Enabling Private Network Deployments Through Software Defined Radio and Shared Spectrum

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Abstract

Implementation of shared spectrum mechanisms can significantly reduce the cost of deploying wireless networks, while also increasing the overall spectrum utilisation and efficiency.

This thesis presents multiple research contributions focusing on the development of dynamic spectrum access mechanisms with Software Defined Radio (SDR) technology in support of enabling private mobile network deployments in challenging operating environments. TV White Space (TVWS) and the Citizens Broadband Radio Service (CBRS) frameworks are targeted for this work, as they have precedent for use in commercial networks. Initial research focused on the challenges of rural networks, as the business case for such deployments is often more challenging than their urban equivalents.

As part of an Orkney TVWS pilot project, connecting several ferries and fixed premises, software tools were developed to aid network design. This provided an interface to shared spectrum access systems to enable parameter gathering, validating hardware operations, and automating data collection.

Work completed as part of the 5G RuralFirst project investigated how existing hardware ecosystems could be used with spectrum access mechanisms to create economical network deployments. A 3GPP-compliant LTE SDR basestation was integrated with regulatory compliant TVWS and CBRS spectrum access frameworks to provide proof-of-concept demonstrations. Both solutions followed their respective inter-device communication specifications and associated operating workflows.

Other areas typically challenging for providing mobile connectivity are underground rail environments. This thesis presents research contributions, completed as part of the 5G RailNext project, deploying one of the first 5G Stand Alone (SA) networks in the UK. This development work involved configuring, integrating, and lab-testing multiple independent network elements to create a fully 5G-compliant end-to-end solution.

This culminated in on-location field deployment, tests, and a live trial in the Glasgow subway, where the network delivered content for passengers on a moving subway carriage. The research contributions and knowledge gained as a result of this work represent a significant development milestone in the operating capabilities of private mobile network deployments and directly enabled a number of world-first installations for the media and television production use case. It also demonstrated that private mobile networks can be deployed and administered by independent providers without a large Mobile Network Operator (MNO) partner.

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I told you all it would get finished eventually...

Contents

List of Tables

List of Figures

List of Publications

D. Anderson, S. Koratagere Anantha Kumar, D.Crawford, and R. Stewart, “Evolving spectrum sharing methods and standards: TVWS, CBRS, MulteFire and more”, *Spectrum Sharing: The Next Frontier in Wireless Networks*, 2019.

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Abbreviations

3GPP 3rd Generation Partnership Project.

5G NR 5G New Radio.

5G-MAG 5G Media Action Group.

5GIC 5G Innovation Centre.

5GNT 5G New Thinking.

5GPC 5G Packet Core.

5GRF 5G RuralFirst.

5GRN 5G RailNext.

ACLR Adjacent Channel Leakage Ratio.

ADC Analogue-to-Digtial Converter, Analogue-to-Digital Conversion.

AFC Automated Frequency Coordination.

AFH Advanced Frequency Hopping.

AI Artificial Intelligence.

AMF Access and Mobility Management Function.

AP Access Point.

API Application Programming Interface.

APT Asia-Pacific Telecommunity.

ARPU Average Revenue Per User.

ASA Authorised Shared Access.

AUSF Authentication Server Function.

AW2S Advanced Wireless Solutions and Services.

AWS Amazon Web Services.

BAS Broadcast Auxiliary Service.

BBU Baseband Unit.

BDUK Broadband Delivery UK.

BPSK Binrary Phase Shift Keying.

BSS Basic Service Set.

BTS Base Transceiver Station.

C-RAN Cloud-RAN, Centralised-RAN.

CAPEX Capital Expenditure.

CBRS Citizen's Broadband Radio Service.

CBSD CBRS Device.

CCA Combinatorial Clock Auction.

CEPT European Conference of Postal and Telecommunications.

CLI Command Line Interface.

COTS Commercial-off-the-Shelf.

CP Control Plane.

CP-OFDM OFDM Cyclic Prefix.

CPE Customer Premise Equipment.

CPRI Common Public Radio Interface.

CRS Cell Specific Reference Signal.

CSMA Carrier Senese Multiple Access.

CSMA/CA Carrier Senese Multiple Access / Collision Avoidance.

CSV Comma Separated Values.

CU Centralised Unit.

CUPS Control and User Plane Separation.

CWSC Centre for White Space Communications.

DAC Digital-to-Analogue Converter, Digtial-to-Analogue Conversion.

DAS Distributed Antenna System.

DCMS Department for Digital, Culture, Media, and Sport.

DDR Digitial Dividend Review.

DFH Dynamic Frequency Hopping.

DFS Dynamic Frequency Selection.

DFT-s-OFDM Discrete Fourier Transform-spread-OFDM.

DL_EARFCN Downlink E-UTRA Absolute Frequency Channel Number.

DP Domain Proxy.

DRMS Demodulation Reference Signal.

DSA Dynamic Spectrum Access, Dynamic Spectrum Allocation.

DSIT Department for Science, Innovation, and Technology.

DSO Digital TV Switchover.

DSP Digital Signal Processing, Digital Signal Processor.

DSS Dynamic Shared Spectrum.

DTT Digital Terrestrial Television, Digital Television Transmitter.

DU Distributed Unit.

DYSPAN-SC Dynamic Spectrum Access Network Standards Committee.

E2E End-to-end.

EBU European Broadcasting Union.

ECC Electronic Communication Committee.

ECMA European Computer Manufacturers Association.

eCPRI Enhanced CPRI.

EE Everything Everywhere.

EIRP Equivalent Isotropically Radiated Power.

eMBB Enhanced Mobile Broadband.

eNB Evolved NodeB.

ePC Evolved Packet Core.

ESC Environmental Sensing Capability.

eSIM Electronic SIM.

ESN Emergency Services Network.

ETSI European Telecommunications Standards Institute.

EUTRAN Evolved Universal Terrestrial Radio Access Network.

FCC Federal Communication Commission.

FDD Frequency Division Duplexing.

FH Fronthaul.

FPGA Field-Programmable Gate Arrary.

FWA Fixed Wireless Access.

FWS Fixed Wireless System.

GAA General Authorised Access.

GEO Geostationary Orbit.

gNB next Generation NodeB.

GPRS General Packet Radio Service.

GSM Global System for Mobile Communications.

GUI Graphical User Interface.

HLS Higher Layer Split.

HSS Home Subscriber Server.

IBC International Broadcasting Convention.

ICMP Internet Control Message Protocol.

IEEE Institute of Electronic and Electrical Engineers.

IETF Internet Engineering Task Force.

IMSI International Mobile Subscriber Identity.

IMT International Mobile Telecommunications.

IoT Internet of Things.

IP Internet Protocol.

IPF International Production Feed.

ISM Industrial Scientific and Medical.

ISP Internet Service Provider.

ITU International Telecommunication Union.

JOTS Joint Operator Technical Specification.

JSON JavaScript Object Notation.

LAA Licence Assisted Access.

LAL Local Access Licence.

LAN Local Area Network.

LEO Low Earth Orbit.

LLS Lower Layer Split.

LoS Line of Sight.

LSA Licence Shared Access.

LTE Long Term Evolution.

LTE-A LTE Advanced.

LTE-M LTE-M2M.

LTE-U LTE Unlincenced.

M2M Machine to Machine.

MAC Media Access Control.

MAN Metropolitan Area Network.

MBSFN Multimedia Broadcast Single Frequency Network.

MCS Modulation and Coding Scheme.

MEC Mobile Edge Compute.

MH Midhaul.

MIMO Multiple Input Multiple Output.

MME Mobility Management Entity.

MMTC Massive Machine-Type Communication.

MNO Mobile Network Operator.

MOCN Multi-Operator Core Network.

MORAN Multi-Operator Radio Access Network.

MSM Mobile Station Modem.

NaaS Network as a Service.

NB-IoT Narrowband IoT.

NHIB Neutral Host In-Building.

NHOD Neutral Host Out-Door.

NICT National Institute of Information and Communications Technology.

NPN Non-Public Network.

NSA Non-Standalone.

NTIA National Telecommunications and Information Administration.

NTN Non-Terrestrial Networks.

O-RAN Open-RAN.

OAM Operation, Administration, and Maintenance.

OEM Original Equipment Manufacturer.

Ofcom Office of Communications.

OFDM Orthogonal Frequency Division Multiple.

OFDMA Orthogonal Frequency Division Multiple Access.

OPEX Operating Expenditure.

OSI Open Systems Interconnection.

P-GW Packet Gateway.

P2MP Point-to-Multi-Point.

P2P Point-to-Point.

PA Priority Access.

PAL Priority Access Licence.

PAN Personal Area Network.

PAWS Protocol to Access White Space.

PCF Policy Control Function.

PCRF Policy and Charging Rules Function.

PDCP Packet Data Convergence Protocol.

PHY Physical.

PLMN Public Land Mobile Network.

PMSE Programme Making and Special Events.

POE Power Over Ethernet.

PPA PAL Protection Area.

PPDR Public Protection Disaster Relief.

PSD Power Spectral Density.

QAM Quadrature Amplitude Modulation.

QMI Qualcomm MSM Interface.

QoS Quality of Service.

QPSK Quadrature Phase Shift Keying.

RAN Radio Access Network.

RAT Radio Access Technology.

RLC Radio Link Control.

RRC Radio Resource Control.

RRH Remote Radio Head.

RRM Radio Resource Management.

RRU Remote Radio Unit.

RSRP Reference Signal Received Power.

RSSI Received Signal Strength Indicator.

RU Radio Unit.

S-GW Serving Gateway.

SA Standalone.

SAL Shared Access Licence.

SAP Service Access Point.

SAS Spectrum Access System.

SC-FDMA Single Carrier Frequency Division Multiple Access.

SCH Superframe Control Header.

SCTP Stream Control Transmission Protocol.

SDL Supplementary Downlink.

SDR Software Defined Radio.

SFT Scottish Futures Trust.

SIB System Information Block.

SME Small-and-Medium Enterprise.

SMF Session Management Function.

SMS Short Message.

SNR Signal to Noise Ratio.

SRN Shared Rural Network.

SSB Synchronisation Signal Block.

SSP Statement of Strategic Priorities.

STA Station.

TCP Transmission Control Protocol.

TDD Time Division Duplexing.

TDF Traffic Detection Function.

TVHT Television Very Hight Throughput.

TVWS TV White Space.

UDP User Datagram Protocol.

UE User Equipment.

UHF Ultra High Frequency.

UKPM UK Prediction Model.

UKRI UK Research and Innovation.

UMTS Universal Mobile Telecommunications Service.

UoS University of Strathclyde.

UP User Plane.

UPF User Plane Function.

URI Uniform Resource Identifier.

URLLC Ultra-Reliable Low-Latency Communication.

USO Universal Service Obligation.

VM Virtual Machine.

VOIP Voice Over IP.

VoLTE Voice-over-LTE.

VPN Virtual Private Network.

vRAN Virtualised RAN.

VSAT Very Small Aperture Terminal.

WISP Wireless ISP.

WLAN Wireless Local Area Network.

WMAN Wireless Metropolitan Area Network.

WRAN Wireless Regional Area Network.

WRC World Radiocommunication Conference.

WSD White Space Device.

WSDB White Space Database.

XML Extensible Markup Language.

XSD XML Schema.

Chapter 1

Introduction

There are a number of ways to enable connectivity and access to the Internet, with both wired and wireless technologies able to contribute to end-to-end communications networks. One of the fundamental resources required for the deployment of wireless networks, regardless of intended application, is radio spectrum for the transmissions to occur. The exact spectral requirements will differ depending on the desired wireless network implementation [1].

As radio spectrum is a finite resource, it is important for Governments and their regulators to properly, and effectively, coordinate spectrum utilisation in order to maximise deployment efficiency, enable innovations and new technologies, and protect the frequencies used by critical services from interference.

Regulators should be consistently aware of the spectral requirements of new and existing technologies or applications in order to implement appropriate spectrum planning and authorisation mechanisms. For example, as the key components of 6G become more apparent, there may be further demands on the allocation of spectrum for mobile broadband networks. A critical aspect of ensuring efficient spectrum planning is monitoring the frequency utilisation of current deployments and applications in order to identify potential areas of improvement.

The roll-out and development of 5G, and subsequently 6G, presents an opportunity to consider new methods for accessing spectrum, supplementing traditional exclusive-operation licence mechanisms to increase the availability of spectral resources to new users and for new applications. This increased access to spectrum will provide more opportunities for people, businesses and other organisations to set up and run their own private wireless networks and enable innovative connectivity solutions to address real-world problems.

One viable solution, which has already seen significant development at both a technical and regulatory policy level, is the use of shared spectrum methods to improve efficiency of spectral utilisation.

This thesis presents research contributions focused on the development and implementation of automated shared spectrum access technologies, in combination with Software Defined Radio (SDR) platforms, to create private wireless network deployments in challenging operating environments.

1.1 Research Background

1.1.1 Introduction to Shared Spectrum

In the UK it is illegal for anyone, apart from the Crown, to operate radio equipment without the authority of a granted licence from Ofcom, unless the deployment is considered exempt based on conformance with further regulations [2].

Licence-exempt frequency bands, as the name suggests, are those that can be used by devices without this prior formal authorisation. However, this does not mean that operation is unregulated [3]. Devices using these bands must still conform with pre-defined technical rules and performance criteria to maximise coexistence and minimise interference [2].

Most licence-exempt frequency bands are internationally harmonised, to enable economy of scale for device manufacturers. One such example are the Industrial, Scientific, and Medical (ISM) frequency bands. Despite the name, the most well known applications deployed in these bands are short-range, low-power communication systems such as Wi-Fi routers, LoRaWAN sensors, and Bluetooth devices.

Licence-exempt frequency bands are also one of the most well known examples of spectrum sharing, where a common frequency range is shared among multiple devices and applications. To enable this, wireless technologies use different mechanisms to manage coexistence requirements and interference. For example, Bluetooth uses a system of dynamic channel selection to avoid other users called Adaptive Frequency Hopping (AFH) [4]. Similarly, Wi-Fi networks implement time separation methods, such as Carrier Sense Multiple Access / Collision Detection (CSMA) which involves random back-off periods in transmissions if interference is detected [5].

For some applications, such as mobile broadband networks, licence-exempt spectrum is not a practical deployment option, due to the risk of potential interference or channel contention, and instead a prospective network operator will need to apply for a licence to ensure they have the exclusive, legal, spectrum access to provide sufficient quality of service (QoS) to customers. This could be for a small area, for a single deployment site, or possibly span the entire country. For commercial mobile networks, the latter of these scenarios has traditionally been the most applicable.

Acquisition of a spectrum licence gives the holder exclusive use of the specified frequency band, across the defined operating area. However, as highlighted further in Chapter 2, those network operators who have national spectrum licences typically do not make use of all frequency bands at every location in the country, even when permitted to do so.

To optimise spectrum utilisation, and maximise the achievable coverage area for connectivity services, operating frequencies can be shared among other potential spectrum users in a manner that prevents additional harmful interference. Ideally, an implemented sharing scheme should maintain the rights of the licence holder to deploy their services where and when they want, within the licence criteria, without additional complexity or effort required on their part.

One of the simplest mechanisms for mitigating interference in shared spectrum implementations is through geographic spacing — ensuring that the emission coverage areas of co-channel devices do not overlap.

It is possible for different devices to co-exist in the same frequency channel and geographic area. One way to do this is to ensure there is no overlap in the time of operation. Depending on the technologies used, the timing increments could be very small or span hours and days. It could also be achieved through *spectrum underlay* approaches, where a device operates at sufficiently reduced transmit power levels so that the resulting output RF emissions occur below a level detectable by other users [6].

Shared spectrum users can also look at collaborative mechanisms, where additional communication takes place to allow for synchronisation of non-interfering operating parameters or conditions. Collaborative sharing could also extend to forms of pre-deployment agreements between parties, where a licence holder grants a partner an allocation, duration, and potentially location for access to otherwise licenced spectrum [7], [8]. This form of shared spectrum, occasionally referred to as the *Complementary Licence Model*, best describes the licenced Shared Access (LSA) or Authorised Shared Access (ASA) paradigms [8].

Other examples of pre-arranged access mechanisms are the Shared Access Licence (SAL) and Local Access Licence (LAL) processes that were introduced by Ofcom in 2019, which enabled access to a number of mobile broadband supporting frequency bands for different deployment scenarios and applications [9].

While implementations of collaborative pre-determined sharing mechanisms are important, there are a number of associated challenges. Initially, it may be feasible to administer spectrum allocations manually. However, these kind of agreements are likely to entail a very bureaucratic process, taking time and resources from the regulator or existing licence holder to review and respond to each submitted application. The process would also become more challenging as the volume of concurrent applications increased. Frequency allocations would also be purely static, as high-agility processes are practically incompatible with manual intervention mechanisms.

In 2023, Ofcom opened a call-for-input regarding the future of the SAL programme [10]. This included the prospect of expanding the applicable frequency bands, while also re-affirming a transition towards automated mechanisms for licence management and allocation under the framework.

One of the alternatives to pre-arranged sharing agreements, that addresses the outlined challenges, is to use automated mechanisms of Dynamic Spectrum Access (DSA), also referred to as Dynamic Spectrum Allocation.

1.1.2 Introduction to Dynamic Spectrum

DSA is the process of making near real-time adjustment to the operations of radio devices to enable access to spectrum that would otherwise be unused by licence holders. Typically these implement a combination of time-based and geographic spacing interference mitigation mechanisms.

DSA is different to other automated shared spectrum implementations like the Bluetooth AFH mechanisms mentioned previously, as the latter process assumes all devices have equal right to use the shared spectral resource and the aim is purely to minimise interference caused to a device's own transmissions with no responsibility to protect other users.

DSA is also different to sharing frameworks such as LSA or the SAL, due to its inherently automated nature. This means that spectrum allocations can change on a shorter term basis, or at a more granular level, than could be accommodated by pre-arranged contracts.

For a DSA system, the aim is to enable multiple additional users to access frequencies within a spectrum band that also contains other users who have exclusive operation privileges for certain channels, i.e. spectrum licence holders or *Protected* users. Under this paradigm, the aim is to enable additional *Opportunistic* users to use the spectrum without causing interference with the operations of the licence holder.

A successful implementation of spectrum sharing is achieved by appropriately managing the interference mechanisms. By combining geographic spacing and dynamic channel selection, opportunistic users can operate within a spectrum band in a physical location that does not have coverage overlap with a protected user, also referred to as an *Incumbent User*.

When a protected user becomes detected in the area, other users must ensure they do not cause any interference, even if that involves changing their operating parameters to accommodate the protected user. The process of determining the presence of protected user operations could involve the use of spectrum sensing to determine available channels, or by automated communication with a regulated, authorised device controller, or using a combination of both techniques.

Using this dynamic access method, the use of operating frequencies with a spectrum band is granted until such time that a licence holder wishes to operate within it, at which point an opportunistic user must make the resource available. As such, DSA differs from a static sharing access method, where use of spectrum may be granted for a fixed time period.

Some regulatory bodies refer to this as a "lightly-licensed" spectrum framework, with this term becoming synonymous with implementations of DSA mechanisms [11].

The work in this thesis primarily targets two DSA technologies: TV White Space (TVWS) and Citizens Broadband Radio Service (CBRS). These implementations have comparable methods for enabling shared spectrum, and are both reviewed in more detail as part of Chapter 3.

1.2 Research Motivation, Aims, and Objectives

1.2.1 Research Motivation

One of Ofcom's primary responsibilities is to maximise the benefits that people, communities, organisations, and businesses can extract from spectrum across the UK [12]. For a number of years, Ofcom has publicly highlighted the benefits of shared spectrum access as a regulatory model which enables that primary responsibility.

The endorsement is clearly reflected in a number of recently implemented policy decisions. This includes adoption of the TVWS regulations [13] and in implementation of the aforementioned SAL and LAL processes in 2019 [9].

These policy implementations from the regulator are firmly aligned with the aspirations of the UK Government. The work presented in this thesis is also strongly aligned with these policies, and future technical aims.

In the 2019 Statement of Strategic Priorities (SSP), the Department for Digital, Culture, Media, and Sport (DCMS) highlighted the need to further develop licence arrangements that facilitate spectrum sharing [14]. The statement also details the importance of *"developing frequency agile equipment with the capability of communicating with a central database"*.

In a 2023 publication, the Department of Science, Innovation, and Technology (DSIT) outlined its principles for future spectrum policy [15]. This includes ambitions for further implementation of shared spectrum, and emphasised DSIT's commitment to the introduction of DSA mechanisms.

In that period, Ofcom has also released a number of documents outlining its future policy work areas and plans. The "Spectrum Management Strategy for the 2020s" [16] and "Technology Futures" [12] consultations both extensively discuss the potential of automated management tools as shared spectrum enablers.

In 2022, Ofcom released its Spectrum Roadmap documents [17], [18] describing how they intend to deliver on the outlined management strategy. A number of work programmes are defined, with many relating to further shared spectrum and DSA implementations.

One example of this is the introduction of "spectrum sandboxes" to allow for the evaluation of different spectrum sharing scenarios in the 3.8 - 4.2 GHz range currently covered by the SAL framework. Similarly, database driven spectrum mechanisms are noted as being an area of ongoing investigation.

These recent publications from policy makers and the national regulator strongly highlight that automated tools and DSA will significantly impact future policies for UK spectrum, and that there will be a strong drive towards practical and commercial implementation of enabling shared access technologies and strategies through such mechanisms.

As Ofcom begin to explore dynamic spectrum access mechanisms again in earnest, the same technical challenges as seen in similar frameworks such as TVWS and CBRS will manifest. Therefore the research discussed and demonstrated throughout this thesis is complementary to the current publicised regulatory aspirations, with contributions made towards the development and deployment of automated tools for spectrum management.

1.2.2 Research Aims and Objectives

The primary research aim of this thesis is to prove the use of shared spectrum mechanisms in combination with technologies that are used to provide mobile broadband connectivity. The most common implementations of such networks are developed by the 3rd Generation Partnership (3GPP) — a collection of standards bodies — who define both the Long Term Evolution (LTE) and 5G New Radio (5G NR) protocols and architectures, which are targetted in this thesis. Broadband technologies are more challenging to implement in shared spectrum than narrowband, simply because it is easier to accommodate smaller carriers within the frequencies ranges defined for communal usage.

There is a particular focus on addressing the problem of providing mobile coverage in hard-to-reach areas, such as in remote locations or underground subway environments. This research is of particular significance in rural areas where the business models for 3G and 4G have resulted in less than optimum coverage. There is also an emphasis on targetting private network deployments, where infrastructure is deployed and managed by an independent company, community, or organisation rather than a commercial public network operator. The adoption and deployment of such networks is increasing across multiple industries, and is expected to continue to grow.

The primary objective of this thesis is to highlight the capabilities, limitations, and associated challenges of practical, real-world, implementations for shared private networks to enable coverage in challenging deployment areas. DSA technologies, particularly those used in existing commercial network deployments, are prioritised for this work as lessons learned will contribute to the wider UK spectrum policy.

Research will predominantly be used to enable mobile broadband in both TVWS and CBRS shared spectrum, in a regulatory compliant fashion, by improving, or supplementing, the capabilities of existing systems. Other contributions will look at enabling proof-of-concept deployments, to highlight current technical or commercial viability of shared spectrum and private networks.

Where appropriate, practical implementations will use Software Defined Radio (SDR) platforms. SDRs are flexible multi-band radios capable of supporting different air interfaces and protocols. By implementing high-resolution Digital-to-Analogue Converters (DAC) and Analogue-to-Digital Converters (ADC), often with Field Programmable Gate Array (FPGA) hardware, using SDR equipment allows for a reconfigurable, frequency flexible, network deployment [19].

1.3 Research Contributions

The main contributions of this work are considered to be:

1. Characterisation of TVWS Equipment For Rural Pilot Network Deployment

Following ratification of the UK TVWS operating regulations, the Scottish Government was interested in assessing the technology capabilities in support of their initiatives to enable connectivity. As part of this, a 2015 project to create a rural TVWS testbed in the Orkney Islands is described in Chapter 3. This shared spectrum network deployment was used to provide broadband connectivity to the passengers and crew on three ferries during voyages between islands, and also to several fixed premises.

Research contributions made in support of the development and deployment of this trial network included equipment characterisation as part of in-lab bench tests, assessment of network performance following installation.

The pilot deployment was a significant contribution to Ofcom's assessment and evaluation of the proposed TVWS spectrum access mechanism, as well as qualification of the geolocation database used in the project.

In addition, the trial contributed to research on the potential for interference from TVWS transmitters to other spectrum users. The co-existence evaluation carried out on the Orkney network equipment indicated low probability of harmful interference to higher-priority spectrum users, which became part of the body of evidence used by Ofcom to determine TVWS regulations. The equipment testing presented in this thesis was a significant part of this contribution.

This work was recognised internationally by the Dynamic Spectrum Alliance, with the *"Award for a Student-Led initiative or Research on New Opportunities for Dynamic Spectrum Access"* presented at their 2017 Global Summit in Cape Town [20].

2. Development of software tools to aid shared spectrum network design.

For any practical wireless network deployment it is best practice to develop a frequency plan for transmitting equipment. This is particularly important when operating in a shared spectrum environment to ensure a high level of coexistence between users and compliance with regulatory frameworks.

In the early practical implementations of TVWS shared spectrum networks, such as the Orkney pilot discussed previously and in Chapter 3, it was desirable to validate the dynamic selection of operating frequency by transmitting devices. Assessing the equipment capability in this way required the ability to communicate with the geolocation database to receive comparative results.

To facilitate this, a program was developed by the author to provide a human interface to the required systems, which was an otherwise missing feature that was lacking from geolocation database implementations at the time. This tool was used to retrieve valid operating parameters from live systems for spectrum planning, validation of the automated channel selection capabilities of TVWS systems, or for creating system simulations.

The software developed and presented in this thesis significantly increased the amount of data that could be extracted on the operating performance and capabilities of geolocation database systems, which was then shared with Ofcom to aid their regulatory decision making.

3. Implementation of an LTE basestation compliant with TVWS geolocation database access mechanisms.

One of the most significant barriers to the deployment of mobile broadband networks has traditionally been the cost of a spectrum licence. While this has slightly improved in the UK, with implementation of the shared spectrum regionalised licensing programmes [21], [10], there are other spectrum bands that have the potential to support network deployments while maintaining access to the significant 3GPP equipment ecosystem.

One possible example of this would be to take advantage of licence-exempt TVWS spectrum, as there would be no associated licence cost if completed in a regulatory compliant manner. Such an implementation would reduce the overall network Capital Expenditure (CAPEX), which leads to increased opportunities for new deployments.

The work presented in Chapter 4 demonstrates the integration of a Release 14 LTE-A basestation stack, with an Ofcom-approved TVWS geolocation database. This creates a 3GPP compliant eNB that satisfies the ETSI specification on system operation, and which also provides a frequency deployment that is compatible with Commercial-Off-The-Shelf (COTS) mobile devices.

To ensure the frequency agility required for a dynamic spectrum approach, the system was designed for deployment on SDR platforms. Some aspects of regulation compliance, such as the unwanted emissions level, are dependent on the hardware implemented in deployment.

This work demonstrates how aspects of a regulated DSA framework can be incorporated by existing eNB systems, while simultaneously maintaining compliance with LTE standards. It has been demonstrated that the requirements of TVWS regulation conformance, such as the spectral agility to sufficiently protect incumbent transmissions, can be handled through existing LTE techniques.

4. Implementation of an LTE basestation compliant with CBRS SAS access mechanisms.

As mentioned previously, as part of Research Contribution 3, implementing regulatory compliant networks using licenced-exempt frequencies would remove the CAPEX requirements of a spectrum licence. Although not presently part of UK legislation, in the United States under

FCC regulations, implementations of CBRS networks would also satisfy this criteria.

Chapter 5 presents work completed as part of the 5G RuralFirst (5GRF) project, where a Release 14 LTE-A stack and SDR basestation were enabled to operate in shared spectrum through use of CBRS protocols. At the time of work completion there were no commercially implemented CBRS networks, which reduced the ecosystem of compliant hardware and software. This meant developments were undertaken using COTS equipment that was available.

The outlined research contribution demonstrates that the CBRS protocols and access mechanisms can be implemented in any frequency range covered by 3GPP specifications regardless of duplex type or carrier size. This increases the potential scope of deployment beyond the CBRS frequency range as currently implemented, and shows the potential for implementation in wider, automated, forms of shared spectrum access.

To facilitate implementation of the CBRS-compliant eNB system, the author developed a new channel selection algorithm that is applicable to multiple 3GPP-defined frequency bands.

The work presented in this thesis, across outlined Research Contributions 3 and 4, represents the entirety of the development activities completed within the 5GRF project for the DSA work package. This meant that the presented results were extremely visible to both the UK Government, who funded the project, and also to Ofcom.

5. Development and deployment of the first end-to-end 5G SA Network in the UK.

The work presented in this thesis covers the development of the first end-to-end 5G SA network in Scotland, and one of the earliest deployments in the UK.

As part of 5G RailNext (5GRN), a UK Government funded collaborative project with South Korea partners, a 5G SA private network was deployed in the Glasgow Subway to provide track-to-train connectivity for interactive media applications.

As part of this project, the author completed on-location site surveys, installation activities, field evaluation, and participated in the final project trial.

This research contribution represent a significant development milestone in the operating capabilities of private mobile network deployments, compared to what had previously been demonstrated from installations completed in both industry and academia.

Prior to the work presented in this thesis, none of the network components had been fully integrated as part of an end-to-end 5G SA solution. The author was responsible for setting up and configuring each element of the network to ensure successful interoperability and coherent operation. Learning how to work with low-level system parameters and hardware drivers, as many of the now-standard software packages to simplify certain processes did not exist at the time of work completion, was essential research for successfully completing this project. Without the work presented in Chapter 6, it would not have been possible to implement, or later replicate, the full end-to-end 5G SA network implmentation.

The success of the 5G RailNext network resulted in a follow-up research project, and was directly responsible for multiple world-first and record-setting proof-of-concept deployments in the media production market vertical. The successful installation in the Glasgow underground also demonstrated that private mobile networks can be deployed by independent solution providers and, where shared spectrum frameworks are available, can be done without the input of major Mobile Network Operators (MNOs).

1.4 Thesis Structure

The work presented in this thesis investigates and demonstrates the viability of dynamic shared spectrum techniques, policies, and technologies. In particular, the focus is on the deployment of private cellular networks, using geolocation database spectrum access methods, predominantly targetting deployments addressing connectivity applications in hard-to-reach and challenging operating environments.

Background information on mobile broadband in the UK is provided in Chapter 2, with an introduction to the 4G and 5G technologies used throughout this thesis. This Chapter also describes the current state of mobile coverage across the UK, and the role of private networks in addressing connectivity challenges.

The concepts of shared and dynamic spectrum are introduced in Chapter 3, including a discussion of the main features of two implementations that make use of geolocation database systems: TV White Space (TVWS) and Citizens Broadband Radio Service (CBRS). Both of these spectrum access methods are used further in later chapters. Chapter 3 also provides an overview of the author's contributions to a TVWS pilot network deployment carried out across the Orkney Islands.

Chapter 4 presents information on the Protocol to Access White Space (PAWS), used in TVWS systems as part of the communication between transmitting devices and the geolocation database. Work is presented on the development of a software tool to aid the design and deployment of shared spectrum TVWS networks by providing an interface to the geolocation database system. A further research contribution, an implementation of a 3GPP-compliant basestation system that has been integrated with an Ofcom-approved TVWS geolocation database is presented.

Chapter 5 presents the shared and dynamic spectrum research activities that were completed as part of *5G RuralFirst*. This multi-partner co-innovation project was part of the UK Government DCMS 5G Testbed & Trials programme. One of the key concepts in the project was the use of shared spectrum technologies. This Chapter primarily presents the development and implementation of an automated dynamic spectrum system for 5G systems, that leverages CBRS technologies and protocols, with a bespoke channel selection algorithm.

Chapter 6 presents the author's contributions to the development and deployment of the first end-to-end 5G SA network in Scotland and one of the earliest deployed in the UK. This was completed as part of *5G RailNext*, another UK Government funded project, to explore the use of 5G in underground transport systems to deliver enhanced mobile connectivity.

Finally, Chapter 7 summarises the thesis, reviews the overall research contributions, and discusses potential areas of future work.

Chapter 2

Mobile Connectivity in the UK

The demand for data in the UK continues to grow, with the monthly consumption of mobile data demonstrating significant growth year-on-year since 2018. Traffic volumes grew by 21% from 2023 to 2024 [22]. The number of connected devices in the UK also continues to increase, with smartphones owned by four-fifths of consumers [23], and over 116 million active mobile subscriptions in 2023 [22].

The four major MNOs in the UK are Vodafone, Everything Everywhere (EE), Three UK (Hutchison Group), and O2 UK, also known as Telefonica UK or Virgin Media O2 (VMO2).

The availability of broadband continues to improve in the UK, with ongoing funding programmes, commercial investment, and infrastructure development improving both fixed premise and mobile connectivity.

This chapter will provide background information on the 3rd Generation Partnership (3GPP) 4G and 5G mobile broadband technologies, and their roll in providing connectivity across the UK, to give context for the research contributions and development work presented throughout this thesis.

Section 2.1 provides an overview of the architectures and protocols used in provision of 4G and 5G mobile broadband services. These technologies are fundamental to the work presented in this thesis.

Section 2.2 reviews the annual regulator report on the UK's digital infrastructure, as of 2024, providing statistics on the availability of different connectivity services. This includes a discussion of the *"Shared Rural Network"* (SRN), a joint arrangement by the UK Government and the four MNOs to address rural connectivity issues. This section also highlights some of the challenges behind delivering of rural connectivity, particularly in the provision of mobile broadband solutions, and the potential for private networks to address certain connectivity challenges. These topics will both provide context for the primary research aims of the thesis.

2.1 Overview of Mobile Broadband Technologies

In the 2018 Communications Market report [24] Ofcom highlight that surveyed users claim an average of 24 hours each week online. Of this, 62% of all adult minutes are spent on a smartphone. This is particularly prevalent in commuters, where 42% consider Internet access essential for them to complete personal tasks during journeys, with 35% claiming to use it for work activities. In addition, consumers are moving away from traditional Short Message (SMS) and voice services, which have both seen a decline in usage in recent years [24], to Internet-based applications such as WhatsApp to remain connected. Ofcom also found that, while outside of their home, almost 65% of app usage time for surveyed Android smartphone users was conducted through a mobile network.

While it is possible to achieve data connectivity using 2G or 3G technologies, most commercial operators are beginning the processes of "sunsetting" these networks, as they approach their technical end-of-life expectancy. In 2019, 90% of mobile, or *cellular*, data traffic in the UK was carried over 4G technology [23]. Therefore, this thesis will focus primarily on 4G and 5G solutions.

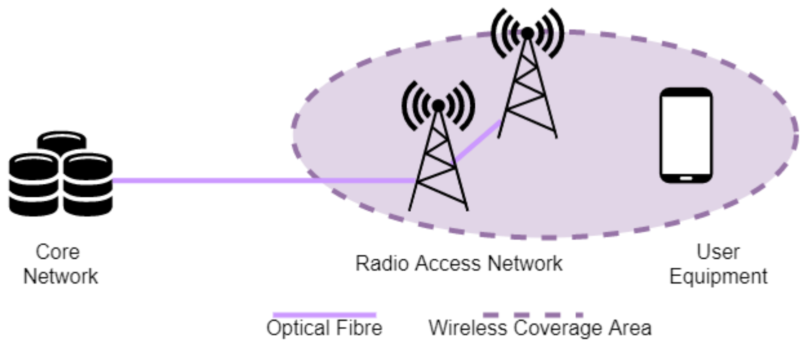


Figure 2.1: Representation of a mobile broadband network architecture.

2.1.1 LTE Network Overview

4G, from *Fourth Generation*, describes systems that meet a set of outlined criteria from the ITU, known as the International Mobile Telecommunications-Advanced (IMT-Advanced) specification. Among other details, this requirement includes meeting a peak data rate of 100 MBit/s for high mobility communication and 1 GBit/s for stationary or slow moving users.

One of the candidate technologies for this classification was the 3GPP Long Term Evolution (LTE) standard. Initially, this technology was only recognised as 4G due to the significant performance improvements compared to 3G systems, but following 2011 enhancement, referred to as LTE Advanced (LTE-A), in 3GPP Release 13 the IMT-Advanced technical requirements were also met.

The architecture for a 4G LTE network is shown in Figure 2.2, and can be considered to have three main sections: User Equipment (UE), Radio Access Network (RAN), and Core Network.

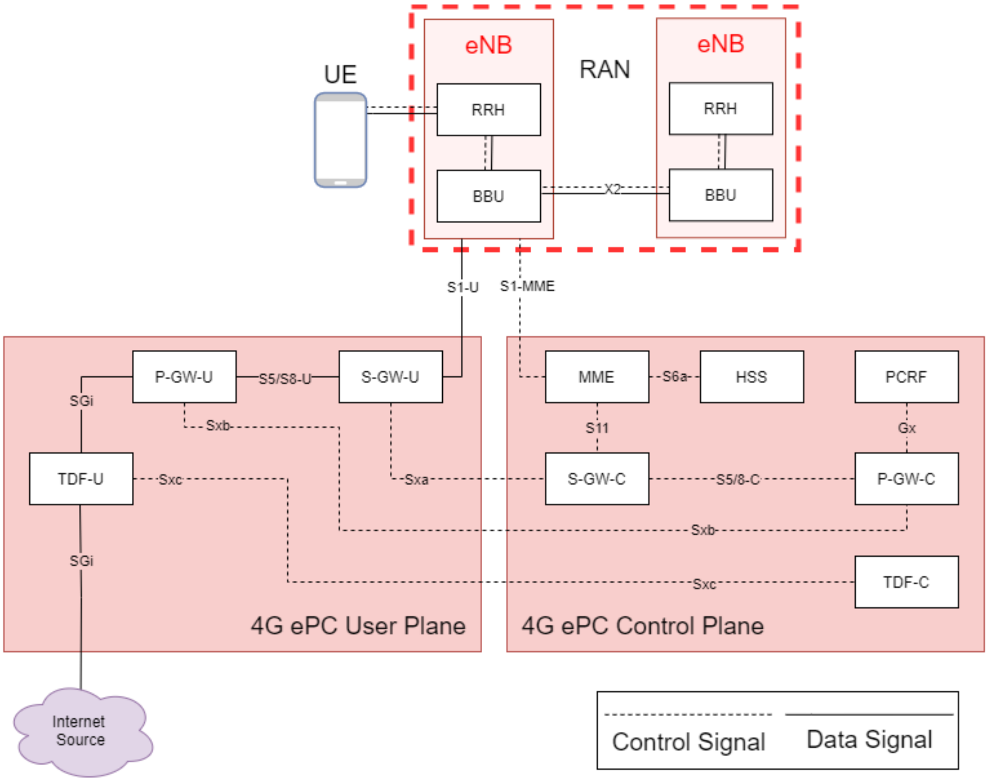


Figure 2.2: Architecture of an LTE Radio Access Network (RAN) and Evolved Packet Core (ePC).

User Equipment (UE)

The UE refers to the devices looking to connect to the wider network, for access to voice or data services. Typically this will be a mobile handset or tablet computer, but there is a growing ecosystem of devices capable of connecting to mobile networks. For example, there are available COTS Wi-Fi routers, which use the cellular network as an Internet bridge, as seen in the 5G RuralFirst (5GRF) project discussed further in Chapter 5.

These devices will contain either a physical SIM card, or a programmed electronic SIM (eSIM), which contains information and cryptographic values to verify and authenticate devices connecting to the network.

Radio Access Network (RAN)

The UE will connect to a transceiver referred to as an evolved NodeB, or eNodeNB (eNB), as part of the second main architecture segment known as the Evolved Universal Terrestrial Radio Access Network (EUTRAN), or simply RAN. The names from these systems are derived from the previous 3G Universal Mobile Telecommunications System (UMTS) specification.

Connection between eNB and UE uses Orthogonal Frequency Division Multiple Access (OFDMA) for the downlink, eNB to UE, and Single Carrier Frequency-Division Multiple Access

(SC-FDMA) for uplink, UE to eNB. SC-FDMA is preferred for uplink communication due to increased power efficiency, which is important for implementation on low-power UE.

The LTE-A specification allows for up to 8x8 Multiple Input Multiple Output (MIMO), carrier aggregation for up to 100 MHz of spectrum, and 128-order Quadrature Amplitude Modulation (QAM) in the downlink. Combining these techniques allows for a theoretical data rate well exceeding the 1 GBit/s outlined by IMT-Advanced.

The LTE-A Pro amendment was initially part of the 3GPP Release 13 with further additions in Release 14. These two Releases incorporate a number of additional features as enhancements towards the 5G certification. This included support for new applications such as Internet of Things (IoT), using Narrowband-IoT (NB-IoT) technology, and Machine-To-Machine (M2M) communication with LTE-M2M (LTE-M).

Under LTE Release 14, the number of potential carriers that can be aggregated is increased to 32 which, combined with modulation rates of up to 256 QAM and massive-MIMO techniques, enables theoretical data rates of over 3 Gbps.

Core Network

The RAN connects the UE to the third architecture segment, the Core network. This is responsible for authorising and authenticating a connecting UE, or more specifically the SIM card, and then enabling connection to the Internet, for data services, or the PSTN for telephone service once approved. The LTE network Core can be thought of as a collection of elements, connected by a set of standardised signals, in the evolved Packet Core (ePC) architecture.

While earlier core architectures supported circuit switching, primarily for transmission of voice and SMS, this was removed for the 4G architecture in favour of using packet-switching within an Internet Protocol (IP) network for transportation.

As part of 3GPP Release 14 it was decided that the end user data, referred to as the User Plane (UP), would be separated from the signalling information, referred to as the Control Plane (CP). This effectively split the Serving Gateway (S-GW), Packet Gateway (P-GW), and Traffic Detection Function (TDF) elements to provide an equivalent, but separate, component for the control plane and for the user plane.

This functional separation allows for systems carrying out operations on these planes to developed, enhanced, or scaled independently. This Control and User Plane Separation (CUPS) offers a number of benefits to network operators, and is a fundamental concept to the implementation of the 5G Packet Core (5GPC) architecture.

In network diagrams or documentation, CP and UP components are typically denoted by the -C or -U descriptors respectively. For example, the S-GW used for the control plane would be annotated as *S-GW-C*.

As each S-GW-C and P-GW-C can connect with multiple S-GW-U or P-GW-U, the control plane can dynamically select a data plane to use for a connection depending on factors such as UE location. This gives the ability to have the routing and processing of the user data located physically closer to the end user, greatly reducing the experienced latency. This is important, as different types of user application will have different technical requirements for the user plane. For example, streaming services such as Netflix might use more data functions, impacting the S-GW-U and P-GW-U, but require fewer control signals once the connection is established. A messaging or chat service might require more control resources, from the S-GW-C and P-GW-C, for a relatively low amount of data.

2.1.2 5G Network Overview

3GPP Release 15, delivered in Q2 2018, included the first 5G New Radio (5G NR) specification for a Radio Access Technology (RAT) beyond the capabilities of LTE [25]. These developments are intended to meet the technical requirements for 5G systems outlined by the ITU. The IMT-2020 standard, named according to the expected completion date, incorporates some key draft specifications that were published in 2017. This includes a peak downlink rate of 20 Gbit/s and a bandwidth requirement of at least 100 MHz, along with requirements for aspects such as latency and spectral efficiency [26].

Overall Network Architecture

The design of the 5G RAN and core inherently allows for flexible deployment options for use alongside legacy systems. The new gNodeB (gNB), from *next generation NodeB*, and 5GPC can be installed alongside existing 4G entities.

The overall 5G network architecture has been defined to facilitate system rollout depending on which generation of basestations are used in the RAN, and what core implementation is used.

A RAN comprised of multi-generational eNB and gNB, served by a common ePC, creates what is referred to as a Non-Standalone (NSA) network, as shown in Figure 2.3.

Under this arrangement, the eNB manages control and mobility signalling, establishing what is referred to as an anchor connection, while the gNB provides data connectivity. Consequently, the end user traffic is predominantly carried by the 5GNR RAT. As expected, a network of eNB and gNB units should outperform an equivalent network using entirely 4G LTE technology when deployed with the same core infrastructure elements.

NSA deployments are currently used in commercial networks as part of consumer 5G services, such as those discussed in Section 2.2, as it allows providers to leverage existing network assets for delivery of improved data rates and lower latency, without having to deploy completely new end-to-end infrastructure. Implementation in this way then offers a number of pathways towards developing to a fully 5G infrastructure.

A network deployment made up entirely of 5G systems —- a gNB RAN served solely by a 5GPC — is referred to as Standalone (SA) mode. Under this arrangement, both user data and control data from a gNB is handled entirely by a 5GPC, while any eNBs are served by a connected ePC.

Under current specifications, in both SA or NSA deployments, the communication between UE and gNB uses Cyclic Prefix OFDM (CP-OFDM) in the downlink, with the option to use either CP-OFDM or Discrete Fourier Transform-spread-OFDM (DFT-s-OFDM) in the uplink.

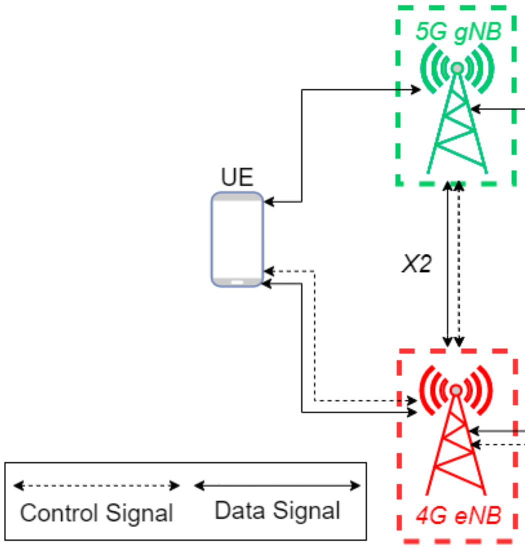


Figure 2.3: Architecture of a 5G NSA deployment.

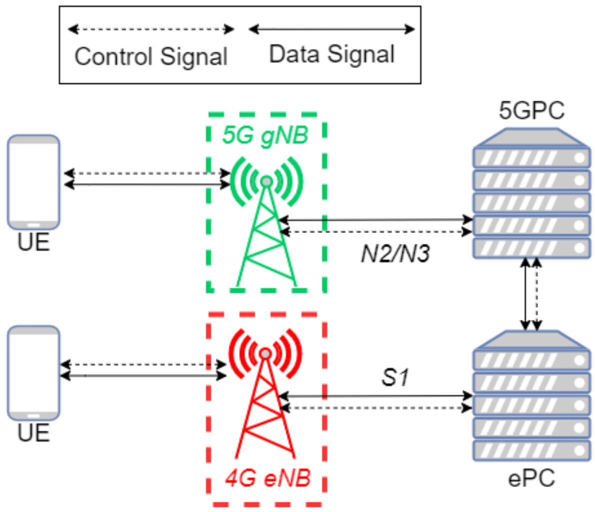


Figure 2.4: Architecture of a 5G SA deployment.

The 5GNR standards are still developing at time of writing. However, by taking advantage of the existing legacy support, 5G NSA services are being offered by MNOs in the UK, discussed further in Section 2.2.

Establishing an SA 5G network allows for users and operators to take full advantage of the 5GPC capabilities. This will allow for improved performance, relative to an equivalent NSA network, and enable new use cases with strict technical performance requirements.

