio design environment using MATLAB, Simulink, and the RTL-SDR" (journal), in IEEE Comms. Mag., vol. 53 no. 9, pp. 64-71, Sep 2015.
Available: https://doi.org/10.1109/MCOM.2015.7263347

In the last five years, the availability of powerful DSP and communications design software, and the emergence of relatively affordable devices that receive and digitize RF signals, has brought SDR to the desktops of many communications engineers. However, the more recent availability of very low cost SDR devices such as the RTL-SDR, costing less than $20, has brought SDR to the home desktops of undergraduate and graduate students, as well as professional engineers and the *maker communities. Since the release of the various open source drivers for the RTL-SDR, many in the digital communications community have used this device to scan the RF spectrum and digitize I/Q signals that are being transmitted in the range 25 MHz to 1.75 GHz. This wide operating range enables the sampling of frequency bands containing signals such as FM radio, ISM signals, GSM, 3G and LTE mobile radio, GPS, and so on. In this article we will describe the opportunity and operation of the RTL-SDR, and the development of a handson, open-courseware for SDR. These educational materials can be integrated into core curriculum undergraduate and graduate courses, and will greatly enhance the teaching of DSP and communications theory, principles, and applications. The lab and teaching materials have recently been used in senior (fourth year undergraduate) courses and are available as open course materials for all to access, use, and evolve.*

[G] R. Stewart, K. Barlee, D. Atkinson, L. Crockett, "Software Defined Radio using MATLAB & Simulink and the RTL-SDR" (textbook), Strathclyde Academic Media, Sep 2015.
Available: www.desktopSDR.com/download

The availability of the RTL-SDR for less than $20 brings SDR to the home and work desktops of EE students, professional engineers and the maker community. The RTL-SDR device can be used to acquire and sample RF (radio frequency) signals transmitted in the frequency range 25MHz to 1.75GHz, and using some official software add-ons, these samples can be brought into the MATLAB and Simulink environment for users to develop receivers using first principles DSP algorithms. Signals that the RTL-SDR hardware can receive include: FM radio, UHF band signals, ISM signals, GSM, 3G and LTE mobile radio, GPS and satellite signals, and any that the reader can (legally) transmit of course!



In this free book we introduce readers to SDR methods by viewing and analysing downconverted RF signals in the time and frequency domains, and then provide extensive DSP enabled SDR design exercises which the reader can learn from. The hands-on examples begin with simple AM and FM receivers, and move on to the more challenging aspects of PHY layer DSP, where receive filter chains, real-time channelisers, and advanced concepts such as carrier synchronisers, digital PLL designs and QPSK timing and phase synchronisers are implemented. Towards the end of the book, we demonstrate how the RTL-SDR can be used with SDR transmitters to develop a more complete communications system, capable of transmitting text strings and images across the desktop.

Strathclyde Academic Media, September 2015, ISBN 978-0-9929787-2-3

[H] K. W. Barlee, R. W. Stewart and L. H. Crockett, "The teaching and learning of DSP enabled Software Defined Radio using MATLAB & Simulink and the RTL-SDR" (poster), Presented at 8th New England Workshop on Software Defined Radio, Worcester, USA, May 2015.
Available: https://pureportal.strath.ac.uk/en/publications/the-teaching-and-learning-of-dsp-enabled-software-defined-radio-u

[I] H. Mohamed *et al.*, "Partial discharge detection using low cost RTL-SDR model for wideband spectrum sensing" (conference paper), ICT'16, Thessaloniki, pp. 1-5, May 2016.
Available: https://doi.org/10.1109/ICT.2016.7500353

Partial discharge (PD) is one of the predominant factors to be controlled to ensure reliability and undisrupted functions of power generators, motors, Gas Insulated Switchgear (GIS) and grid connected power distribution equipment, especially in the future smart grid. The emergence of

> *wireless technology has provided numerous opportunities to optimise remote monitoring and control facilities that can play a significant role in ensuring swift control and restoration of HV plant equipment. In order to monitor PD, several approaches have been employed, however, the existing schemes do not provide an optimal approach for PD signal analysis, and are very costly. In this paper an RTL-SDR (Software Defined Radio) based spectrum analyser has been proposed in order to provide a potentially low cost solution for PD detection and monitoring. Initially, a portable spectrum analyser has been used for PD detection that was later replaced by an RTL-SDR device. The proposed schemes exhibit promising results for spectral detection within the VHF and UHF band.*

[J] H. Mohamed *et al.*, "Partial discharge detection using software defined radio" (conference paper), ICSAE'16, Newcastle upon Tyne, UK, pp. 373-376, Oct 2016.
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> *Partial discharge (PD) is an electrical discharge that occurs within part of the dielectric separating two HV (High Voltage) conductors. PD causes damage to the dielectric which typically deteriorates with time. If left untreated, PD may result in catastrophic insulation failure, destruction of HV equipment, and disruption of power supply. The emergence of wireless network technology and software defined radio has opened new opportunities in PD monitoring and early detection of failures. This paper proposes the use of Universal Software Radio Peripheral (USRP) technology for PD detection.*

[K] H. Mohamed *et al.*, "Partial discharge localization based on received signal strength" (conference paper), in ICAC'17, Huddersfield, UK, pp. 1-4, Sep 2017.
Available: https://doi.org/10.23919/IConAC.2017.8082028

> *Partial Discharge (PD) occurs when insulation containing defects or voids is subject to high voltages. If left untreated PD can degrade insulation until, eventually, catastrophic insulation failure occurs. The detection of PD current pulses, however, can allow incipient insulation faults to be identified, located and repaired prior to plant failure. Wireless technology has paved the path for PD detection and monitoring. Software Defined Radio (SDR) is a promising technology. Signals from two PD sources are received at six outdoors locations using an SDR USRP N200 which is connected to a laptop. PD sources, thereafter, are localized based on received signal strengths.*

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