Core Network

The 5GPC architecture reorganises, and updates, the 4G ePC components into a number of service-oriented functions, which improves system modularity. These functions can then be interconnected to create a standard architecture, which is shown in Figure 2.5.

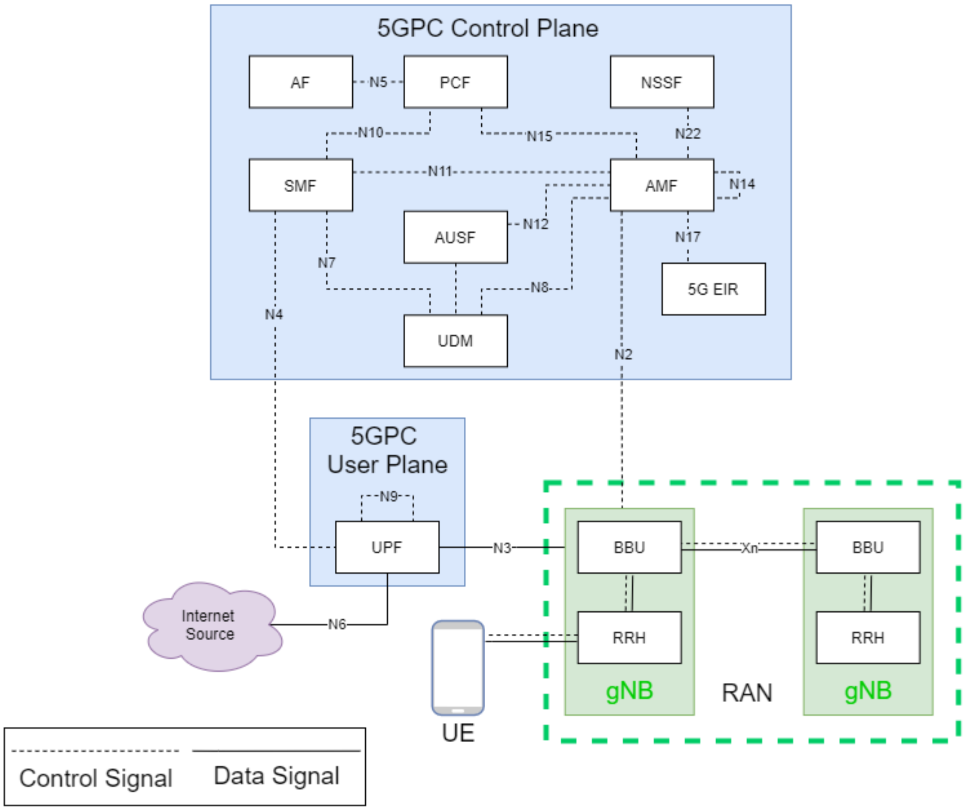


Figure 2.5: Architecture of a 5GNR RAN and 5GPC.

Implementation of the 5GPC as a number of service-oriented functions enables *virtualisation*, where some or all of the network functions are completed by software packages operating on computing platforms rather than on dedicated hardware systems. Increasing the deployment flexibility in this way enables support for concepts such as network slicing, where single resources can be arranged to create virtual networks each supporting different use cases or applications.

The idea of implementing network components as a series of connected Virtual Machines (VMs) or containers is not restricted to the 5GPC, and the role of virtualisation in the RAN is an ongoing area of discussion and development within both academia and industry. This has become even more prevalent with recent advancements in RAN architectures, combined with the ongoing movement towards further disaggregation and open interfaces.

Radio Access Network (RAN)

The traditional Base Transceiver Stations (BTS), used in the access networks of 2G Global System for Mobile Communications (GSM) and General Packet Radio Service (GPRS) systems, were typically constructed using an all-in-one, or *monolithic*, architecture where a single physical unit contained the demodulation, signal detection, and baseband management functions.

A connecting antenna was then typically placed on the roof of these units and connected via RF cable pairs. It is important that the antenna is placed a certain distance from the processing unit, as the radiation characteristics of the transmission can cause interference. This long, but necessary, link introduces loss and delay in the system, which impacts the achievable coverage area and decreases energy efficiency.

The placement limitation issue described above is addressed through RAN disaggregation, where the single-unit basestation systems are substituted with multiple separate functional entities. This increases flexibility of deployment options. At the same time, such deployments can provide improvements in network efficiency, reduced time-to-market, and lower probability of vendor lock-in.

The concept of RAN disaggregation was not introduced with the implementation of 5G. 4G LTE systems already took advantage of such concepts, where distributed, or *split* architectures are commonly implemented. This style of deployment, shown in Figure 2.6, is a two-unit architecture comprising a Baseband Unit (BBU) and Remote Radio Head (RRH) connected over a short optical fibre interface.

This basestation implementation was commonly used throughout the 5GRF project discussed in Chapter 5, and was the primary architecture targetted by the work throughout this thesis.

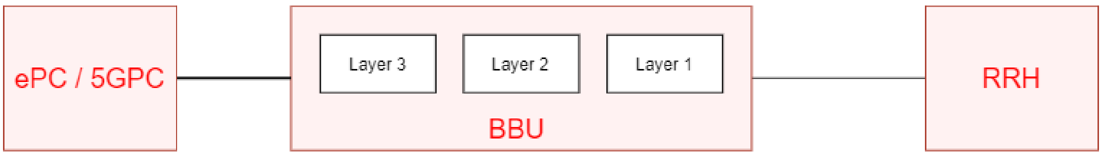


Figure 2.6: High level representation of distributed architectures for a 4G/5G RAN

The BBU is responsible for enabling connectivity to the core network, performing signal detection, providing a system clock for synchronisation, baseband management, and other operations across the physical layer.

It also controls the transfer of user data, session management, and mobility functions that define the communication link between users. The BBU can either be on-site at the tower, typically located at the base in a secure cabinet, or in a more central location, where resources are pooled together at a data centre and likely deployed in VMs. These centralised BBUs are then connected to the towers they serve via optical fibre.

The RRH, also sometimes referred to as the Remote Radio Unit (RRU), performs the transmit and receive RF functions, handles sampling, frequency shifting and quantisation of the in-phase and quadrature components, before transmitting data to the BBU. When a signal is received from a nearby connected antenna, it is filtered, amplified, and converted to a digital format before being routed via the fibre interface to the BBU. Conversely, digital signals from the BBU are converted to RF before being amplified and sent to the antenna for transmission.

The RRH would typically be positioned at the top of a network tower, next to the associated antenna system. This will increase overall implementation performance and efficiency by making it easier to maintain the correct distancing between signal source and antenna, while also reducing the quantity of RF cabling and subsequently the loss and delay in the system.

The connection between BBU and RRH, referred to as the fronthaul, uses the Common Public Radio Interface (CPRI) as the de facto industry standard [27].

The newest iterations of mobile broadband technology further develop the concept of RAN disaggregation, and what began with a separation between the BBU and RRU has now been expanded. With the aim of enabling further RAN disaggregation, the 3GPP defined eight functional split options [28], [29]. These are shown in Figure 2.7. Under this specification, the distributed architecture, where the RRHs retain the RF functions and the other main functions are placed in the BBU, would be considered as an Option 8 split.

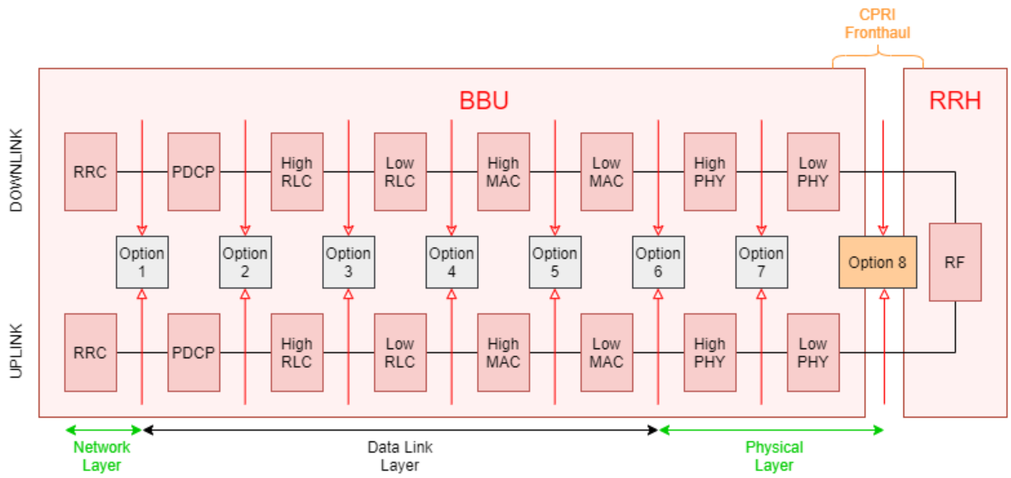


Figure 2.7: Representation of a disaggregated architecture showing an Option 8 Lower Layer Split (LLS).

In most recent 3GPP specifications, in Release 15 onwards, the overall BBU functionality has been further distributed — with the constituent elements now positioned between two replacement components. A Distributed Unit (DU) is responsible for the real time functions, and a Centralised Unit (CU) for non-real time functions. The DU is located closest to the RRU, or simply the Radio Unit (RU), as shown in Figure 2.8 [29], [28].

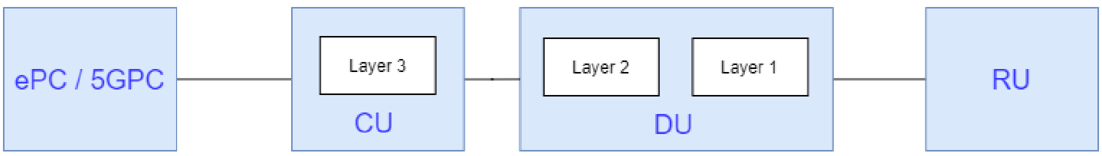


Figure 2.8: High level representation of next-generation disaggregated architectures for a 5G RAN

Connection between the DU and RU is referred to as the fronthaul (FH), while connection between the CU and DU is known as the midhaul (MH). The CPRI specification was updated, now referred to as enhanced CPRI (eCPRI), to support not only Option 8 and the other lower-layer splits (LLS) for the fronthaul, but also the higher-layer splits (HLS) of the midhaul.

The RAN implementations discussed throughout Chapters 4, 5, and 6 of this thesis are compliant with Release 14 of the 3GPP specification [30]. Chapter 6 focuses on the practical development and deployment of an end-to-end 5G system compliant with Release 15.

It is a noted item of future work to investigate the impact of the next-generation architecture overhaul to the outlined research contributions. The role, and implementations strategy, of shared spectrum frameworks within future RAN architectures is one of the key topics of the *TUDOR (Towards Ubiquitous 3D Open Resilient Network)* project, which is ongoing at time of writing [31].

2.1.3 Providing Wireless Connectivity to Premises and Buildings

In the UK, delivery of broadband connectivity to premises will most commonly takes place over wired infrastructure [32] via an internet gateway to the Internet Service Provider (ISP).

While optical fibre solutions provide the best performance with regards to latency and throughput, the cost of installing, expanding, or upgrading these wired connections is significant. The civil engineering CAPital EXpenditure (CAPEX) for installation of a new fibre infrastructure to existing premises, a brown field project, can account for 80 - 90% of the total network cost [33]. In an attempt to mitigate some of these deployment costs, alternative technologies, can be used to provide connectivity to premises and buildings.

As part of a Fixed Wireless System (FWS) or Fixed Wireless Access (FWA) architecture, a Wireless ISP (WISP) will operate a network of basestations with a high capacity backhaul to an Internet gateway. Rather than connecting directly to user devices or dongles, most premises will be fitted with an external receiver antenna, directed towards the transmitting basestation. This increases the quality of signal received. A single basestation can be used to serve multiple users, as shown in Figure 2.9.

FWA can also be delivered through the same network infrastructure used to simultaneously deliver 4G and 5G mobile broadband services, as shown in Figure 2.10. Typically in these kind of FWA deployments, the customer is given an indoor router that connects to the network, although some providers will also supply an external antenna to increase the received signal strength.

FWA services offered by MNOs over 4G or 5G networks will share the network capacity with the other mobile users. This means carefully managing the demands of both sets of customers, and as a result there may be areas where FWA can't be offered due to the high demand of mobile services [34].

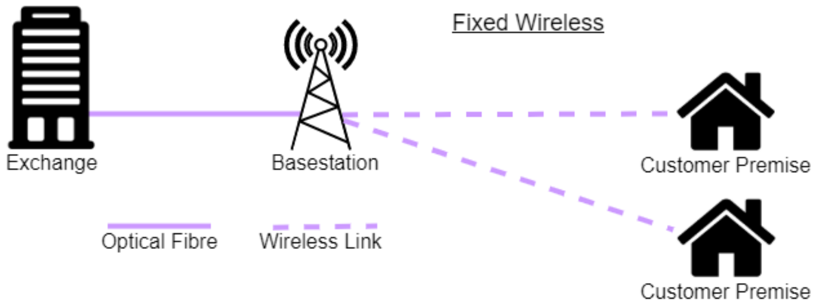


Figure 2.9: Example architecture for a dedicated FWA network deployment.

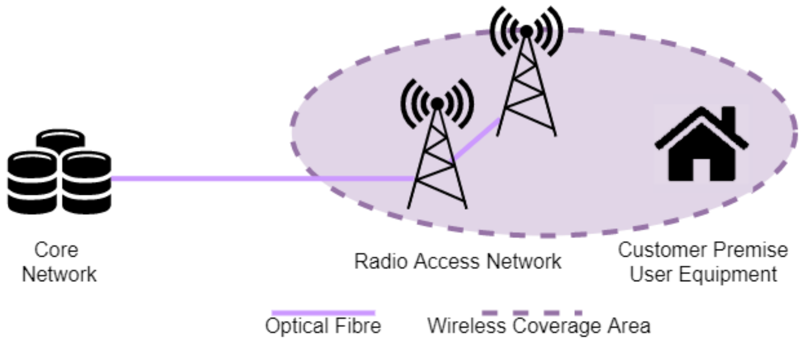


Figure 2.10: Example architecture where FWA services are provided in parallel with mobile connectivity.

The protocols used for communication over WISP microwave links vary depending on equipment provider, deployment terrain, network topology, and desired operating frequency among other factors. This could be a bespoke, custom, protocol or a specification such as IEEE 802.11. This family of standards dictates operations for a Wireless Local Area Network (WLAN), with a number of versions available. An alternative technology is IEEE 802.16, commonly referred to as WiMAX, from *Worldwide Interoperability for Microwave Access*. This wireless Metropolitan Area Network (WMAN) standard also has different versions available, including an amendment to allow for use in provision of mobile broadband services.

An example of WISP-provided FWA connectivity in the Orkney Islands, using IEEE 802.11 protocols enabled by TV White Space shared spectrum technology, is presented as a research contribution in Chapter 3.

Another technology that is commonly used to provide wireless connectivity to premises, particularly in rural locations, is satellite broadband. Traditionally this was delivered through satellites operating at Geostationary Orbit (GEO), which connected to users through Very Small Aperture Terminals (VSAT) at their premises.

Recent commercial developments, investments, and deployments from companies such as Starlink [35], OneWeb [36], and Amazon [37] have resulted in a significant increase in the availability of Low Earth Orbit (LEO) satellite systems to deliver broadband connectivity. As these satellites are not operating at a constant location above the Earth's surface, users will connect to multiple orbiting constellations rather than the same satellite as in a GEO VSAT deployment.

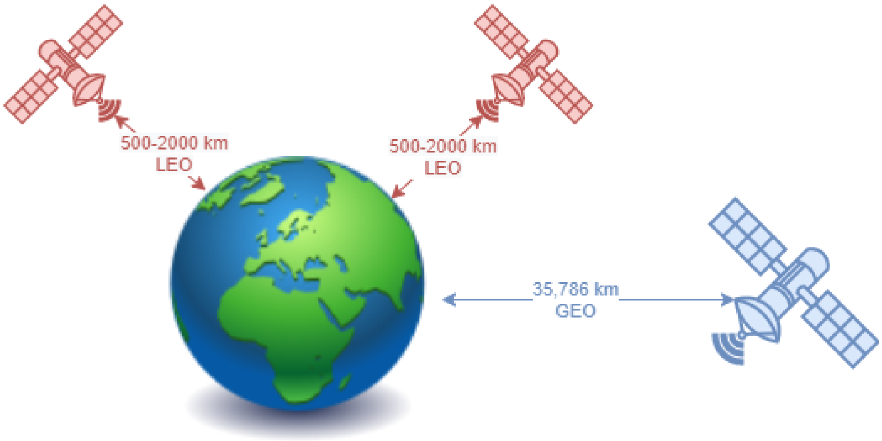


Figure 2.11: High level representation of LEO and GEO satellite deployments.

While this technology provides an excellent coverage range and high degree of deployment flexibility, there are a number of associated issues. Currently, hardware costs to the customers are potentially relatively high, as are the monthly subscription costs. Again this is potentially off-putting for customers, especially when combined with monthly data caps in-place due to limited link capacities. As the bandwidth of a connection to a given satellite is shared among all users in a particular area, locations with a high density of users can experience network congestion at peak usage times.

Similarly, the minimum round-trip latency, due to the orbital distances involved, can greatly impact the use of real-time services such as voice-over-IP (VOIP) applications and some virtual private network (VPN) implementations. However, this is typically more of an issue for traditional GEO VSAT implementations than LEO systems.

Although the exact operating frequencies for satellite-based communications will can vary depending on deployment architecture and provided, typically systems delivering broadband connectivity will use the 12-18 GHz *Ku-band* or the 26.5-40 GHz *Ka-band* [38]. Due to these high transmission frequencies, the established links can also be susceptible to weather conditions and effects such as rain fade. This is when atmospheric moisture and precipitation absorb radio frequency signals, causing link degradation and reduced achievable data rates. This issue is exacerbated by the increased communication distance and use of the higher frequencies. However, through the use of proper planning, power control, and appropriately designed ground systems these adverse weather effects can be mitigated.

One of the main challenges associated with satellite broadband is that the cost of increasing the coverage area, by launching more satellites, is astronomical. Therefore, in unserved or over-contested areas consumers must consider other alternatives until such time that further services are provided. Some options include waiting for improved terrestrial-based infrastructure development, through schemes such as the Shared Rural Network (SRN) discussed in Section 2.2.2, or development of independent private networks, discussed further in Section 2.2.4.

2.2 Mobile Coverage and Performance in the UK

Connected Nations is an annually published report from regulator Ofcom, which collates information from fixed and mobile service providers to inform on the UK's communications infrastructure, focusing on network coverage and performance [39].

Section 2.2.1 presents statistics extracted from this report and Ofcom's corresponding interactive datasets [40] outlining the continued development of 4G LTE networks and progress on the rollout of 5G NR networks.

In addition, Section 2.2.2 provides an overview specifically of the "Shared Rural Network" (SRN) initiative — a joint venture between the UK Government and mobile network providers to address connectivity deficiencies in rural locations.

To better understand the underlying potential causes for the observed rural connectivity levels, Section 2.2.3 briefly discusses the challenges associated with deploying networks in these environments.

Finally, Section 2.2.4 highlights the role and potential for private networks, such as those discussed throughout this thesis, to address issues of connectivity availability or provide services for applications with specific performance metrics.

2.2.1 4G / 5G Mobile Coverage and Not-Spots

Areas that cannot receive coverage from all four mobile providers are referred to as types of partial not-spots, while those that have no coverage at all are known as complete not-spots. Both of these not-spots limit the consumer choice for customers that live or work in these areas.

Section 2.2.1.1 will review the availability of 4G LTE connectivity and prevalence of not-spots across the UK, while Section 2.2.1.2 will focus only on the availability of commercial 5G services.

2.2.1.1 4G LTE Network Coverage

For the Connected Nations report, a premise or area is considered covered with 4G by a provider if there is 98% probability that the signal strength at the location will enable a download speed of 2 Mbit/s [23].

Table 2.1 presents the most up-to-date statistics showing 4G coverage from all 4 MNOs for both urban and rural locations. Details are provided for geographic coverage, as well as for both inside and outside premises [40].

Conversely, table 2.2 presents statistics highlighting where there is no achievable 4G LTE or 5GNR mobile coverage [40].

4G Coverage from all 4 Operators	**Urban**			**Rural**		
	Geographic	Premises Indoor	Premises Outdoor	Geographic	Premises Indoor	Premises Outdoor
UK	98%	93%	>99%	78%	57%	93%
England	99%	93%	>99%	88%	56%	94%
Scotland	98%	95%	>99%	84%	67%	93%
Wales	94%	88%	99%	72%	55%	89%
Northern Ireland	96%	85%	>99%	84%	49%	90%

Table 2.1: Comparison of areas across the UK with 4G coverage from all 4 MNOs [40] (2024).

Coverage from no Operators	**Urban**			**Rural**		
	Geographic	Premises Indoor	Premises Outdoor	Geographic	Premises Indoor	Premises Outdoor
UK	<1%	<1%	<1%	5%	3%	<1%
England	<1%	<1%	<1%	2%	3%	<1%
Scotland	<1%	<1%	<1%	11%	2%	<1%
Wales	1%	<1%	<1%	5%	4%	<1%
Northern Ireland	1%	<1%	<1%	2%	4%	<1%

Table 2.2: Comparison of areas across the UK with no 4G or 5G mobile coverage [40] (2024).

Table 2.1 shows that rural areas have a higher prevalence of partial not-spots, while Table 2.2 highlights that this also the case for complete not-spots. This discrepancy is to be expected, given the associated challenging differences in deployment and business case, which is discussed further in Section 2.2.3.

2.2.1.2 5GNR Network Coverage

At time of writing in early 2025, the commercial 5G roll-out is still underway in the UK with all four of the large MNOs offering 5G services.

These initial deliveries are focused on densely populated areas for both mobile and fixed-access services [23], the majority of which is still being delivered using NSA architectures [34]. Although the number of 5G SA deployments from MNOs is increasing year-on-year, the reported 3300 sites account for just below 15% of the total number of 5G mobile sites in the UK [34].

When Ofcom report on the availability of 5G mobile connectivity, two confidence levels are defined that reflect the likelihood of consumers experiencing on-the-ground coverage.

A *High Confidence* is described as achieving a signal strength of -110 dBm at 80% confidence level, while a *Very High Confidence* is described as achieving a signal strength of -100 dBm at 95% confidence level [34].

Using those definitions, Table 2.3 presents the most recent statistics of geographic, landmass, coverage of 5G for each part of the UK as reported by each MNO [40].

The information from Table 2.3 shows that although 5G networks are commercially available they are far from ubiquitous. Considering also that an overwhelming majority of the achievable

Geographic 5G Coverage	High Confidence				Very High Confidence			
	Vodafone	EE	Three	VMO2	Vodafone	EE	Three	VMO2
UK	15%	42%	23%	28%	8%	35%	9%	21%
England	23%	57%	31%	38%	12%	48%	13%	27%
Scotland	6%	19%	12%	13%	3%	16%	5%	9%
Wales	5%	47%	19%	2%	3%	39%	8%	1%
Northern Ireland	5%	15%	11%	68%	2%	13%	4%	55%

Table 2.3: Summary of Geographic 5G Coverage Reported Per Operator [40] (2024).

connectivity will only be available with 5G NSA architectures.

This highlights that fully 5G SA networks, such as the one presented in Chapter 6, should still be a considered cutting-edge, challenging deployments and an area of ongoing development within both industry and academia.

2.2.2 The Shared Rural Network (SRN)

The “Shared Rural Network” (SRN) was proposed to the UK Government by Mobile UK, the trade association of the UK’s large MNOs, in June 2019 [41] following the initial auction proposals for the 700 MHz and 3.5 GHz bands, two of the key bands expected enable 5G services [42].

As part of the outlined Combinatorial Clock Auction (CCA) format, Ofcom proposed to include a set of coverage obligation “lots”. Bidders choosing to include these binding commitments to improved coverage would receive discounts on the price paid for their spectrum licence [43].

In their responses to the auction consultation, each of the MNOs commented on the coverage obligations, and collectively recommended a publicly funded investment in infrastructure with commercially driven network mast sharing [44], [45], [46], [47].

Under the SRN agreement, £530 million from the four MNOs would be matched with £500 million from the Government. This would be used to establish 4G connectivity across the UK, with a target for each operator to achieve 90% UK landmass coverage, with a combined coverage of 95% by the end of 2025 [23], [48].

In addition to the UK-wide coverage requirements, each of the Home Nations has outlined targets to be achieved by the end of 2026. These requirements dictate a geographic coverage threshold to be reached by all operators as shown in Table 2.4. Additional details from the Connected Nations report are provided which show the level of coverage achieved at the time SRN requirements were drafted.

Key elements of the proposals include an operator-funded mast-sharing arrangement, between all parties, in areas of partial not-spots. In areas of complete not-spots, new Government-funded sites would be built to host all operators. In addition, 292 sites developed as part of the Government-owned Emergency Services Network (ESN) will be made available to operators to

Area	All Operators Coverage Target (2024)	All Operators Coverage Levels (2019)	Projected Increase
UK	88%	66%	22%
England	90%	81%	9%
Scotland	74%	42%	32%
Wales	80%	58%	22%
Northern Ireland	85%	75%	10%

Table 2.4: Comparison of urban and rural premises across the UK with access to Superfast broadband at time of SRN requirement draft [49], [48] (2019).

deliver coverage in rural locations [23].

The SRN deal was agreed with the UK Government in March 2020 [48]. Coverage obligations were subsequently removed from the auction format [50], with SRN coverage commitments made legally binding [51]. The committed obligations include 88% geographic coverage of the UK landmass from each operator by June 2024, with the 90% coverage target to be achieved by the end of 2026 [48].

Ofcom regularly update on the MNO compliance with their SRN coverage obligations. As of the end of 2024, all four operators had met the 88% UK-wide coverage threshold [34], as shown in Table 2.5.

Operator	UK Coverage Levels (2024)
Vodafone	88.7%
Virgin Media O2	88.1%
Three	88.6%
EE	88.9%

Table 2.5: Update on MNO Progress for UK-wide Coverage Obligations as part of SRN [34].

Although all operators have now met the initial geographic coverage obligation within the agreed deadline, work is ongoing to meet the further target by the end of 2026. Some of the challenges associated with deploying mobile networks in rural locations are discussed further in Section 2.2.3.

2.2.3 The Challenges of Mobile Network Deployments

The deployment of network infrastructure in an area represents a commercial investment decision made by an operator, whether it's fixed or mobile broadband applications. This will involve an assessment of the demand and market price point for services, the cost of installing the network, and the cost of maintaining or upgrading the deployment.

There are a number of potential factors that could influence such a financial judgement.

In their 2019 Economic Geography report [52], Ofcom outline several cost and demand factors intended to capture the considerations of potential fixed and mobile network operators. Some factors are applicable to both kinds of deployment. This includes those relating to area population, such as affluence, demography, and density.

Rural locations have a lower population density compared to urban equivalents. This will impact the potential financial return for a prospective operator in a given area. In turn, this significantly influences the business case for a deployment and can have implications on the CAPEX and OPerating EXpenditure (OPEX) available for a network solution.

The network design is further complicated by the environmental factors associated with rural locations, such as topography and increased distances to critical power and backhaul assets. The design costs to overcome these environmental challenges will also impact both CAPEX and OPEX, further influencing the associated business case.

Mobile and fixed networks have different, but related, challenges to overcome with regards to the operating environment. In both cases, the distances involved to provide network backhaul represents a significant CAPEX due to the cost of civil engineering associated with installation of optical fibre.

Considering specifically mobile broadband networks, new deployment sites, referred to as *greenfield* installations, may be necessary to provide the required wireless coverage and could be located away from the existing electrical power grid. This introduces further installation CAPEX through additional civil works.

With these factors in mind, it is evident why the case for investment in rural network deployments is more complicated than for urban equivalents. To mitigate some of the additional rural challenges, there are technical design, equipment, and implementation options that can be employed.

For example, physical network components, such as gNBs, can be selected at a cost level below that of solutions deployed in urban environments, where the Average Revenue Per User (ARPU) is higher. This could mean selecting equipment with lower transmit capabilities such as SDR platforms, while being aware of the potential trade-off with achievable coverage.

This CAPEX reduction could also occur by addressing costs associated with access to spectrum. Methods for accomplishing this through Shared Spectrum are discussed in Chapter 3, with practical implementations and evaluations presented in Chapters 4 and 5.

With appropriate levels of CAPEX and OPEX it becomes more feasible for new network owners and operators to participate in the market, and offer connectivity services independently from the established four large MNOs. These types of deployments and offerings are often referred to as *Private* or *Non-Public* networks. This topic is discussed further in Section 2.2.4.

Another way to address the challenges of network CAPEX and OPEX is through the deployment of Neutral Host architectures, where multiple network operators provide connectivity services from a shared infrastructure deployment. This concept is discussed further as part of

Section 2.2.3.1.

2.2.3.1 Neutral Host Networks

The idea of sharing deployment sites, or network assets, among mobile operators is not a new concept.

It is not uncommon for the Government, or associated organisations such as Scottish Future's Trust (SFT), to provide partial or full subsidy of the CAPEX for a new mast site. This is more likely to occur in rural locations to offset the initial financial burden on MNOs, with the aim of stimulating network rollout and improving coverage over particular areas. These subsidised sites are typically then made available for use by all of the MNOs, depending on the associated contractual agreements. Alternatively, two or more MNOs will sometimes collaborate on the construction of a new deployment site to share some of the associated initial CAPEX costs. Operators are then only required to deploy their network and transmission components, without some of the associated costs for civil engineering, power, and backhaul connectivity.

Having multiple operators deployed on one site can also have the additional benefit of reducing some associated OPEX costs. While utilities such as power and backhaul can scale in price depending on the amount of network infrastructure deployed, so may not see significant reduction by introducing multiple operators to a site, any associated land rental costs could be split between the co-hosted parties.

A representation of a simple site sharing architecture is shown in Figure 2.12. As can be seen, although a mast site may be cohabited, each MNO is running effectively independent network infrastructure.

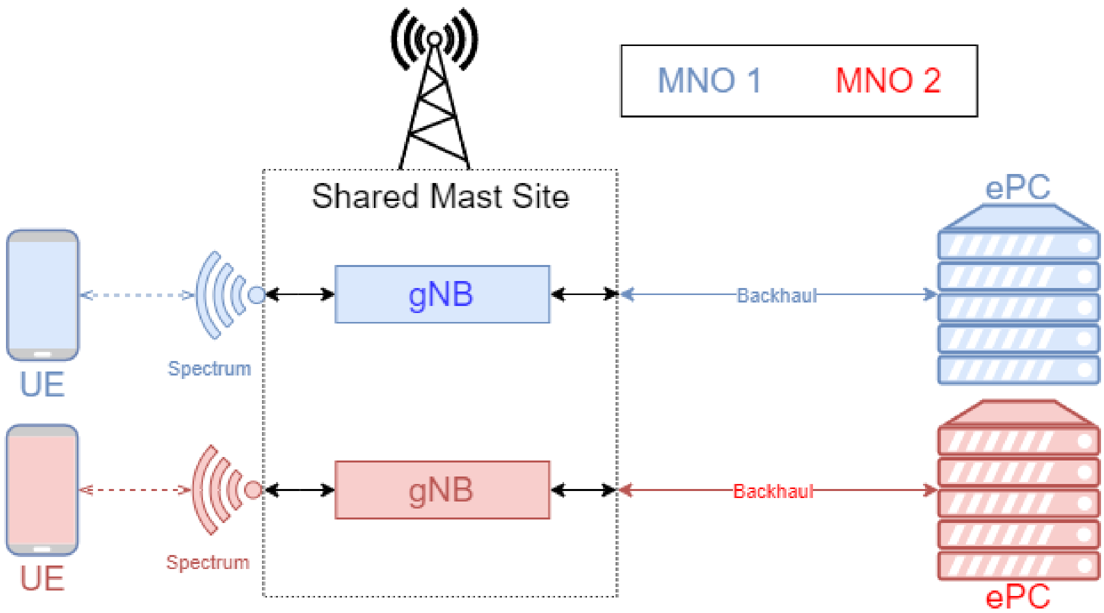


Figure 2.12: Representation of a Site Sharing deployment.

Site sharing is conceptually similar to a Neutral Host deployment, in that it allows for distribution of the CAPEX and OPEX between MNOs. However, unlike site sharing, a true Neutral Host deployment involves also unifying some of the network infrastructure and components.

Typically, Neutral Host architectures are categorised depending on the exact point of demarcation within the network infrastructure for visibility, responsibility, and cost.

In a Multi-Operator RAN (MORAN) deployment, co-located MNOs will share the same radio transmitters and antenna platforms, but with separate dedicated operating frequencies and backhaul connections to their core network [53] [54]. This architecture is shown in Figure 2.13.

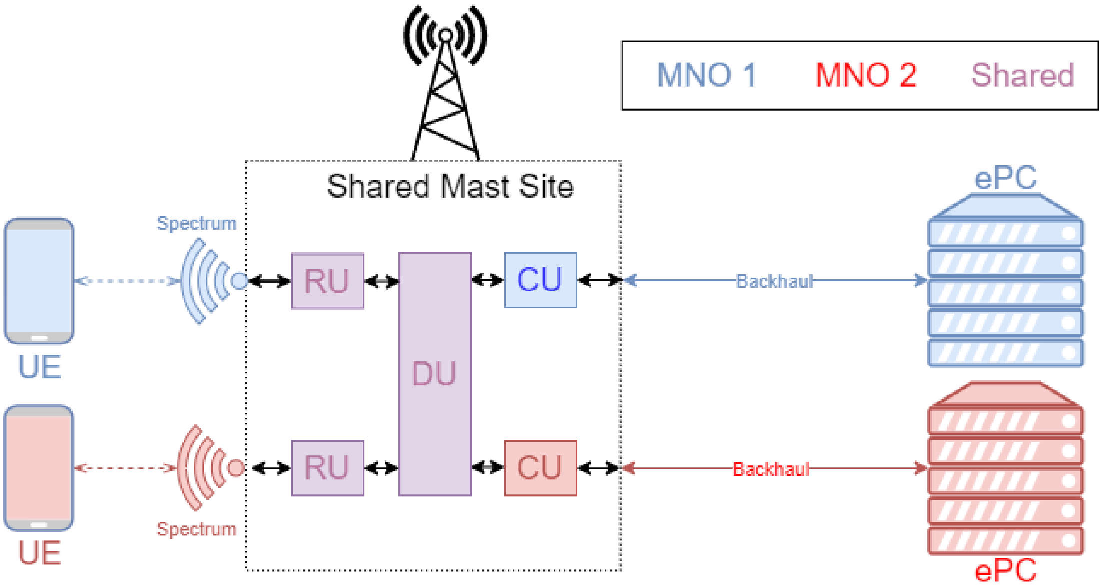


Figure 2.13: Neutral Host Architecture for a MORAN deployment.

In the Multi-Operator Core Network (MOCN) architecture, operators will share the RAN infrastructure and also their spectrum resources. There may also be a unified backhaul connection to the corresponding core network [53] [54]. This is represented in Figure 2.14.

Neutral Host solutions have the potential to enable new business models, such as the use of community or privately owned mobile infrastructure that is then leased or rented to one or more operators. This creates a mutually beneficial operating scenario for MNOs, local communities, and the neutral host infrastructure provider.

To facilitate this shared use of infrastructure in a way that provides the necessary network security, resilience, operating performance, and commercial sensitivity, the Joint Operators Technical Specifications (JOTS) was developed by the JOTS Forum [55].

Initial releases of JOTS specification focused on indoor coverage use cases, primarily targeting large venues such as office buildings, event spaces, or stadiums. This would be done either through the use of Distributed Antenna Systems (DAS) [56] or using *"small-cell"*, low-power, radio platforms following the Neutral Host In-Building (NHIB) specification [57].

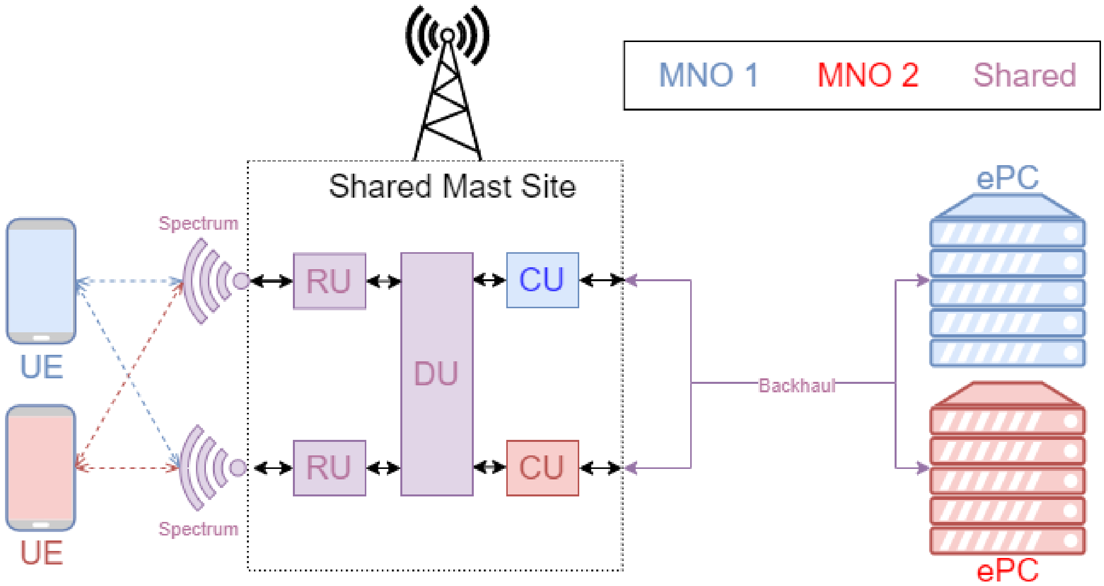


Figure 2.14: Neutral Host Architecture for a MOCN deployment.

Technical requirements for the use of small-cell units in an outdoor environment, the Neutral Host Out-Door (NHOD) specification [58], was completed in October 2024.

As the UK MNOs continue to invest and implement 5G SA in their core network architectures, this capability will also start to become available at Neutral Host deployment sites. This was demonstrated for the first time by VMO2, working with Neutral Host-as-a-Service provider IONX Networks in November 2025 [53].

It would also be possible to deploy a Neutral Host between one or more public MNOs and a private network deployment. This could be done under either the MOCN or MORAN architectures depending on the commercial arrangements in place. By hosting a public MNO, a private network operator could look to subsidise their operating costs or provide additional services for customers from the same installed infrastructure. Further discussion on the wider role of private networks is provided in Section 2.2.4.

2.2.4 The Role of Private Mobile Networks

A growing number of businesses and organisations rely on wireless broadband to deliver products or services, either to customers or as part of in-house operations.

As mentioned in Section 2.2.3, improved hardware availability, and new spectrum access mechanisms, are enabling both MNOs and independent entities to provide customised, dedicated network deployments.

Typically, these deployments are leveraging 5G technology for the increased flexibility and improved technical performance compared to their 4G equivalents. Private networks are chosen for across multiple industries for use cases or applications where there are strict technical performance criteria, such as maximum end-to-end latency or minimum achievable throughput, that may not be practically delivered by the existing available public network deployments.

Certain markets or users may also have security concerns about the use of communal infrastructure and would prefer, or are required, to have greater control of managing their own networks and devices. For example, the US Department of Defence are noted as one of the largest consumers of private 5G infrastructure in the world [59].

Although the large MNOs are engaging in this space, as of July 2024 less than 30 fully operational commercial private networks had been deployed by the mainstream operators [34]. Of those, just over 10 of operated as 5G SA networks [34].

A significant number of non-MNO entities, such as equipment vendors, systems integrators, and specialist providers, are now also offering private network solutions. This could either be as a hardware sale, solution rental, or as part of a Network-as-a-Service (NaaS) subscription. Some are general purpose networks, while others are specific to certain market verticals. As discussed in Section 2.2.3.1, private networks may also be used as part of some Neutral Host architectures.

These independent network deployments, in the UK, almost exclusively make use of the shared spectrum mechanisms from Ofcom, discussed further in Chapter 3.

Examples of private network deployments as part of the 5G RuralFirst project are presented in Chapters 4 and 5.

The first 5G SA private network deployed in the UK by a non-MNO entity was in the Glasgow Underground as part of the 5G RailNext project, and is presented as a research contribution in Chapter 6 of this thesis.

2.3 Chapter Conclusions

This Chapter has reviewed 4G and 5G mobile broadband technologies to provide fundamental background information for the research contributions presented in this thesis.

Details on the architecture and operation of 3GPP 4G LTE and 5G NR networks are provided in Section 2.1. This includes an overview of the three main component sections: the UE; such as a mobile or CPE; the RAN, referring to the combination of eNB and gNB used to provide wireless coverage; and the Core network, following the ePC or 5GPC architectures to authenticate the users and enable connectivity.

Statistics from Ofcom's annual Connected Nations report are presented in Section 2.2 to highlight the current levels of availability for commercial mobile networks across the UK. In particular, it is evident that the current penetration of 5G SA networks is significantly lower than other cellular solutions.

Section 2.2 also included a progress updated on the SRN programme, which has resulted in documented improvement to availability of rural mobile connectivity.

Some of the associated challenges of network deployments, in rural areas and other underserved locations, are also discussed. As the CAPEX and OPEX of network infrastructure improves, along with increased access to spectrum as discussed in Chapter 3, the business case for deployments will improve and become more viable. This also creates opportunities for new network owners and operators to provide connectivity services through private networks. Examples of these kinds of deployments are presented in Chapters 4, 5, and 6.

Chapter 3

Shared and Dynamic Spectrum Access Mechanisms

The concept of shared spectrum has already seen significant regulatory and technical advancement in recent years. In particular, Dynamic Spectrum Access (DSA) mechanisms have been referenced extensively as part of publications from the UK regulator and government. Automated DSA technologies offer an alternative to static, pre-arranged sharing paradigms, and are an enabler for improved flexibility and efficiency in the spectrum licensing process.

Despite the similar nomenclature, the form of DSA discussed throughout this chapter should not be confused with implementations of Dynamic Spectrum Sharing (DSS) as defined by the 3GPP. Implementations of DSS, discussed further in Appendix B, are intended to facilitate network operators in the deployment of 5G NR coverage using existing LTE resources.

Instead, this chapter focuses on providing background information for two established techniques and technologies used to enable shared spectrum through automated DSA. This will provide context for the research contributions outlined throughout Chapters 4 and 5.

Section 3.1 provides an overview of TV White Space (TVWS), one of the earlier implementations of a licence-exempt DSA mechanisms, to provide regulatory and technical background.

Section 3.2 presents work carried out in support of a demonstrator network deployment on the Orkney Islands, which highlighted the technical and commercial viability of shared spectrum to enhance broadband coverage in remote rural locations.

Section 3.3 discusses the Citizens' Broadband Radio Service (CBRS), a DSA implementation currently exclusive to the United States of America. Details on the overall system architecture, key network components, and arrangement of the spectrum band is provided, as these are fundamental to the work discussed in Chapter 5.

Finally, Section 3.4 presents a brief overview of the Ofcom Shared Access Licence (SAL) and Local Access Licence (LAL) programme, introduced in 2019. These UK-exclusive mechanisms enable geographically-constrained spectrum usage, under certain defined conditions.

3.1 TV White Space in the UK

Analogue TV spectrum in Europe, as defined by the International Telecommunication Union (ITU), sits between 470-862 MHz as part of the ultra-high frequency (UHF) band. With the introduction of colour TV, this spectrum was split into 48 transmission channels of 8 MHz bandwidth. Initially, each TV broadcast used one of these available channels distributed geographically to provide country-wide coverage.

Following the analogue to digital TV switchover, completed across the UK in 2012, a number of programmes from the same operator were now multiplexed together within a single transmission channel. This greatly reduced the number of occupied channels within the TV frequency band, allowing for a much more efficient use of spectrum. These unused channels are known as "white spaces" – hence the term TV White Space (TVWS).

The TVWS DSA mechanisms were designed to target these spectral resources that were vacated following the Digital TV SwitchOver (DSO). Although an internationally developed and implemented shared spectrum solution, the work in this thesis primarily considers TVWS in the UK. This is intended to manage the scope of the research, while also reducing complexity with regards to potentially conflicting regulatory details.

Section 3.1.2 discusses the establishment of the UK TVWS regulations, starting with the DSO and 800 MHz spectrum auction, which both completed in 2012.

The development of these regulations lead to the design of an architecture to enable secondary user access to the spectrum in a manner that also facilitates spectral coexistence. This is outlined in Section 3.1.1.

Section 3.1.3 overviews further technical details of the UK TVWS regulations, focusing on power and spectral mask requirements for deployed WSD, as well as device classification and minimum functionality requirements.

A brief discussion on the currently implemented standards for a WSD air interface are presented in Section 3.1.4, with some further technical descriptions provided in Appendix B.

Finally, Section 3.2 presents work carried out in the development and deployment of a TVWS trial network across the Orkney Islands in the North of Scotland.

3.1.1 System Architecture and Operation

The Ofcom-developed architecture for enabling Secondary user access is shown in Figure 3.1.

White Space Devices (WSD) looking to opportunistically operate in the spectrum must first co-ordinate with a regulator approved White Space Database (WSDB). Upon receiving a request from a WSD, the database will begin calculating the usable power limits, based on parameters from the regulator and the requesting device. The database then returns operating conditions to the WSD that will minimise risk of interference to incumbent users.

Each WSD sends information on its geographic co-ordinates, the type of connection intended

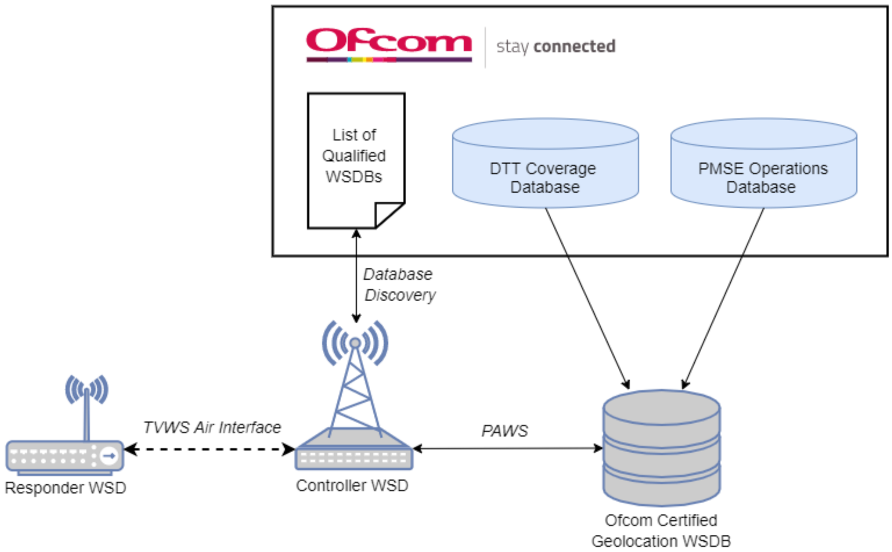


Figure 3.1: The Ofcom approved TVWS architecture [60]

and other parameters relating to the system, such as height of the transmitting antenna. The WSDB uses this information to calculate which channels the WSD should be able to operate in, and at what power levels. The WSD then reports back one of these channels to use, which can then be reflected in the WSDB's channel usage response for other requests. Communication between WSD and a database is typically carried out using the Protocol to Access White Space (PAWS), which is discussed further in Chapter 4.

The WSDB also defines a period of operation for those parameters, after which the WSD must transmit a re-request. Allocating parameters in this way helps minimise the risk of interference to licence holders and other secondary users in the vicinity. This also allows for transmission channels to be used by multiple WSDs simultaneously, as long as there is sufficient distance between known transmissions to avoid interference.

While the exact method required for calculating operating parameters varies according to the rules of the local spectrum regulator, the general process involves combining the supplied WSD details with known information on the spectrum licence holders operating in the requested location.

In addition to complying with local regulator conditions, each database should be product-agnostic to the requesting WSD. This means that the process of supplying the response should not differ among requesting hardware platforms or air interfaces used by the WSD.

3.1.2 Regulatory Development

In September 2005, the UK Government confirmed that the UK's analogue television signals would be switched off systematically between 2008 and 2012 [61]. Ofcom also launched the initial Digital Dividend Review (DDR) in 2005, to address the utilisation of the upcoming available spectrum [62]. Initial proposals were published in December 2006 [63]. After considerable stakeholder feedback and technical studies, these were incorporated into a statement in December 2007 [64]. As part of this statement, Ofcom announced that the majority of the interleaved spectrum would be reserved for PMSE users, and proposed a number of further potential applications for the band.

At WRC 2007, one of the passed resolutions included the allocation of mobile services to the 790—862 MHz range, referred to as the 800 MHz band, harmonised across ITU Region One [65].

In June 2009, Ofcom released a statement outlining their strategy to clear all DTT and PMSE transmissions from the range 790—862 MHz [66]. This would soon be the case across Europe, following the 2010 European Commission Decision regarding harmonisation conditions for the 800 MHz band, technical frameworks to prevent cross-border interference, and the condition that spectrum be released for usage by no later than 2015 [67].

The 800 MHz band was cleared of DTT and PMSE by the end of 2012, which coincided with completion of the DSO. The resulting frequency arrangement in the UK for UHF Bands IV and V, post-clearance and pre-auction, is shown in Figure 3.2.

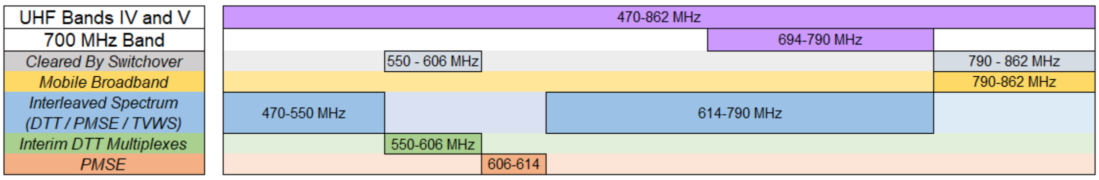


Figure 3.2: UHF Bands IV and V prior to the UK's 800 MHz spectrum auction.

While proceedings were ongoing regarding the spectrum auction of the 2.6 GHz band (2500—2690 MHz) and the newly vacated 800 MHz band, in parallel Ofcom also released a number of consultation documents regarding future usage of the Interleaved Spectrum. Specifically, Ofcom were looking at enabling shared spectrum access to the unused frequencies, or "White Spaces", within the Interleaved Spectrum.

In their December 2007 statement, Ofcom considered the concept of allowing licence-exempt operation for cognitive devices within the Interleaved Spectrum, provided sufficient protection could be given to neighbouring DTT and PMSE services. ETSI define a cognitive radio as *"a radio with learning capabilities, i.e. a radio able to obtain knowledge of the radio operational environment and adjust its operational parameters and protocols accordingly"* [68].

In a July 2009 statement [69], Ofcom concluded that a cognitive device operating in interleaved spectrum could use either spectrum sensing techniques or a geolocation database to determine channel availability in the vicinity. In a November 2009 statement, Ofcom acknowledged some of the discovered limitations of a fully spectrum sensing implementation. In particular, there were concerns regarding the extremely low level of sensing required by devices to minimise interference [70]. This then opened further discussion to implementations focusing on use of geolocation databases to enable DSA.

The proposed approach for the implementation of geolocation spectrum access was published in September 2011 [71]. This resulted in further consultations and technical proposals to determine coexistence requirements and frameworks for DTT and PMSE services, and on the practical requirements for a WSD [72], [73] such as emission masks and authorisation regime. Ofcom also began engaging with potential providers of geolocation databases at this time.

Following these consultations, in September 2014, ETSI published the European harmonised standard for WSD operation [74].

In mid-2014, a number of pilot technology trials were announced across the UK, involving a number of service providers and equipment manufacturers [75]. These trials enabled assessment of various parts of the TVWS frameworks, including the interaction between a WSD and a database. The Glasgow TVWS Pilot, detailed in Appendix A, was one of these approved technology trials.

Following conclusion of these trials, and concurrent coexistence testing and measurement research [76] [77], some amendments were made to the initial draft regulations. This culminated in the 2015 statement "Implementing TV White Spaces" [75], which came into effect as regulation at the very end of 2015 [13].

Under these regulations, devices compliant with the outlined DSA framework could operate within the interleaved spectrum on a licence-exempt basis, with no additional operating costs.

Following completion of the TV band clearance in 2017, carried out in preparation for the 700 MHz spectrum auction, the frequency range of the interleaved spectrum was to be changed. Therefore, the UK TVWS spectrum should be considered to be 470 — 694 MHz [75].

3.1.3 UK TVWS Regulations

The use of radio frequencies in the UK is governed by the Wireless Telegraphy Act [78]. This legislation contains regulation for a number of areas, including spectrum licences and the provision of DSA Services. The previously discussed WSD Exemption amendments were put into effect at the end of 2015. Under these regulations, devices and networks would be exempt from licensing legislation provided they meet the defined eligibility criteria.

The technical specification and requirements for TVWS network components, functional architectures, and high-level processes are dictated by ETSI controlled standards. These regulations are based on research and recommendations from the European Conference of Postal and Telecommunications (CEPT), the European regional organisation for postal and telecommunications issues. One such example is the harmonised European standard for essential requirements of WSDs [74], highlighted in Section 3.1.2, which cites CEPT ECC Report 186 [79] for the underlying methods and principles.

In these regulations, ETSI outline a number of key parameters for WSDs, with either conditional or unconditional conformity. This was done to allow for the creation of accompanying compliance tests, the methodologies for which are also defined within the standard. Some of the key WSD technical parameters are discussed below.

3.1.3.1 WSD Classification

One of the fundamental parameters is the characterisation of a WSD as either a *Controller* unit, also referred to as the *Primary WSD*, or *Responder* unit, also referred to as a *Secondary WSD*. To avoid confusion with the similar nomenclature used to distinguish tiers of spectrum users, this thesis will use the terms of Controller and Responder when describing operation of WSD, which is also the approach taken by Ofcom [80].

Controller units are transmitting devices that are capable of communicating directly with a geolocation database to obtain operating parameters. Responder devices, while still capable of transmission, do not communicate directly with a geolocation database but instead receive operating parameters via a connection to a Controller WSD. This architecture relationship is shown in Figure 3.1.

This functionality is described by the WSD control requirements specification:

- A Controller WSD cannot transmit in the absence of communications with an approved geolocation database.
- A Responder WSD cannot transmit in the absence of communications with a Controller WSD.
- Both Controller and Responder WSDs must configure intended transmissions in accordance with the parameters provided by an approved geolocation database.
- A Controller WSD must only obtain parameters from a database approved by the relevant national authority.

There is no formal ETSI standard for the protocol used for communication between Controller and Responder WSDs, or between WSD and WSDB. The de facto operation uses PAWS, discussed further in Chapter 4.

WSDs can be further categorised as either *Type A* or *Type B* devices. Type A units are intended for fixed location applications, and are able to use external, higher gain antennas. Type B devices can only use an internal or dedicated antenna, and as such are for non-fixed deployments.

3.1.3.2 WSD Spectral and Power Requirements

Under the ETSI standard, WSD operating bands coincide with the European harmonised DTT channel plan. A WSD may operate in a single 8 MHz DTT channel, or simultaneously across multiple channels. The *nominal channel* of a WSD describes the DTT channel, or section of contiguous channels, occupied by the wanted device transmissions. The maximum nominal channel bandwidth that can be occupied simultaneously by a WSD is also dictated by the serving geolocation database, which in turn is under the authorisation of the national spectrum regulator.

The RF power of a WSD, the mean Equivalent Isotropically Radiated Power (EIRP), is limited by the values specified by the geolocation database for that particular channel. Similarly, the RF Power Spectral Density (PSD) of a WSD is defined as the total RF power across a 100 kHz or 8 MHz granularity, and also dictated by the database response.

Along with the information on available RF powers, the database supplies the WSD with a time period for which the parameters are valid, and a separate timer dictating when the Controller device should verify parameters with the database.

Unwanted emissions are defined as any RF transmissions that occur outside of the WSD nominal channel. It is always important to limit the unwanted emissions of any wireless device, to minimise risk of interference with other devices. However, it is particularly relevant in the shared spectrum environment that WSDs are intended to operate in, to improve the protection of incumbent transmissions. The specification dictates limitations for emissions both inside and outside the 470-790 MHz band. For emissions outside the TVWS band, a table of limits for different frequency ranges is provided by the standard, varying between -30 and -53 dBm [60]. Further discussion of device emission requirements is provided as part of Chapter 4.

Any signal power outside the nominal channel bandwidth, but within the 470—790 MHz range, is referred to as out-of-block power, P_{OOB}. The acceptable spectral density of P_{OOB} for a WSD is limited by the TVWS standard. Conformance with this limit is dependent on the Adjacent Channel Leakage Ratio (ACLR). Each WSD is allocated a Device Emissions Class by the Original Equipment Manufacturer (OEM) depending on the measured ACLR. This emissions class parameter is included in the information sent to the geolocation database to determine the power usable within the nominal bandwidth. WSDs with more stringent emission masks are afforded greater available power than those with more relaxed implementations, due to the reduced risk of causing interference.

3.1.4 TVWS Operating Standards

A number of standards have been developed that dictate the operation, or interoperability requirements, of TVWS network equipment [81].

A number of these have been developed by working groups set up by the Institute of Electronic and Electrical Engineers (IEEE), either as new publications or as amendments to existing standards.

Some examples of these include those published by the IEEE Dynamic Spectrum Access

Network Standards Committee (DYSPAN-SC) under the IEEE 1900 working group family. The seven associated standards cover a number of topics across the fields of dynamic spectrum and cognitive radio [82], [83].

Other standards are covered by the IEEE 802 family, which define operation of Local Area Network (LAN), Metropolitan Area Network (MAN), and Personal Area Network (PAN). Some examples of TVWS-specific publications include the IEEE 802.22 and 802.11af standards, which both support methods of spectrum sharing through implementations of geolocation database requests and cognitive sensing techniques. Further details on both of these is included in Appendix B.

Some existing standards within the IEEE 802 family have also been issued with amendments to incorporate TVWS-related features; including IEEE 802.16h, 802.15.4m, and 802.19.1 [81].

In addition to publications by the IEEE, standards organisation Ecma International released the ECMA-392 specification in 2012 [84]. This standard defines media access control (MAC) and physical (PHY) layers for portable cognitive wireless TVWS networks and a number of incumbent protection mechanisms.

However, a standard does not necessarily need to be designed explicitly for operation with TVWS to be used in the frequency range, provided the implementation is compliant with the regulatory conditions. This topic is discussed further in Chapter 4, which outlines research contributions assessing the feasibility of using the 3GPP LTE wireless standard under the ETSI-defined deployment conditions for TVWS operation.

3.2 TVWS Trials in the Orkney Islands

The Centre for White Space Communications (CWSC) was established in 2011, with funding from the Scottish Funding Council. The Centre is hosted at the University of Strathclyde, where the inaugural event was held in January 2013 [85]. The CWSC has engaged with industry, academic, and public sector partners to deliver shared spectrum projects across the UK in both rural and urban environments. Information on TVWS projects completed on the Isle of Bute and the University of Strathclyde Campus in Glasgow can be found in Appendix A.

In 2015, the CWSC and a number of project partners, including SFT and CloudNet IT Solutions, began the development of a trial network in the Orkney Islands. The project, funded by the Scottish Government, looked to build on existing installations to create a rural TVWS testbed, and validate the use of TVWS and spectrum sharing techniques in deep rural locations.

Orkney is a particularly geographically challenging location, with a large number of small inhabited islands, mountainous terrain, significant coverage area, and long distance from the Scottish mainland, all of which impact on the installation of both wired and wireless backhaul networks.

The following section presents research contributions completed in support of the Orkney

TVWS trial. This included equipment characterisation as part of in-lab bench tests prior to in-field deployment, and the assessment of network infrastructure performance following installation.

3.2.1 Project Overview

The project aimed to demonstrate the commercial viability, reliability, and overall performance of TVWS and shared spectrum as a backhaul technology for two simultaneous applications, and to assess if similar solutions could be used to support the Scottish Government's connectivity initiatives.

TVWS was used to provide broadband connectivity to passengers and crew on three ferries during voyages between islands. Based on population data at the time of the trial [86], [87], [88], around 20% of the archipelago population were resident on the non-mainland islands. Even before accounting for any visiting tourists, this represents a significant number of people reliant on these kind of services and who would benefit from the additional connectivity resources.

The same network installation was also used to simultaneously provide connectivity to six fixed premises, located in rural locations around the Orkney mainland. None of these premises had the existing capability of achieving superfast broadband connectivity, but were also outwith the scope of any imminently scheduled infrastructure installation plans or intervention programmes.

The installed topology can be seen in Figure 3.3. The main network node is located at Wideford Hill, near the main settlement and ferry port at Kirkwall. This multi-use tower was fitted with two TVWS basestation units, multiplexed onto a single antenna, with further microwave radios for additional Point-to-Point (P2P) connectivity. These microwave links connected both to other network sites and to a data centre at Ayre of Cara, enabling connectivity to the wider Internet.

In addition to routing the entire backhaul for the network, the TVWS radios at Wideford also provided connectivity directly to three of the fixed premises and also over the three ferry routes.

Four other TVWS basestation sites were established at various locations around the islands. Two of these, at Sanday and Westray Pier, were used to provide additional coverage over the ferry routes, providing connectivity at distances of up to 19 miles. Omni-directional antennae were used for the TVWS links to compensate for variation in the orientation and bearing angle of the ferries during voyages.

The remaining two sites, at Sandy Hill and Power Station, were used to supply broadband access to three additional fixed premises. Each site was established with both TVWS and microwave radios, for coverage and additional backhaul respectively. For the Power Station site, an additional node was established at Keelylang to relay back to Wideford. These deployments

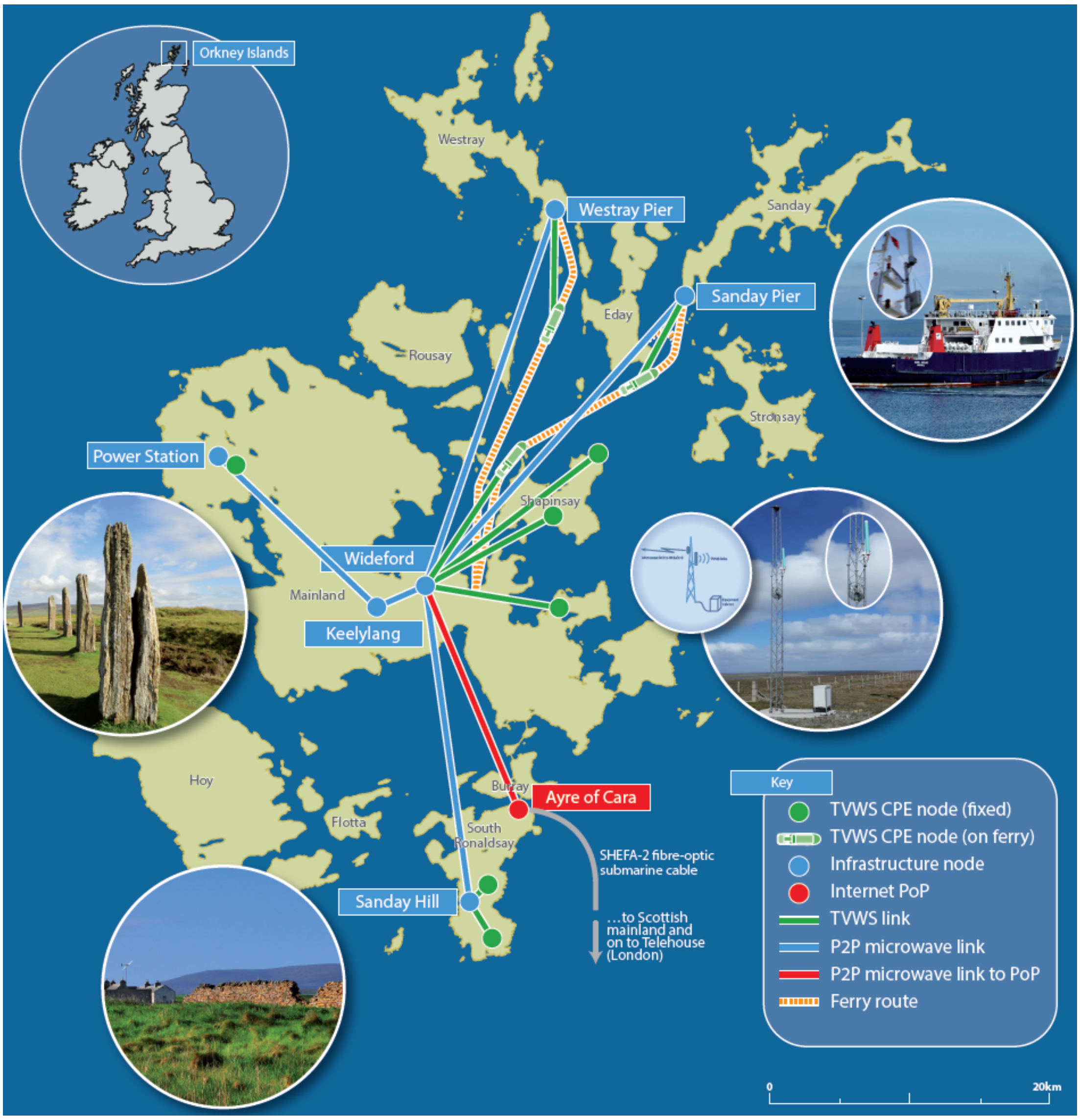


Figure 3.3: Network diagram for the Orkney Nomadic TVWS installation.

used directional antennae to maximise the received signal strength.

Each of the ferries was provided with a client unit, connected to a Wi-Fi AP in the passenger lounge. The client and omni-directional antenna were pole-mounted externally with a Power Over Ethernet (POE) connection to a network switch below deck.

A similar configuration was used at each of the fixed premise sites, however since location and orientation were constant, directional antennas could be used there to facilitate larger antenna gains. As with the Glasgow network installation, discussed further in Appendix A, variations of transmit power, receiver gain, and antenna gain were used to maintain appropriate received signal strength.

Two generations of TVWS radios from 6Harmonics were deployed in the network [89], all connected with database services provided by Fairspectum Oy [90]. Versions of the GWS3000, GWS3008, GWS4008, and GWS4016 WSD, were supplied for use in the network.

All of the deployed radios used a modified version of the IEEE 802.11g/n WLAN standard due to the lack of availability of 802.11af chipsets. This allowed for a theoretical data rate of 26 Mbps per 8 MHz channel, using 64 QAM 5/6 modulation. The GWS4016 units were able to make use of channel bonding techniques, discussed further as part of Appendix B, to allow for 16 MHz of channel bandwidth and therefore a peak data rate of 52 Mbps.

3.2.2 Laboratory Testing and Results

Bench tests performed at the University of Strathclyde, by the author, allowed for initial assessment of practical equipment performances. These tests measured the achievable Modulation and Coding Scheme (MCS), Signal to Noise Ratio (SNR), Received Signal Strength Indicator (RSSI), latency, and data throughput across different channel attenuation levels.

A diagram showing the set-up for these evaluations is provided in Figure 3.4. Corresponding same-generation basestations, referred to as *CAR* units, and client stations, referred to as *EAR* units, were connected in a P2P topology using RF cabling. Fixed and variable attenuators were inserted in series to allow for controlled variation and emulation of transmission channel conditions. A non-attenuating coupler was also inserted to enable a signal analyser deployment at the EAR unit. Parameters for the radio tests are included in Table 3.1.

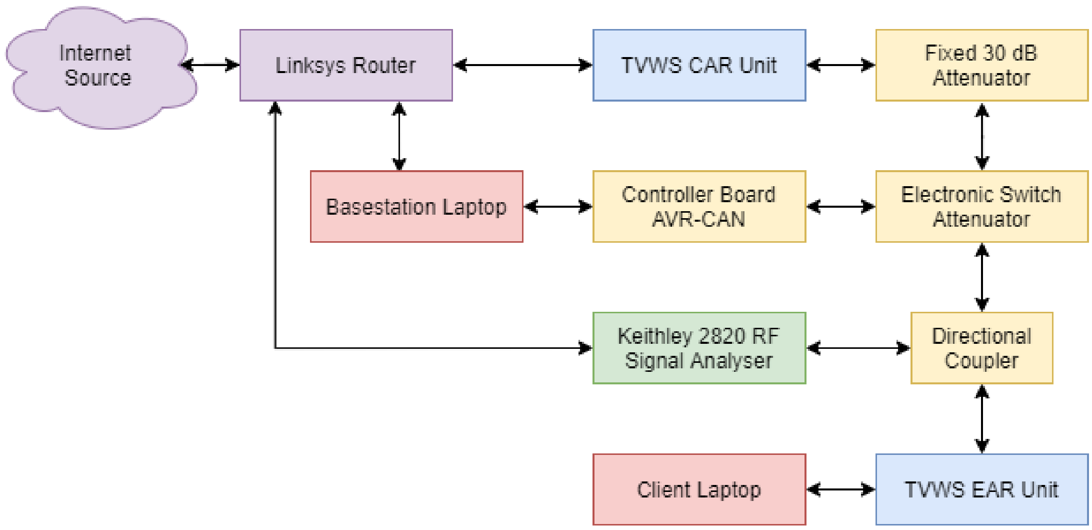


Figure 3.4: Lab set-up for the performance assessment of the TVWS equipment used in the Orkney trial.

Values for MCS, SNR, and RSSI were taken for both EAR and CAR units from their respective Command Line Interfaces (CLIs). Latency measurements were calculated as the average response from the ping utility. Throughput measurements were taken using an online resource, requested from the EAR unit to ensure connection takes place over the RF link, and through the iPerf software [91]. The latter is likely a better representation of the link and

Unit	**GWS3000**	**GWS3008**	**GWS4008**	**GWS4016**	**GWS4016**
CAR Tx Power	18 dBm	18 dBm	18 dBm	17 dBm	17 dBm
CAR Rx Gain	0 dBm	0 dBm	12 dBm	0 dBm	0 dBm
EAR Tx Power	18 dBm	18 dBm	18 dBm	17 dBm	17 dBm
EAR Tx Gain	0 dBm	0 dBm	0 dBm	0 dBm	0 dBm
Bandwidth	8 MHz	8 MHz	8 MHz	8 MHz	16 MHz

Table 3.1: Experiment parameters for the TVWS radio performance assessment.

equipment performance, as this removes the additional effects of the EAR's backhaul connection through the University network to the Internet.

Short scripts were created to automate the iPerf functionality, which allowed for bi-directional measurement of Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) throughput over the RF link. Extracts from the completed tests for the GWS4016 units are included in Table 3.2. These results show that, for a base and client RSSI of approximately -50 dBm, the link throughput peaked at around 20 Mbps and 40 Mbps for 8 MHz and 16 MHz channels, respectively.

8 MHz				**16 MHz**			
RSSI (dB)	SNR	DL TPut (Mbps)	UL TPut (Mbps)	RSSI (dB)	SNR	DL TPut (Mbps)	UL TPut (Mbps)
-47	52	20	20.6	-49	48	41.3	39.8
-52	48	19.7	20.4	-55	43	41.1	40.1
-60	41	20.3	20.5	-60	37	41.4	40.1
-64	37	20.1	20.3	-65	33	40.7	37.7
-69	32	19.9	20.1	-72	27	37.8	28.6
-75	26	15.4	19.4	-76	23	23.6	20.8
-80	22	11.3	11.5	-81	17	15.3	12.2
-84	17	7.6	6	-86	13	10.7	8.22
-89	14	5.6	3.9	-92	7	2.94	3.26
-94	9	1.6	1.57	-93	5	N/A	N/A

Table 3.2: Extract of the bench test results, highlighting the performance of the GWS4016 radio.

The RSSI values presented in Table 3.2 represent a range that would be practically achievable in network deployments. These correspond to an achievable throughput of 10-20 Mbps for an 8 MHz channel, and 15-40 Mbps for a bandwidth of 16 MHz. This throughput would be sufficient to satisfy the Government's requirements of 10 Mbps for what is termed as *Decent* broadband connectivity [92].

While the in-field performance would be dependent on a number of factors, as seen from the network installation on Bute discussed in Appendix A, these tests allowed for performance approximation to aid network design and planning, particularly for configuration of transmit power and gain to maintain the desired RSSI values.

3.2.3 Network Testing and Results

Because installations on the ferries could only be carried out during docked maintenance periods, which only happened on one occasion at the very onset of the project, GWS3000 radios were used for the duration to supply connectivity to the ferries.

Following installation, the tests for latency and throughput described previously were repeated for over-the-air transmissions on the live network. These tests were carried out during a voyage from the Orkney Mainland to Sanday Island. This route can be seen in Figures 3.3 and 3.5, which has a round-trip duration of three hours.

Co-ordinates of the ferry location at measurement points during the journey were taken from a live-updating marine traffic map, shown on Figure 3.5. The results gathered at denoted points A—K are included in Figure 3.6 and Table 3.3.

While assessing the TVWS connectivity performance, it was noted that it was generally not possible to perform simultaneous measurements for the commercial mobile networks due to a lack of consistent availability.

When departing from Kirkwall Harbour, the EAR would be connected directly to the CAR unit at Wideford Hill. As the distance from mainland increased, the received signal strength was seen to fall below a usable threshold, and the EAR began scanning to find an alternative CAR, likely the one located at Sanday Pier. As the EAR reports the networked IP address of the connected CAR unit, the serving EAR at each measurement point can also be determined. Combining this information allows the distance between EAR and CAR to be approximated.

System throughputs were measured using the iPerf network tool, while latency was assessed by observing the mean time difference between Internet Control Message Protocol (ICMP) echo requests and responses, generated by the network standard *ping* utility.

Results from the tests performed onboard the MV Varagen ferry are shown in Figure 3.6 and Table 3.3. Results show that data rates of over 5 Mbps were recorded at connection distances exceeding 15 km.

Handoff, the IEEE 802.11 process where a client device issues disassociation and association frames to serving devices to enable connectivity handover, was not able to be properly established on any generation of the 6Harmonics equipment. This resulted in temporary interruption to the end user services. From the EAR CLI, it was determined that the CAR changes occurred around measurement point E during the voyage.

The drop in performance at measurement point H has been attributed to the surrounding landscape and foliage temporarily blocking portions of the communication link. While TVWS is less dependent on LoS than other technologies, due to its wavelength properties, there is still a chance that significant obstacles can cause disruption. The lack of LoS path is particularly impactful in this specific deployment scenario, as there is minimal multi-path propagation to compensate for obstruction in the direct path, and the EAR unit is non-stationary.

Figure 3.5: Route of the MV Varagen during a 3-hour round-trip voyage from Kirkwall harbour. Noted measurement points correspond to collection locations for data shown in Figure 3.6 and Table 3.3. After Point K, ferry returns to Point F and travels reverse alphabetically to harbour.

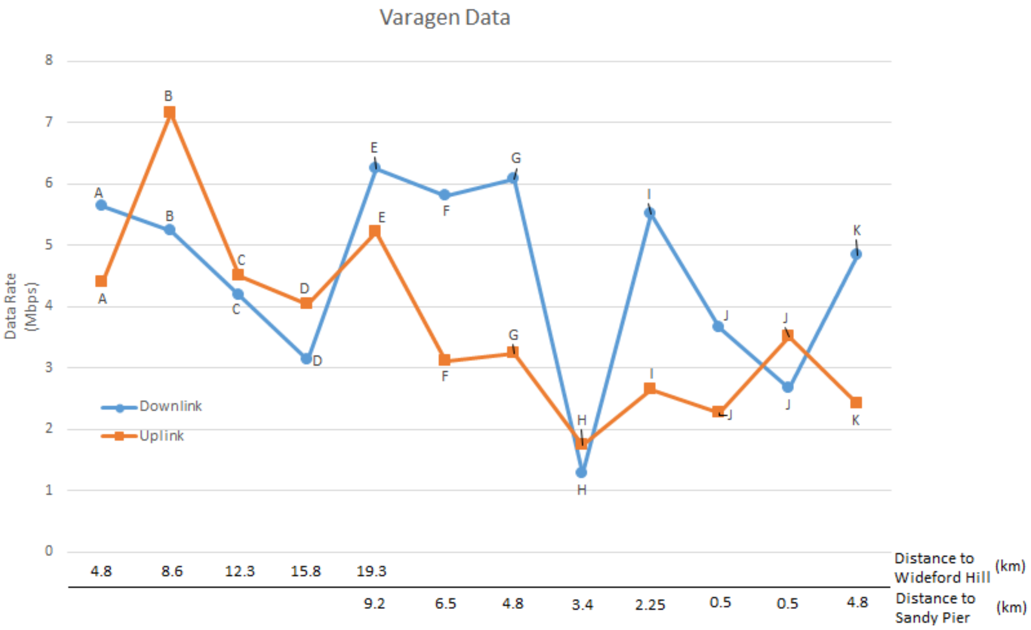


Figure 3.6: Results of throughput assessment relative to distance from associated CAR unit.

Measurement Point	**Downlink** (Mbps)	**Uplink** (Mbps)	**Serving CAR Unit**	**Distance To CAR Unit** (km)
A	5.64	4.39	Wideford	4.8
B	5.23	7.16	Wideford	8.6
C	5.64	4.39	Wideford	12.3
D	3.14	4.03	Wideford	15.8
E	6.26	5.21	Wideford Sanday Pier	19.3 9.2
F	5.8	3.11	Sanday Pier	6.5
G	6.09	3.24	Sanday Pier	4.8
H	1.28	1.74	Sanday Pier	3.4
I	5.51	2.65	Sanday Pier	2.25
J	2.67	3.52	Sanday Pier	0.5
K	4.84	2.41	Sanday Pier	4.8

After Point K, ferry returns to Point F and travels reverse alphabetically to harbour

Table 3.3: Results of throughput assessment relative to distance from serving CAR unit.

Performance of the installed fixed premise links was also assessed through iPerf throughput tests. While the achievable data rates were dependent on a number of factors, such as terrain profile over the link, throughput of up to 30 Mbps was achievable at some locations through use of channel bonding.

3.2.4 Research Impact

The aim of the Orkney project was to demonstrate the technical and commercial viability of TVWS and shared spectrum to enhance broadband coverage in remote rural locations. The Orkney testbed was used to provide the benefits of Internet access to the local community, and was deployed in areas where there were limited, or no, other connectivity options.

As noted in Section 3.2.3, during the assessment round-trip voyage there were availability issues while attempting to connect to the commercial mobile networks. This connectivity challenge would be well-known to the large number of Orkney residents reliant on the ferry services for intra-island travel.

The three on-board Wi-Fi APs in the passenger lounges of the ferries were accessed to provide usage statistics. Over 1000 unique Wi-Fi clients were recorded on the network across a one month period, with an average of 70-80 devices connected per day. Assuming that unique clients are approximately equivalent to unique users per month, this means that this part of the network was serving around 5% of the Orkney population each month [93].

Residents in the fixed premises were also issued with surveys to establish the impact of the installed network. The most common uses for the connectivity were for personal and recreational usage, although some residents took advantage of the connectivity to create new businesses and increase their working efficiency through improved access to online services. This highlights the importance of good connectivity for small businesses, particularly for those in deep rural locations.

The Dynamic Spectrum Alliance, a global cross-industry organisation focused on promoting shared spectrum [94], presented the CWSC with the *"Award for a Student-Led initiative or Research on New Opportunities for Dynamic Spectrum Access"* at their 2017 Global Summit in recognition of the success of the Orkney TVWS project [20].

As the project was funded by the Scottish Government, the results of the demonstrator deployment were reported directly to the devolved authority for rural affairs in Scotland. This increased the visibility of key findings to senior policy makers in Government.

The Orkney testbed location was later revisited as a fundamental part of the 5G RuralFirst (5GRF) project, discussed further in Chapter 5, as part of the DCMS 5G Testbed & Trials programme. 5GRF continued the development of rural broadband connectivity in the area, building heavily on the infrastructure and community relationships that were established as part of the Orkney TVWS pilot.

3.3 Citizens Broadband Radio Service

In 2012, the Federal Communication Commission (FCC) proposed a total of 150 MHz, previously held by the US government, between 3550-3700 MHz be made available for commercial usage. To accompany this, initial proposals for CBRS were developed to enable shared spectrum access to the band and formally adopted in 2015 [95]. The CBRS band was authorised for full commercialised operation at the beginning of 2020 [96].

As with TVWS, the implementation of CBRS-compliant private networks can reduce the CAPEX of deployments by reducing the cost associated with larger scale spectrum licences.

An overview of the CBRS spectrum band and associated operational architecture is given in Section 3.3.1. These technical details will provide context for some of the later development activities discussed in Chapter 5.

In January 2020, the FCC certified four SAS administrators – Google, Sony, CommScope, and Federated Wireless – to authorise full commercial services in the CBRS band [96]. This regulatory update, combined with the 2020 PAL auction discussed in Section 3.3.2, fully enabled the deployment of private mobile networks for potential new services and applications.

One of the most prolific developments in this area is the Network-As-A-Service (NaaS) offering from Amazon announced in December 2021 [97]. Leveraging Amazon Web Services (AWS) to provide a core network and a RAN management platform, the default supported spectrum option in the United States is the CBRS band. At time of writing, this product is primarily being targeted for smart manufacturing applications and those that require low latency, such as virtual reality.

3.3.1 CBRS Overview and Solution Architecture

CBRS uses a multi-tiered authorisation framework for DSA, with three defined levels of priority for spectrum access. Users in the highest tier, those with *Incumbent Access*, are protected from any interference caused by those with lower level access. In CBRS, this authorisation is given to federal government transmissions and fixed satellite services.

The lowest spectrum access tier defined in CBRS is *General Authorised Access* (GAA). GAA users under CBRS are comparable to the Secondary users in the TVWS regulations. Compliant operation must obey specifically calculated operating parameters, and GAA operators receive no interference protection or QoS guarantees.

The middle tier of users, those with *Priority Access* (PA), receive a licence for a specific geographic area. This provides interference protection guarantees from GAA users, but not from the transmissions of Incumbents. While a Priority Access Licence (PAL) provides authorisation within a defined location, referred to as a PAL Protection Area (PPA), the exact operating frequencies are not explicit. Specific channels for Priority Access users are dictated by a Spectrum Access System (SAS), which also allocates operating parameters for GAA users.

The functional architecture of CBRS is shown below in Figure 3.7.

The SAS, similar to a TVWS WSDB, accounts for information received from an FCC database of currently valid PALs, the Incumbent Informer, the Environmental Sensing Capa-

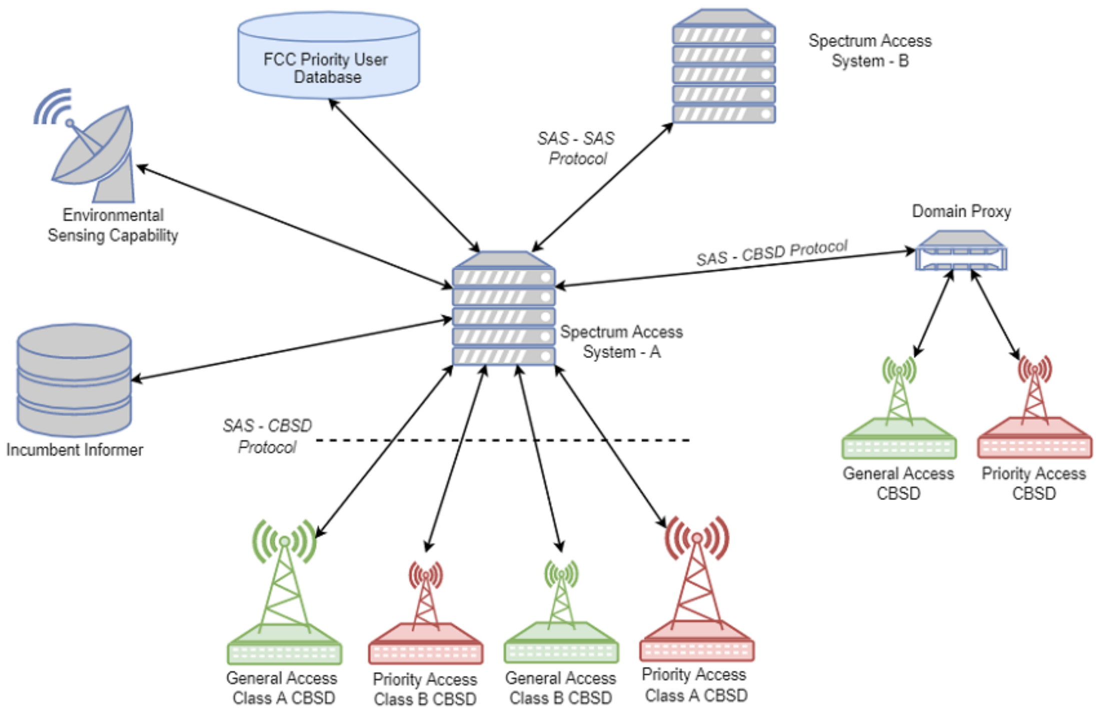


Figure 3.7: CBRS Functional Architecture [98].

bility (ESC) entity, and details on local terrain, among other parameters, to calculate operating conditions for a requesting CBRS device (CBSD). All CBSDs must be certified and registered with a SAS before being authorised for operation in the spectrum band [98].

The ESC uses cognitive spectrum sensing to detect the presence of Incumbents and PAL holders within the serving PPA, and communicate this information to a SAS [99]. The SAS then ensures that appropriate protection is established, including sending requests to CBSDs to vacate operating channels. The ESC provides the SAS with information on the frequencies which require the highest level of protection.

Additional sensing information from these entities is fed back to the SAS to be accounted for as part of the CBSD frequency allocation. Information on the frequency bands allocated to secondary users is stored in the Incumbent Informer, and is used to monitor the network utilisation and authenticate users. Even though the SAS receives information from the FCC database, for security reasons it does not include sensitive details on Incumbent transmissions. Therefore, the ESC and Incumbent Informer are required to ensure the accuracy of Incumbent information.

The Domain Proxy (DP) is an optional component in the framework. The DP is a logical entity that can engage with the SAS on behalf of potentially multiple CBSDs, while also operating as a translation unit for legacy systems that operate in the band.

Following the 2015 regulation finalisation, members of the Wireless Innovation Forum (WInnForum) established the Spectrum Sharing Committee to create a number of baseline standards for CBRS deployments covering multiple different areas.

One of the critical developments was the WInnForum SAS test specification, WINNF-TS-0065 [100], and associated open source test harness to assess compliance, to facilitate SAS certification [101]. The test harness was turned over to the National Telecommunications and Information Administration (NTIA) in May 2018 [102].

An important aspect of compliance with the test harness is implementation of the WInnForum standards that outline the technical requirements for inter-system communication. In addition to protocols for interaction between a SAS and CBSD [103], there is an additional protocol for SAS-to-SAS communication which enables exchange of spectrum usage data to manage interference [104]. The SAS-CBSD protocol will be discussed further as part of Chapter 5.

3.3.2 Operating Spectrum and 2020 PAL Auction

The CBRS band is divided into two portions, with different levels of availability. The portion 3550-3650 MHz is further divided into 10 MHz channels. Of these, a maximum of seven channels can be used at any one time in a PPA by users with a PAL. Any unused spectrum in this range is also then made available for GAA users.

The portion 3650-3700 MHz is also allocated for authorised GAA usage, but not made available for PAL access. This means that at least 80 MHz of spectrum can be accessed through GAA mechanisms within any PPA, although depending on PAL uptake this could be as much as 150 MHz. This spectrum arrangement is shown in Figure 3.8, which also highlights the relationship with 3GPP-defined Band 48.

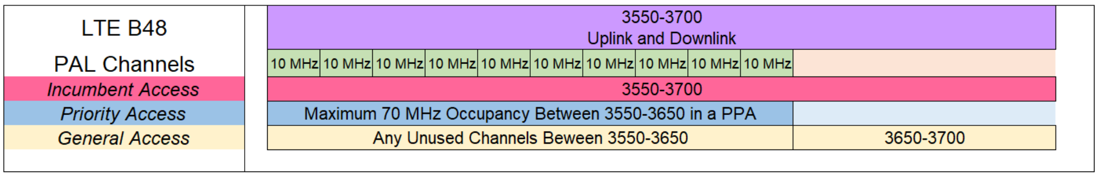


Figure 3.8: The CBRS (3550-3700 MHz) frequency band

While a PAL provides authorisation for use of one or more channels within a PPA, the exact operating frequencies are not defined. Specific channels for Priority Access users are dictated by the SAS, which also allocates operating parameters for GAA users.

Following a short delay, caused by the COVID-19 pandemic, the FCC concluded the CBRS PAL auction in August 2020 [105]. *Auction 105* offered the largest number of licences ever in a single auction across the 3550-3650 MHz range [106].

With 7 PALs available in 3233 counties, that meant 22,361 licences across the United States, although bidders were limited to a maximum of 4 PAL per PPA. The standard terms had licence validity period of 10 years and were subject to build-out obligations, with support for secondary market options such as leasing or sale [106].

At auction conclusion, over $4.5 billion in gross proceeds had been raised, with over 200 winning bidders from a number of different market verticals [107]. While large communication companies, such as Verizon and Dish Network, and smaller Internet Service Providers (ISPs) were expected as auction participants, other licence winners included utility providers looking to establish private networks for their own use-cases. One such example of this is Alabama Power, who spent over $18 million to secure 271 PAL [108].

3.4 Ofcom Shared Access and Local Access Licensing

In December 2018, Ofcom released a consultation outlining two key proposals to enable shared spectrum in the UK [109]. The aim of these changes was to promote innovation and enable new services by allowing access to frequency bands with an existing, developed equipment ecosystem.

Some of the provided example applications included deployment of private networks for coverage and IoT solutions, rural broadband and FWA services, and to address indoor or outdoor connectivity not-spots.

Under the proposed changes, new users would be able to apply for a localised licence in defined shared access bands, and additionally would be entitled to appeal for access to any band previously awarded at spectrum auction. These changes were finalised in a July 2019 statement [9], with applications for access to the shared bands beginning in 2020.

This section will briefly overview details for both the “Shared Access Licence” (SAL) and the “Local Access Licence” (LAL) spectrum access mechanisms.

3.4.1 Shared Access Licence Overview

In the UK, shared licence access has been allocated to the 1800 MHz , 2300 MHz, and 3.8-4.2 GHz bands on a first-come first-serve basis. A portion of 26 GHz spectrum has also been designated as a shared band, for indoor use only. These bands will be reviewed in the following subsections.

3.4.1.1 The 1800 MHz, 2300 MHz and 3.8-4.2 GHz Bands

The “three shared access bands” refer to the frequency ranges 2390-2400 MHz, 3800-4200 MHz, and 1781.7-1785 MHz paired with 1876.7-1880 MHz. These frequency ranges overlap with standardised 3GPP operating bands for LTE and 5G NR.

The available 1800 MHz spectrum is covered by LTE Band 3 and NR Band 3, as shown in Figure 3.9. These FDD arrangements span a total of 1710-1880 MHz. Each band specifies 75 MHz allocation for uplink transmission, in the range 1710-1785 MHz, and downlink transmission, in the range 1805-1880 MHz. However, while the minimum channel bandwidth in LTE B3 is 1.4 MHz, in Band N3 the minimum is 5 MHz, making it ineligible for operation under this framework. The minimum bandwidth allowed by the framework in this band is 3.3 MHz.

The 2300 MHz spectrum is covered by TDD arrangements in LTE Band 40 and NR Band 40, both spanning 2300-2400 MHz, as shown in Figure 3.10. The minimum channel bandwidth supported in both bands is 5 MHz, which make both applicable candidates for compliant deployment, although the carrier bandwidth that can be used under the sharing framework in this band is strictly 10 MHz.

Finally the 3800-4200 MHz spectrum is covered by NR Band 77, which is also a TDD arrangement, as shown in Figure 3.11. There are currently no defined LTE bands that overlap with this frequency range. Although other options are available in the technical standard, the sharing framework only permits carrier bandwidths of 10, 20 30, 40, 50, 60, 80, and 100 MHz.

New users can receive access to these bands for network deployments by submitting a request to Ofcom for a localised licence. Applications are handled on a first-come first-served basis, with a common approach for all three bands, and two types of licences offered. The annual fee for each licence is set to cover Ofcom's administrative costs of managing the spectrum. Once a licence has been acquired, applicants have 6 months to utilise the spectrum before the award is revoked, and must make continuous use from that point onwards.

Lower power licences are offered for a geographic area, with a radius of 50 m around a specified centre location. Any number of basestations can be deployed within this area. Coverage for larger areas would require acquisition of multiple licences, and it is up to the licensee to determine if the coverage areas should overlap, to allow for nomadic end user devices. The 2300 MHz band is only available for indoor deployments, while the 1800 MHz and 3.8-4.2 GHz bands facilitate indoor and outdoor coverage. The maximum basestation power available under a low power licence is 24 dBm per carrier, with different power level limits for end user devices in each band.

Medium power licences are issued per basestation installation, and limited to rural locations due to the higher permitted power levels. The maximum power that can be used by a basestation is 42 dBm per carrier, for bandwidths equal to, or less than, 20 MHz. For operations in larger bandwidths, only applicable to the 3.8-4.2 GHz band, the power is limited to 36 dBm per 5 MHz.

There are some exceptions specifically applicable to 3.8-4.2 GHz operations. Under a medium power licence, the end devices are limited to fixed location units and cannot be nomadic. In addition, all transmitting equipment must be relatively flexible in its operating frequency, for the purpose of spectrum planning and interference mitigation. Finally, 3.8-4.2 GHz deployments are not subject to the antenna height limit of 10 m above ground level that is applied to the other bands.

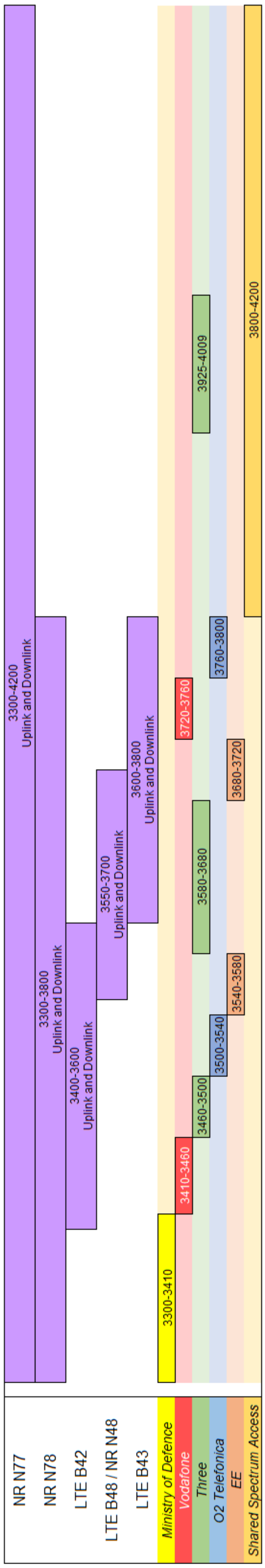


Figure 3.9: The 1800 MHz frequency band.

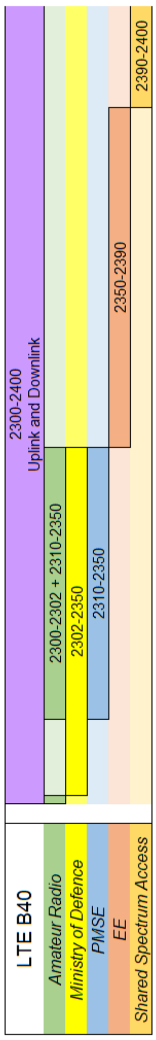


Figure 3.10: The 2300 MHz frequency band.

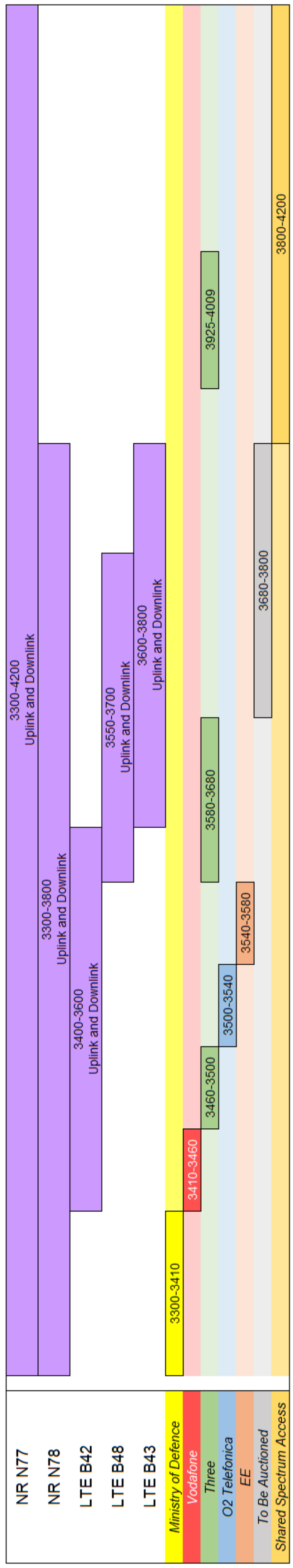


Figure 3.11: The 3300-4200 MHz frequency band.

3.4.1.2 The 26 GHz Band

Between the December consultation [109] and July statement [9], the lower portion of the 26 GHz band was added to the sharing framework. This mmWave band has been harmonised across Europe, and under a European Commission decision. This framework allows for access to 2.25 GHz of spectrum between 24.25-26.5 GHz, for indoor applications.

While the full 26 GHz band, 24.25-27.5 GHz, overlaps with multiple 3GPP-defined NR bands, as shown in Figure 3.12, the spectrum covered by this framework only covers NR Band 258. This TDD arrangement spans the 24.25-27.5 GHz range and allows for channel bandwidths of 50, 100, 200, or 400 MHz, although the latter is not permitted under the sharing framework.

Users can apply for a licence in the same way as any other shared access band. When allocating spectrum, Ofcom will account for the operations of other spectrum users in the band, such as radio astronomy sites. The annual licence fee is fixed, regardless of requested channel bandwidth, and once a licence has been received the spectrum must be utilised within 6 months.

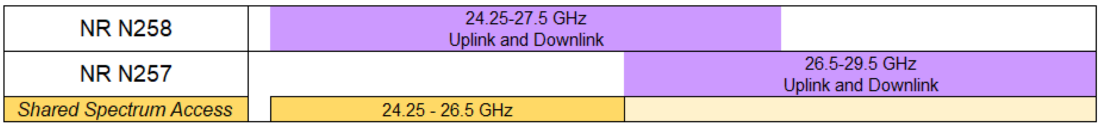


Figure 3.12: The 26 GHz frequency band

The LAL mechanism enables new users to access spectrum covered by the Mobile Trading Regulations, but only in areas where it is not currently being used, or is being planned for use, by the national licence holders within a 3-year period. This creates a shared access method for the 800 MHz, 900MHz, 1400 MHz, 1800 MHz, 1900 MHz, 2100 MHz, 2300 MHz, 2600 MHz, and 3.6 GHz bands. This framework is designed to create a simplified approach for new users, without placing constraints on the existing national licence holders.

Under this approach, users can apply directly to Ofcom for short-term access to specific mobile frequencies that are not being used in a given location by the Incumbent user.

Applicants must provide technical details of the proposed deployment, and supporting justification that the spectrum is not being used in that area. The application could cover a single basestation deployment, or operations across a wider area. Ofcom then assesses the impact of introducing a new user in that location, considering the amount of requested spectrum, the proposed location, and the supplied technical parameters. Once these initial checks have been passed, Ofcom engages with the relevant Incumbent licence holder to inform of the potential supplementary user operation.

If the licence holder raises a reasonable objection, then the application could be declined. This could be because of existing or planned deployments in the area, or that the proposed application would cause harmful interference. If the Incumbent agrees that the applicant's deployment does not adversely impact their planned use of the spectrum, then a Local Access Licence would be issued by Ofcom. If a reasonable objection is raised by the Incumbent, Ofcom will try to mediate a compromise, which could include commercial terms to enable access or reduced licence period for the applicant. As new bands are introduced into the Mobile Trading Regulations, these will also included under the framework. However, newly awarded bands would not be eligible for a significant period to give the licence holders time to determine deployment strategies.

3.5 Chapter Conclusions

This chapter has discussed two established automated shared spectrum access mechanisms that implement DSA to provide context for the research contributions outlined in Chapters 4 and 5.

Section 3.1 introduced TVWS, a regulatory framework that was designed and implemented to enable DSA in the spectrum vacated following the DSO. This included a regulatory and technical background, as well as a review of the solution architecture.

This section also described work carried out in support of a demonstrator deployment on the Orkney Islands to highlight the technical and commercial viability. A TVWS network was used to provide connectivity for ferries and premises around the archipelago. The author's contributions to this project included pre-installation equipment evaluation and post-installation network performance measurement.

Providing Internet access to the, otherwise unserved, ferry passengers and crew as part of the Orkney TVWS pilot highlights the potential for independently deployed wireless networks as a candidate solution for localised connectivity challenges. The research activities presented in this chapter, testing and evaluating TVWS equipment in the lab and field, was instrumental to the success of the pilot project.

Section 3.3 discussed the CBRS regulatory framework, a multi-tier DSA mechanism that provides different levels of transmission protection. Details on the overall system architecture, key network components, and arrangement of the spectrum band were provided as these are fundamental to the work discussed in Chapter 5.

Although conceptually similar, TVWS has not seen the same widespread commercial adoption as CBRS — in the United States or elsewhere. However, the scale and success of the 2020 PAL auction is a testament to the wider demand for private wireless solutions.

Finally, Section 3.4 provided an overview of the SAL and LAL policies introduced by Ofcom in 2019. These shared spectrum mechanisms facilitate geographically constrained frequency access for users to deploy private networks in support of multiple use cases. Without access to these frameworks, it would be extremely challenging for operators to deploy commercial private mobile network solutions, such as those developed and discussed as part of Chapter 6.

Chapter 4

TVWS Access Mechanism and Protocol

Chapter 3 discussed various implementations of shared and dynamic spectrum, each of which primarily targets different operating spectrum bands. In addition to these frequency variations, each implementation has its own associated mechanism for accessing the spectrum and allocating operating parameters. These mechanisms can either be static or slowly-changing allocations, such as the Ofcom SAL, or dynamic allocations, such as TVWS or CBRS.

It may be feasible to administer static spectrum allocations manually. However, as the volume of concurrent applications increases, as number of users increases, or if a high level of spectral agility is required, such as in CBRS, it becomes necessary to implement an automated spectrum allocation and management system.

Facilitating these kinds of automated systems and frameworks could include aspects built-in to the network devices and equipment that will be used. This will require design and implementation of communication protocols and messages.

This chapter will focus on the mechanism and protocol implemented by the TVWS spectrum access method. As mentioned in Chapter 3, there is no formal definition within the ETSI harmonised standard for the communication protocol used between a WSD and WSDB. This specification was left for industry and the equipment market to determine. The de facto standard to emerge, at least within the UK and US markets, is the Protocol to Access White Space (PAWS) standard from the Internet Engineering Task Force (IETF) [110].

Two research contributions are presented and discussed in this Chapter, both focused on integrating implementations of PAWS in both an emulation environment and with a real transmitting hardware platform.

In the first instance, the author developed and created a WSD emulation program to communicate with WSDB in a standards compliant manner. This tool was used to aid network planning, by providing a human interface to the WSDB, and for simulation, by automating data collection.

The second contribution to research is the integration of a Release 14 LTE eNB system with an Ofcom approved TVWS geolocation database, building on the prior PAWS development. This work demonstrates how aspects of a regulated DSA framework can be incorporated by an eNB while simultaneously maintaining compliance with LTE standards. This allows for TVWS operations with the significant LTE equipment ecosystem. This increases the opportunities for network deployments to enable new applications and enhanced services.

Section 4.1 provides an introduction to the PAWS standard, for communication between WSD and WSDB, where the six main components of the specification are discussed. Details on some of the fundamental underlying technologies framework are provided in Appendix B. This includes the JavaScript Object Notation (JSON) data format, for creation and transmission of data objects containing parametrised information, and the Hypertext Transfer Protocol (HTTP) methods, for data exchange.

Section 4.2 details the design, implementation, and testing of the Python WSD program for use with WSDB, using the PAWS protocol. This tool was used to provide an efficient interface to spectrum access resources to aid network planning, and was used as part of the Orkney TVWS project discussed in Chapter 3.

Section 4.3 presents work completed by the author to establish communication between a WSDB and an SDR-based eNB, which enabled LTE transmission, in the700 MHz frequency range, using TVWS spectrum access mechanisms. This includes a review of spectral allocation requirements, an overview of comparable solutions found in literature prior to the development work, and a review of the system operation and testing carried out.

Finally, an overview of the impact from presented research contributions is provided in Section 4.4. This includes use by other members of the StrathSDR research team as part of their own studies and development work. Investigation and creation of the TVWS eNB system also contibuted to the DSA use case within the 5G RuralFirst project, discussed further in Chapter 5.

4.1 Protocol to Access White Space (PAWS)

This section will briefly discuss the six main component operations within the PAWS specification. These components generally take the form of a message exchange, using defined structures containing mandatory, conditional, and optional parameters.

The majority of operations consider communication between a Controller WSD and a WSDB. As discussed in Section 3.1.3, Responder devices do not contact a WSDB directly and instead retrieve parameters via Controller device communication. Such interactions will be indicated where relevant in the necessary PAWS components.

Some regulatory domains, or database implementations, may mandate specific components or parameters within messages. If applicable, these would supersede any optional status in the PAWS specification. The described implementations across this thesis are regulatory compliant under the ETSI harmonised standard and use the associated PAWS rule set.

4.1.1 Database Discovery

Database discovery is a mandatory component for Controller WSDs, as it ensures the device is able to find and communicate with an appropriate WSDB. This starts with device pre-configuration. A Controller WSD can be set up with either a catalogue of Uniform Resource Identifier (URI) addresses for direct database communication, assumedly ranked in a preferential order, or with the URI for a certified listing server. In the latter arrangement, the server will respond to the WSD with URI information for the available databases.

The above described model is supported in the UK, as discussed in Chapter 3, as Ofcom maintains control of a listing server of approved providers. This represents a robust implementation, as addition of new databases or modifications to existing entries can be completed autonomously.

A database is able to change its associated URI once established, however it must indicate any upcoming changes to all WSDs that contact it, prior to making any updates. This is captured by the, otherwise optional, *DbUpdateSpec* parameter that is included as part of all database response messages.

If a WSDB is unavailable for use by a WSD, either due to inactivity or reception of one of the appropriate error messages, a device should be able to select an alternative. In the event that a Controller WSD does not have a WSDB to contact, the correct resolution at any point will be dictated by the regulator.

Under the Wireless Telegraphy Act, if a device loses connection to a WSDB it must stop transmitting within the defined *update period*. This value effectively determines how long a WSD is able to operate before making contact with its registered WSDB [78].

4.1.2 Initialisation

The initialisation component describes the message exchange between WSD and WSDB to configure all necessary information that was not completed as part of the pre-configuration component.

The WSD sends an *INIT_REQ* object, and receives an *INIT_RESP* object from the WSDB, as shown in Figure 4.1.

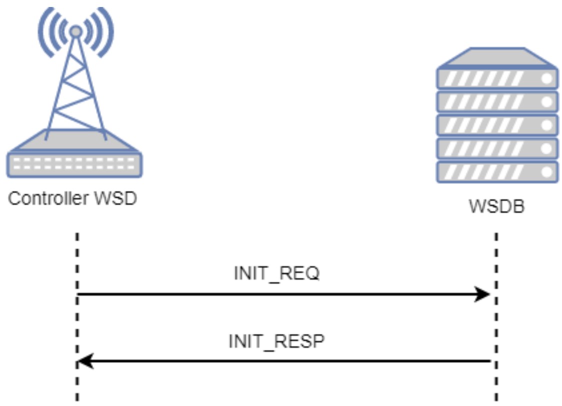


Figure 4.1: The Initialisation Message Exchange

4.1.3 Registration

Some regulatory domains, such as the FCC, may require that the WSDB implement device registration as an independent message exchange. Alternatively the WSDB may complete registration as part of the Available Spectrum component, as similar message parameters are supplied. Ofcom does not mandate a specific registration process, but it is included in this protocol operation discussion for completeness.

The registration message exchange is shown in Figure 4.2.

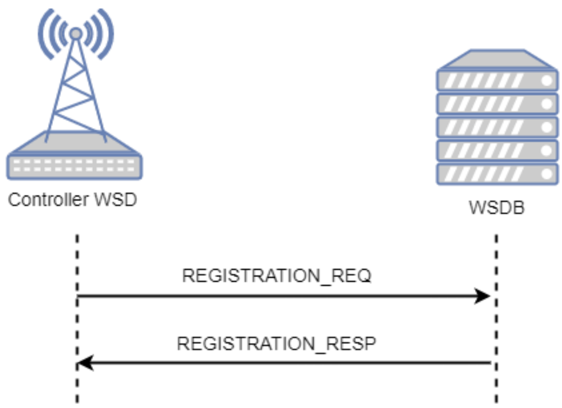


Figure 4.2: The Registration Message Exchange

4.1.4 Available Spectrum Query

The available spectrum query component allows a Controller WSD to obtain valid operating parameters from a WSDB for either itself or an associated Responder device. The intended end recipient of the parameters will determine the exact message exchange to be carried out.

A Controller WSD requesting only on behalf of itself follows the process shown in Figure 4.3. This exchange, as a minimum, encompasses the *AVAIL_SPECTRUM_REQ* message and an *AVAIL_SPECTRUM_RESP* message. Alternatively, an *AVAIL_SPECTRUM_BATCH_REQ* message and corresponding *AVAIL_SPECTRUM_BATCH_RESP* message are used if multiple locations are to be specified within the same request transmission.

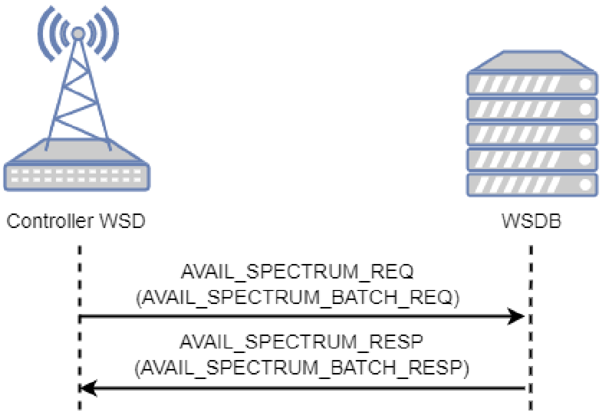


Figure 4.3: The Available Spectrum Message Exchange between Controller WSD and WSDB

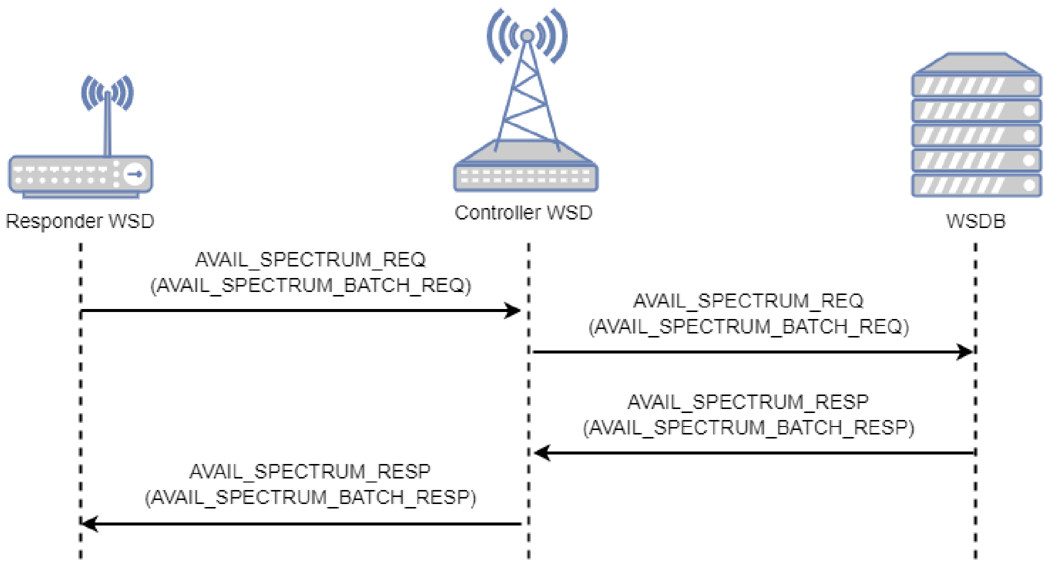


Figure 4.4: The Available Spectrum Message Exchange between Responder WSD and WSDB

Within these messages the *needsSpectrumReport* parameter indicates if, under the operating ruleset, the WSD is required to inform the WSDB of the spectrum that is anticipated to be used. The process for reporting intended spectral utilisation to the WSDB is discussed further in Section 4.1.5.

Depending on the regulatory domain, the device validation component may be inserted as part of the available spectrum query. This is discussed further in Section 4.1.6.

4.1.5 Spectrum Use Notify

As mentioned previously, this PAWS component is required if indicated by the WSDB using the *needsSpectrumReport* parameter within either the *AVAIL_SPECTRUM_RESP* or *AVAIL_SPECTRUM_BATCH_RESP*. This will result in one of two message exchanges depending on depending on whether the available spectrum query originated from a Controller WSD, as seen in Figure 4.5, or from a Responder WSD, shown in Figure 4.6.

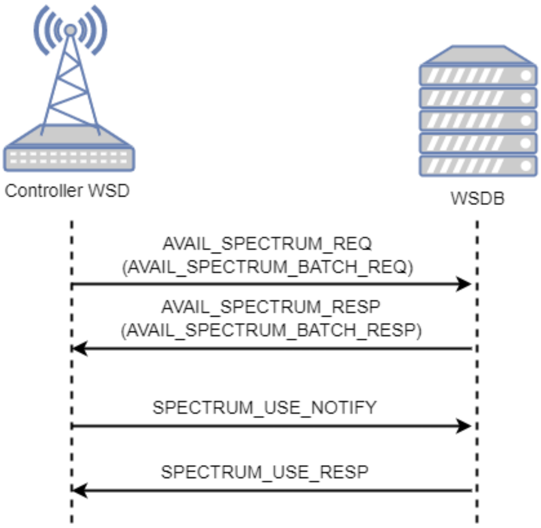


Figure 4.5: The Available Spectrum Message Exchange between Controller WSD and WSDB, where a spectrum report is required

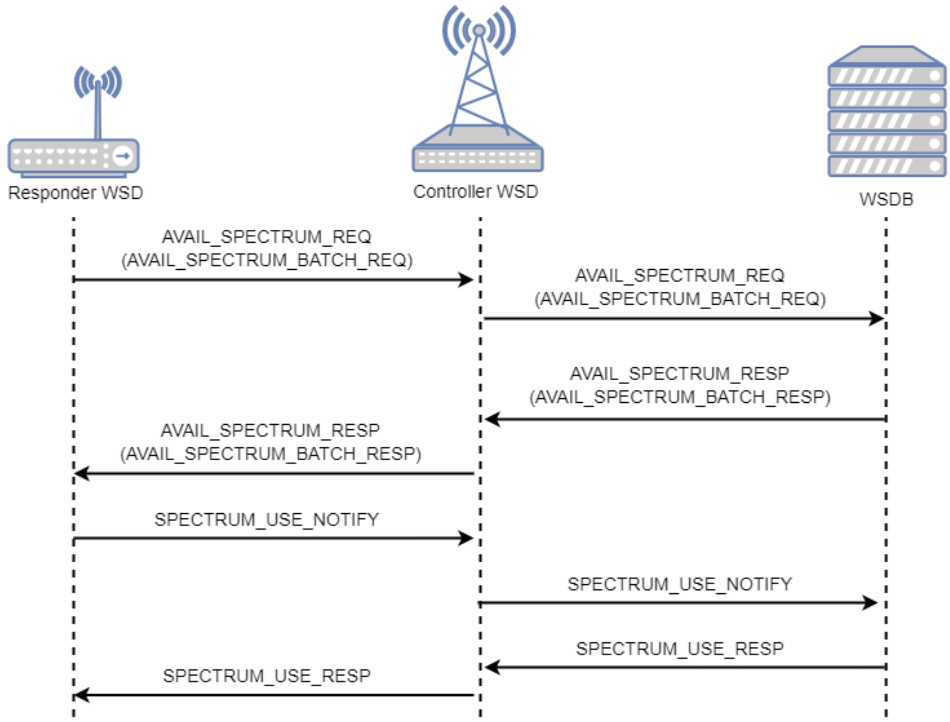


Figure 4.6: The Available Spectrum Message Exchange between a Responder WSD and WSDB, via a Controller WSD

4.1.6 Device Validation

As established in previous sections, a Responder WSD must communicate with a WSDB through an associated Controller WSD. Under some regulatory domains, the Controller WSD may also need to validate with the WSDB that the Responder WSD is permitted to operate.

This can be achieved through the typical available spectrum query process, as the *DeviceDescriptor* associated with the Responder WSD is supplied during this process, and therefore validated upon receipt of the *AVAIL_SPECTRUM_RESP*.

However, some TVWS regulations allow for temporary caching of available spectrum data in the Controller WSD. In this situation, if Responder WSD validation is required, the Controller WSD must begin the device validation component.

As shown in Figure 4.7, this involves an additional message exchange comprising the *DEV_VALID_REQ* and corresponding *DEV_VALID_RESP* messages.

Following receipt of the *DEV_VALID_RESP*, the Controller WSD will complete the available spectrum component and respond to the Responder WSD using the data cache. This may then be followed up with the spectrum use notify component, as discussed in Section 4.1.5.

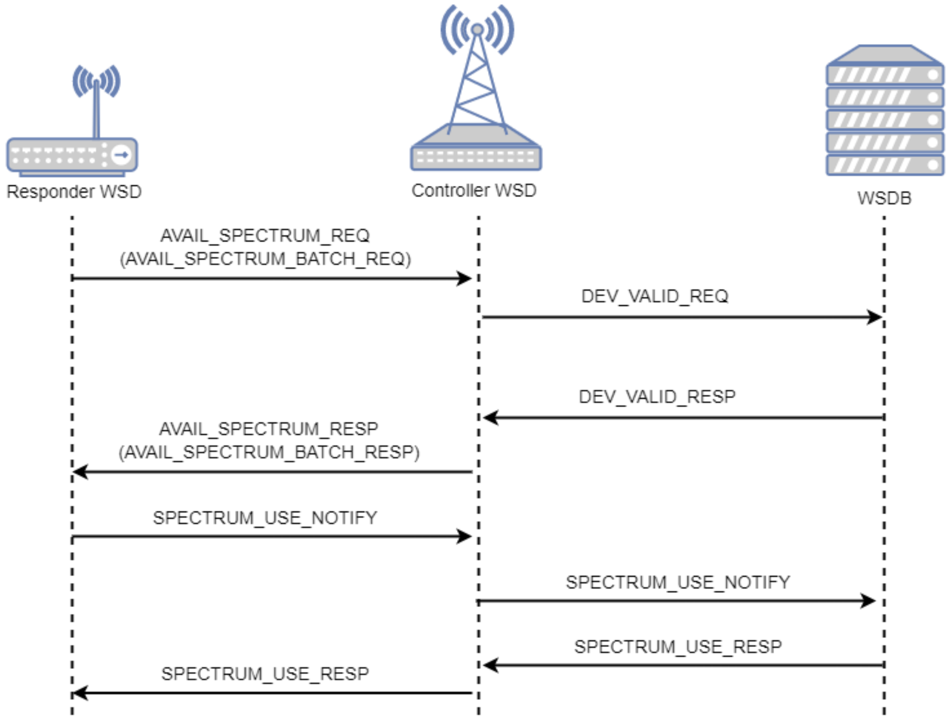


Figure 4.7: The Device Validity Message Exchange between a Controller WSD and WSDB while there is an existing cache of available spectrum data.

4.2 Development of TVWS Database Client

For any practical network deployment, TVWS or otherwise, it is good practice to develop a frequency plan for any transmitting equipment.

During the Orkney TVWS trial, discussed in Chapter 3, WSDB services were provided by Fairspectrum Oy. The 6Harmonics radios deployed in the project used PAWS to communicate autonomously with the database, but could also be manually configured to use specific channels.

As an early test and development network, it was desirable to be able to validate the WSD channel selection process, as well as its emission performance. While the latter could be achieved using a conventional spectrum analyser, assessing the ability of WSD to determine operating parameters required the capability to communicate with the Fairspectrum WSDB and receive comparative results.

Although it was possible to use software such as cURL [111] to send JSON structures to the database, this process was a strong candidate for automated scripting due to the repetitive nature and potential for user error. The introduction of automation scripts also gave the opportunity to implement other convenience features, such as message structure validation and pretty-printing to improve readability. This was carried out using Python, discussed in Section 4.2.2.

The solution uses HTTP Methods to communicate directly with a WSDB to send the PAWS messages. Interaction with a WSDB exclusively makes use of the GET method, designed to request a specific indicated resource. More information on this standard method is provided in Appendix B.

4.2.1 Examples in Literature

At the time of this work completion, there were no publicly available high-profile implementations of PAWS client software. Despite the absence of releases from officiating bodies or WSDB providers, which remains true at time of writing in 2025, it is possible that entities regularly engaging with a commerical WSDB had internally developed tools for this process that were not widely distributed.

In early 2018, as part of Project Belgrade [112], Microsoft released an open-source PAWS client for use with the UK WSDB provided by Nominet [113].

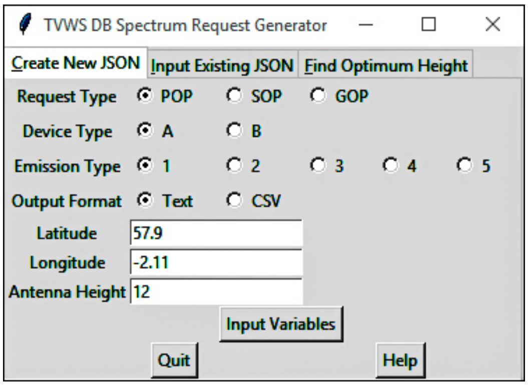
While nominally similar to the research contribution presented in this thesis, there are key differences between the author's solution and Microsoft's implementation - before considering the variation in programming language used for creation.

One major difference is the introduction of an additional networking entity within the architecture of the latter solution. A Stream Control Transmission Protocol (SCTP) Agent is introduced, which bridges connectivity between the eNB, PAWS client, and serving MME. This architectural difference fundamentally changes the intended role of the PAWS client. In the author's design, it is intended to directly configure the eNB solution while simultaneously providing a simplified, human readable, interface to a WSDB platform. By comparison, the Microsoft PAWS client is dependent on the SCTP-Agent to act as an interfacing entity for other intra-network components, rather than communicating directly. As part of the enabling the interconnection, the SCTP-Agent also controls data-flow between the eNB and MME by providing the S1 interface over a TCP connection. The additional network element in the Microsoft architecture is necessary due to the limited features of the small cell software implemented as part of the project [112].

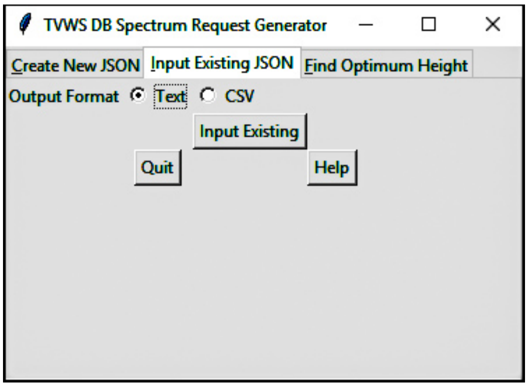
4.2.2 Development in a Python Environment

The Python implementation of the PAWS client builds on the de facto standard Tkinter Application Programmable Interface (API) for the Tk Graphical User Interface (GUI) toolkit [114]. A simple interface, shown in Figures 4.8a through 4.8c, gives users three functionality options.

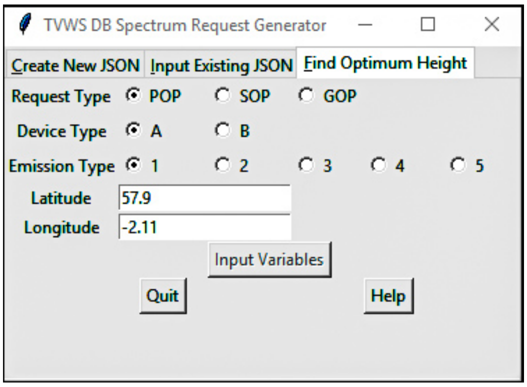
The first option, shown in Figure 4.8a, allows for the creation of new *INIT_REQ* and *AVAIL_SPECTRUM_REQ* messages using parameters entered in the GUI fields. Some variables within these messages were locked for simplification, but fundamental aspects such as location and device type were made available. These parameters significantly influence the GeoLocation and DeviceDescriptor variables, and hence the calculations for channel powers that are carried out by the WSDB.



(a) Creating new INIT_REQ and AVAIL_SPEC_REQ using user input parameters.



(b) Creating new INIT_REQ and AVAIL_SPEC_REQ using an existing JSON format input.



(c) Creating new INIT_REQ and AVAIL_SPEC_REQ using user input parameters to find maximal antenna height

Figure 4.8: GUI for Python WSDB Client

The user is also given a choice of two formatting options for the WSDB response. As shown in the example messages given throughout Section 4.1, while the JSON WSDB response is human readable, often there will be more information than is necessary for network frequency planning. To aid this, the Text output option removes superfluous data and formats the response in a plaintext format. Alternatively, the program can generate a Comma Separated Values (CSV) file, which will extract only the permitted transmit power levels per 8 MHz channel.

For either output format selection, the program also saves the unformatted JSON files for all messages sent to and from the WSDB.

The second program tab, shown in Figure 4.8b, allows the user to input an existing JSON file, which is then sent to the WSDB. This will skip the initialisation process, which may need to be completed prior depending on the WSDB implementation. Consequently, the only input required from the user is the choice of output format, and location to save the WSDB JSON response. Both the CSV and prettyprint text output options are available.

The third program option, shown in Figure 4.8c, is similar to the first, with one key difference. The user can no longer input a value for antenna height, effectively introducing a wildcard for this parameter. The program then carries out the available spectrum process multiple times, incrementally varying the height value submitted to the WSDB each time. A maximum value of 40m was set as the WSDB response would not significantly vary at heights above this, and larger values were considered inviable in practice.

The program will determine the "best" antenna height for the WSD based on the collected responses, and generate outputs accordingly. For this implementation, the "optimal" height was defined as the one that returned the greatest number of channels permitting the maximum 36 dBm transmit power. As this option returns more than just channel information, only the prettyprint text output is supported.

Although it would be expected that the tallest antenna height would always return the greatest number of maximum power channels, this also increases the potential for interference with primary users. This relationship leads to a variation in "best" height responses, depending on proximity to other spectrum users.

In addition to the GUI, an automated version was developed, using the same code structure, which reads all necessary parameters from input files. This allows for a volume of requests to be generated, and responses saved, autonomously.

Any PAWS messages sent or received by the client were validated using JSON schema structures that were created for each type of message.

Similar structures were created and applied to all messages exchanged between client and WSDB. This ensures all communication meets the PAWS standard. Each schema was tested using an online verification tool [115], which ensures that the created templates are suitable for a supplied example message.

In addition to the standard Tkinter class [114], which defines functions and elements needed for the GUI, three additional classes were created to represent the PAWS messages.

The UML diagram for these classes is shown in Figure 4.9. While the overall design is functional, it is definitely inefficient in its current form. As can be seen, the classes share a number of common functions and variables. Therefore, it would be better programming practice to take advantage of class inheritance, and create a parent class covering all messages. The updated architecture would remove a significant amount of redundancy from the codebase while also improving readability. This is currently considered an item of future work.

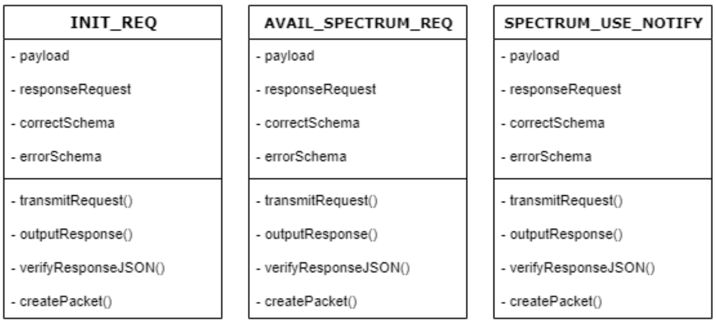


Figure 4.9: UML Diagram for the Python PAWS client

Although the developed code is likely not to a commercial production standard, the implementation and lessons learned were instrumental in the development of the TVWS eNB, discussed in Section 4.3, and for the 5G RuralFirst project, discussed in Chapter 5.

4.2.3 Testing and Evaluation

Solution operation was tested using the Postman API Platform [116]. This development tool is able to, among other features, generate and respond to HTTP methods in a GUI environment.

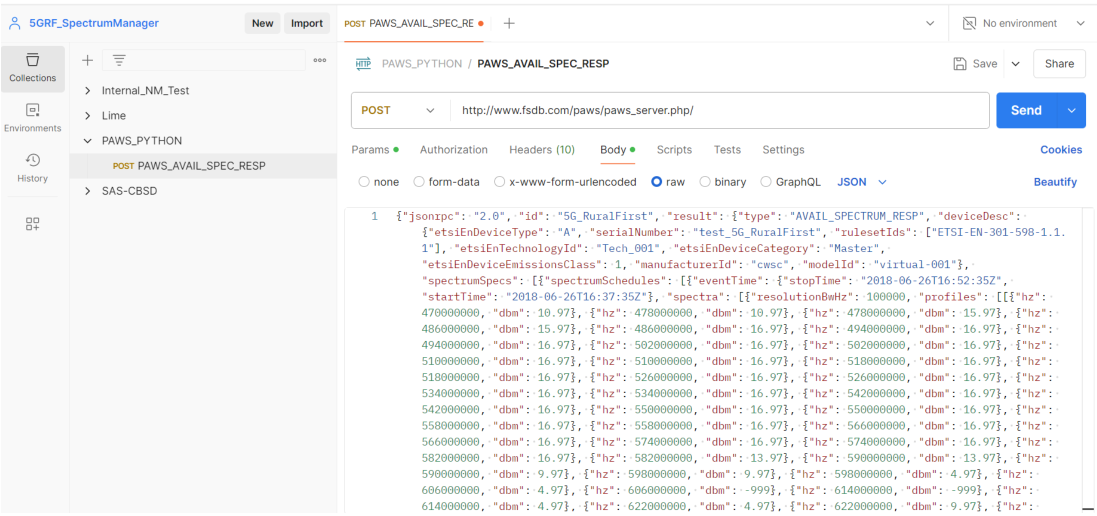


Figure 4.10: Extract showing the Postman API Platform [116].

Initial tests focused on ensuring the outgoing messages, to the WSDB, were correct. However, at time of testing, the Fairspectrum Oy WSDB was outside of the development stage and fully in production. Therefore it was important that tests were performed in such a way that would not cause issue to a commercial service.

A set of baseline, pre-defined parameters were established, which were then kept consistent for further tests. Each of these created JSON messages, which were then sent by the Postman software to the WSDB. This allowed for an inspection of the WSDB response messages, to ensure results were as expected, and for local copies to be cached; effectively creating a test set of verified request and response messages. Intentionally incorrect request messages were also sent in order to retrieve copies of the WSDB error responses.

Each software platform was then tested with the creation of these test request messages using the pre-defined parameters. To verify transmission capability, the destination Internet address for the WSDB was replaced with a localhost interface linked to Postman. This allowed for visibility of both the header and body of the message for manual verification.

While these tests were important to verify correct operation, there was a reduced possibility of error in this aspect compared to some other system operations. This is because all created outgoing messages are subject to a JSON schema validation which, if failed, would block the transmission and flag an error.

In turn, these schemas were developed and verified against established, legacy PAWS messages that were used in the live Orkney TVWS trial discussed in Chapter 3. An online tool was also used to validate the schemas [117].

Once it was confirmed that the system was able to generate PAWS message with the correct syntax, the next stage was to verify the handling and processing of returned responses. This was done in the same way, using Postman with the localhost interface, but rather than simply examining the contents, the corresponding stock response message was sent as a reply by Postman.

As before, intentionally incorrect messages were also transmitted to Postman to ensure the client systems were capable of appropriately handing error responses, although this involved temporarily disabling the schema validation to allow for the transmission.

A summary of the tests carried out is provided in Table 4.1.

While part of this test involved verifying the program flow of the client, the main test was to ensure that parameters were being extracted from the response messages correctly.

Once the full message exchange process had been tested end-to-end, using Postman as the proxy WSDB, the system was then fully tested again using the live Fairspectrum Oy WSDB and found to function entirely as intended.

The impact of PAWS client operation on processing overheads of the Linux-based system can be determined in multiple ways, keeping in mind that most modern CPU are multi-processor systems. Regardless of exact measurement mechanism, the methodology involves assessing overall CPU utilisation while first running only the Amarisoft vRAN software, and then again while simultaneously the PAWS client. For this assessment, the *Glances* utility [118] was used to provide a readable representation of total CPU usage.

As can be seen from Table 4.1, the observed variation in CPU utilisation was around 1-3% of additional load when running each of the scripts. This can be attributed to the relatively short JSON structures that are being parsed, and the simplistic messaging mechanisms implemented.

Test Description	Result	Estimated CPU Impact
Generate valid INIT_REQ Message	Pass Schema Validated Message Created	<1%
Handle invalid INIT_RESP Message	Pass Appropriate Error Message Returned	$\sim$1%
Handle valid INIT_RESP Message	Pass Set values. Proceed to next phase	$\sim$1%
Generate valid AVAIL_SPECTRUM_REQ Message	Pass Schema Validated Message Created	<1%
Handle invalid AVAIL_SPECTRUM_RESP Message	Pass Appropriate Error Message Returned	$\sim$1%
Handle valid AVAIL_SPECTRUM_RESP Message	Pass Set values. Proceed to next phase	$\sim$1%
Generate valid SPECTRUM_USE_NOTIFY Message	Pass Schema Validated Message Created	$\sim$3%
Handle invalid SPECTRUM_USE_RESP Message	Pass Appropriate Error Message Returned	$\sim$2%
Handle valid SPECTRUM_USE_RESP Message	Pass Set values. Update user interface	$\sim$2%

Table 4.1: Summary of Completed Tests with PAWS Client

4.3 Integration of LTE eNB with a TVWS Geolocation Database

The work presented here demonstrates the integration of a 3GPP-compliant LTE-A stack with an Ofcom-approved TVWS geolocation database, provided by 5GRF partner Fairspectrum Oy, in a frequency deployment that is compatible with COTS mobile devices. This results in a 3GPP compliant eNB that also satisfies the ETSI specification on systems operation and transmit power.

4.3.1 Review of Spectrum Allocations and Definitions

In 2008, following the results of the International Telecommunications Union (ITU) World Radiocommunication Conference 2007, a spectrum working group was established by the Asia-Pacific Telecommunity (APT) [119]. This resulted in two consensus band plans, finalised in September 2010 [120], for TDD and FDD implementations.

Following further technical study and investigation on out-of-band emissions, presented in a 2011 report [121], both band plans were standardised by 3GPP as part of LTE Release 11.1. Band 28, the FDD arrangement, has an allocated 45 MHz of spectrum for uplink, between 703-748MHz, and downlink, between 758—803 MHz, with a fixed duplex separation, or frequency offset, of 55 MHz. Carrier bandwidths of 3 ,5 ,10 ,15 and 20 MHz are supported. Due to the relatively wide bandwidth, implementation within a UE requires two duplexers [122]. LTE band 44 is a TDD band, over the same 703—803 MHz range, supporting 3 ,5 ,10 ,15 and 20 MHz carrier bandwidths. Both bands are shown in Figure 4.11.

In particular, the APT FDD arrangement saw widespread adoption throughout Asia-Pacific, including in Australia, India, and New Zealand; and in South America, in countries such as Columbia, Peru, and Brazil [119]. This makes it one of the best harmonised band plans in the world [123]. Following WRC 2015, the ITU identified the 694-790 MHz band for mobile [124], and added both the APT FDD and TDD plans to the recommended allocation list [125].

In a 2015 report [126], the CEPT Electronic Communication Committee (ECC) identified a channelling arrangement for member states which harmonised with the lower duplexer to the APT plan. This creates a paired arrangement with 30 MHz of spectrum available between 703-733 MHz and 758-788 MHz, as well as a 25 MHz duplex space. This band plan would aid inter-ITU region harmonisation and benefit global markets, while also offering flexibility to spectrum administrators to control the application of both the 25 MHz duplex gap and the guard bands. The resulting arrangement is shown in Figure 4.11. While there are a number of potential uses for the 25 MHz duplex gap, including Public Protection and Disaster Relief (PPDR) services, Ofcom identified in a 2016 statement that this spectrum would be used in the UK for supplementary downlink (SDL) and form part of the 2020 spectrum auction [127].

The near-global adoption of the APT plan has led to a wide implementation by equipment manufacturers. As the 700 MHz band has been identified as one of the key bands to enable 5G [42] across Europe, it was decided that this frequency plan would be incorporated into the TVWS eNB system. However, Ofcom stated that with commencement of the 700 MHz clearance the TV band, and hence the interleaved spectrum, should be considered 470-694 MHz [75].

As discussed in Chapter 3, the 700 MHz band later became used in the UK to deliver mobiles services following the 2020 spectrum auction [42].

Following the regulatory change in 700 MHz, the only LTE band defined for operation in the updated TVWS frequencies is LTE B71, shown in Figure 4.13. Band 71 was standardised by the 3GPP in Release 15.0 as an FDD band. Carrier bandwidths of 5, 10, 15 and 20 MHz are supported. Although, at time of writing, handset support is not as prevalent as other sub-GHz bands, such as Band 28, implementation by large device manufacturers, including Apple and Samsung, is increasing.

Given the significant 600 MHz deployments carried out by T-Mobile in the US following the 2017 auction [128], the 2019 Canadian auction [129], and the 2023 auction in Mexico [130], there are motivations to move towards a wider harmonisation in the band.

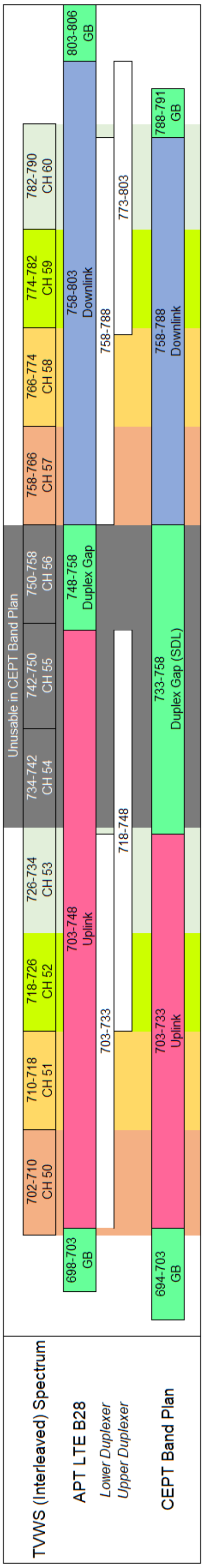


Figure 4.11: 3GPP B28 (APT) Overlap with TVWS Spectrum.

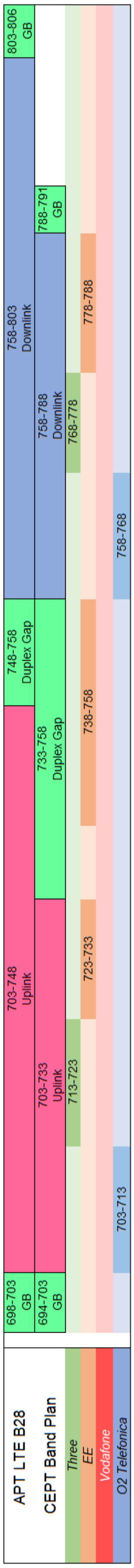


Figure 4.12: Results of the UK 700 MHz Auction.

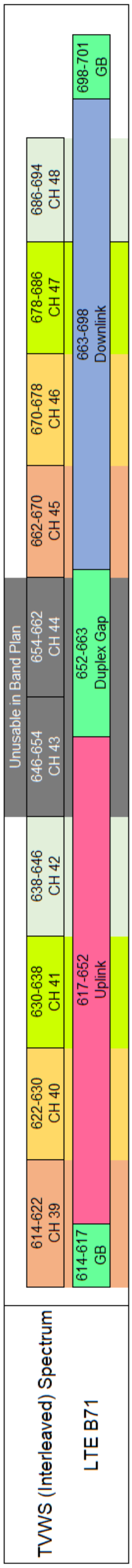


Figure 4.13: 3GPP B71 Overlap with TVWS Spectrum.

4.3.2 Solution Overview

The implementation presented in this thesis demonstrates that requirements of TVWS regulation conformance, such as the spectral agility to sufficiently protect incumbent transmissions, can be handled through LTE handover techniques. Deployment also takes advantage of the capabilities of a UE-based, recently used frequency listing to speed up the connection process following a change of operating channel.

To ensure the frequency agility required for a dynamic spectrum approach, this system has been designed for deployment on SDR platforms using LTE software stacks.

A commercial eNB stack from Amarisoft [131] was used to provide the RAN functionality, and generate the MAC and PHY layer signals. Using this stack, the targeted SDR platform will create a standard compliant wireless network with parameters dictated by supplied configuration files.

These files have a syntax very similar to JSON, and contain definitions for hundreds of parameters across the PHY, MAC, RLC, PDCP, and *Radio Resource Control* (RRC) layers which all govern aspects of the RAN software set-up.

The serving core network is also provided by Amarisoft [131], although connection to other ePC implementations is supported via the standardised S1 interface. This software compact core provides Mobility Management Entity (MME), Serving Gateway (S-GW), Packet Gateway (P-GW), and Home Subscriber Server (HSS) functionality. The solution, similarly controlled with formatted configuration files, is able to operate simultaneously on the same CPU used to run the ePC stack. By operating an independent ePC, it was possible to use the same SIM cards and Public Land Mobile Network (PLMN) identification number as the deployed 5GRF network. More information on the research activities of the 5GRF project can be found in Chapter 5.

The combination of an Amarisoft stack with SDR platforms is well established in deployments of LTE testbeds, particularly within lab environments and for dynamic spectrum applications. One such example is from the 2017 paper by Marojevic *et al* [132]. This publication describes the LTE testbed on the Virginia Tech campus, which features SDR equipment from multiple manufacturers. The testbed uses a combination of commercial LTE stacks, from Amarisoft, and open-source implementations, such as SRS RAN [133] and Open Air Interface [134].

For the LTE in TVWS implementation developed in this thesis, a PAWS client was constructed in a Python environment. This is similar to the one discussed in Chapter 4. However, rather than values being used in simulation, parameters are used in the automated generation of the configuration files for the Amarisoft stack. Control elements for the system are enabled through the API with a browser-based GUI, effectively making the developed client into a *shim* library, or the eNB stack.

The client is designed to be co-located on the same platform as the eNB stack, and written to allow simultaneous operation with both the eNB and ePC stacks.

This implementation primarily used an SDR platform from Lime Microsystems with an accompanying Intel NUC, with i7 processor, to run the Amarisoft eNB and ePC stacks as well as the PAWS client.

4.3.3 Examples in Literature

Some aspects of the development work discussed throughout Section 4.3 have been explored and suggested in other academic publications.

4.3.3.1 Towards Unlicensed Cellular Networks in TV White Spaces

As part of Microsoft's Project Belgrade [112], Baig *et al* presented a conceptually similar work in 2017, outlining their *Cell-Fi* architecture solution [135]. In this paper, the authors highlight issues with the MAC and PHY layers of the IEEE 802.11af TVWS standard, discussed in Chapter 3. Through experimentation they note that LTE outperforms 802.11af over long-distance links.

As part of the Cell-Fi construction, an ETSI-compliant database client, using PAWS, was constructed and implemented with an LTE small-cell. These two units, alongside an additional intra-channel interference management system, were combined to create a Cell-Fi Access Point (AP).

In the paper by Baig *et al*, the AP was implemented without the Interference Management entity as the small-cell component used did not support all the required LTE standard features. The PAWS client was deployed on a separate PC, rather than an integrated platform alongside the LTE stack as in the work presented in this thesis. The geolocation database used was provided by Ofcom-approved supplier, Nominet. The client algorithm to select channels is not described in the paper.

Practical implementation of the Cell-Fi AP required modification to the LTE chipsets used on programmable reference platforms, in contrast to an accompanying piece of software operating beside an existing commercial application, as in this work.

The authors of [135] outlined several challenges in the face of LTE deployment using TVWS that were to be addressed by Cell-Fi. Those challenges include high dependency on expensive proprietary equipment in a closed ecosystem, and a dependency on licenced spectrum with no built-in provisioning to avoid incumbent transmissions.

The work discussed throughout Section 4.3 addresses issues with expensive equipment by targeting SDR platforms with the Amarisoft stack. This allows for lower cost implementations, while ensuring all standard compliant features are present. Integrating the PAWS client removes the dependency on licensed spectrum for operation in the same way that Cell-Fi achieves.

4.3.3.2 Software-Defined LTE Evolution Testbed Enabling Rapid Prototyping and Controlled Experimentation

The idea of frequency agility through handover was suggested by Marojevic *et al* in their 2017 paper [132]. While describing their shared spectrum research, two handover mechanisms are suggested to make cell occupants vacate to an alternative carrier.

The first is to simply switch off any cell that is identified as interfering with Incumbent transmissions, which forces devices to reconnect to an alternative cell. Assumably this is in lieu of a basestation-triggered handover signal. The second method is to gradually decrease the transmit power in an interfering cell to cause any UE to begin looking for alternative carriers.

It is important to note that, while the handover strategy is similar, there are fundamental differences between the work presented in this thesis and that of Marojevic *et al.* In the latter, their eNB deployment creates multiple parallel cells in adjacent channels, and would allow UEs to connect to either cell. In the work discussed throughout Section 4.3, there is only one cell for UEs to connect to, until the handover process begins.

Having multiple simultaneous active cells enables the use of simple handover techniques, at the cost of increasing the minimum amount of spectrum required. The practical deployment described in the Marojevic paper also did not use TVWS spectrum, instead operating in LTE Band 7 (2500-2690 MHz). Therefore the system had no interaction with a geolocation database, instead relying entirely on spectrum sensing to detect potential Incumbent transmissions. Finally, while the authors suggest that new cells could be rapidly created to facilitate handover as required, they do not outline a methodology for doing so.

4.3.4 System Operation

The flowchart detailing functionality of the PAWS client is shown in Figure 4.14. Prior to operation, the basestation must be configured to target a specific frequency range, either 600 or 700 MHz.

The basestation system begins by carrying out the "Initialisation" and "Available Spectrum Query" processes. This involves generating and sending both the INIT_REQ and AVAIL_SPECTRUM_REQ messages, and appropriately handling their corresponding responses from the WSDB. These message generation processes are all highlighted orange in Figure 4.14, are standardised according to the PAWS protocol. Locally valid operating parameters are returned from the WSDB within the AVAIL_SPECTRUM_RESP message.

From these, the client will attempt to find DTT channels that are suitable for use in the FDD arrangement dictated by the target LTE band and, in the case of already commercialised 700 MHz spectrum, the regulator dictated frequency plan. The current implementation of PAWS client does not allow for operation over multiple DTT channels, i.e the nominal bandwidth under the ETSI specification will not exceed 8 MHz. Because of this, the maximum LTE

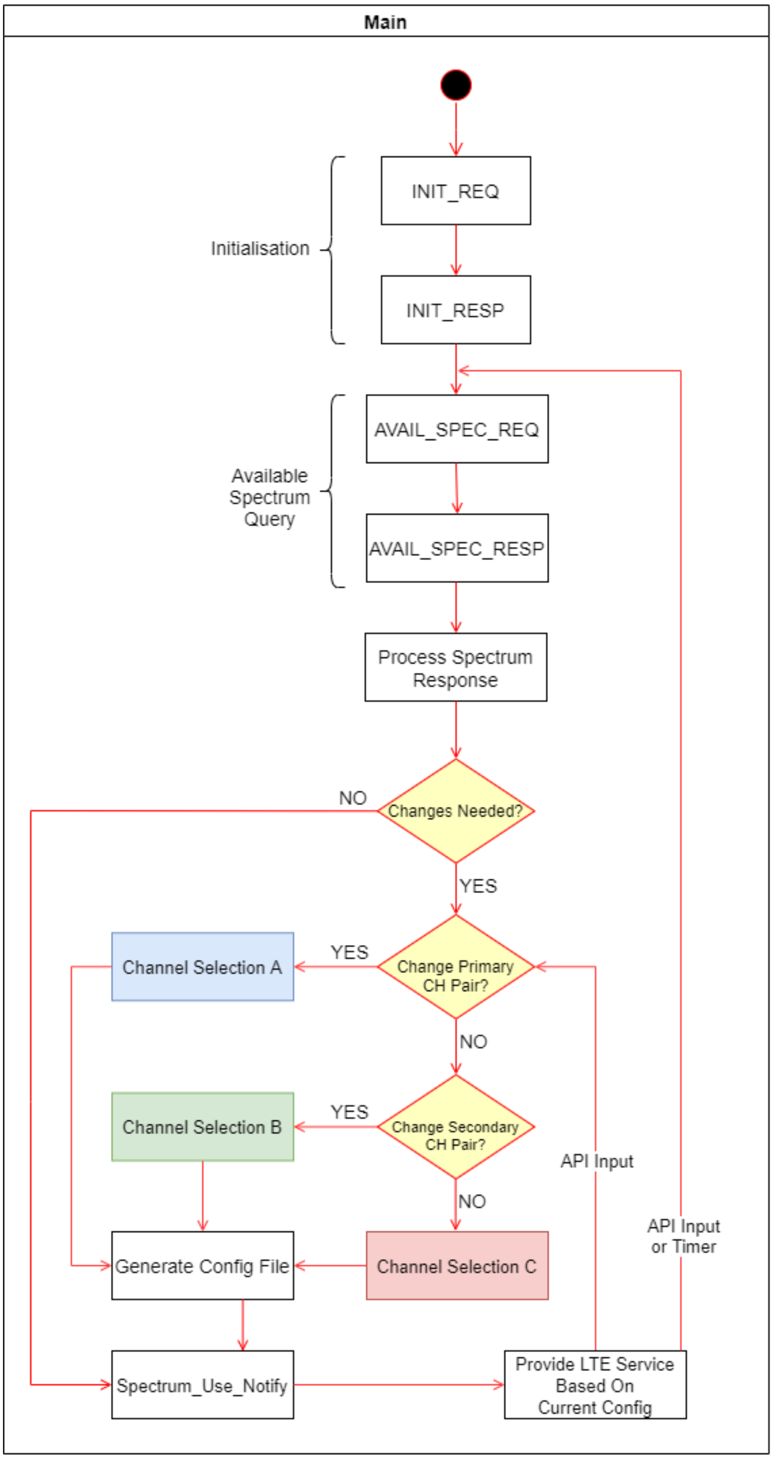


Figure 4.14: Flowchart of operation for the TVWS basestation system.

carrier that can be used is 5 MHz. This simplifies the calculations required by the client, while also providing a small "guardband" around the LTE carrier to help improve achievable ACLR. An implementation suitable for multi-channel operation and wider carrier bandwidths is presented in Chapter 5.

Considering a deployment using the harmonised frequency plan, shown in Figure 4.11, 30 MHz is allocated between 703-733 MHz and 758-788 MHz for uplink and downlink respectively. Therefore, while there needs to be a centre frequency offset of 55 MHz between downlink and uplink, equivalent to seven DTT channels, there are additional requirements to be considered when selecting appropriate channel pairings.

DTT Channels 54 (734-742 MHz), 55 (742-750 MHz) and 56 (750-758 MHz) are not considered candidates as they lie within the duplex space of the frequency plan. This leaves four paired combinations that meet all of the criteria: Channels 50/57, 51/58, 52/59 and 53/60.

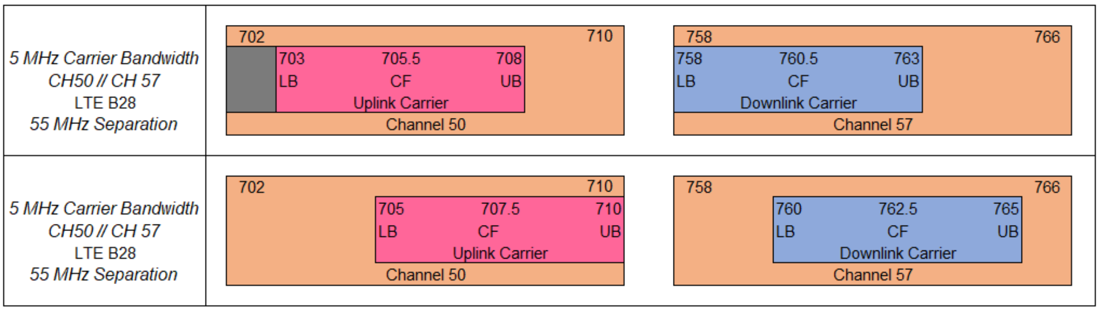
Since Band-28 is specified with a lower bound of 703 MHz, and TVWS Channel 50 is defined with a lower bound of 702 MHz, the frequency plan places a constraint on the lower end of the 700MHz spectrum; the lowest possible uplink carrier centre frequency, for a 5MHz bandwidth, is 705.5 MHz. Similarly carriers within Channels 53/60 have regulatory constraints imposed by the frequency plan. Although possible under the Band 28 specification, the upper bound of 788 MHz means the highest centre frequency that can be deployed, within Channel 60 for a 5 MHz carrier, is 785.5 MHz. This corresponds to a paired centre frequency of 730.5 MHz within Channel 53. These limitations are represented in Figure 4.15. While the overlap in available spectrum would still allow for use of 5 MHz carriers in these scenarios, practical deployment would be dependent on hardware quality to ensure adequate ACLR and incumbent protection as there is no "guard band" available between the LTE carrier and the boundary of the DTT channel.

If the deployment targets 600 MHz spectrum, the PAWS client will assign frequencies according to LTE Band 71, shown in Figure 4.13. Under this specification 35 MHz is allocated for downlink, between 617-652 MHz, and uplink, between 663-698 MHz. This leaves a fixed carrier centre frequency separation of 46 MHz, or six DDT channels. Consequently there are four possible paired combinations within 600 MHz: Channels 39/45, 40/46, 41/47, and 42/48. Channels 43 and 44 cannot be used as they lack a channel pair within the spectrum band or sit in the duplex space of the band definition, respectively.

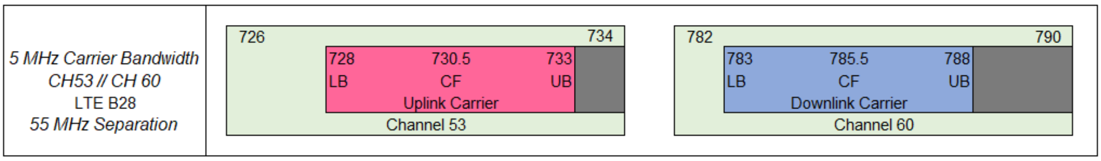
However, as Band 71 has a downlink lower bound of 617 MHz this creates a deployment limitation within Channel 39 (614-622 MHz). This is also the case looking at the uplink lower bound of 663 MHz within Channel 45 (662-670 MHz). Although this leaves sufficient spectrum to implement a 5 MHz carrier, for these scenarios, as within the 700 MHz band, practical implementation will be dependent on the hardware to ensure an adequate ACLR response. A representation of these carrier frequencies is shown in Figure 4.15.

Once the operating parameters have been processed, and appropriate DTT channel options have been identified, the "Process Spectrum Response" method then selects two FDD channel combinations; a "Primary" combination and a "Secondary" combination.

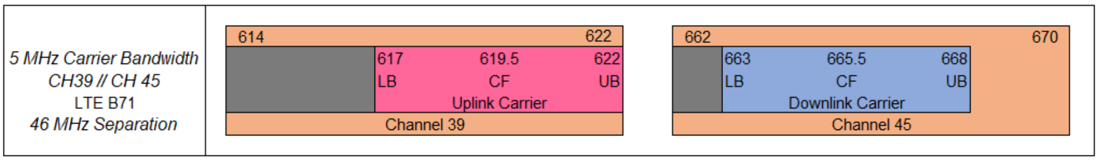
The Primary pair have been identified as the option which should maximise the available transmit power for uplink and downlink carriers. The Secondary pair offer an alternative



5 MHz Carrier Bandwidth, CH50 & CH57, LTE B28, 55 MHz Duplex Separation



5 MHz Carrier Bandwidth, CH53 & CH60, LTE B28, 55 MHz Duplex Separation



5 MHz Carrier Bandwidth, CH39 & CH45, LTE B71, 46 MHz Duplex Separation

Figure 4.15: Edge Cases of 5 MHz LTE Carriers in TVWS Channels.

combination that are used to enable frequency agility.

A simple channel selection algorithm is implemented for this identification. First the client removes any pairs that have channels with a transmit power limit from the database lower than 12 dBm. Remaining candidate pairs are scored on the mean power available across both channels, and the magnitude of the difference between uplink and downlink carriers. This creates a bias towards channel pairs that have relatively equal transmit powers in both carriers, which was implemented as the client has no understanding of which of the carriers is to be used for uplink or downlink.

However, it may instead be beneficial to introduce a bias towards channel pairs with higher transmit power available in the downlink carrier, given the magnitude of difference between the performance of an eNB and typical UE. The channel selection implementation forms the basis for algorithm presented in Chapter 5.

Once Primary and Secondary pairings have been identified from the database response, the client checks to see if there have been any changes in frequency or corresponding transmit power since previous consultation. If there are any differences, the system will begin the cycle to create new configuration files for the Amarisoft stack.

Starting this cycle will result in use of one of three selection and update processes, depending on what has been modified.

In the event that only the Secondary channel pair selection must be updated, triggering the process highlighted in blue in Figure 4.14, the system will maintain the currently operational Primary pairing and select a new combination for the Secondary. As the Primary channel pair will remain active throughout this process, there will be no service disruption to the end user.

If the Primary channel pairing must be modified, but with no change to the Secondary, either based on database response or because the user has requested an operational change through the API, discussed in Section 4.3.4.1, the process highlighted red in Figure 4.14 is employed.

The system will power down the current Primary downlink channel, and simultaneously raise the transmit power in the Secondary downlink channel. Any connected users will appear to have left the operating area of their serving cell and automatically attempt to connect to a known neighbouring cell, which will appear as the now active Secondary downlink frequency. This minimises the service disruption to the end user. This process is elaborated on further in Section 4.3.4.2.

The final possibility is that both Primary and Secondary combinations are simultaneously invalidated by the database response. This outcome is highly unlikely as the main Incumbent users, depending on the target deployment band, will be fixed operation DTT transmitters or other mobile networks.

One scenario where this could occur would be the introduction of PMSE licence holders within the interleaved spectrum. Given the size of the band available for PMSE allocation, it would be unlikely that the eNB would transition from being allocated Primary and Secondary channels to having no valid combination. However, in the event that this incident occurs, this can be resolved through the process highlighted in green.

In this case the Primary downlink is powered down but the Secondary is not made active. Instead, completely new channels are selected for operation and used to generate the service. This would result in minor disruption to the end user, as connection to both serving and known neighbouring cells would not seem possible. To resolve this the UE will begin to scan the last connected to LTE-band, in which it will quickly find the updated Primary downlink channel and resume connectivity.

Following identification of the correct Primary and Secondary pairs, based on the most recent database request, the client will transmit a PAWS specified SPECTRUM_USE_NOTIFY message to the database informing of intent to use the specified spectrum.

If changes are required to the Amarisoft LTE service, new configuration files are automatically generated from a created template. Modifications can be made to the transmit power of the eNB, the maximum uplink transmit power reported to the UE in the System Information Block (SIB), and Downlink E-UTRA Absolute Frequency Channel Number (DL_EARFCN).

The DL_EARFCN is a standardised representation of the centre frequency of the downlink carrier that also provides information on the LTE band. This value is calculated using Equation 4.1 [136].

$$NDL = 10 * (f_c - F_{DL\_Low}) + N_{Offs\_DL} \tag{4.1}$$

where *NDL* represents the DL_EARFCN and f_c is the carrier centre frequency. The value for N_{Offs_DL}, the downlink offset, is taken from Table 5.7.3-1 in the 3GPP TS 36.104 standard [136]. F_{DL_Low} is the lower boundary for the downlink spectrum of the target LTE band, e.g. in Band 28 this would be 758 MHz, or for Band 71 this would be 617 MHz.

The Amarisoft LTE network service is then modified using the new configuration files. Once established with validated operating parameters, the LTE service runs continually, until one of three mechanisms is triggered to cause a revision.

Either the time period for parameter validity expires, which prompts a new database query, or the API is used to manually trigger a database query, or the user prompts a switch between Primary and Secondary pairs, again through the API.

4.3.4.1 System API and GUI

The client is accompanied by a browser-based API shown in Figure 4.16. This GUI provides the user with information on the current operating status of the eNB, a representation of the geolocation database response, and a countdown to the next automatic database query.

Channel pairs for the target FDD deployments are colour coded, with the currently active pair highlighted with a bold outline. The GUI also allows the user to force an update request from the database, without waiting for the time-controlled operation, which has the potential of triggering changes in Primary and Secondary pairs. Alternatively, the user can force a swap between the Primary and Secondary pairs.

4.3.4.2 Providing Channel Agility using Neighbouring Cell Information

In order to facilitate a high user experience, the spectrum use constraints imposed by the ETSI standard can be adhered to through the use of an intra-eNB handover.

To achieve this, additional alternative cells are pre-defined for operation by the eNB software, on different carrier frequencies within approved TVWS channels. These cells are not made active unless operation in the currently selected cell is required to stop.

The LTE neighbouring cell list information, provided by the eNB, is available to notify currently connected UE of nearby cells to connect to, for mobility or in the event of signal loss [137]. In this application, handsets are notified about other adjacent cells, but also additional cells that could potentially be created by the eNB. This facilitates an intra-cell handover.

During normal operations, the eNB operates according to the selected Primary channel pairing while maintaining a Secondary channel pair, as discussed in Section 4.3.4. The neighbouring cell list notifies UEs of the existence of another cell that uses the Secondary channel pair, and provides the associated DL_EARFCN. When a change in current Primary carrier is

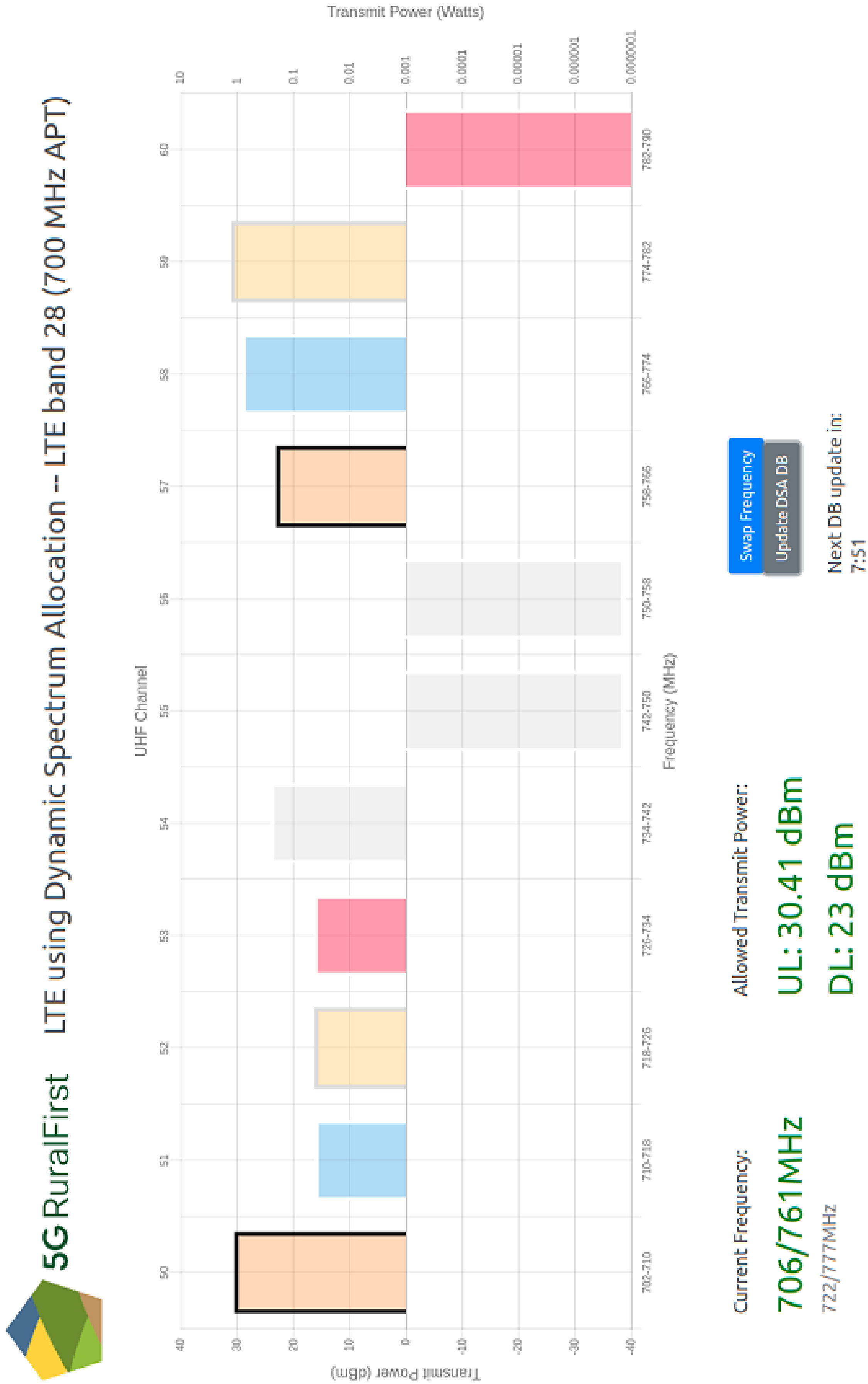


Figure 4.16: Browser-based GUI for the TVWS system.

required, the UE is prompted to attempt a handover to the previously advertised neighbouring cell, which has since been made active by the eNB.

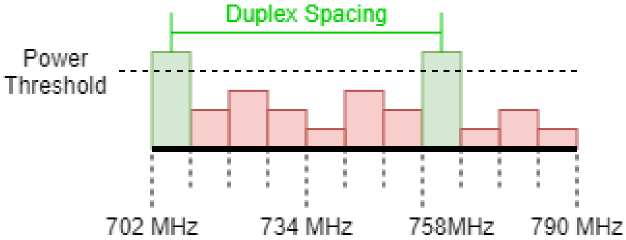
In this configuration, each physical eNB is responsible for more than one Cell ID within the LTE network. This is outside typical deployment convention, and should be considered during the allocation of Cell ID numbers throughout a full network implementation.

In a scenario where a UE is unable to locate the LTE network, due to a loss of service during the period where a fallback frequency was being announced as a neighbour, the handset will carry out a scan of the band and attempt to identify a carrier broadcasting the same PLMN identifier.

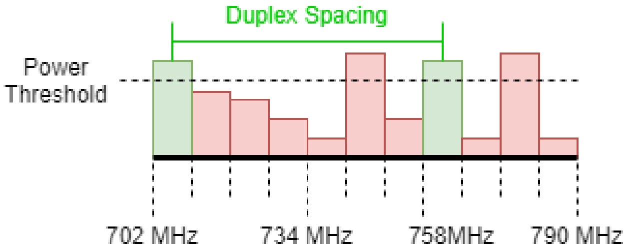
4.3.5 System Testing

The code for communication with the WSDB was based on the implementation discussed, and tested, in Chapter 4. This meant that minimal evaluation was required on the system's ability to send requests to the WSDB, but the solution was required to demonstrate the ability to appropriately handle any response messages. This included error messages, both from the HTTP mechanisms and the WSDB itself.

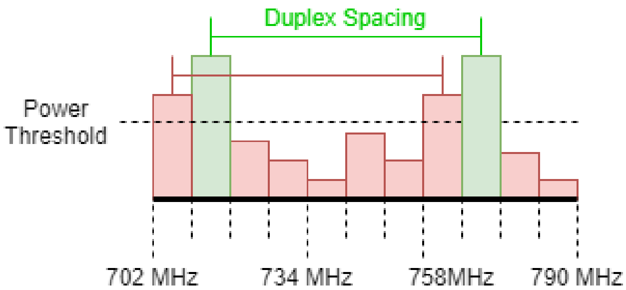
Tests carried out in Chapter 4 established a cache of WSDB response and error messages. Using the Postman API Platform [116] these were sent to the eNB in response to its request messages to create a series of test scenarios. These are shown in Figure 4.17.



Scenario A) Single Duplex Pair of Candidate Channels



Scenario B) Single Duplex Pair of Multiple Candidate Channels



Scenario C) Strongest Duplex Pair of Multiple Candidate Channels

Figure 4.17: FDD Testing Scenarios for the TVWS eNB.

For each described scenario, the eNB will deploy a 5 MHz carrier signal according to the B28 frequency arrangement. This means the uplink and downlink carriers will each be in their own TVWS channel.

In **Scenario A**, there is only one pair of channels that allows for high enough transmit power while also having the correct duplex spacing.

Scenario B shows that multiple channels can facilitate the appropriate transmit power, but only one combination of channels have correct duplex spacing.

Finally, in **Scenario C**, there are two combinations of channels, at the correct duplex spacing and enabling appropriate transmit powers. In this situation, the eNB selects the combination that produces the highest mean power with the minimal differential between uplink and downlink powers. If a weighting bias was to be applied towards the downlink channel power availability, it would be considered at this stage of the decision making process.

A custom *AVAIL_SPECTRUM_RESP* message, containing a spectrum representation for the specific test scenario, was sent to the PAWS client using Postman. The resulting *SPECTRUM_USE_NOTIFY* message, sent automatically by the client, was then inspected to make sure that appropriate TVWS channels were picked for operation.

Scenarios A and B only have one valid channel pairing, with correct transmit power levels and duplex spacing, while **Scenario C** had multiple options to be chosen between. In each scenario, the correct channels were requested. This shows that the PAWS client successfully responded to the supplied information and is working as intended for FDD operation in TVWS.

4.3.6 Lessons Learned and Future Work

One potential modification, which should be implemented to better conform with the ETSI regulations, involves changes to the AVAIL_SPECTRUM_REQ process within the PAWS client. Currently the system performs a single database query, using worst case parameters from the eNB, and assumes the results are valid for both the eNB and the served UE. These parameters include emissions class, device type and, most critically, the latitude and longitude. This assumption is fundamentally flawed and, while relatively acceptable for lab proof-of-concept or demonstration, it is not feasible for practical use within a network deployment. Importantly, reporting incorrect parameters does not grant spectrum licence exemption under the terms of the Wireless Telegraphy Act, as the risk of interference to Incumbent users is increased without accurate information.

It is unlikely that a UE and eNB will share a device emission class. Understating performance of the eNB will result in a lower power response from the database, which will decrease the efficiency of a network.

Another issue is the difference between a Type-A and Type-B device. A typical UE will be non-fixed with an integrated antenna, while an eNB will be fixed and use an external antenna. In addition, as the UE does not communicate directly with a database, the associated parameters should be calculated for a Responder WSD, rather than for a Responder device such as the eNB. These discrepancies will result in incorrect power levels being made available to the UE, which increases the risk of interference.

Finally, reporting an identical fixed location for both the UE and eNB is not an accurate representation within a mobile network deployment. The end user is very rarely co-located with the eNB, instead moving around the operating cell. Assuming the channel response is constant across the entire eNB operating cell, especially using parameters calculated from the cell centre, will again increase the power available to UEs. This is particularly relevant when considering UEs near the cell edge, where these parameters could be a complete mis-representation due to the distance from point of calculation at the eNB. The end result is a significant increase in the risk of interference.

A potential resolution for this is suggested by Baig *et al* [135] where independent database queries are carried out for uplink, based on the UE characteristics, and for downlink, using the eNB parameters.

As performing separate database queries for each UE is not practical at scale, there needs to be a resolution of determining a set of operating parameters applicable to all UE. This can be achieved using the “generic Responder” option within the PAWS protocol [110]. Using this categorisation allows certain parameters, including device location, to be omitted when querying a database, changing the calculations that are carried out.

The end result is a lower power allocation for the uplink, due to the increased uncertainties, with a reduced risk of Incumbent interference. This method would increase the reporting accuracy of the system and bring implementations further in-line with the TVWS regulations.

An alternative to using a generic Responder request is to take advantage of the other location reporting parameter format within the PAWS protocol. While the most common approach is to specify a fixed point latitude and longitude, there is also the option to specify location as a region, using a standardised polygon shape as defined in [138].

To implement this in a PAWS compliant request, a number of latitude and longitude values are provided to define up to 15 non-overlapping vertices of a WSD operating area. By providing a polygon approximately equivalent to the eNB cell, calculated through coverage simulation, the calculations carried out by the database could be made more accurate and result in higher power allocations than obtained using a generic Responder. However, this comes with the additional risk of approximating the cell size. If this is not accurate, this could result in incorrect power allocation to the UE and an increased risk of potential interference.

4.4 Research Impact

The work presented throughout this chapter has contributed to further research projects and development activities.

One example of this was part of the *“Enabling Affordable Rural Internet Access with Dynamic Spectrum Access and Software Defined Radio”* project, referred to as the Affordable Rural Internet Access (ARIA) project [139]. This Engineering and Physical Sciences Research Council (EPSRC) funded initiative investigated how the use of TVWS and DSA, combined with SDR, could be used to enable effective and efficient wireless networks to be deployed at scale in developing countries, and thus used to support affordable Internet access. The research contributions of this thesis were shared and used by with the wider project consortium — which consisted of the University of Malawi, the University of Ghana, Copperbelt University in Zambia, and Strathmore University in Kenya — to further their studies and development activities in their respective countries.

The PAWS client, discussed in Section 4.1, and the codebase developed for the TVWS database clients, discussed in Section 4.2, was later used by other members of the StrathSDR research group as a validation tool for their own development work as part of a further research projects. For example, the work presented in this chapter was used as part of an implementation of a TVWS database; both as an example of system message exchange and to validate the responses of the created database.

The development activities of the SDR eNB system, implementing PAWS messaging and integrating with the Fairspectrum Oy WSDB, were completed in the initial stages of the 5G RuralFirst (5GRF) project as part of the DSA workstream —- although the initial research activities had been carried out prior to official start of the project. More information on the further DSA development activities of 5GRF is provided in Chapter 5.

4.5 Chapter Conclusions

This Chapter presented two research contributions focused on developments with the PAWS protocol, which is used for communication between WSD and WSDB as part of the TVWS spectrum access mechanism.

An overview of PAWS is provided in Section 4.1, which covers the six component operations of the specification.

The first research contribution presented in this Chapter is the development of a WSD emulation program. This software provides an efficient interface to WSDB resources.

Work presented in Section 4.2 described the Python development, testing methodology using the Postman software, and performance results. The developed system was found to operate as expected for all regulatory required messages involved in the PAWS processes.

Initially this tool enabled frequency planning for the Orkney TVWS network, discussed in Chapter 3, and was later used by other members of the StrathSDR research group to validate their own shared spectrum development work.

Section 4.3 presents the second research contribution; integration of an SDR-based eNB with an Ofcom approved WSDB. The system used LTE Band 28 in 700 MHz to provide a service that is compliant with 3GPP specifications, as well as the control and authorisation frameworks of TVWS regulations. The associated spectral agility requirements are handled through the SDR implementation and intra-eNB handover signalling.

This work represented a significant contribution to the shared spectrum research activities of the 5GRF project, discussed further in Chapter 5.

Finally Section 4.4 briefly reviewed some of the further research items that have occurred as a result of the presented work. This included contributions to the EPSRC-funded ARIA project, which focused on TVWS and DSA with SDR in developing countries, with partner Universities from Kenya, Malawi, Ghana, and Zambia.

Chapter 5

CBRS Dynamic Spectrum in the 5G RuralFirst Project

As part of the Autumn Budget Statement in 2016, the UK Government announced over £1 billion of funding to improve digital infrastructure. As part of this, the 5G Testbed & Trials programme was a nationally co-ordinated initiative for investment in 5G development and deployment. In March 2018, DCMS announced support for six projects under the first phase of the programme.

The 5G RuralFirst (5GRF) project, led by Cisco Systems Ltd alongside principal partner University of Strathclyde, was one of the funded projects and ran from June 2018 to September 2019. The aim of the project was to support and inform development of the UK's 5G eco-system to address the needs and aspirations of rural communities and businesses [140]. To fulfil this aim, a range of technology trials and use cases were developed to explore the potential for rural 5G deployments.

The use cases implemented within 5GRF were established to represent genuine challenges faced by rural communities and industries as they strive to develop viable ways of ensuring that they are digitally connected. Each use case demonstrates one or more approaches to the three aspects of 5G acknowledged by DCMS: enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC) services, and Massive Machine-Type Communications (MMTC).

One of the key concepts across 5GRF was the use of shared spectrum and DSA technology. Part of this research involved the development of the TVWS LTE eNB system presented in Chapter 4, which involved a 3GPP-compliant operating stack implemented on an SDR platform that connects with an Ofcom-approved geolocation database.

This chapter presents a research contribution that was developed in support of the DSA work package of 5GRF. This work was proposed to, formally agreed by, and reviewed by DCMS as part of the pre-established project deliverables and milestone acceptance. The author designed and implemented an LTE eNB system that employs DSA mechanisms using the CBRS architecture and protocols. This involved creation of a client-side control platform, and a channel selection algorithm that is applicable to multiple 3GPP-defined frequency bands.

A brief overview of the 5GRF project is provided in Section 5.1 to provide context for the outlined research contribution. This includes a summary of all work completed as part of the shared and dynamic spectrum use case.

Section 5.2 presents the design, implementation, and evaluation of the DSA-enabled LTE eNB system. This includes an overview of the high-level 5GRF network architecture and a review of the SAS-CBSD protocol from the CBRS standard, as this message exchange is a critical component of the development work.

A bespoke channel selection algorithm was designed by the author. This was used in the 5GRF CBSD system to select an operating frequency from information provided by the 5GRF spectrum management platform in response to availability queries. A literature review of comparable solutions for this process is provided, as well as an overview of the overall system testing.

Finally, details of the impact from the presented research is provided in Section 5.3. This includes contributions made to UK spectrum policy-makers and a further project, also funded by DCMS, building on the established Orkney Island testbed.

5.1 Overview of the 5GRF Project

5.1.1 Project Consortium and Objectives

The 30-member 5G RuralFirst consortium, shown in Figure 5.1, combined experience from industry, public sector, academia, and a number of Small-and-Medium Enterprise (SME) partners.

The consortium's belief was that 5G must be more than simply "faster 4G" with lower latency and that, to fully address the digital divide, the business models and barriers to deployment must be addressed.

The project therefore looked at new ways of doing things — employing 'new thinking' in business operating models, applications and services, infrastructure sharing, and spectrum sharing. The aim was to enable new approaches for rural communities and alternative communications providers to deploy 5G services in areas where the traditional MNOs do not operate or, where appropriate, provide enhanced services that complement existing deployments.

The project also focused on research into new deployment techniques and network architectures to reduce the cost of installations and improve energy efficiency. This included the use of low power, reconfigurable SDR technology, deployment of distributed basestation architectures with disaggregated BBU and RRH, and implementation of future network architecture features

Figure 5.1: The 5G RuralFirst Project Consortium.

such as Mobile Edge Compute (MEC), and neutral hosting. Network deployments were designed to use a number of different wireless technologies and frequencies, in both licensed and unlicensed bands. More information on the network architectures and deployed technologies can be found in the project conclusions report [140].

In addition to research on DSA, the StrathSDR team were also responsible for a multi-site network deployment on the Orkney mainland. Like the TVWS network discussed in Chapter 3, this 5GRF installation was used to provide supplementary wireless connectivity for the residents and visitors to the island.

Through these network design and deployment activities, the author was introduced to the Amarisoft software stack, the SDR-based RRH from AW2S, and the use of modems as UE devices. All of these would be crucial in the later development of an end-to-end 5G SA network for the Glasgow Underground, which is discussed further in Chapter 6.

5.1.2 DSA Development within 5GRF

The dynamic and shared spectrum activities completed as part of 5G RuralFirst can be grouped into two overarching work areas.

Regulation and Policy

The first work area focused on the development of shared spectrum policy and regulation, as well as the dissemination of technical information. In support of that, a collaborative discussion paper on spectrum and neutral hosting was completed in conjunction with the University of Surrey's 5GIC and two other 5G Testbeds & Trials projects — AutoAir and the Worcestershire 5G Consortium [141]. The author made contributions to that publication as part of multiple in-person workshops and during the draft document review. The “5G Spectrum and Neutral Hosting” paper covered various topics in areas of standards, regulation, and policy that would potentially impact the scalability of 5G in national deployments.

The 5G RuralFirst consortium findings were contributed to the IET Further Faster Initiative [142], a group of companies and academics developing new approaches for the allocation of mobile spectrum in the UK. This resulted in a document outlining support for the market expansion model described by the Government as part of their Future Telecom’s Infrastructure Review [143]. The author also contributed to an independent white paper on the subject [144], published by the 5GRF consortium.

Technical Development

The second shared spectrum research area covered by 5GRF was the development of an automated DSA framework for implementation with next-generation wireless networks.

To enable CBRS-like activities across the Orkney testbed location, a number of operational licenses for both 700-800 MHz and 3400-3600 MHz spectrum were obtained from Ofcom to create a DSA sandbox — an isolated, controlled, environment that allows for different spectrum sharing paradigms to be demonstrated and tested.

A bespoke SAS system was developed by project partner Fairspectrum Oy, referred to as the Incumbent Manager.

This management system was used to facilitate access to the spectrum sandbox. Incumbent users could be generated, either manually through a GUI or with an API, that would then be accounted for and protected when a new device requests operating parameters.

The main benefit was the ability to take the interface, architecture, and incumbent protection calculation specifications from the CBRS standard and apply them to frequency bands beyond the archetypal 3550-3700 MHz range.

The calculations performed by the Incumbent Manager to protect transmissions was compliant with the FCC regulations, except the necessary frequency range modifications required to be compliant with the Ofcom licencing rather than the standard CBRS frequencies.

The Incumbent Manager would interact with a requesting CBSD as a normal SAS would. Communication follows the standardised architecture, presented initially in Chapter 3 and further discussed in Section 5.2.1, while all intra-device communication used the WIF SAS-CBSD interface [103], as discussed in Section 5.2.2

To accommodate the variation in targetted frequency band, and allow for use of the existing hardware ecosystem, a bespoke CBSD platform was designed and implemented by the author. This work is discussed further in Section 5.2.

5.2 Implementing the 5GRF CBSD Solution

As presented in Chapter 4, an LTE eNB system had previously been integrated with an Ofcom-approved geolocation database for operation in TVWS. The author's aim for that piece of work was to develop a system capable of exploiting the significant LTE equipment ecosystem in combination with licence-exempt spectrum.

As highlighted in Section 5.1, to allow eNB systems at the Orkney testbed to communicate with the Fairspectrum Incumbent Manager, a CBSD solution was developed by the author. A brief overview of the high-level architecture of this implementation is provided in Section 5.2.1.

While this work is comparable to the PAWS TVWS system outlined in Chapter 4, there are a number of fundamental differences. The primary changes is the underlying messaging protocol and data format, which uses the SAS-CBSD standard interface, as discussed in Section 5.2.2.

The program structure was also significantly changed. While the TVWS system operated as a shim library with a GUI for control, the CBSD implementation was designed to be completely automated and more flexible. To accommodate this functionality, programming followed an object-orientated design, with a top level class encompassing all operational requirements for a CBSD. This was performed partly because the communication and control requirements for CBRS are more complicated than under TVWS standards. It was also an intentional design choice to create a more modular implementation. Further discussion on program structure and operation flow is provided in Section 5.2.3.

One of the foremost decisions carried out by the 5GRF CBSD is the choice of operating frequency based on data provided by the Incumbent Manager. More information on this, including a review of other reference publications on the subject, is provided in Section 5.2.4.

5.2.1 High-Level Network Architecture

Figure 5.2 shows a high-level representation of the DSA sandbox environment created at the Orkney testbed location, based on the standard CBRS implementation. In this example, multiple 5GRF CBSD systems are connected to a single serving ePC, which bridges connectivity to the Internet and other resources.

Through the ePC, devices connect to the 5GRF Incumbent Manager using the SAS-CBSD protocol discussed in Section 5.2.2. This could also occur over a local network, rather than the Internet, which would be beneficial when dealing with messages transmitted with time constraints defined by the SAS-CBSD protocol.

Each CBSD is responsible for communicating with its preferred SAS or Incumbent Manager, determining its operating parameters, and generating its own configuration file accordingly.

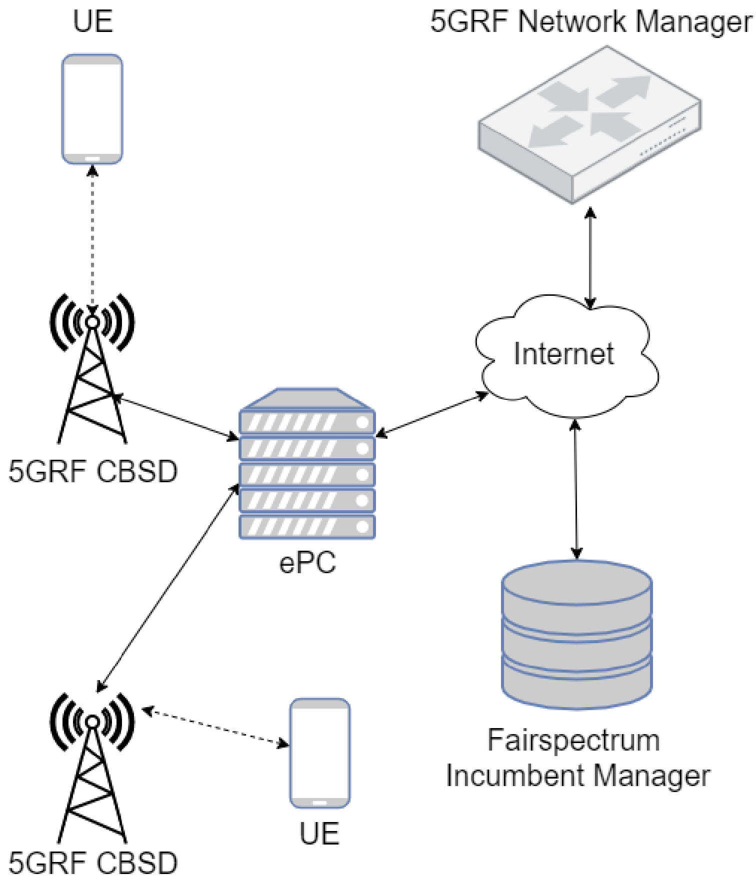


Figure 5.2: High-level overview of the DSA framework architecture in 5GRF.

5.2.2 SAS-CBSD Interface

As discussed in Chapter 3, formal FCC regulations were adopted in 2015 to enable dynamic spectrum access to 150 MHz in the range of 3550-3700 MHz, subsequently referred to as the CBRS band.

Two protocols are specified; one for communication between SAS and CBSD [103], with the other for SAS-to-SAS communication [104]. In both cases, the protocol takes the form of a message exchange, using defined structures containing mandatory, conditional, and optional parameters.

Unlike TVWS, the CBRS standard was intended for both FWA and mobile broadband applications. This impacts the interference and primary user protection calculations carried out by the SAS, compared to those performed by a TVWS geolocation database, and also on the requirements for network nodes and end user devices.

The remainder of this section will focus on the two main processes implemented for SAS-CBSD communication, as outlined by the WIF specifications for commercial operations [145], and the SAS-CBSD API technical specification [103].

CBSD requests are sent in the form of defined JSON objects, containing the standardised name value pair options and various mandatory, conditional, and optional parameters. Response messages from the SAS are sent in the same fashion. This is conceptually the same as the PAWS operations discussed in Chapter 4.

5.2.2.1 Registration

Under the previously mentioned regulations, a CBSD must first register with a SAS before it can request authorisation for over-the-air operations. This is completed by sending a formatted *Registration Request* message.

If registration is successful, indicated as part of the SAS response, the CBSD will then be able to send further requests to the SAS. A CBSD will remain registered until a period of inactivity, or a *Deregistration Request* is sent to the SAS. This is captured by the state diagram shown in Figure 5.3.

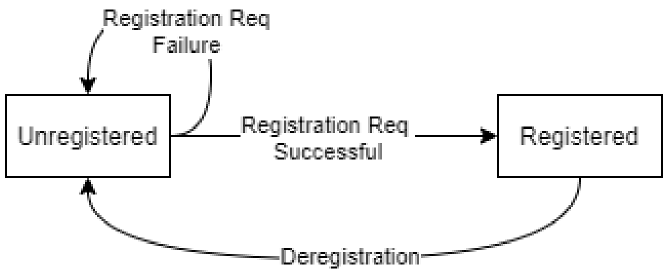


Figure 5.3: State Machine for CBRS-SAS Registration Process

5.2.2.2 Spectrum Grant and Authorisation

A registered CBSD can use the *SpectrumInquiry* procedure to request information on available spectrum from the SAS. This query can be set for a specific range of frequencies. This is because a PA user has fewer potential deployment channels within a PPA, while a GAA user would likely look for availability over the full frequency range.

The SAS *SpectrumInquiry Response* contains the information needed by the CBSD to form a *GrantRequest*.

A CBSD can hold multiple simultaneous Grants with a SAS. This is necessary for reserving non-contiguous spectrum blocks. While this is achievable under the specification, and required for FDD deployments, TDD implementations are the primary frequency arrangement consideration. There are also no standardised methods for creating a Grant based on these response parameters, for either GAA or PA users. These topics are discussed further in Chapter 5.

Once an acceptable Grant is received by the SAS, the *GrantResponse* returns a number of important parameters for the CBSD. This includes the specific ID value for the Grant, confirmation of the over-the-air operating parameters, an expiry date for that specific Grant, and a time period for mandatory check-in with the SAS referred to as the Heartbeat interval.

Grant validity periods are at the discretion of the SAS, with the 5GRF Incumbent Manager set to authorise for 24 hours. A CBSD can extend the validity period by re-requesting the Grant, using the same parameters, to maintain the same Grant ID and increase likelihood of renewal. If a CBSD allows the Grant to expire, any over-the-air transmissions must stop until a new Grant can be approved. In addition to the implied break in service, a PA user runs the risk that previously reserved spectrum is reallocated by the SAS, which could impact delivery to the end user. For the opportunistic GAA spectrum users, this risk is always present.

Even once a Grant has been confirmed by the SAS, a CBSD cannot begin over-the-air operation without first completing a *Heartbeat* process. These types of protocols are commonly used to monitor a shared resource and synchronise parts of a computer system.

The *HeartbeatRequest* is used to inform the SAS that a CBSD wishes to use its allocated spectrum, while also providing an opportunity for the SAS to suspend or terminate current Grants. As part of the *HeartbeatResponse*, the SAS includes a *transmitExpireTime* parameter indicating the period for acceptable over-the-air operations. Typically, this will be a duration of 60 seconds, to match the time required to discontinue transmission following Grant suspension or termination.

A Heartbeat must be transmitted for each Grant. This adds complexity to FDD implementations, as multiple Heartbeat messages must be co-ordinated to allow service provision to the end users. Once the SAS has confirmed the Heartbeat, the CBSD can commence over-the-air transmission using that parameter set. This functionality is captured by the state diagram shown in Figure 5.4.

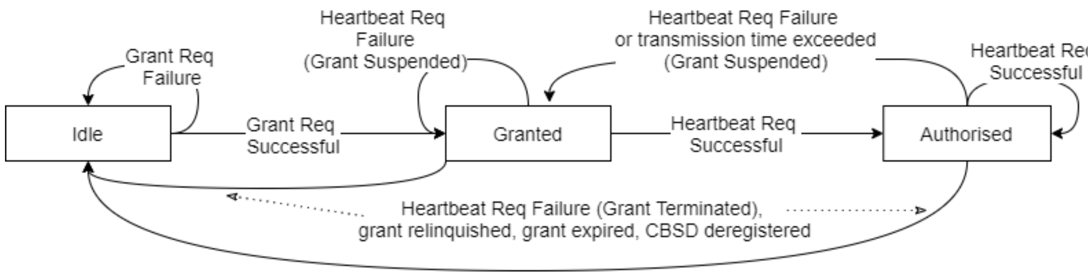


Figure 5.4: State Machine for CBRS-SAS Grant Process

Under these operating requirements, the operational flow for a CBSD to go from the initial unregistered state to authorised and transmitting is shown in Figure 5.5. Assuming that all messages are transmitted by the CBSD, received by the SAS, and returned with no issues, the CBSD will go through the outlined processes and begin a loop of the Heartbeat process. This will continue until one of the possibilities shown in Figures 5.6 to 5.8 is reached.

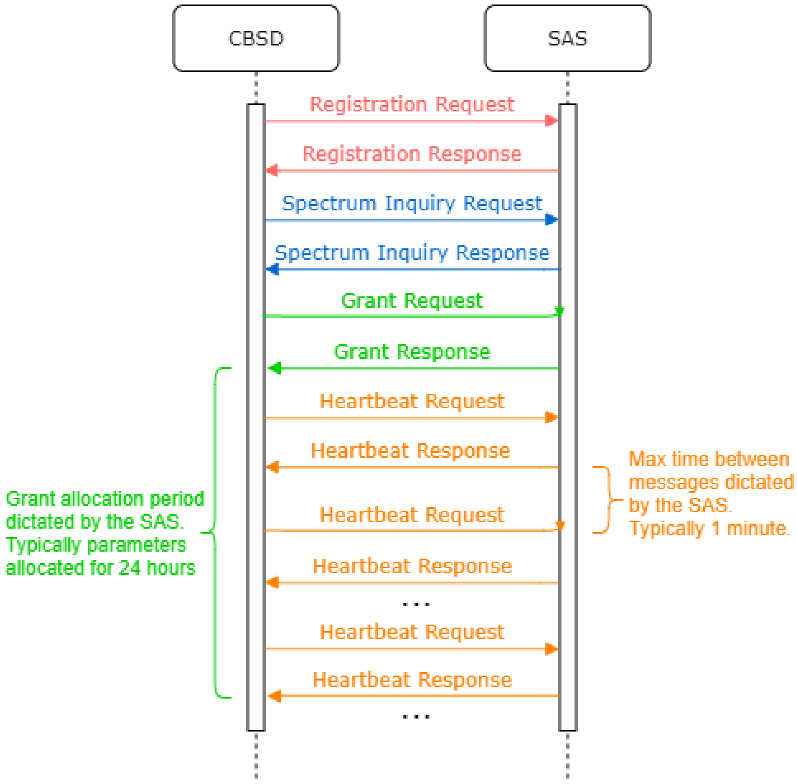


Figure 5.5: Flowchart of system operation covering Registration through to initial Heartbeat.

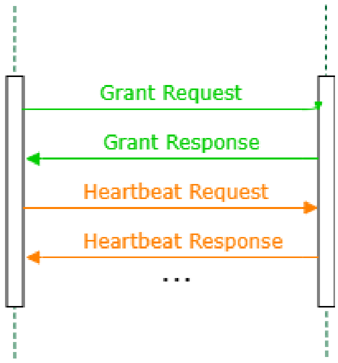


Figure 5.6: Flowchart of system operation covering Grant and Heartbeat processes.

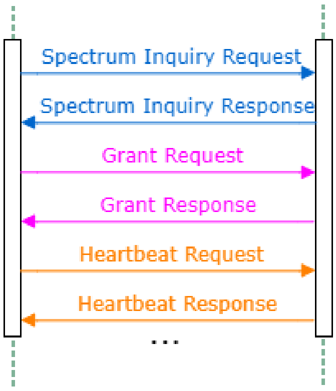


Figure 5.7: Flowchart of system operation covering Spectrum Inquiry, Grant, and Heartbeat processes.

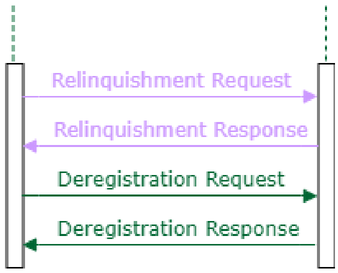


Figure 5.8: Flowchart of system operation covering Relinquishment and Deregistration processes.

As the Grant validity reaches expiry, the system can resubmit the *GrantRequest* under the same parameters and resume operation. This is likely what a PA user would do, assuming there have been no changes in spectrum availability. This is shown in Figure 5.6.

If there have been changes in spectrum availability, indicated as part of the SAS *GrantResponse*, or the Grant has expired, the CBSD should begin the process of creating a new Grant as shown in Figure 5.7. This involves getting updated information on channel availability, from the *SpectrumInquiryResponse*, and selecting new parameters. Once approved, the CBSD can restart the Heartbeat process.

The final option shown in Figure 5.8 is carried out when there is a valid Grant in place with the SAS, but the CBSD does not wish to continue operations. The *RelinquishmentRequest* terminates a specific Grant with the SAS, before a *DeregistrationRequest* is sent.

5.2.3 5GRF CBSD Software Architecture

To accommodate the state-based operation and program flow of the CBSD system, an object-orientated design approach was taken. Each communication process was created as an individual class object, each derived from a top level *CBRS_Message* class, to allow for communal functions to be defined for all child classes.

The shared features included functions to validate the inputs and prospective outputs against created Schema files, a function to package the JSON structures with the correct headers and packet formats, and a function to transmit the packaged messages over an IP port using HTTP methods.

The UML diagrams for the created *CBRS_Message* class and its children are shown in Figure 5.9. Each child message class contains the parameters needed to create its defined message structure, and for the storage of the corresponding response from the SAS.

The bespoke *Configuration* message was designed to follow the same format of the CBRS standard messages, and was used to control operations within the Incumbent Manager to enable development in the project.

To allow the CBSD to operate for any LTE band, a specific container class was created to represent 3GPP frequency definitions. For any supplied band number, up to Release 14, the class pre-sets key parameters from an existing file. It is necessary to have access to specific LTE band parameters, such as duplex spacings, operating mode, uplink and downlink frequency ranges, for the channel selection calculations as discussed in Section 5.2.4. The class also contains helper functions for the conversion between centre frequency and EARFCN, and vice-versa. The UML for this class is shown in Figure 5.10.

The *CBSD_Device* class is used to represent any device that follows the CBRS standard. It can be considered as a container object for the *CBRS_Message* and *LTE_Band* objects, although it contains a number of additional parameters necessary for file storage and management, for flexible calculation of operating parameters, and for co-existence with the software that provides the LTE service. The UML diagram for this class is shown in Figure 5.10.

Functions included within the CBSD class either carry the message exchange with the SAS, or interact with the Amarisoft LTE service. For the latter, this operation is performed in the same way as described in Chapter 4, with a Primary and Secondary channel. The currently active selection is changed as required by the response contents from the SAS. The CBSD class

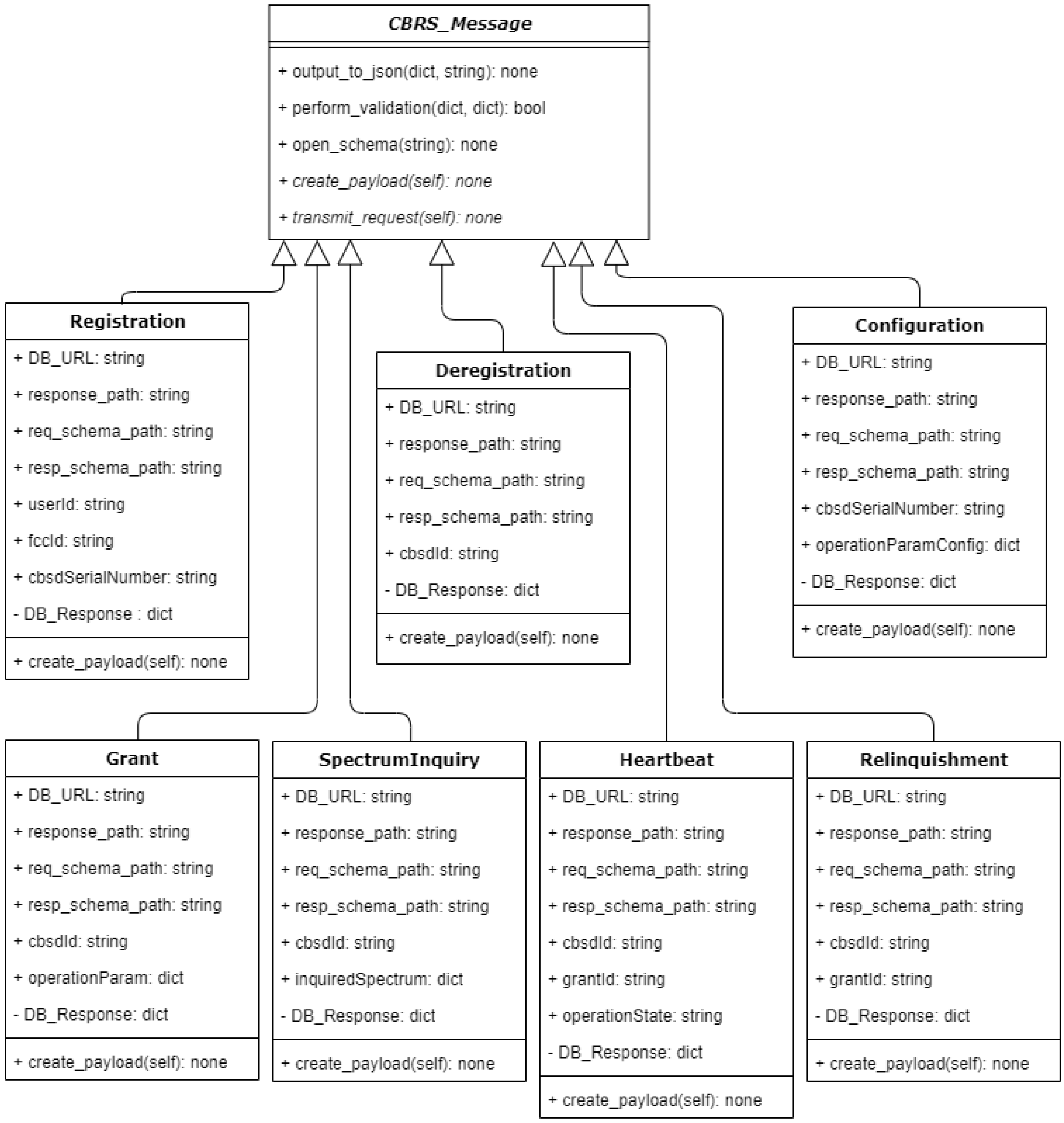


Figure 5.9: UML for each *CBRS_Message* Class.

also contains the functions to select operating channels from the provided SAS response. This is discussed further in Section 5.2.4.

To enable the message exchange processes discussed in Section 5.2.2 and take advantage of the created classes a short program was developed for the eNB client. In order to achieve the flexibility and time critical components operating as intended, the program has multiple parallel computation threads. A flowchart for the main operation of this program is shown in Figure 5.11, with flowcharts for the thread operations shown in Figure 5.12.

Internal event triggers are used to control program flow between different threads as some operations are triggered by the completion of others, while some are dictated by the elapsed time. Some events, such as the Heartbeat transmission, cannot occur while the Grant process is ongoing, so event triggers are used to prevent sequence driven operations from occurring.

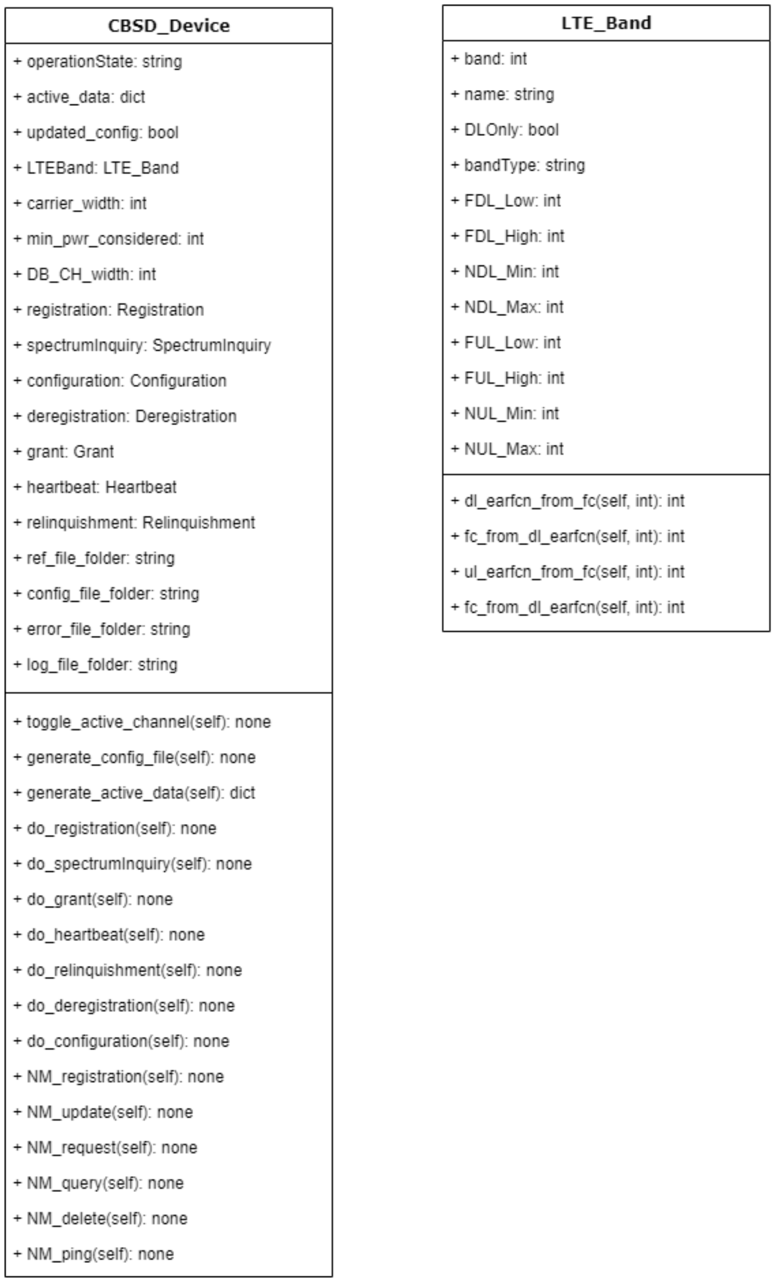


Figure 5.10: UML for *CBSD_Device* and *LTE_Band* Classes.

Thread numbering dictates the level of priority given to each task. The task controlling the Grant renewal with the SAS is the highest priority communication, while the upkeep Heartbeat transmission is essential but reliant on the Grant.

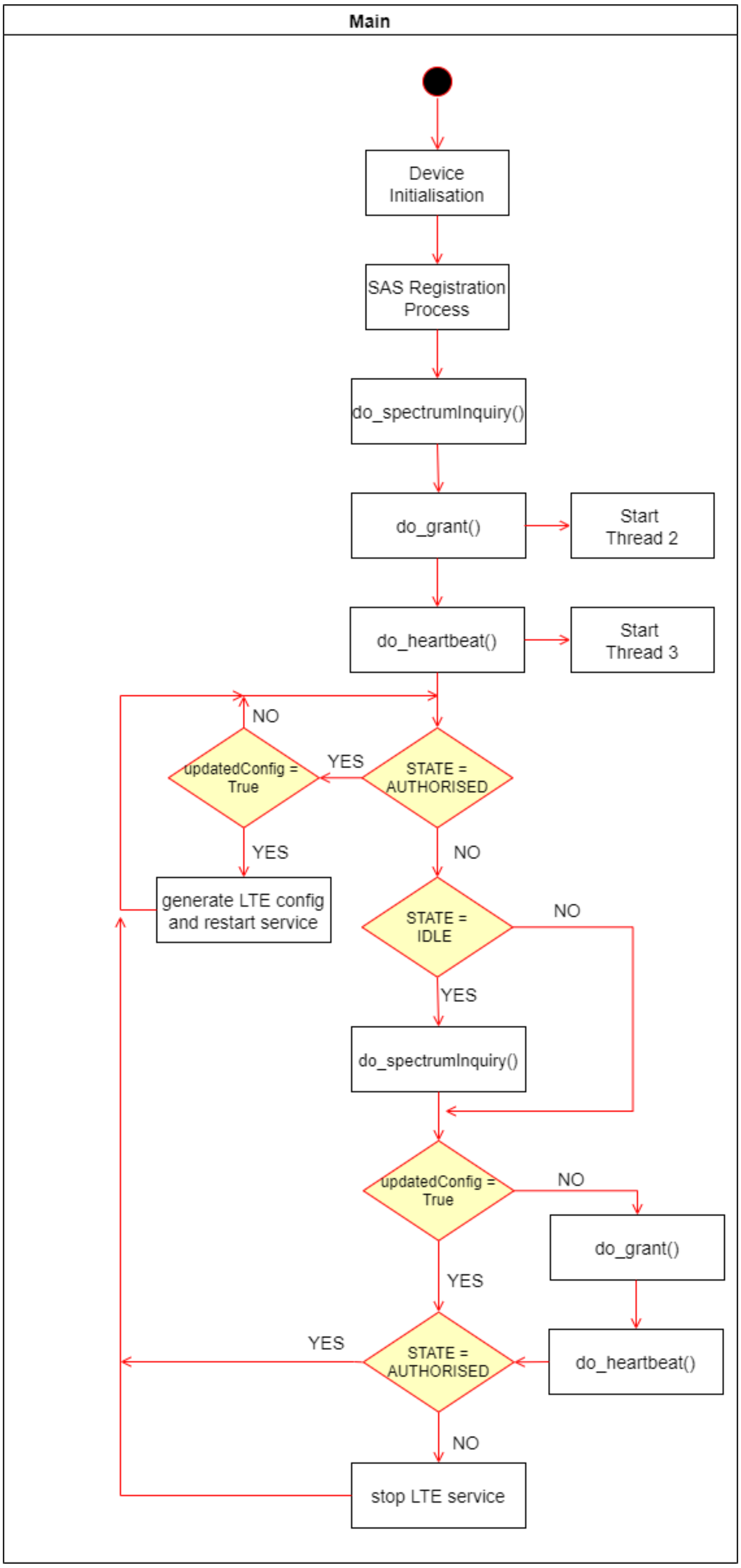


Figure 5.11: Flowchart for the operation of the main program processing thread.

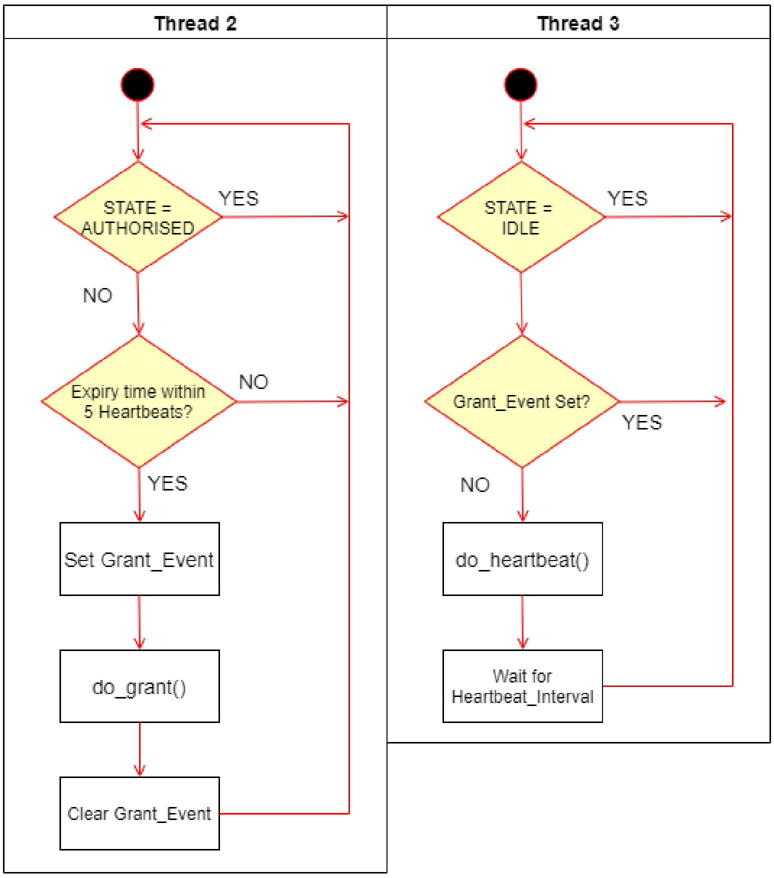


Figure 5.12: Flowchart for the operation of the program threads processing in parallel.

5.2.4 Channel Selection Algorithm

This section will overview work completed by the author designing and implementing a bespoke channel selection algorithm for use in the 5GRF CBSD when working with the Incumbent Manager.

Section 5.2.4.1 presents a brief review of similar work items and examples found in literature and commercial CBSD deployments, while details on the low-level design of the algorithm are provided in Section 5.2.4.2.

5.2.4.1 Examples in Literature

There are a number of published works focusing on channel allocation for CBRS systems. These publications typically focus on methods that can be implemented as part of the SAS functionality, as this is an area with defined requirements and significant challenges. A SAS must account for multiple scenarios when determining the CH information returned to a CBSD or DP. The most fundamental differential is between responses given to PA users compared to GAA.

For the response to a PA CBSD, the SAS must consider the protection contour to minimise potential interference, and two contiguity requirements defined by the FCC. Geographical contiguity means that, where feasible, PALs issued to a PA user should occupy the same channels in geographically overlapping, or adjacent, PPA. Similarly, to enable spectral contiguity, if PALs for multiple channels within a PPA are held by a single PA, where feasible the allocated spectrum should be contiguous. Due to the tiered access structure, the requirements for GAA systems are significantly different, such as the removal of protection obligations.

Different models and algorithms have been proposed by Yang *et al* [146], Manosha *et al* [147], and Sahoo [148]. These papers largely focus on the algorithm's for allocation implemented by the SAS, rather than on selection by an enquiring CBSD.

Other options are presented that require modifications to the SAS beyond the WIF specifications. For example, Ying *et al* [149] outlined dedicated channel management components for GAA and PA users.

In a 2018 paper, Baig *et al* [150] discussed a system referred to as F-CBRS, designed to be deployed on top of SAS and LTE basestations to allow for co-ordinated channel assignment for licence-exempt users. The proposed system also takes advantage of the intra-eNB handover method discussed in Chapter 4.

A 2020 US patent filed by Ericsson [151] outlines a channel selection process for reconfigurable systems operating under the CBRS framework. The described process focuses on the use of RSSI measurements, from one or more CBSDs in an area served by the same DP, to indicate when to change the operating parameters for a specific device. An additional network entity is described to enable this process, referred to as the CBSD Sensing Entity.

While these publications do all address channel utilisation in CBRS networks, they either do not solely consider methodologies for CBSD or DP to select parameters based on the SAS provided information as standard, or they require additional network components beyond the base specifications.

This is also the case in publications outlining similar development work. For example, in the 2019 paper by Liu et al [152], the channel allocation algorithm used by the DP is not provided; and instead it is listed as an item of further work. This is also the case in the 2019 paper by Chen *et al* [153].

As discussed in Chapter 3, four SAS administrators were certified to authorise commercial CBRS services in January 2020 [96]. Although these implementations were not available when the outlined contributions to research were being developed, it is pertinent to examine current industry functionality.

As well as being one of the certified SAS providers, Google are one of the founding members of the OnGo Alliance (formally the CBRS Alliance) [154]. Their SAS platform is available to Google Cloud Business customers [155], with supporting APIs, management portal, and documentation.

Unlike the Fairspectrum Incumbent Manager, the Google SAS is proactive in the process of allocating and recommending channels to the requesting CBSD [156]. This reduces some of the requirements of the CBSD to be self-coordinating in its channel selection.

By providing a ranked list of recommended channels, the SAS also enables a level of coexistence between the lower tier of spectrum users. This ranked list accounts for estimated channel quality and interference probability, rather than simply available transmit power. However, it is still important that a CBSD can correctly select the appropriate channel for operation from the provided options received from the SAS. The algorithm presented throughout this section is able to fulfil this capability, as shown in Section 5.2.5.

5.2.4.2 Algorithm Design and Implementation

As mentioned previously, there is no standardised method for a CBSD to select an operating channel based on information provided by the *SpectrumInquiryResponse*, outside of the limitation placed on PAL deployments to within the 3550-3650 MHz range. The problem is compounded by the multi-band operating requirement of the CBSD program. This introduces complications regarding FDD arrangements, variations in uplink and downlink frequency ranges, and plans that are not easily accommodated by the channelised reporting mechanism.

For example, consider LTE Band 3, as used in the 5G RuralFirst eMBB use case and the Ofcom shared spectrum framework. The 3GPP definition for the band spans 1710-1785 MHz for uplink, and 1805-1880 MHz for downlink. The 5 MHz offset at the upper bound of the uplink and lower bound of the downlink is already inconvenient with 10 MHz channelisation. However, when considering the practical frequency plan of 1800 MHz spectrum in the UK it is clear that a granularity of 10 MHz is insufficient, as allocation is specific to the level of kHz. This can be seen from the MNO spectrum holdings within the band, shown in Table 5.1.

Operator	**Uplink** (MHz)	**Downlink** (MHz)	**Band Widths** (MHz)
O2 (Telefónica)	1710.1-1715.9	1805.1-1810.9	5.8 + 5.8
Vodafone	1715.9-1721.7	1810.9-1816.7	5.8 + 5.8
Three (Hutchison UK)	1721.7-1736.7	1816.7-1831.7	15 + 15
EE	1736.7-1781.7	1831.7-1876.7	45 + 45
Ofcom Shared Access	1781.7 -1785	1876.7-1880	3.3 + 3.3

Table 5.1: Summary of the 1800 MHz frequency band plan in the UK.

It is clear that, while a 10 MHz channel arrangement is suitable for CBRS, as a new band developed during the standardisation process, it will be challenging to retrofit a single solution suitable for multiple existing bands.

The simplest solution would be to incorporate additional fields in the *SpectrumInquiryRequest* sent to the Incumbent Manager to indicate the intended operating band. This would allow the response to be channelised appropriately for the technical specification and frequency plan, at the cost of additional complexity in the Incumbent Manager.

This would also require that the system performing the request is capable of carrying out flexible channel selection. As part of the 5GRF development, the entity created for the CBSD is not limited to 10 MHz channel allocations.

The algorithm begins by establishing a value set, C, of candidate centre frequencies, f_c. This set contains every 500 kHz multiple in the range returned by the SAS, excluding the upper and lower boundary frequencies, i.e the range 700-800 MHz would initially have 198 potential values:

$$C(f_c) = \{700.5, 701, 701.5...789.5, 799, 799.5\} \tag{5.1}$$

The system then removes any values from the set that do not sit within the uplink and downlink ranges defined by the band.

$$C \ni f_c,\ if \begin{cases} f_{UL_{LOW}} \leq f_c \leq f_{UL_{HIGH}} \\ f_{DL_{LOW}} \leq f_c \leq f_{DL_{HIGH}} \end{cases} \tag{5.2}$$

Following this, the system considers the intended carrier bandwidth. Centre frequencies that do not allow for carrier creation within the uplink and downlink ranges of the band are discounted.

$$C \ni f_c,\ if \begin{cases} f_{UL_{LOW}} \leq f_c + \frac{1}{2}BW \leq f_{UL_{HIGH}} \\ f_{DL_{LOW}} \leq f_c + \frac{1}{2}BW \leq f_{DL_{HIGH}} \end{cases} \tag{5.3}$$

The system then associates each candidate centre frequency with the lowest transmit power allowed in any of the SAS channels that a carrier would overlap with. Any centre frequencies that do not meet a minimum power threshold, of default 20 dBm, are eliminated.

$$C \ni f_c,\ if \begin{cases} [f_c - \frac{1}{2}BW](TxPwr) \geq 20\ dBm \\ [f_c]\ (TxPwr) \geq 20\ dBm \\ [f_c + \frac{1}{2}BW](TxPwr) \geq 20\ dBm \end{cases} \tag{5.4}$$

If the target LTE band is TDD then there are no further changes to the list of candidate values. For FDD deployments the system removes any f_c that do not have a corresponding paired value, exactly separated by the defined duplex spacing DP_{SPACE} of the band, within the set.

$$C \ni f_c,\ \text{if}\ f_c \pm DP_{SPACE} \in C \tag{5.5}$$

Once the candidate frequency list has been minimised, the system selects a Primary and Secondary centre frequency, as in the TVWS system discussed in Chapter 4. For TDD, the frequencies associated with the highest transmit powers are considered to be the best solutions. For FDD, as with the TVWS implementation, the channel pairs are ranked to ensure that there is a high average power between uplink and downlink, without significant difference in the values.

It would also be possible to add a selection weighting towards the channel pair that facilitated the higher transmit power used by the downlink carrier signal. In this case, the 3GPP band definition will determine the appropriate frequency range selected.

Once the centre frequency values have been selected, the system identifies which channels must be reserved with the SAS, accounting for both the carrier and channel widths used. This information is then formatted as required by the *GrantRequest*.

5.2.5 System Testing

To allow for thorough testing of the channel allocation algorithm, a number of test scenarios were defined for both TDD and FDD frequency arrangements. These are discussed in Sections 5.2.5.1 and 5.2.5.2, respectively.

Messages would be generated by the CBSD and sent to the Postman API Platform [116]. A prepared response, specific to the outlined test scenario, was manually returned using Postman. This was received and processed by the querying CBSD, with the resulting channel selection verified to ensure the results were as expected.

5.2.5.1 TDD Operating Scenarios and Test Results

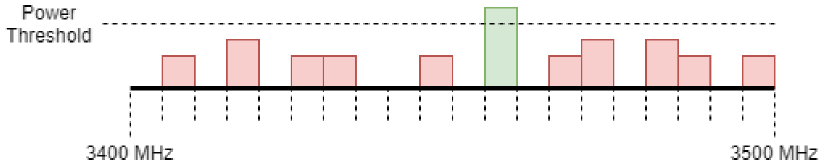
Evaluation of the TDD allocation capabilities made use of the LTE Band 42 arrangement over the subset of 3400-3500 MHz range. This frequency range was separated into ten lots of 10 MHz channels, although any integer channel denomination would be supported by the selection algorithm.

The five scenarios for TDD evaluation, shown in Figure 5.13, were created as formatted *SpectrumInquiryResponse* messages and returned by the Postman API platform to the CBSD.

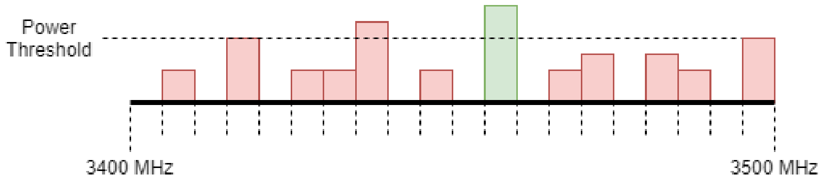
Scenario A illustrates a spectrum response where the intended carrier can be contained within a single channel, so in this instance 10 MHz, with only one channel response presenting power availability above a defined acceptance threshold.

Scenario B is similar to **Scenario A**, however multiple channel responses indicate a power availability above the acceptance threshold. In this case, the algorithm would select the channel with the highest permitted power level.

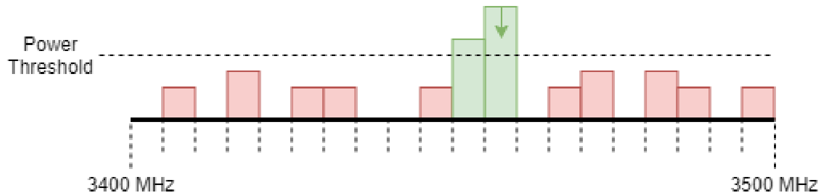
In **Scenario C**, the intended carrier signal bandwidth is greater than the span of a single channel. This means that multiple contiguous channels are required, both over the acceptable power threshold.



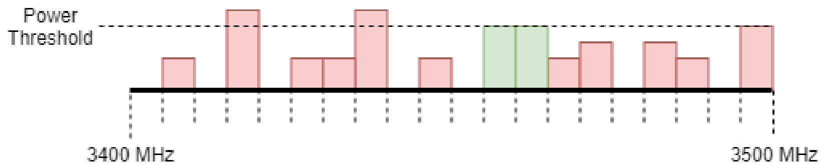
Scenario A) Single Candidate Channel



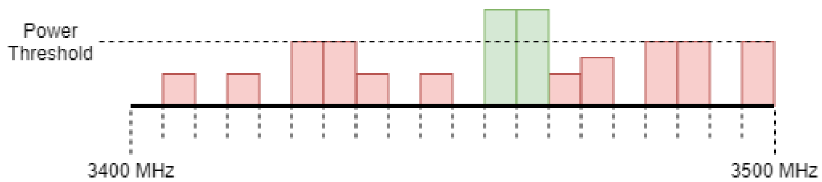
Scenario B) Strongest Candidate Channel



Scenario C) Only Candidate Channels



Scenario D) Only Contiguous Candidate Channels



Scenario E) Strongest Contiguous Candidate Channels

Figure 5.13: TDD Testing Scenarios for the CBSD Channel Selection.

As mentioned in Section 5.2.4, for contiguous channels the algorithm considers only the lowest power value of the pair. This is highlighted in Figure 5.13 by an arrow indicating where a lower transmit power would be used than could be authorised. In **Scenario C**, where only one pair of contiguous channels presents availability above the acceptable power thresholds.

Similarly, in **Scenario D**, there is only one pair of contiguous channels that present a usable transmit power at the defined acceptance threshold. Although there are a number of individual channels presenting higher usable power levels, there is only one appropriate, contiguous pair.

Finally, in **Scenario E**, there are multiple contiguous pairs indicating appropriate power availability. In this case, the algorithm would select the contiguous channel pairs with highest permitted power levels.

For each of the above scenarios, the *GrantRequest* JSON message sent by the 5GRF CBSD to Postman, containing the channel arrangement selected by the algorithm, included a request for the correct spectrum channel. As all of the described scenarios have only one acceptable result, this indicates that the algorithm is appropriately parsing the supplied information and working as intended when determining parameters for TDD operation.

5.2.5.2 FDD Operating Scenarios and Test Results

As expected, the inflexible duplex spacing between the carrier centre frequencies in FDD arrangements places additional requirements on both the algorithm implementation and the testing process.

Evaluation of the FDD allocation capabilities made use of LTE Band 28, covering 700 MHz, as shown in Figure 4.11 in Chapter 4. As with the TDD operating scenarios, the frequency range was separated into 10 lots of 10 MHz channels, and multiple scenarios were created as a series of formatted *SpectrumInquiryResponse* messages. These are shown in Figure 5.14.

For **Scenarios F, G, and H**, the intended uplink and downlink carrier sizing can be contained within one SAS channel each. In **Scenario F**, there is only one pair of channels with correct duplex spacing that also facilitates the available power requirements.

This is similar to **Scenario G**. However, in this case there are multiple channels presenting acceptable power levels, but only one candidate pair that also has correct duplex spacing.

In comparison with **Scenario H**, there are two pairs of candidate channels, with correct duplex spacing and available channel powers. In this instance, the algorithm selects the candidate pair that provide the aggregate highest available power. As mentioned previously, if a weighting scale was to be applied to the downlink channel power availability, it would be considered at this stage of the decision making process.

In **Scenarios I-L**, the intended uplink and downlink carrier sizing exceeds the width of a single SAS channel and so will require multiple sequential channels to accommodate. For example, in **Scenario I**, there are two sets of contiguous channels forming a single, appropriately duplex-spaced, pair of candidates.

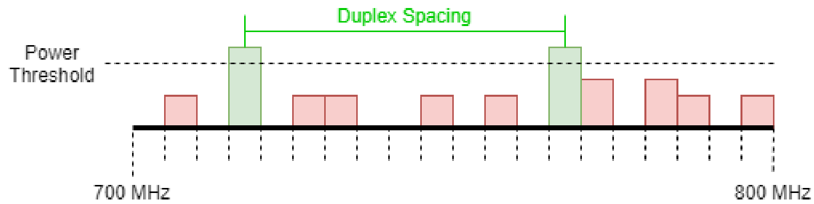
In **Scenario J**, there a multiple sets of contiguous channels presenting power availability above the defined threshold, however again there is only one appropriately duplex spaced pair that the algorithm can select.

For **Scenario K**, there are two pairs of channel set candidates that meet both the power and duplex spacing requirements. In this instance, the algorithm selects the pair of candidates that facilitate the highest power levels. As with **Scenario H**, if there is a weighting to be applied to the power available to channels spanning the downlink carrier, this would be considered at this decision stage.

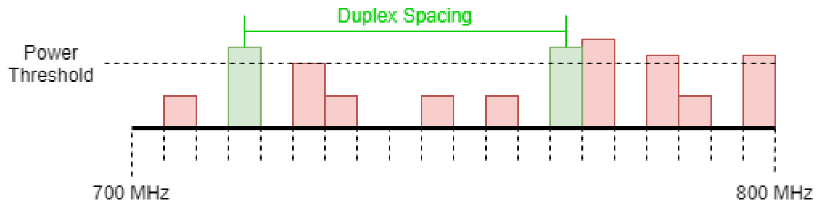
Similarly, with **Scenario L**, two pairs of channel set candidates meet both power and duplex space requirements. As with **Scenario K**, the algorithm selects the candidates that enable the highest power transmission. However, in this scenario involving contiguous channels, the algorithm only considers the lower power value of the pair. In this instance, one of the contiguous pairs enables a lower transmit power due to one of the channels involved, which is impacts the candidate pair selected by the algorithm.

As with the previous set of TDD test scenarios, a custom *SpectrumInquiryResponse* message was sent to the CBSD using Postman. The resulting *GrantRequest* message was then inspected to ensure the algorithm has correctly identified the appropriate channel arrangements from the provided spectrum mapping.

Scenarios F - L only have one valid channel pairing, with correct transmit power levels and duplex spacing. For each, the CBSD correctly responded and requested the requisite channels. This shows that the algorithm has successfully parsed the supplied information and is also working as intended when determining parameters for FDD operation.

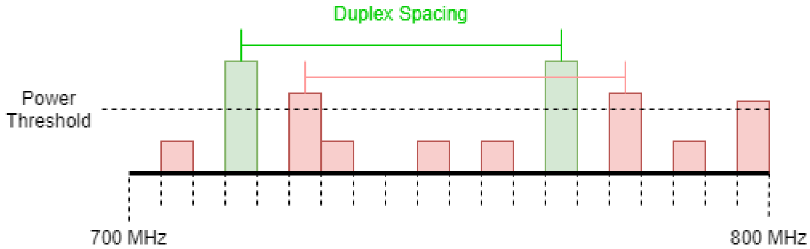


Scenario F) Single Duplex Pair of Candidate Channels

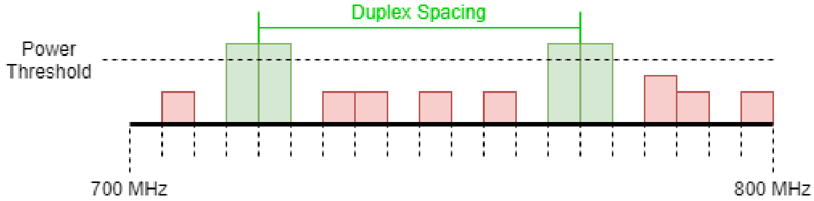


Scenario G) Single Duplex Pair of Multiple Candidate Channels

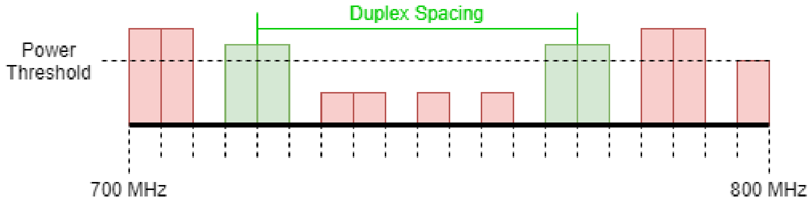
Figure 5.14: FDD Testing Scenarios for the CBSD Channel Selection.



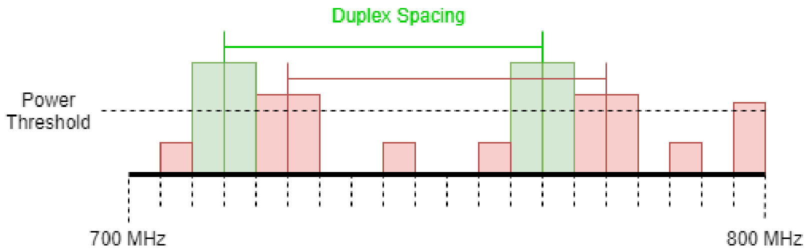
Scenario H) Strongest Duplex Pair of Multiple Candidate Channels



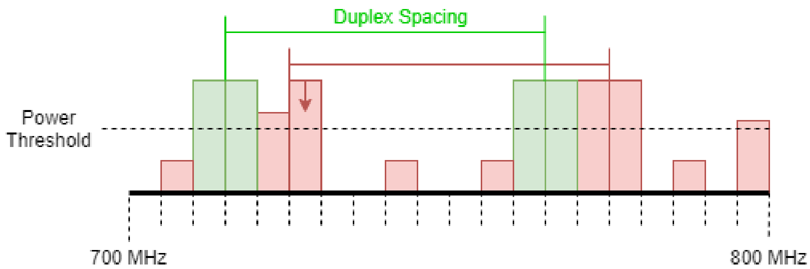
Scenario I) Single Duplex Pair of Contiguous Candidate Channels



Scenario J) Single Duplex Pair of Contiguous Candidate Channels



Scenario K) Strongest Duplex Pair of Multiple Candidate Pairs



Scenario L) Strongest Duplex Pair of Multiple Candidate Pairs

Figure 5.14: FDD Testing Scenarios for the CBSD Channel Selection.

5.2.6 Lessons Learned and Future Work

One of the key lessons learned from this work is that the presented channel selection algorithm is suitable for multiple 3GPP spectrum bands, and highlights the potential wider applicability of the CBRS framework and protocols, beyond where it is currently implemented by the FCC.

From this learning, an area of future work would be able to investigate the implications of deploying this spectrum access framework in other 3GPP frequency ranges that are being considered for DSA implementations. One band where this could be particularly applicable is in the 6 GHz frequency range which is, at time of writing in November 2025, currently subject to International regulatory debate on future purpose. Discussions are largely focused on establishing either exclusive or co-primary licencing for Wi-Fi and/or cellular technology. The idea of using the existing, established, CBRS standard mechanisms, in combination with the channel selection algorithm presented in this chapter, could be appealing to policy makers. Further discussion on this topic is provided in Chapter 7.

Another area of future work is to investigate mechanisms for improved spectral coexistence among GAA users. By improving this coordination, the number of simultaneous network deployments in a geographic area could increase, and thus improving the overall utilisation of spectrum. This would begin by researching, and possibly implementing or refining, some of the existing mechanisms defined by established standards bodies.

WInnForum have published three different standards focusing on GAA-GAA coexistence, with SAS vendors able to select any of them for implementation [157]. Each approach has different mechanisms, complexity, and priorities for optimising bandwidth and transmit powers [158] [159] [160].

The OnGo Alliance have also published a specification which covers details and best practices for CBRS deployments, which includes areas on GAA operation and coexistence [161]. One of the main topics discussed on the topic of coexistence is on the configuration and synchronisation of the TDD frame structure used by operating CBSD and their UE. If structures, and timing schedules, for these are not appropriately aligned among devices in the same geographic location then there is an increased risk of potentially harmful interference.

For example, without implementing TDD frame structure synchronisation it is possible that the higher power transmissions from a CBSD, in the downlink, could be scheduled for the same time period as lower power transmissions from a nearby UE, in the uplink. Even with non-overlapping operating frequencies, in close geographic proximity adjacent channel leakage from the higher power devices could cause signal degradation and interfere with the operations of nearby lower power UE. An example of networks operating with asynchronous TDD frames is shown in Figure 5.15, where there could potentially be issues in subframes 3,4,8, and 9

An element of future work would be to investigate the coexistence criteria for private 5G network deployments. This is discussed further in Chapter 7.

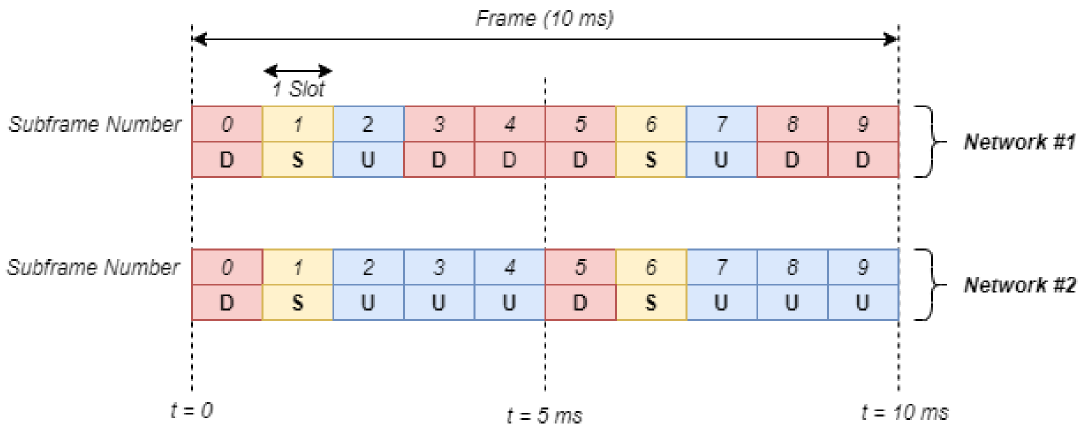


Figure 5.15: Representation of two networks running asynchronous TDD frame structures.

5.3 Research Impact

One of the primary research aspirations was to demonstrate to policy makers and Ofcom the potential practical benefits of shared spectrum, particularly for mobile networks, and for implementations of DSA mechanisms.

As a formal project deliverable, this research was presented to DCMS at an arranged presentation event in August 2019, as part of the final project conclusion report, and as a separate submitted use case white paper.

In April 2019 a delegation from Ofcom, including the Spectrum Group Director and Director of Spectrum Policy, travelled to Orkney to engage with 5GRF consortium members regarding deployments of shared and dynamic spectrum. The visit included demonstrations of the DSA use case presented throughout this chapter, site visits to the installations around Orkney, and discussions about spectrum policy in the UK.

One of the central discussion points of this visit was the Ofcom consultation released in December 2018, which outlined two key proposals to enable shared spectrum in the UK [109]. The aim of these changes was to promote innovation and enable new services by allowing access to frequency bands with an existing, developed equipment ecosystem.

Following completion of the Testbeds & Trials programme, the *Rural Connected Communities* initiative was announced by DCMS. This competition funded multiple research and development projects, over a two year period, to explore and demonstrate the capabilities of 5G in rural environments.

Building on the success of 5GRF, a subset of the project consortium chose to continue collaboration, with some additional partners, as part of the *5G New Thinking* (5GNT) project. As with 5GRF, one of the key themes of 5GNT was to demonstrate and enable implementations of shared spectrum technologies. Work completed as part of the 5GNT project is considered out of scope for this thesis.

The experience gained by the author working with the AW2S and Amarisoft products contributed significantly towards the pre-requisite knowledge required to implement a fully end-to-end 5G SA network. This further contribution to research is discussed in Chapter 6.

5.4 Chapter Conclusions

This Chapter presented a research contribution developed in support of the 5GRF project. An LTE eNB system was developed to communicate through the SAS-CBSD protocol to enable operation using DSA mechanisms. As part of this, a bespoke channel selection algorithm was also created.

Section 5.1 introduced the multi-partner 5G RuralFirst project, which aimed to inform and develop the 5G ecosystem in the UK. One of the primary use cases focused on facilitating the technical requirements, and developing the regulatory positions, of DSA and shared spectrum. The research contributions presented in Chapter 4 were also a part of this use case.

A new system was created that implemented the CBRS spectrum access mechanisms and protocols, which communicated with an Incumbent Manager from consortium partner Fairspectrum Oy. As presented in Section 5.2, the created Python program allows for control of an eNB and enables communication with the Incumbent Manager.

The developed channel selection algorithm is able to calculate an appropriate carrier signal centre frequency for any 3GPP defined operating band. This channel selection procedure was tested and evaluated using five scenarios for a TDD implementation, and a further seven FDD scenarios. The algorithm performed as expected for each test scenario.

The research contributions discussed throughout this chapter were submitted to DCMS as part of formally reviewed deliverables for the 5GRF project, and also presented to policy makers in-person at a demonstration event. As highlighted in Section 5.3, the overall success of 5GRF also lead to research continuation as part of the successor 5G New Thinking project.

Chapter 6

Deploying A 5G Standalone Network in the Glasgow Underground

As mentioned in Chapter 2, Release 15 of the 3GPP standard was feature frozen in Q2 2018, although the full specification was not completed until September 2019 [25]. The 5GRF project discussed in Chapter 5 ran from June 2018 until September 2019. This timing overlap meant it was not feasible to obtain COTS standard-compliant 5G equipment as part of that project, and as a result the majority of network deployments focused on enabling the high-quality LTE mobile broadband connectivity.

5G RailNext (5GRN) was an 18-month multi-partner project, with a collaborative international element, that looked to explore the use of 5G in underground transport systems to deliver enhanced mobile connectivity. This would be leveraged to improve the overall passenger experience, and to enable new marketing channels and revenue streams for advertisers and operators through support of "infotainment" applications. Like 5GRF, the 5GRN project was supported by DCMS as part of the 5G Testbeds & Trials programme [162].

One of the main technical development requirements within 5GRN was to establish a UK-based 5G demonstrator network, to twin with a similar deployment being installed in the Seoul Metro in South Korea. This would allow for the interactive media applications, that were also being developed by the project consortium, to be tested and evaluated in both countries.

This chapter focuses on the development and deployment of the first end-to-end 5G SA network in Scotland, and one of the earliest deployed in the UK. This was originally built and tested in the University of Strathclyde, before being installed in the Glasgow Subway for further evaluation and live trials.

This work represents a significant development milestone for private network technology. It also set operating precedent for future solution deployments, and demonstrated that a successful rollout is achievable without a large MNO partner.

Section 6.1 briefly describes the 5GRN project to provide context for the 5G SA development research contribution. This includes an overview of the consortium, as well as other activities that were carried out as part of the wider project completion.

Section 6.2 presents the work completed implementing a 5G SA network for the 5GRN project in the challenging operating environment of the Glasgow underground. This includes an overview of the overall network architecture, key components, and a review of other 5G SA deployments from industry. This section will also present the lab development activities and tests, the network field deployment, and the final 5GRN live trial.

Results from the in-field assessment demonstrated that the 5G SA network could successfully support the throughput and latency requirements of the Augmented/Mixed Reality (AR/MR) application developed by members of the 5GRN consortium.

Finally, Section 6.3 outlines further projects and outcomes that have occurred as a direct result of this 5G SA development research contribution. This includes a follow-up DCMS funded project further examining the use of 5G within the rail sector, as well as two internationally significant deployments within the broadcast market vertical.

6.1 Overview of the 5GRN Project

The 5GRN project aimed to demonstrate innovative methods of delivering advertising content and "infotainment" using 5G-enabled connectivity with AR/MR applications. The project ran from October 2019 to March 2021.

The project consortium within the UK consisted a mixture of academia, large companies, and SMEs within the technology, marketing, and transport sectors. Cisco were the lead partner, working alongside the University of Strathclyde, AmpleTime, Sublime, Strathclyde Partnership for Transport (SPT), and Glasgow City Council.

The project also involved collaboration with a co-consortium in South Korea who developed a complementary connectivity solution. This was led by the Electronics and Telecommunications Research Institute (ETRI) with partners Dankook University, CleverLogic, Wilus, and the Seoul Metro.

Although the final 5G track-to-train connectivity solutions implemented by the two testbed deployments were different from one another, the interactive media applications that ran over the networks were identical and developed fully as part of 5GRN.

In South Korea, the underground network used mmWave technology operating at around 24 GHz, with a total bandwidth utilisation of 600 MHz. For the UK testbed, there was a desire to build on the learnings from the 5GRF project and implement a 3GPP compliant 5G SA network.

Figure 6.1: The 5G RailNext Project Consortium [162].

Within the UK consortium, StrathSDR was responsible for the design, installation, testing and trial of a 5G-enabled end-to-end connectivity solution in the Glasgow subway. This would allow for testing and evaluation of both the overall network technology and the developed AR/MR application.

The final network solution comprised a private 5G SA link, connecting trackside infrastructure to a moving train carriage, which provided wireless backhaul access to an on-board Wi-Fi network for end-user connectivity. The design and implementation of this network is discussed further in Section 6.2.

6.2 Implementing End-to-End 5G SA Connectivity

This section will review the design and testing of a fully 3GPP-compliant, end-to-end 5G SA network in the StrathSDR lab, as well as the final field deployment and evaluation of the solution in the Glasgow Subway.

Section 6.2.1 will present a review of 5G SA deployments, both trials and commercial rollout, at the time of work completion for the 5GRN project and at time of writing in Q1 2025.

Section 6.2.2 presents an overview of the 5G SA network installed in the Glasgow Subway. This includes a summary of the deployment environment, an overview of critical network components, overall operational flow, and the targetted operating spectrum.

Prior to field deployment, the network was developed and tested in the labs at the University of Strathclyde. These processes are reviewed in Section 6.2.3.

Section 6.2.4 discusses the network installation in the Glasgow Subway, the 5GRN UK field trial of the overall solution, and further deployment tests that were carried out as part of the project.

6.2.1 Examples in Industry

As highlighted in Chapter 2, the rollout of 5G networks from the major service providers is still ongoing at time of writing in early 2025. The initial rollout of these services were based on 5G NSA architectures, as operators developed and invested towards SA implementations of the core network.

One of the earliest noted commercial deployments of 5G SA connectivity was by Vodafone, with a pilot programme rolled out in London, Manchester, and Cardiff in the Summer of 2021 for selected collaborative partners [163]. A further customer pilot was carried out in high-density population centres accross the UK in early 2023 [164].

However, these are not the first trials that Vodafone championed in the pursuit of 5G SA implementations. One of the earliest publicised deployments, touted as the first in the UK, was with Coventry University in July 2020 [165]. This was used as a method of delivering an interactive teaching curriculum [166]. It is not clear from the available press releases what UE devices were used as part of this pilot project.

The press releases from Vodafone suggest that the work with Coventry University occurred around the period where development work was being carried out as part of the 5GRN project.

The key differences between the two networks are the method of implementing the 5GPC, and the targetted use case. In Coventry, the network used a cloud-native 5GPC from Ericsson [165] [167] and was deployed with relatively static UE on the University campus facilities. As discussed in Section 6.2.2, the 5GPC and all other network components for 5GRN were dedicated pieces of infrastructure installed for the end user, with UE moving at maximum speeds of 54 km/h between stations.

It is believed that the 5G SA network deployed for 5GRN was not only the first of its kind deployed in Scotland, but also the first in the UK to be deployed independent of one of the large nationally established MNO.

In October 2021, Ferrovial claimed the UK's first operational 5G SA private network at their site in London [168]. However, as presented in Section 6.2.4, this project happened several months after the activities of 5GRN. The network used a Nokia solution, in the same N77 frequency band as deployed in the Glasgow Subway.

6.2.2 Network Overview

The Glasgow Subway is recognised as the third oldest underground railway in the world, after London and Budapest [169] and is operated by SPT. The Subway forms a small circle in the centre-west of Glasgow, with fifteen stations along the 10.5 km circuit. The route is formed of two individual underground tunnels, at a varying depth from 7 to 155 feet below the surface. Trains operate simultaneously in both tunnels, with clockwise travel on the "outer circle" and anti-clockwise travel on the "inner circle" as shown in Figure 6.2.

For 5GRN, the section of the subway selected to be covered by the 5G SA network was the outer circle between the Buchanan Street and St. Enoch stations. This is one of the shorter sections of the route, between two high population stations in the city centre. At the time of selecting the deployment site, it was envisioned that this would lead to higher participation in project field trials. Unfortunately, due to the COVID-19 pandemic, this would not be the case. More information on the 5GRN trial is provided in Section 6.2.4.4.

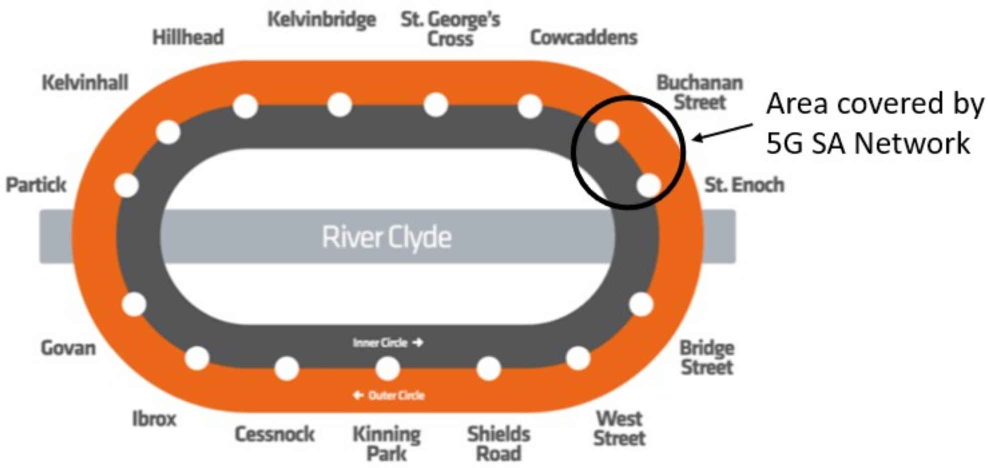


Figure 6.2: Map of the Glasgow Subway [170].

6.2.2.1 5G SA Equipment Overview

This section will present the major network components that were used in the development and implementation of the 5G SA network.

As mentioned in Chapter 5, the infrastructure deployed previously on Orkney as part of 5GRF by the StrathSDR team was based on the Amarisoft software [131], running on COTS hardware, with an AW2S SDR RRH transmitter [171].

One of the significant benefits of implementing a 5G network in this way is that key component features of the solution are all defined in software. This provides a high level of overall flexibility and customisation in the solution.

A further benefit is that the path for upgrade requires minimal additional hardware. With an Amarisoft software patch and an AW2S firmware upgrade, the same infrastructure used previously to provide an LTE network on Orkney could be updated to fully 5G compliant for use in 5GRN.

Because of the overlap in frequency bands, discussed further in Section 6.2.2.4, a legacy B42 LTE RRH, shown in Figure 6.3, could also be used as a 5GNR N77 or N78 RRH. This unit would allow for a maximum transmit power of 43 dBm over the frequency range 3400-3600 MHz.

To run the Amarisoft gNB and 5GPC software, a COTS Cincoze computer, shown in Figure 6.4, was selected. This ruggedised platform used an Intel i7 CPU to ensure there was sufficient processing capability.

To allow the BBU to connect with the Blackhawk RRH, a PCIe card from AW2S was connected to an expansion slot on the Cincoze motherboard. This would enable communication using the CPRI standard, as discussed in Chapter 2, with potentially up to 4 simultaneous RRH units per BBU.

Figure 6.3: The AW2S Blackhawk RRH [171].

Figure 6.4: The Cincoze Fanless Computer used as a BBU [172].

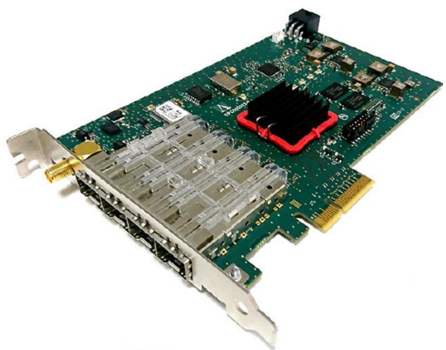


Figure 6.5: The AW2S PCIe to CPRI interface card installed in the BBU [171].

To finish the trackside RAN infrastructure, the RRH was connected to an Alpha Wireless AW3014 panel antenna [173], shown in Figure 6.6, to provide high-gain coverage towards the on-train UE.

While there was a relatively straightforward path to upgrade for the RAN and 5GPC through software, this was unfortunately not the case with the UE equipment.

There is always a significant delay between completion of a standard and widespread implementation in consumer hardware. This is to expected, considering the scale of design, testing, and mass production associated with devices like mobile handsets.

Figure 6.6: The Alpha Wireless AW3014 Directional antenna used on the platform [173].

It was only with the beta release of Apple's iOS 17, in June 2023 [174], that COTS handsets became available for use with private 5G SA networks [175]. Although many devices had the technical capability to connect to 5G SA implementations, operating system design choices and network operator whitelisting meant that they were not usable on independent private networks — only on those specifically from the large MNOs.

The delay in access to fully functional COTS handset UEs meant that, for a number of years following Release 15 completion, the only devices capable of 5G SA connectivity were dedicated modem boards, typically in limited form factors.

For 5GRN, a SIM8200-EA modem from SIMCom [176] was used as the 5G SA UE. As the modem, based on a Qualcomm Snapdragon x55 modem-to-antenna chip, is simply the transceiving interface card, it was necessary to connect it with a suitable compute platform. This required a USB cradle to hold the network SIM card and convert from the modem M.2 format, as shown in Figure 6.7.

The Intel NUC, a small form factor computer, was selected as the secondary part of the compound UE solution. This unit had a number of responsibilities within the overall network operation in addition to being the 5G UE, as discussed further in Section 6.2.2.3. This meant more processing power was required than could be provided by something like a Raspberry Pi, hence the choice to select a platform with an i7 desktop-grade CPU.

In the lab environment, small low-gain antennae were used to simplify the overall physical set-up. The field deployment as part of the 5GRN trial, discussed in Section 6.2.4.3, would need a more powerful option to compensate for mobility and the operating environment. It was decided that a lightweight AW3374 antenna from Alpha Wireless, shown in Figure 6.8, would

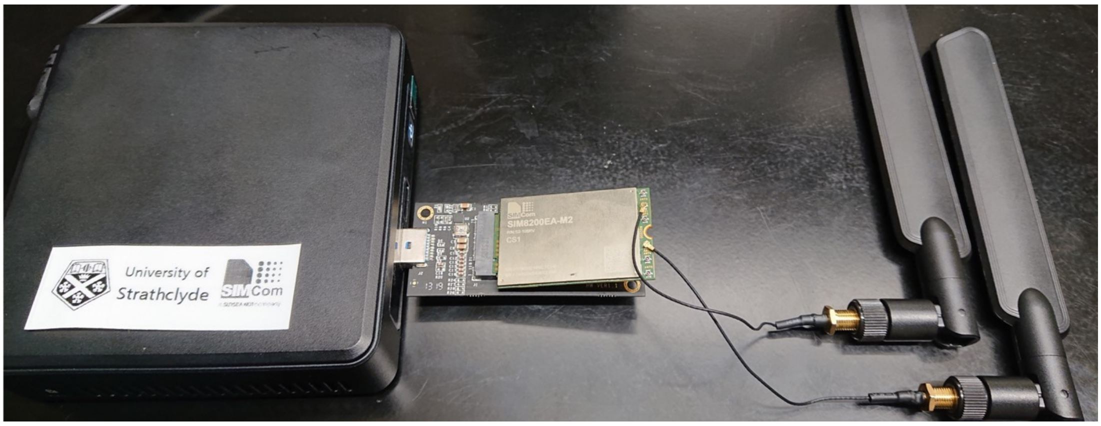


Figure 6.7: The SIMCom SIM8200-EA modem [176] used as the network UE connected to the Intel NUC.

be used. An omni-directional antenna was selected to give more flexibility in the mounting options on the train carriage, as this removes any need to consider equipment orientation.

Figure 6.8: The Alpha Wireless AW3374 Omni-directional antenna used on the train carriage [177].

As discussed further in Section 6.2.2.2, a Wi-Fi AP was implemented in the final 5GRN deployment architecture. This was used as a network bridge to allow the UE devices supporting the AR/MR application to use the 5G SA track-to-train solution, as the COTS equipment available at the time of the trial did not directly support that connectivity.

6.2.2.2 Network Architecture

When designing the high-level network architecture, it was critical to be aware of the physical constraints within the deployment environment. Glasgow Subway tunnels are only 3.4 metres in diameter. The clearance between the walls and train carriages varies at different points along the route, but is only around 10 cm maximum at any stage. This narrow spacing means it is impossible to safely deploy equipment inside the tunnels themselves. Therefore, the directional antenna and AW2S RRH for the gNB would need to be located in the platform area, at a location that would also allow for coverage down the tunnel.

The architecture for trackside network infrastructure is shown in Figure 6.9.

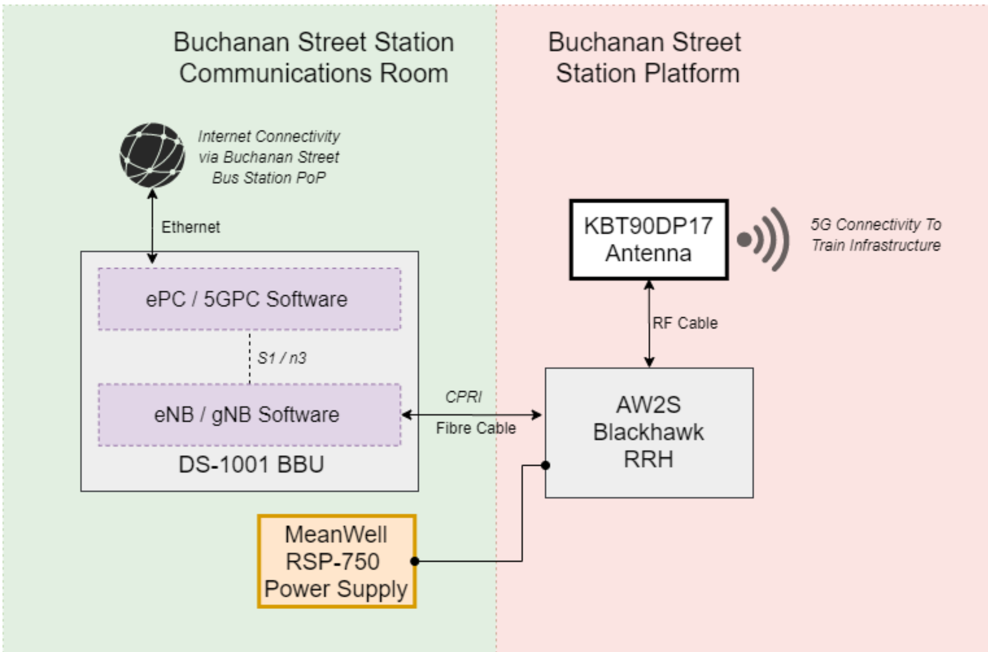


Figure 6.9: Diagram Showing Network Infrastructure on the Trackside.

The Cincoze BBU, running the Amarisoft gNB and 5GPC software, was located within the platform communications room. This would ensure it would be physically accessible to StrathSDR engineers, and be able to connect to an SPT provided Internet point.

For health and safety reasons, the RRH power supply was also located in the secure communications room. Fibre and power cables then connect to the RRH using ducts above ceiling panels, out of sight and access to passengers.

Subway trains are normally formed of three carriages, each 12m long, as this is the maximum length that can be accommodated in each station. Under automated control, trains have a maximum speed of 54 km/h although also limited to lower speeds for tighter curves on route.

Individual carriages are not permanently coupled together, and it is common for cars to be replaced at various times throughout a service. Therefore it is not possible to assume that a given carriage would always be in use, or that it would always be located at the same point in a train arrangement.

This means it was necessary for any train-based infrastructure to be highly portable and deployable on arbitrary carriages as required. The designed solution, shown in Figure 6.10, is largely contained within a single wheeled “Peli Case” and requires no prior installation activities.

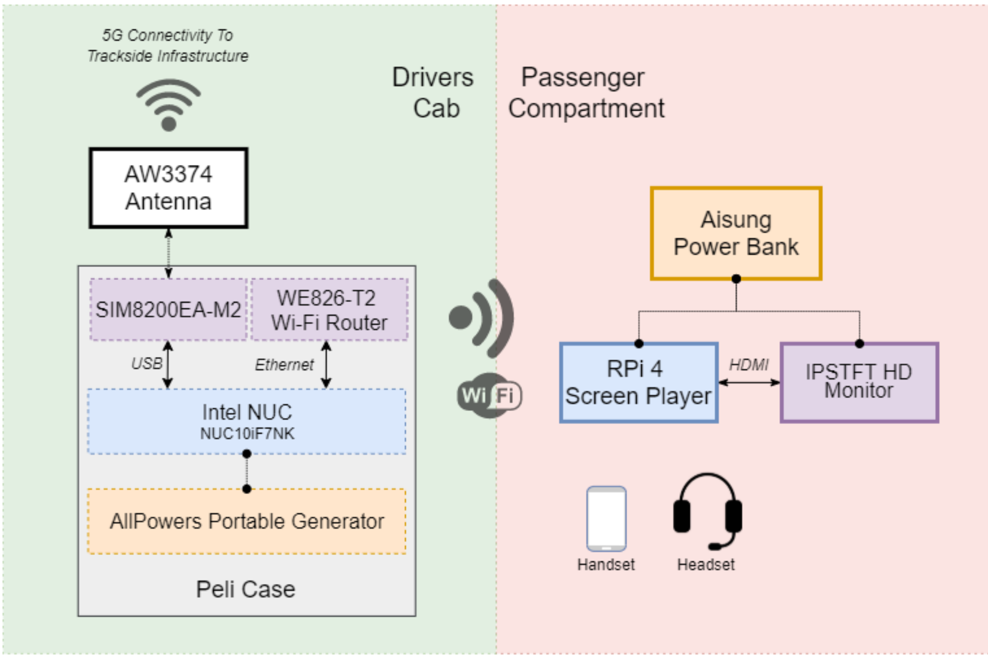


Figure 6.10: Diagram Showing Network Infrastructure on the Train.

A Wi-Fi AP was also located inside the Peli Case and is powered via PoE while attached to the NUC. A small portable generator was included to avoid having to connect anything to the train.

In addition to the network equipment, a small screen and media player were mounted in the carriage, which were used as part of delivering the advertising content. These were also both powered from a small portable battery bank.

The 5GRN trials, discussed further in Section 6.2.4.4, were conducted with both Samsung Galaxy S20 mobile handsets [178] and Jorjin J-Reality J7EF headsets/smart glasses [179] connected over the carriage Wi-Fi network to display the AR/MR content.

6.2.2.3 Network Operation

The call flow diagram for the AR/MR advertising application over the 5GRN network is shown in Figure 6.11.

At start-up, the NUC begins the 3GPP-defined connection and authentication process, through the modem to the RRH and on to the 5GPC. Once the UE SIM card has been verified, the Cincoze enables connectivity through the SPT intranet and firewall to the wider Internet for cloud-based services from AmpleTime.

The Intel NUC acted as an IP traffic gateway, routing packets between the 5G SA network and UEs on the Wi-Fi network. The NUC was also used to host the controller software for the Cisco Wi-Fi AP, authenticating the user devices there, and a media server for parts of the

Sublime AR/MR content.

Connection to the AmpleTime program, hosted on Amazon Web Services (AWS), is triggered initially by a URL QR code displayed on the screen to be scanned by the user. The AWS server response indicates to the on-device advertising application which stored content, from the NUC, should be displayed based on what was scanned.

6.2.2.4 Network Spectrum

As mentioned in Section 6.2.2.1, the AW2S Blackhawk RRH that was eligible for 5G upgrade was a unit designed initially for operation with LTE B42. As can be seen from Figure 6.12 this 200 MHz operating frequency range overlaps with both N77 and N78 5G bands.

For 5GRN, the carrier centre frequency was set to 3.52 GHz. The network had an operating bandwidth of 20 MHz due to UE hardware limitations at the time.

As the 3.51-3.53 GHz frequency range was licensed to O2 Telefonica, now Virgin Media O2, operation for 5GRN was conducted under an Innovation and Trial licence.

Network deployment pre-dated the start of Ofcom's LAL programme, discussed in Chapter 3. Under this mechanism it would be possible to apply for a commercial operating licence for this frequency range. Success of the application would be dependent on demonstrating that the Incumbent licence holder, in this case O2 Telefonica, would not be impacted by operation. In underground railway environments, this becomes a viable way of obtaining access to spectrum, as it is unlikely that above-ground MNO operation would be impacted by services in the tunnels.

Another attractive option would be to instead target the 400 MHz of spectrum between 3.8-4.2 GHz enabled by an Ofcom SAL. At the time of the 5GRN project, there was not a significant ecosystem of RAN equipment for this upper section of N77 spectrum. However, as highlighted in Section 6.3, as the hardware availability improved, the viability and overall potential for private 5G SA networks grew significantly.

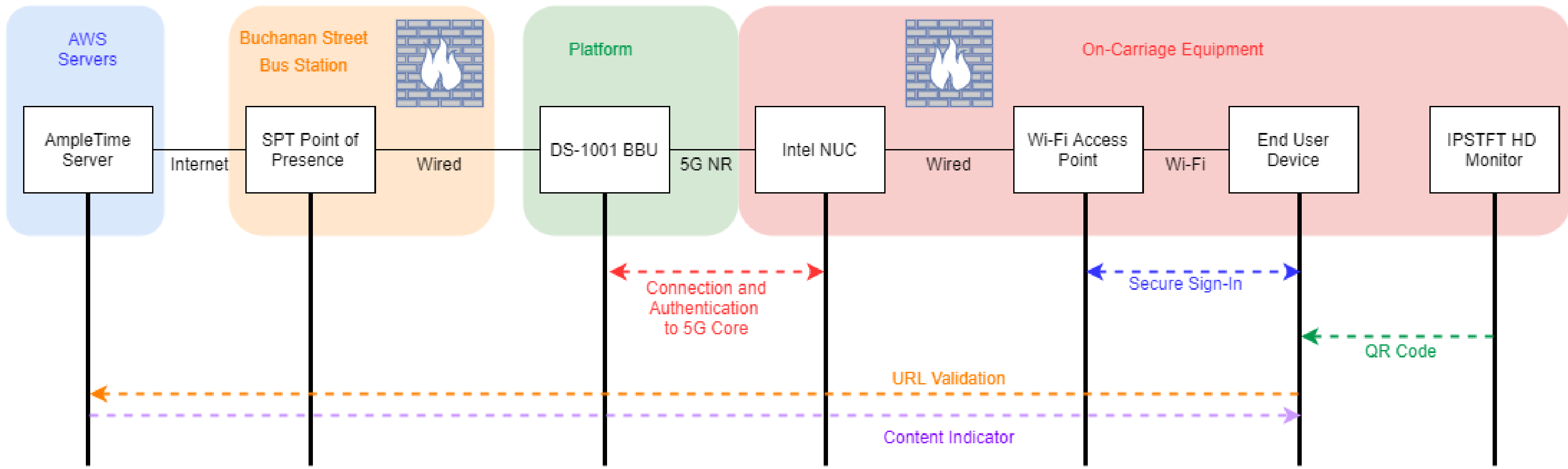


Figure 6.11: Call Flow Diagram for the 5GRN Network.

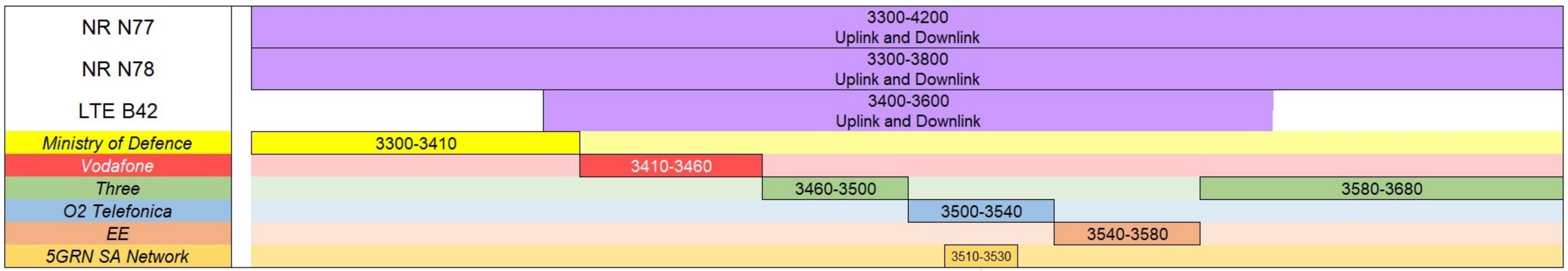


Figure 6.12: A representation of the 3500 MHz frequency band showing the 5GRN spectrum utilisation.

6.2.3 Lab Development

Prior to the work and research contribution presented in this thesis, none of the independently developed 5G SA network components had been fully integrated as part of an end-to-end solution. Although each piece had been tested by the respective OEM, there was still a significant amount of effort required to complete the full network development and create a solution capable of real-world deployment.

This section will review the work items that were completed by the author, as part of the 5GRN project, to set-up and configure each element, on both network-side and UE, to ensure successful interoperability.

6.2.3.1 Network Development

As discussed in Section 6.2.2.1, the 5GRN network used the established, validated, infrastructure from the 5GRF project deployments discussed in Chapter 5. This involved upgrading multiple elements; the gNB software to be compliant with the Rel. 15 RAT, the 5G core software to operate in SA mode, and the RRH unit to use the 5GNR RAT rather than 4G LTE.

Although the base software for the gNB and Core were both commercial releases from Amarisoft, and the updates providing 5G SA capability were part of their scheduled releases, the underlying configuration files that define the operating parameters had to designed and implemented to be compatible with the radio hardware, targetted UE devices, and intended network configuration. This involved correctly identifying the critical variables, and their appropriate values, controlling multiple aspects of the RAN and Core set-up.

For gNB cell configuration this included characteristics such as the RAT, carrier centre frequency, bandwidth, and broadcast PLMN, among others. It is essential that these parameters are compatible with those set on the UE, discussed in Section 6.2.3.2, to allow the connectivity and registration processes to be completed. For interoperability with the 5G Core, modifications were made to parameters defining the N3 data connection, to the User Plane, and with the N2 connection, to the Control Plane.

Finally, to enable over-the-air 5GNR transmissions using the AW2S equipment it was necessary to update both the firmware on the Blackhawk RRH and also on the CPRI interface card in the BBU. Modifications to the hardware drivers in the Ubuntu OS were carried out to provide the appropriate PCIe line-speeds necessary for the communications overhead of 5GNR operation.

6.2.3.2 UE Development

As discussed in Section 6.2.2.1, the only available UE devices that were fully compliant with 5G SA connectivity were dedicated modem units. It was still necessary to update the firmware of the SIMCom 8200-EA modem to be compliant with 3GPP Rel.15 and enable 5G SA support in the N77 frequency range.

It is now standard for most GNU/Linux distributions, such as Ubuntu, to come with pre-included drivers for most 5G modem devices, through the default mobile broadband management package *NetworkManager* [180], accompanying daemon *ModemManager* [181], and their underlying software libraries. However, at the time of 5GRN project development the most recent Ubuntu version (Ubuntu 20.04.1 LTS in August 2020 [182]) did not have a ModemManager implementation that could support modems using 5G SA. Specifically, the library for working with the Qualcomm MSM Interface (QMI), *libqmi* [183], had not been fully updated and was only available as an under-development software repository.

This meant that, in order to gain access to the low-level configuration parameters and operational statistics of the modem, it was necessary to rely on either low-level ATtenion, or *AT*, Commands using the standard Linux serial port driver, or QMI messages sent using the *qmicli* tool included as part of Ubuntu OS [184]. The former were used to configure aspects and parameters of the modem, while the latter were only used to validate the set-up.

After making the necessary modifications to the default driver source code to allow Ubuntu to properly recognise the module, specific AT Commands were sent using the terminal CLI from the Ubuntu Linux host computer. These were used to carry out the modem set-up process for 5G SA operation, in a way that would now typically be automatically configured by the ModemManager daemon.

For example, the *AT+CGDCONT* command, which is used to specify context parameters for the Packet Data Protocol (PDP) session [185], was used to set details about the Access Point Name (APN) of the 5G network — which had to match the value configured in the Amarisoft gNB software. Similarly, the *AT+CNMP* command, which controls the modem operating mode [185], was used to ensure the 5GNR RAT was the default selection.

Once the modem had been set-up, appropriately aligned with the network configuration in the Amarisoft RAN and core software, QMI messages were used to validate the configuration, as they provided more verbose response messages to make verification easier. This is shown and discussed further in Section 6.2.3.3.

6.2.3.3 E2E Integration and Testing

Following completed configuration of the RAN, Core, and UE components, initial E2E tests were carried out to validate that full SA connectivity has been achieved.

Figure 6.13 shows extracts from the Amarisoft gNB software stack (left) and SA 5GPC software (right).

The gNB extract shows that N77 5GNR technology is being used, indicated by the report of RAT and BAND response from the *cell* command. It also indicates that there is no 4G ePC connected to the gNB, as there is no *S1* interface to report on, but there is an established

```
(enb)   cell
[gnb0012345]   PLMN=23504  gNB_ID=0x12345
Cell      TAC     RAT   BAND   dl_arfcn   pci   prach_seq   dl_gain   ul_dis   plmn
0x001  0x000064   NR    n77    632628    500       1          0.0       N      23504
(enb)   s1
S1 connection state:
(enb)   ng
NG connection state:
   -  server=127.0.1.100:38412 state=setup_done PLMN=23504
```

Figure 6.13: Extracts from the Amarisoft gNB software [131] showing end-to-end 5G SA connectivity.

```
This software is licensed to University of Strathclyde
Support and software update available until 2021-09-09
(mme)   ue
     IMSI              IMEISV       M-TMSI/5G-TMSI   REG          TAC   #BEARER  IP_ADDR
235047364000069   8642840400316400     0xd946dcb9      Y   23504   0x64     0
(mme)   gnb
PLMN    RAN_ID           IP:Port   #UEctx   TACs
23504   0x12345    127.0.1.1:51120     0     0x64
```

Figure 6.14: Extracts from the Amarisoft core software [131] showing end-to-end 5G SA connectivity.

connection to a 5G core, shown by the response to the *ng* command. A lack of ePC highlights that the connection must be fully 5G SA and not 5G NSA.

Similarly, the 5GPC software is reporting that there is a gNB, not an eNB, connected and also that a UE has successfully attached to the RAN and completed the registration process within the core network.

All commands, across RAN and Core, report an associated PLMN of *23504*, which is exclusively licensed to the University of Strathclyde [186] and was programmed into the sim cards used for the 5GRF and 5GRN project. This unique identifier is also reflected in the first digits of the custom IMSI (*235047364000069*).

This IMSI, also shown in the Amarisoft core report, comes from the SIM card used with SIMCom 8200-EA modem, as highlighted in Figure 6.15.

```
AT+CPSI?
+CPSI: NR5G_SA,Online,235-04,0x64,19088641,500,632544,-440,-100,400

OK

AT+CIMI
235047364000069

OK
```

Figure 6.15: AT Command responses SIMCom modem showing exclusively 5G SA connectivity [185].

The *AT+CIMI* command is used solely to request the IMSI of the device's sim card [185].

This proves that the modem successfully attached to the 5GSA RAN and registered with the core network.

In addition, the *AT+CPSI?* command can be used to probe a number of different aspects of the UE system [185]. The response indicates that the current operating mode is SA 5GNR and that the PLMN it is connected to is 235-04. This command also provides a value of the modem's measured RSSI, which was later used as part of lab and field tests to assess the RF coverage and overall performance.

To finish validating the 5G SA connection, the QMI commands were used to get formatted, verbose, details from the modem about its current status. Results from the *–nas-get-system-info* query [184] are shown in Figure 6.16.

```
[/dev/cdc-wdm0] Successfully got serving system:
        Registration state: 'registered'
        CS: 'detached'
        PS: 'attached'
        Selected network: 'unknown'
        Radio interfaces: '1'
                [0]: '5gnr'
        Roaming status: 'off'
        Data service capabilities: '0'
        Current PLMN:
                MCC: '235'
                MNC: '4'
                Description: ''
        Roaming Indicators: '1'
                [0]: 'off' (5gnr)
        Detailed status:
                Status: 'available'
                Capability: 'ps'
                HDR Status: 'none'
                HDR Hybrid: 'no'
                Forbidden: 'no'
        Full operator code info:
                MCC: '235'
                MNC: '4'
                MNC with PCS digit: 'no'
```

Figure 6.16: QMI Message response from the SIMCom modem showing 5G SA connectivity at the UE [187].

Similar to the AT Command responses, the modem indicates that it is using 5GNR connectivity, with a PLMN of 23504, and has successfully registered with the core network.

As clearly shown in Figures 6.13 to 6.16, E2E 5G SA connectivity was achieved from UE through the RAN to 5GPC.

With the 5G SA solution established, further tests in the lab were conducted to assess the link performance and the equipment's response to variation in channel quality.

The distance between the modem and transmitting gNB antenna was varied from 0-10m. The reported RSSI was taken from the response to the *AT+CPSI?* AT Command, while the achievable throughput was measured using the iPerf utility [91] similar to the testing process presented in Chapter 3. Results from this small-scale lab-based performance assessment are presented in Table 6.1, with throughput and RSSI results shown in Figures 6.17 and 6.18 respectively.

Distance (m)	**Throughput** (Mb/s) **RSSI** (dBm)					**Average Throughput** (Mb/s)	**Average RSSI** (dBm)
0	56.5	56.8	54.6	54.7	56.3	55.78	-51
	-51	-51	-51	-51	-51		
1	49.8	55.9	54.4	56.1	54.9	54.24	-75
	-75	-75	-75	-75	-75		
2	46.2	46.4	46.3	44.7	43.2	45.36	-81
	-81	-81	-81	-81	-81		
3	53.4	54.4	52	52.9	53.1	53.16	-79
	-79	-79	-79	-79	-79		
4	46.3	45.7	46.3	44.6	47.7	46.12	-83.8
	-85	-85	-83	-83	-83		
5	40.8	41.8	42.3	40.7	41	41.32	-87
	-87	-87	-87	-87	-87		
6	23	22.8	23.7	25.2	23.6	23.66	-92.2
	-93	-91	-91	-93	-93		
7	25.4	28.7	28.9	28.7	27.5	27.84	-89
	-87	-89	-89	-89	-87		
8	39.7	41.2	40.7	41.6	41.2	40.88	-85
	-85	-85	-85	-85	-85		
9	26.9	25.4	25.8	27.2	28.4	26.74	-91
	-91	-91	-91	-91	-91		
10	34.2	34.7	34.1	35	33.2	34.24	-87
	-87	-87	-87	-87	-87		

Table 6.1: Experimental Results from Initial Bench Testing showing Throughput and RSSI Values.

As expected, the increased distance between UE and transmitter generally resulted in a decrease in achievable received signal level and therefore a reduced throughput. However, the main purpose of the tests was to further validate the E2E 5G connectivity, which was a success and sufficient to proceed with field testing.

While the lab development activities were ongoing, to accommodate SPT's schedule it was necessary to also carry-out some aspects of the field deployment work in parallel. This is discussed further in Section 6.2.4.

6.2.4 Field Deployment

This section will overview the activities carried out in installing, field-testing, and trialling the E2E 5G SA network for the 5GRN project. This included an initial survey session in August 2020, network installation and testing in October 2020, and then final E2E operational trial in March 2021.

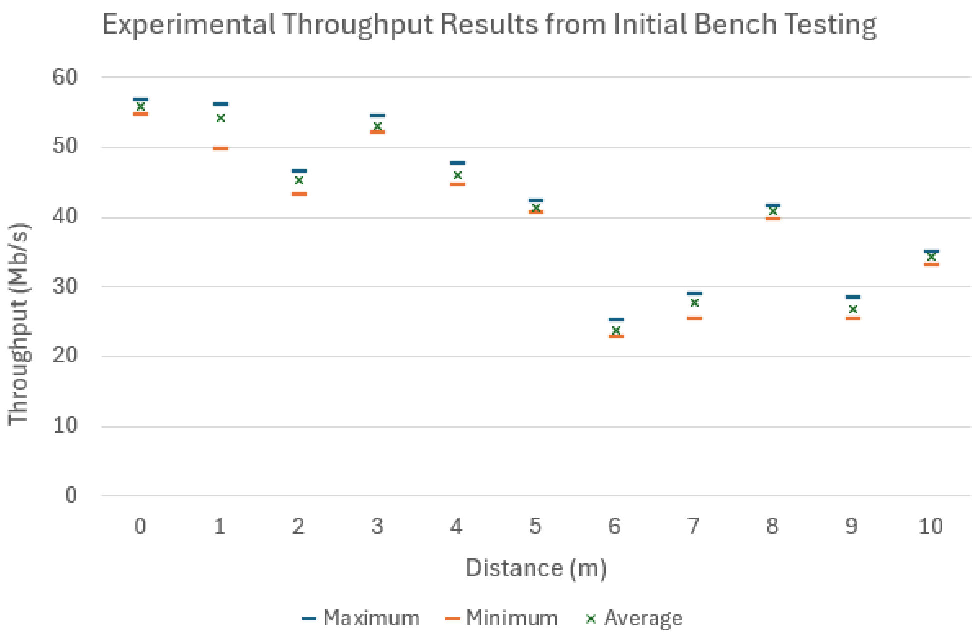


Figure 6.17: Experimental Results from Initial Bench Testing showing Throughput.

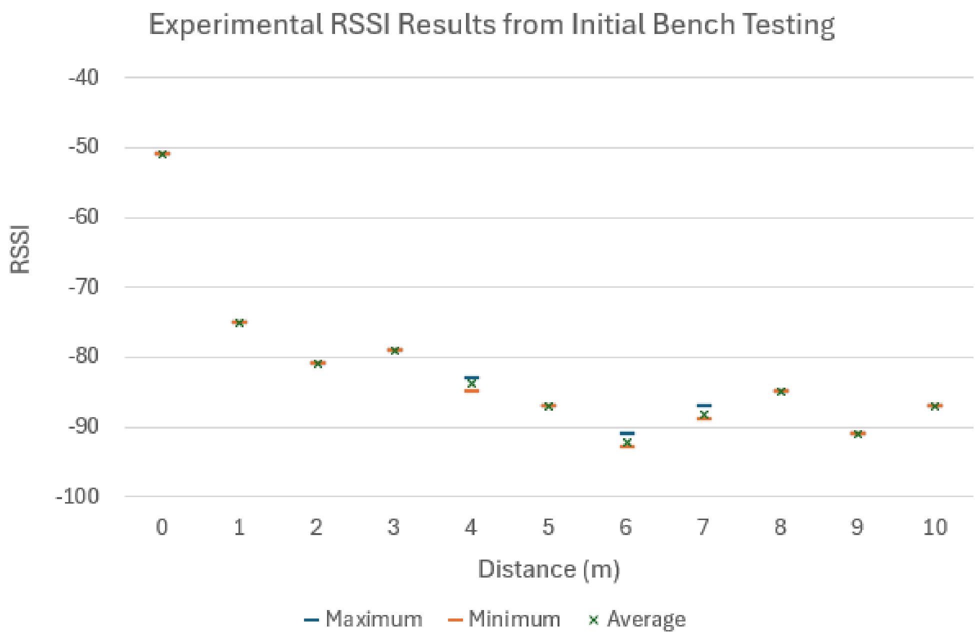


Figure 6.18: Experimental Results from Initial Bench Testing showing RSSI.

6.2.4.1 Pre-Deployment Field Testing

As part of the pre-deployment assessment, an RF survey of the LTE Band 42 frequency range was carried out in the Buchanan St. and St. Enoch locations, to measure the capabilities of any existing MNO network deployments in the vicinity and assess the potential for interference.

These surveys were conducted using an Anritsu Field Master Pro Analyser, as seen on the platform floor in Figure 6.19.

Figure 6.19: StrathSDR Engineers completing the RF Survey for 5GRN using the Field Master spectrum analyser.

Results from the survey, shown in Figure 6.20, indicated that although MNO deployments were present above the Subway they were not detectable at the underground platform level, approximately 11 feet below the surface. This meant that there was no possibility of these networks interfering with the 5GRN deployment, or vice-versa.

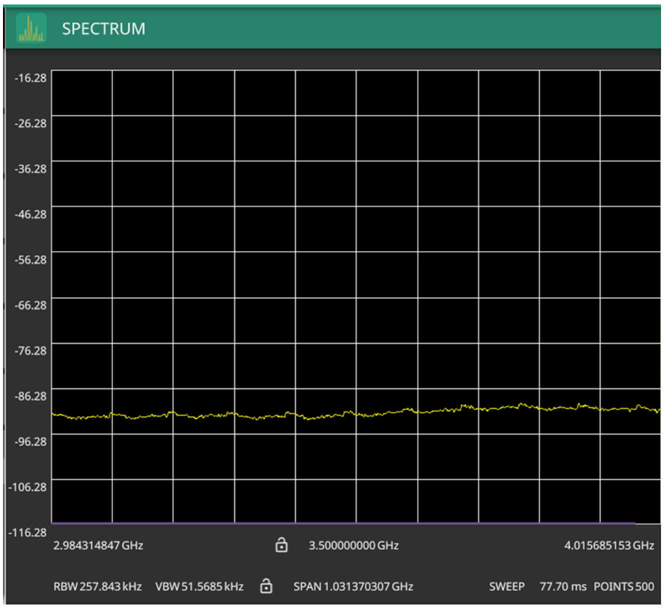


Figure 6.20: Spectrum Analyser response showing no spectral utilisation detected in the Glasgow Subway.

At this stage, it was unclear how much of the tunnel would receive mobile coverage from platform-based equipment. Once it was confirmed that there was minimal risk of interfering with commercial operations, it was desirable to establish how well a carrier signal would propagate at those frequencies within the operating environment.

A pop-up network was set-up in the mouth of the tunnel leading away from Buchanan Street Station towards St. Enoch. This temporary deployment would allow for measurements to be taken at distance intervals while walking along the 500m tunnel between platform areas.

As the 5G SA features of the modem UE were still under development at the time of field testing, an LTE network was used instead. The modem connected wirelessly by 4G via an omni-directional antenna, and simultaneously tethered to a laptop running Ubuntu OS by USB. As with the lab development activities, discussed in Section 6.2.3, the *AT+CPSI*? AT Command was used to the RSSI measurements.

Although not the same RAT as would be used in the real deployment, the measured RSSI would still be relatively reflective of the overall RF performance in the environment and give indication of the achievable network coverage. Results from this RSSI assessment, captured in the tunnel at varying distances from the transmitter, are shown in Table 6.2.

Distance from Antenna (m)	**RSSI** (dBm)
270	-99
290	-101
340	-103
350	-111
390	-110
400	-112
420	-98
430	-106
470	-107
480	-92

Table 6.2: Results from Field Testing showing RSSI measurements at distances along the tunnel.

No further readings were taken from beyond a distance of 480m, as this had already crossed the threshold into the St. Enoch platform area.

The collected RSSI measurements indicated that, despite the challenging environment, it was possible to cover the full tunnel with a single RRH instance. Based on this information, it was decided that one gNB network was sufficient rather than a more complicated configuration involving multiple gNBs and carrier signal handover.

6.2.4.2 Network Installation

On the first evening of installation, work began by mounting the panel antenna horizontally on the vertical structs above the traveller information sign on the platform, as shown in Figure 6.21.

The RRH needed to be mounted in proximity to the antenna, to minimise the length of RF cable required and hence the induced signal attenuation. A suitable space was identified above

Figure 6.21: The author installing the AW3014 directional antenna at Buchanan Street Subway Station.

the ceiling panels close to the antenna, also near the cable trays necessary for accessing the communication room at the end of the platform around 50m away.

The BBU and power supply were mounted inside the equipment room as shown in Figure 6.22.

The BBU was attached to mounting brackets and screwed to a wooden board on the equipment room wall, with the RRH power supply also located nearby. Fibre and power cables were then routed through a small ingress in the equipment room wall into the cable tray and towards the RRH as mentioned in Section 6.2.2.2.

6.2.4.3 Network Testing

Following the BBU installation activities further tests were carried out to ensure the network was operating correctly and providing the expected levels of coverage.

Figure 6.24 shows the operating 20 MHz carrier signal from the 5GRN gNB where previously, as shown in Figure 6.20, there was no detectable spectrum utilisation.

With the completion of lab development activities, discussed in Section 6.2.3, it became possible to utilise more functions of the 5G modem. This included access to a more extensive suite of low-level measurement parameters. Therefore, unlike the initial field evaluation, performance tests were based on the UEs recorded Reference Signal Received Power (RSRP) rather than RSSI values.

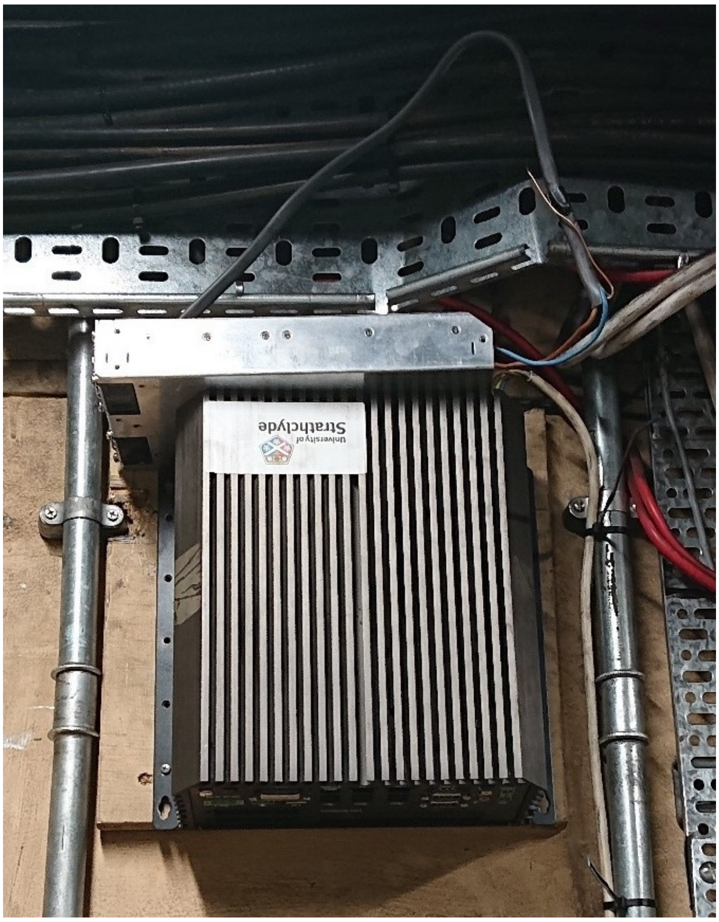


Figure 6.22: Installation of the 5GRN BBU in the SPT Communications Room.

By assessing RSRP, effectively the power measured within specific signal sub-carriers, rather than RSSI, a more general measurement of power received, it would be possible to get a more accurate overview of the network performance.

As with the initial field survey, measurements were taken at distance intervals from the transmitter while walking the tunnel between the Buchanan Street and St. Enoch stations. The collected RSRP results are show in Table 6.3.

The first measurement was taken at the tunnel mouth, which is estimated to be a maximum of 15m away from the mounted antenna. Therefore, 15m has been added to each of the distance points along the tunnel.

To contextualise the results of Table 6.3, Ofcom has previously indicated that a “good quality” RSRP signal threshold would be $\geq -105dBm$ [188]. This performance assessment is achievable by the 5GRN network even at the maximum distance from the transmitting antenna.

Figure 6.23: StrathSDR engineers completing RSRP measurements in the tunnel between Buchanan Street and St. Enoch Subway Stations.

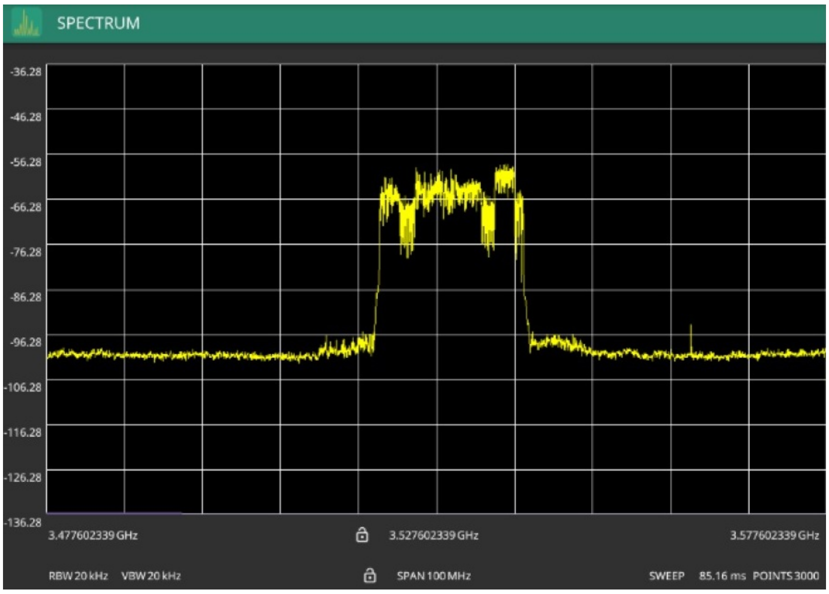


Figure 6.24: Spectrum Analyser response showing active spectral utilisation in the Glasgow Subway.

Distance from Antenna (m)	**RSRP** (dBm)
15	-52
45	-62
70	-68
85	-69
115	-67
165	-70
215	-79
265	-81
315	-80
365	-80
415	-82
465	-89
515	-90

Table 6.3: Results from Field Testing showing RSRP Values at distances along the tunnel.

6.2.4.4 Project Trial

A live user trial was conducted in March 2021, during normal subway service hours. This involved the testing of the E2E 5G network installation and the AR/MR "infotainment" content delivery application.

During initial project scoping, it was envisioned that the trial would involve members of the public interacting with the 5GRN infrastructure over an extended period. This would give sufficient time for both a technical performance evaluation, and for a large-scale participant feedback survey of user experience and opinions on the potential for this mechanism of content delivery.

Instead, to comply with the restrictions in place due to the COVID-19 pandemic, the project trial became a shorter, supervised evaluation session with a small group of trialists who were known to the project consortium over a single day. This gave sufficient time for users to familiarise themselves with the AR/MR experience, while simultaneously allowing for measurement of technical performance metrics.

The subway train used in the trial was simultaneously being used to serve passengers, although a dedicated carriage at the rear was reserved for the 5GRN testing activities. As mentioned in Section 6.2.2.1 the 5G SA solution was designed to be fully portable so had to be set up on the train carriage prior to the trial commencing, as shown in Figure 6.25.

As the network was only available for one segment of the 15-station subway route, tests could only occur around once every 25 minutes (the time required to complete one full circuit of the subway route). In between test sessions, participants filled out surveys on their opinion of the AR/MR application. In total, 14 trialists participated in the day's session, some of whom are shown in Figure 6.26.

Technical performance tests were also carried out during the periods when the subway carriage was within the coverage area of the 5G SA network.

Figure 6.25: The author setting up 5GRN Trial Equipment.

Network Performance Test Results & Analysis

One of the critical metrics to assess was the achievable network throughput, both in the downlink (trackside to carriage) and in the uplink (carriage to trackside). These measurements were initially taken between the DS-1001 BBU and Intel NUC, to ensure that only the performance of the 5G SA link was being assessed with no impact from either the Wi-Fi technology or SPT internet backhaul. Peak throughput results for this set-up are shown in Table 6.4.

For comparison the complete E2E throughput, between the user device and Internet source, was also captured and shown in Table 6.5. As expected, there is a difference between the achievable performance due to the logical, and physical, separation of the measurement endpoints.

Another key performance metric to assess, particularly for the AR/MR application, is the latency introduced by each stage of the network. This was measured using the Ping utility, across different network segments, with the results shown in Table 6.6.

In this deployment, the critical latency measurement path was between the Intel NUC, where the local content was stored, to the UE, travelling through the Wi-Fi AP. For AR/MR applications, the maximum acceptable end-to-end latency for content display to head mounted terminals is 5-8 ms to avoid introducing motion sickness to the user [189]. As shown in Table 6.6,

Figure 6.26: Trialists (including the author) engaged in live evaluation of the AR/MR application over the 5GRN network.

this performance metric was achieved by the 5GRN deployment, with no trialists complaining of application-induced motion sickness.

The results in Tables 6.4 to 6.6, and corresponding graphs in Figures 6.27 to 6.29, demonstrate the importance of having on-location resources, particularly for media applications, rather than relying exclusively on internet- or cloud-based content when there are requirements for higher throughput or low latency communication.

Transmission Direction	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**
BBU to SIM8200-EA (DL)	95.4 Mbps	95.2 Mbps	86 Mbps	90.3 Mbps	84.6 Mbps
SIM8200-EA to BBU (UL)	15.7 Mbps	16.1 Mbps	16.3 Mbps	16.4 Mbps	16.3 Mbps

Table 6.4: Peak Throughput Measurements for Track-to-Train 5G SA Connectivity

Transmission Direction	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**
Internet to User Device (DL)	78.6 Mbps	75.8 Mbps	80.6 Mbps	80.1 Mbps	80.1 Mbps
User Device to Internet (UL)	12.6 Mbps	13.3 Mbps	12.5 Mbps	12.5 Mbps	8.41 Mbps

Table 6.5: Peak Throughput Measurements for End-to-End Track-to-Train Connectivity

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**
Wi-Fi AP to User Device	3.95 ms	3.84 ms	3.35 ms	3.36 ms	4.02 ms
NUC To User Device	4.01 ms	3.82 ms	3.98 ms	3.76 ms	4.19 ms
BBU to User Device	50.7 ms	48.7 ms	36.2 ms	44.1 ms	32.6 ms

Table 6.6: Latency Measurements for End-to-End Track-to-Train Connectivity

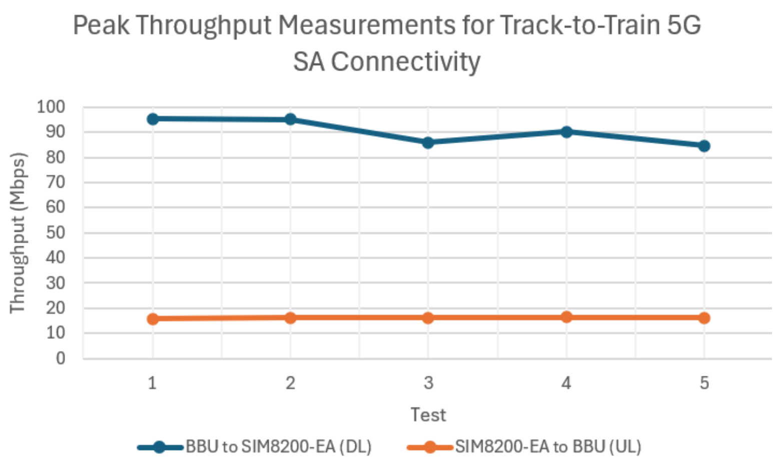


Figure 6.27: Peak Throughput Measurements for Track-to-Train 5G SA Connectivity.

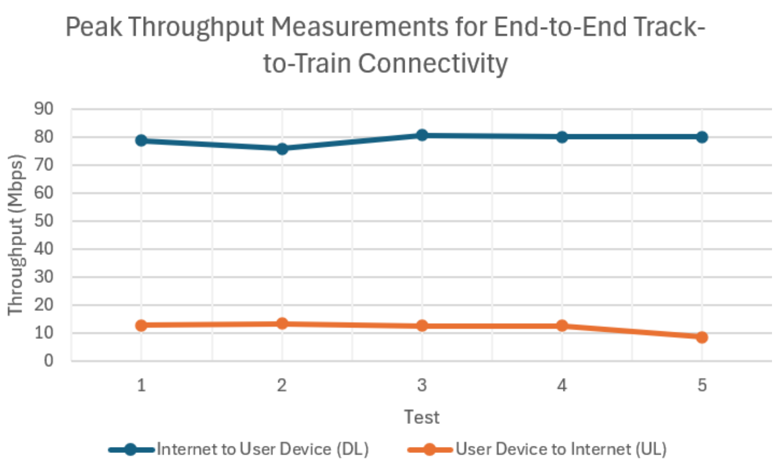


Figure 6.28: Peak Throughput Measurements for End-to-End Track-to-Train Connectivity.

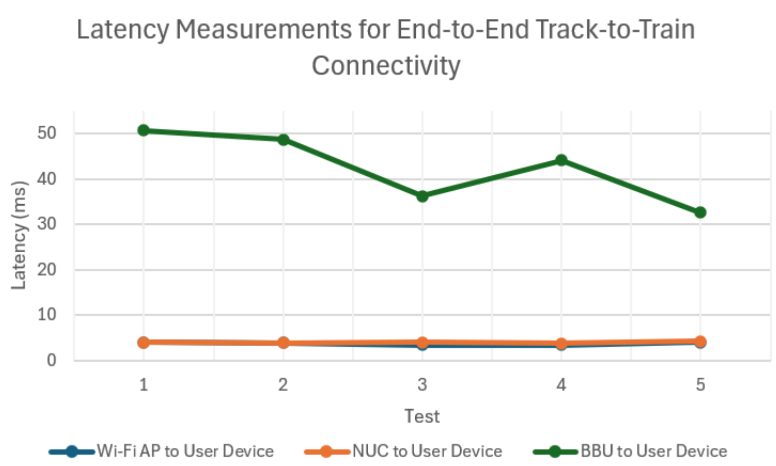


Figure 6.29: Latency Measurements for End-to-End Track-to-Train Connectivity.

Results from the 5GRN trial, shown across Tables 6.4 to 6.6 and Figures 6.27 to 6.29, indicated that even in a relatively immature development phase, the 5G SA network implementation could successfully meet the operating conditions for the AR/MR application.

The success of this 5G SA solution installation highlights that private networks, deployed independently of a major MNO partner, are a viable candidate solution for use cases with strict technical performance requirements, even in challenging deployment environments such as underground railways.

Further research was carried out following conclusion of the 5GRN project exploring how to further optimise the 5G SA network performance for use cases with specific operating requirements, such as within a video content production environment. These uses cases are discussed further in Section 6.3.

6.3 Research Impact

The success of the 5G RailNext project, and the 5G SA network, resulted in a number of follow-up projects, work items, and research areas that are still continuing at the time of writing in early 2025.

Building on the engagement with SPT, a subsequent project called 5G SubConnect was established within the DCMS 5G Testbeds & Trials initiative, which is discussed further in Section 6.3.1.

Other potential applications and use cases for private 5G SA networks are numerous and well documented. One industry that consistently explores the potential for 5G solutions is the media and content production space. The European Broadcasting Union (EBU) [190] launched the *5G Media Action Group* (5G-MAG) [191] in October 2019 to investigate and influence the development of 5G for the benefit of the media industry [192]. With inspiration and guidance from BBC contacts in this working group, StrathSDR and University of Strathclyde spin-out company Neutral Wireless [193] began research and development activities into the potential for private 5G deployments within content production environments. Building on the outlined research contribution from the 5GRN project, the resulting outputs included the world's first private 5G SA network for broadcast, discussed in Section 6.3.2.

6.3.1 5G SubConnect

While 5G RailNext focused on the benefits of providing on-train connectivity for passengers and the AR/MR applications, during the project SPT conveyed that they were also interested in exploring the potential role of 5G connectivity in other activities.

In particular, subway maintenance was highlighted as an area where 5G connectivity could potentially improve the efficiency or effectiveness of inspection and repair tasks. Further discussions with DCMS resulted in a follow-on project within the 5G Testbeds & Trials programme, called 5G SubConnect [194], which ran from November 2021 until March 2022.

Maintenance is a key aspect of subway operation and comprises two main activities: periodic inspection of critical assets and infrastructure, as well as the repair or replacement of anything that has been noted as requiring attention. Therefore, the key features identified for optimising these tasks were the ability to access critical information from inside the tunnel environment, the ability to carry out real-time video conferencing between team members in the tunnels or depot, and the ability to provide accurate positioning in the absence of Global Navigation Satellite Systems (GNSS) [194], as such signals are typically unavailable due to the underground operating environment.

Once the essential operations were identified, a private 5G test network was created in order to test and demonstrate the desired use cases. Due to the short duration of the project, it was not possible to deploy the test network in the Glasgow Subway tunnels, as in 5G RailNext. Instead a representative N77 5G SA network was set up in the StrathSDR laboratory in a way that, as best as feasible, emulated the targetted tunnel environment. Use case tests were carried out with representatives of SPT, to ensure accurate recreation of what would occur in real-world scenarios.

The investigations and results of the 5G SubConnect project identified a number of potential benefits associated with deploying a private 5G network in the Subway to help with maintenance activities, as well as the current technical limitations that need to be addressed in order to make it commercially viable. The next steps for the research area would be a fully engaged pilot, which would allow the project team to test, confirm, and refine any assumptions underpinning the envisaged network requirements and architecture.

6.3.2 World's First Private 5G SA Network For Broadcast

The opportunities presented by Private 5G networks (also referred to in the media market vertical to as Non-Public Networks (NPNs)) for PMSE have been the subject of several collaborative research projects [195] [196]. Remote production using NPNs can provide a number of benefits to the creation of live events coverage compared to traditional wireless broadcast workflows.

Although sometimes used in parallel with public network bonding solutions, as a further interface to aggregate over, Wi-Fi is not often used in professional production workflows. Even with dedicated deployments, it is generally accepted that the dependency on licence-exempt spectrum, limited QoS enforcement, and non-seamless handover mechanisms make the technology unappealing to the majority of the industry.

Private 5G network deployments for PMSE can use the same COTS encoder-transmitter equipment as standard wireless production workflows.This means the NPN can provide all of the same benefits, while simultaneously addressing potential constraints around coverage and capacity.

Following the publicised success of the 5GRN deployment, StrathSDR and Neutral Wireless were invited to supply a shared spectrum private 5G SA network for a world-first demonstration of live video production, which was a MotoGP broadcast to a global audience from Silverstone racetrack [197] [198].

A handheld Vislink 5G camera was positioned on the starting grid, while an onboard 5G camera was used to display video and images from the back of the media bike to bring live high-speed images from track. These devices were connected to the Neutral Wireless Private 5G SA network, which covered the pitlane, paddock, and part of the circuit. Video content was then supplied to the Dorna Sports production team, responsible for creating the International Production Feed (IPF), and then shared with worldwide rights-holders, including BT Sport.

After this world-first proof-of-concept deployment Neutral Wireless began to further refine the 5G SA network solution; moving from the initial design completed by the author for the 5GRN project to implementations more optimised for media production use cases.

A significant portion of this came through engagement with an International Broadcasting Convention (IBC) Accelerator Innovation Project in 2022. This allowed for further demonstration of private 5G SA networks in live production environments [199].

6.4 Chapter Conclusions

This chapter has presented work completed to develop, test, and deploy the first end-to-end 5G SA network in Scotland.

The work was completed by the author in support of the 5G RailNext project, discussed in Section 6.1, which aimed to demonstrate innovative methods for delivering AR/MR content in an underground subway environment.

Section 6.2.3 presents the work completed implementing the 5G SA network for deployment in the Glasgow subway to facilitate track-to-train connectivity. This included a review of the overall solution architecture and operation flow, key hardware and software components, operating spectrum, and a discussion on previous comparable example deployments.

The completed integration activities to develop the E2E 5G SA connection are discussed in detail, where the author was responsible for modifications and configuration to RAN, core, and UE network elements. Following lab tests, three field deployments were carried out over the span of several months to conduct RF surveys and propagation investigation, install and test the network on-location in the subway, and finally conduct full solution trial at the conclusion of the 5GRN project. The developed 5G SA network met all performance metrics of throughput and latency expected during the trial.

The success of the 5GRN deployment highlighted that the developed 5G SA solution could successfully meet the necessary operating requirements for AR/MR applications. In addition, the installation successfully demonstrated that private networks can be deployed without a major MNO partner, to deliver for use cases with strict technical performance criteria in challenging operating environments.

Finally, Section 6.3 outlines some of the further research and commercial outcomes that have occurred as a direct result of the successful contributions presented in this chapter. A follow-on research project, 5G SubConnect, was completed with SPT to further assess the potential for 5G as part of routine subway maintenance activities. In addition, commercial work with University spin-out company Neutral Wireless, building on the 5G SA development activities, has resulted in a world-first deployment within the media production sector at Silverstone racetrack.

Chapter 7

Conclusions

The research work presented in this thesis focused on the use of SDR platforms with implementations of automated shared spectrum access technologies in order to enable private wireless network deployments in challenging operating environments, such as rural locations and the Glasgow Subway.

The TVWS and CBRS spectrum access mechanisms were selected as the two DSA frameworks to investigate, as both solutions have defined regulatory requirements while also being used in commercial network deployments. Practical implementations all make use of SDR platforms to create reconfigurable, operating-frequency flexible, network deployments.

Publications from the UK Government and Ofcom strongly highlight that automated tools and DSA will play a significant role in future UK spectrum policy. The research discussed and demonstrated throughout this thesis is complementary to this regulatory aspiration, with the contributions made focusing on the development and deployment of automated tools for spectrum management and the rollout of private 5G networks.

Section 7.1 provides a brief summary of each Chapter, including the outlined research contributions completed by the author.

Section 7.2 reviews the most significant outcomes from the presented work, and briefly discusses the impact of the author's research contributions.

Finally, Section 7.3 discusses potential areas of future work and research that can be, or are in the process of being, enabled by the research presented in this thesis.

7.1 Thesis Review

A number of research contributions have been presented including the development of supporting software tools, investigation into performance capabilities of existing hardware solutions, and proof-of-concept deployments. A summary of this work will be provided in this section.

Chapter 1 introduced the motivation, background, objectives, and research aims for the work presented in subsequent chapters. It was noted that the focus on the implementation of automated shared spectrum mechanisms is complementary to recent policies from Ofcom and publications from the UK Government.

Chapter 2 presented an overview of the current state of mobile connectivity in the UK. To provide technical context, this featured an introduction to the 4G and 5G 3GPP-standard mobile broadband solutions, including details of the currently implemented RAN and Core architectures. An indication of the current state of the UK's connectivity infrastructure was also provided, with reference to statistics published in Ofcom's annual Connected Nations reports.

The concepts of shared and dynamic spectrum were introduced in Chapter 3. Both the TVWS and CBRS spectrum access frameworks were reviewed, including descriptions of general operation and accompanying regulations. This provides context for the research contributions presented throughout the thesis.

Chapter 3 also presented details of, and research contributions towards, a TVWS pilot in the Orkney Islands. This 2015 trial involved the provision of connectivity to multiple ferries and fixed premises through an installed shared spectrum wireless network. This project received an industry award for *"Student-Led initiative or Research on New Opportunities for Dynamic Spectrum Access"* at the DSA Global Summit in 2017 [20].

Chapter 4 focused on activities implementing the PAWS protocol, the de facto standard for communication between WSD and WSDB under the TVWS framework. Two research contributions were presented. The first was the development and testing of a Python software solution emulating a WSD, to communicate with a WSDB. Implementing the PAWS protocol as part of this package allowed for the creation of a human-operatable interface, enabled live parameter gathering, automated data collection, and facilitated network spectrum planning.

The second presented contribution was the integration of a 3GPP-compliant SDR eNB system with an Ofcom-approved TVWS WSDB. This work expanded on the previous research contribution to create a proof-of-concept deployment and demonstrated that aspects of regulated DSA frameworks could be incorporated to existing 3GPP equipment, while maintaining compliance with the requisite operating standards.

Chapter 5 introduced the 5GRF project, but focused specifically on the author's contributions to the dynamic and shared spectrum research conducted for that particular work package. This included input to white papers and conference demonstrations in addition to technical development activities. The main research contribution discussed was an automated shared spectrum system, compliant with CBRS regulations and protocols, integrated with an SDR basestation solution as an evaluated proof-of-concept implementation. In addition, a bespoke channel selection algorithm was developed to facilitate operation in spectrum bands beyond those where it is currently implemented by the FCC.

Finally, Chapter 6 focused on the development and deployment of the first end-to-end 5G

SA network in Scotland, and one of the earliest deployed in the UK, as part of the 5GRN project. The network was installed in the Glasgow Subway for evaluation and live trial, while supporting the delivery of an interactive media use case.

This chapter reviewed the development activities completed for both the track-side and on-train infrastructure to enable end-to-end 5G SA connectivity, including an overview of the low-level system parameters and hardware driver configuration. Details were provided on the completed lab tests, as well as on three subsequent field deployments. Results gathered from the full solution trial highlighted that the developed 5G SA network met all technical performance metrics, in both throughput and latency, necessary for the AR/MR applications.

7.2 Core Outcomes and Impact

Recent publications from Ofcom, and strategy documents from the UK Government, have indicated that automated tools will have a role in the future of spectrum access and administration. Similarly, DSA and data-base driven mechanisms are noted as an area of consideration and ongoing investigation.

As regulatory policies continue to evolve and spectrum becomes more accessible, the adoption of private cellular networks is increasing across multiple commercial industries [200]. Several forecasts project a significant uptake towards 2028 and beyond [201] [202].

This section will review the main outcomes of the research presented throughout this thesis, which are complementary to the ongoing regulatory trajectory and the future potential for private 5G network deployments.

The 2015 Orkney TVWS pilot project, discussed in Chapter 3 provided readily-available connectivity to the Orkney community across popular ferry crossing routes. Over 1000 unique devices connected to the TVWS-enabled Wi-Fi on the ferries over a one-month period. The success of this TVWS network installation highlights that independently deployed wireless networks are a viable candidate solution for localised connectivity challenges.

In addition to providing connectivity for local residents, the network also contributed to the Scottish Government's rural connectivity initiatives and was an important case study for Ofcom's evaluation of the TVWS framework.

Because of this initial deployment work, the Orkney testbed was later able to be revisited and expanded as part of the 5GRF project. This led to further developments and contributions to private networks and rural connectivity. These were discussed as part of subsequent chapters of this thesis.

The work presented in Chapter 4 demonstrated that aspects of a regulated DSA framework can be incorporated into existing eNB systems and simultaneously adhere to the 3GPP LTE standards. It was proved that the spectral agility requirements of ETSI TVWS regulation conformance can be handled through existing LTE techniques, such as intra-eNB handover, and implementation of SDR hardware platforms. This work represented a significant contribution to the shared spectrum research activities of the 5GRF project.

The PAWS software tool presented in Chapter 4 was later leveraged in international TVWS projects and proposals, including the EPSRC-funded ARIA project with multiple partner Universities. The PAWS client has also been used as a communication benchmark in the development activities of other researchers, as a validation tool for their own software creation work in further research projects.

Chapter 5 presented research demonstrating that the CBRS access mechanisms and protocols can be implemented in any frequency range covered by the 3GPP specifications, regardless of duplex type or carrier size, by implementing an appropriate channel selection algorithm, developed by the author, with SDR hardware. This increases the potential scope of deployment beyond just the CBRS frequency range as currently implemented, and has potential for implementation in wider, automated, forms of shared spectrum access.

The outlined 5GRF research contributions were presented directly to Government and submitted as part of formally reviewed deliverables for the project. This maximised the visibility of the research to UK policy makers.

Following the success of 5GRF, a subset of the project consortium chose to continue collaboration, with some additional partners, as part of the *5G New Thinking* (5GNT) project. As with 5GRF, one of the key themes of 5GNT was to facilitate implementations of shared spectrum technologies, further expanding on the research contributions presented in this thesis.

The experience gained through deploying the AW2S and Amarisoft products on Orkney contributed significantly towards the author's capabilities to implement the 5G SA network presented in Chapter 6.

The developed 5G SA solution, and deployment in the Glasgow Underground, demonstrated that private networks can be deployed to deliver for use cases with strict technical performance criteria, in challenging operating environments, without input from a major MNO partner.

The overall success of the 5GRN project resulted in a further research engagement, 5G SubConnect, to examine the use private networks within the rail sector with Glasgow Subway operator SPT.

With the lead in private 5G SA network development capabilities gained by the work presented in Chapter 6, Neutral Wireless and StrathSDR deployed the world's first private 5G SA network for broadcast at Silverstone in August 2022.

The impact and success of the research contributions presented in Chapter 6 continues at time of writing in early 2025. This is true in an academic environment, through the research projects completed by StrathSDR, and commercially, through contracts undertaken by spin-out company Neutral Wireless. Some examples of these are provided in Section 7.3.

7.3 Future Work and Areas of Investigation

This section briefly details some areas of ongoing research, and provides suggestions for future work arising from the contributions of this thesis.

7.3.1 Ongoing Research Projects

Ofcom's commitment to future implementation of dynamic spectrum frameworks is shown by the licensing approach applied to the shared access bands, discussed in Chapter 3, and they have indicated that upcoming work will assess the transition to a dynamic spectrum framework [109].

Work completed by both StrathSDR and Neutral Wireless continues to inform Ofcom with regards to future policy. In particular, demonstrating the current capabilities, cost, and complexities of frequency agile SDR equipment.

The UK Government continue to fund various programmes focusing on the research and development of 5G. The Department for Science, Innovation and Technology (DSIT), replacing the former DCMS, have a number of initiatives ongoing as on February 2025. This includes the *5G Innovation Regions* [203], the *Spectrum Sandbox Competition* [204], and the *Open Networks Ecosystem Competition* [205]. As part of the latter programme, both StrathSDR and Neutral Wireless are part of the consortium behind project *ON-SIDE (Open Network Shared Spectrum Innovation and Design Environment)* [206]. This represents a continued collaboration of the lead project partners, Cisco and UoS, which has been ongoing from the initial 5GRF work, through the 5GRN and 5G New Thinking projects.

ON-SIDE focuses specifically on the challenges associated with commercial private 5G SA network deployments, particularly using shared spectrum access mechanisms. This supports both DSIT and Ofcom's broader telecoms and spectrum management strategies, while also addressing the real-world experience for consumers. This project concluded in September 2025.

One area of research completed as part of the ON-SIDE project involved a work package delivering a series of real-world test and measurement activities to assess the accuracy of currently used propagation models, and analyse the coexistence requirements for private 5G networks. The latter involved measuring the impact of deployments in adjacent frequency bands, while varying parameters such as TDD frame structures. As highlighted in Chapter 5, if networks are deployed in close geographic proximity without frame synchronisation, there is an increased probability of cross-network harmful interference.

Further work is required to both quantify the amount of induced interference between networks operating in adjacent frequency ranges, and to qualify the various parameters that could impact the achieved results.

Another ON-SIDE work package focused on the design and development of spectrum sensing technology, and to explore the potential for integration to future spectrum management platforms. One of the noted items of further research to come as a result of this work package was to investigate the potential role of Artificial Intelligence (AI) in decisions on frequency allocation. This could involve combining spectrum sensing details, with propagation simulations and channel selection algorithms, to provide automated licencing services on behalf of a regulator.

7.3.2 Further Research Areas

As Ofcom and the UK Government's regulatory aspirations continue to evolve, any newly developed spectrum management mechanisms should be similarly integrated with SDR platforms, to create 3GPP compliant infrastructure, and suitably evaluated for use in delivering connectivity for hard-to-reach areas. The future work items presented here are complimentary to these policy aims, and to wider industry trends, with the aim of enabling future private network solutions through dynamic spectrum access mechanisms.

Chapter 2 notes the need for further investigation into the impact of new RAN architectures to the implementations of the shared spectrum frameworks discussed throughout this thesis. This is also one of the topics explored as part of the *TUDOR (Towards Ubiquitous 3D Open Resilient Network)* project, in which StrathSDR were participating and concluded in September 2025 [31].

As the developments towards the 3GPP 6G standard continues, further research will be required to ensure shared and dynamic spectrum technologies are appropriately addressing the challenges of future network deployments. For example, some of the spectrum challenges associated with the roll-out of Non-Terrestrial Network (NTN) deployments [207], particularly when integrated with traditional terrestrial networks, could potentially be addressed by shared spectrum technologies [208].

In chapter 4, a further work concept was outlined to investigate the use of a different parameter within the PAWS protocol as part of an alternative method of specifying WSD location. The protocol allows for the definition of an operation region, rather than a fixed location, by providing details for a standardised polygon shape. By defining a region, approximately equivalent to the WSD coverage area as determined by RF simulation, the calculations carried out by the WSDB could potentially facilitate higher power allocations to requesting devices. This would result in improved the operating performance for WSD compared to using the generic request.

The challenge of testing and developing this alternative method comes from the lack of access to a qualified WSDB, as all providers have since ceased operation in the UK [209]. However, this could potentially be of interest for international deployments, in countries where TVWS operation is still operational.

Following on from successful deployment at Silverstone racetrack, the role of private 5G networks continues to be widely explored within the media production sector, by Neutral Wireless and others within the industry. This will further enable the ongoing transition from traditional broadcast technology to wireless IP operation and integration with cloud production services [210].

In September 2025, Ofcom released a consultation outlining a new *"short notice, short duration"* spectrum licence mechanism for a portion of the 2300 MHz range [211]. Although accessible for a range of different use cases, the primary focus is to enable pop-up, temporary, private network deployments. These could be used to enable coverage of breaking news, sports, music festivals, or similar events. By reducing the application time for a spectrum licence, Ofcom have made private 5G technology practically deployable within the timescales demanded by the broadcasting and media production sector.

Further work will be carried out with partners in the industry to assess the suitability of this new spectrum access mechanism as the regulations become fully implemented in the UK.

While using SDR platforms has been proven as a viable solution for the 5G RAN, the implementations of UE are typically based on traditional modem platforms that follow the 3GPP standards.

With the appropriate platform, an SDR RAN can facilitate wireless network deployments, based on the 5G NR RAT, in non-3GPP specified spectrum ranges. The issue with this strategy is that there would then be no UE devices able to connect to the network, as all COTS devices would only operate in the standard frequencies.

By developing an SDR-based UE platform, it would be possible to create end-to-end wireless network deployments, using 5G NR technology, in any frequency band available under the local regulations [212]. This could be unlicensed spectrum or lightly-licensed frequencies, such as the Broadcast Auxiliary Service (BAS) band in the United States [213].

By facilitating network operation in spectrum with minimal administrative overhead, the overall time to deploy new networks can be reduced. This is particularly relevant for use cases that operate to strict schedules, such as live event production or for PPDR.

As discussed in Chapter 5, there is an ongoing regulatory discussion regarding future use of the 6 GHz frequency range. Specifically, whether the band will be used exclusively for Wi-Fi, cellular, or a hybrid shared approach.

In February 2025, Ofcom released a consultation outlining their preference towards the shared approach [214], as represented by Figure 7.1.

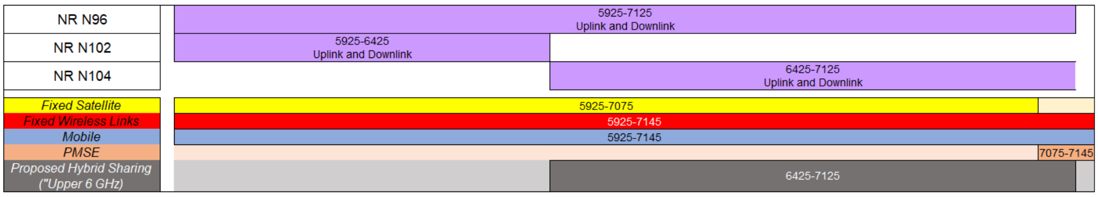


Figure 7.1: The Ofcom proposed 6 GHz frequency band.

The consultation notes that sharing mechanisms will be introduced in future, once European harmonisation has matured. An area of further work would be to investigate use of the existing CBRS standard mechanisms, in combination with the channel selection algorithm presented in this thesis, to facilitate shared spectrum access to this 700 MHz segment. This would also require research into parallel mechanisms, such as the Automated Frequency Coordination (AFC) platform that will be used for authorising Wi-Fi users.

Appendix A

UK TVWS Projects

This appendix reviews two TVWS deployment projects completed by the CWSC in Scotland between 2011 and 2015, prior to the commencement of the Orkney TVWS Pilot discussed in Chapter 3.

A.1 Isle of Bute

In 2011 a TVWS trial network was established on the Isle of Bute, in the West of Scotland, by a six-partner consortium including BT, BBC R&D, and the University of Strathclyde with support from the UK Government's Technology Strategy Board.

This 18-month project investigated various aspects of early TVWS implementation, with the intention of aiding and informing Ofcom's decisions in the development of UK regulations. The project also provided opportunity to assess the overall technology performance, as an alternative to fixed infrastructure, in an area with terrain that would otherwise be challenging for wireless systems.

These challenges come from a large number of hills and a high density of forest and woodland, limiting the opportunities for line-of-sight (LoS) dependent links, as well as a dispersed population. The single telephone exchange on the island is located at Rothesay, which was not upgraded to optical fibre until 2014. This greatly impacted the achievable connectivity for local residents and businesses while also limiting the availability of mobile broadband, due to the lack of suitable backhaul.

The project aimed to deploy a network providing wireless last-mile connectivity between the telephone exchange and eight premises using two prototype TVWS technologies in a Point-to-Multi-Point (P2MP) topology.

At the time of the trial, the DSO had not been completed, so non-interfering operating parameters were defined by project partner BBC R&D, accounting for terrain information, details on nearby DTT transmitters, and measurements taken around the island.

Due to the terrain, there were eleven DTT transmitters providing coverage to the island, with five main transmitters and six relay systems. During the trial period all but one had completely switched from analogue transmissions. Because of this, the network was operating under a non-operational test licence which allowed for three 8 MHz channels to be used if required within the TV band. As formal TVWS regulations or standards, such as those outlined in Chapter 3, had not been ratified at the time, prototype bespoke equipment was used to enable connectivity.

Equipment from Airspan Networks provided TVWS connectivity based on the IEEE 802.16e WiMAX standard. The equipment was configured to operate within an 8 MHz channel, with 2x2 MIMO and a total transmit power for 36 dBm (33 dBm per MIMO port). Similarly, the University of Strathclyde's CWSC developed a system based on the XR7 Wi-Fi technology from Ubiquitti Networks. Channel bandwidth was configured to 5 MHz, and was limited to a maximum transmit power of 35 dBm.

A high capacity 18 GHz microwave link was established to connect a telephone exchange at Kilchattan Bay, on the South of Bute, and West Kilbride, on the mainland. This link, over 12km, provided backhaul connectivity to BT's infrastructure to enable Internet access.

At the telephone exchange, because of the large target coverage area, two basestation units were installed; each serving half of the connecting premises. One prototype technology was used for each group, both using TDD to connect the basestation with premises.

White space transceivers were fitted externally to premises, referred to as the CPE units. Each CPE was connected to a small internal pre-configured Wi-Fi router via Ethernet, which also provided power using POE.

Figure A.1: Showing the geographic layout of the Bute TVWS trial.

The performance of the installed network was assessed based on a number of criteria, including achievable data rates, latencies and end-user experience.

Both designs of White Space equipment were tested under laboratory conditions, using RF attenuators through coaxial cable, to obtain a set of expected results for varying signal levels. These could then be compared with in-field measurements.

To obtain throughput data from the live network, both models of CPE equipment were fitted to mobile survey vehicles, which were also equipped with pump-up masts extendable to 10 metres. This allowed emulation of the typical end-user installation at a number of identified test locations across the island. These results could then be used to supplement additional measurements carried out at trialists' premises.

Similarly, the impact of TVWS broadband on DTT reception was first tested under laboratory conditions. Fourteen DTT receivers were subject to a number of tests with several candidate TVWS technologies, including the two employed in the network, to assess their sensitivity to co-channel and adjacent channel interference.

A key aim of the trial was to assess the impact of white space transmissions on DTT reception in the vicinity of the network, to aid Ofcom in the development of white space regulations. To that end several measurements of DTT signals were carried out on Bute, before and after network installation. This allowed for measurement of co-channel and adjacent-channel interference, and could be compared with theoretical values calculated using the UK Prediction Model (UKPM) [75]. This aided validation of the UKPM, before being used within a geolocation TVWS database for the UK. No co-channel or adjacent channel interference was recorded, and no disruption was reported by trialists.

Difference between UKPM median predictions of DTT signal levels and measured in field values was log-normally distributed, with a mean of zero and a standard deviation of approximately 6 dB. These results compared favourably with the accepted value of 5.5 dB. These tests indicated that, even at this early development stage, TVWS technology with shared spectrum was a candidate solution for the provision of rural connectivity.

The primary focus on co-existence testing should be, from a regulatory standpoint, to ensure adequate protection is given to the Incumbent spectrum users. When a WSD requests authorisation from a database, the returned parameters are designed to reduce the risk of interference to the Primary transmissions. Secondary spectrum users receive no guarantees of protection, from either the Primary or Secondary users.

As part of the co-existence assessment, the potential impact of DTT transmitters on WSDs was carried out. It was found that, in around 25% of channels measured, the residual DTT field strength was above an acceptable threshold for practical deployment of a WSD. Similar results were found by the BBC and Arqiva as part of a TVWS trial in Cambridge [215], where local DTT transmitters were the cause of co-channel interference.

One of the key findings from the trial was regarding the antenna height from a WSD. While a higher antenna would typically result in a lower path loss component, a lower antenna reduces the interference received from DTT transmissions. This creates a performance trade-off, and the height of the antenna must be carefully selected to maximise the achievable results.

A.2 Glasgow

Shortly after the conclusion of the Bute TVWS trial, the DSO was completed in the UK. As discussed previously, a number of TVWS trials were authorised by Ofcom in 2014 [75], as shown in Table A.1.

Service Provider	**Database**	**Devices**	**Trial Location**
CWSC	Spectrum Bridge	6Harmonics	Glasgow
Click4Internet	N/A	Neul 6Harmonics	Isle of Wight
Cloudnet IT Solutions	Fairspectrum Oy	Carlson Wireless	Orkney Islands
CYP (UK) Ltd	Spectrum Bridge	MELD Technologies	Shepperton
Google London Zoo	Google	Mediatek 6Harmnonics	London Zoo
Kings College	Spectrum Bridge Fairspectrum Oy	Sinecom Carlson Wireless Eurecom Runcom Interdigitial NICT	London
Love Hz Ltd Nominet Ltd	Nominet	Adaptrum	Oxford
NICT	NICT	NICT	London
Nominet Ltd	Nominet	Eurecom	Oxford
Peerless AV	Spectrum Bridge	MELD Technologies	Watford

Table A.1: Table summarising the UK TVWS Trials [75].

The Glasgow TVWS pilot commenced in March 2014. The CWSC designed and installed a TVWS testbed network on the University of Strathclyde campus, serving as an urban technology demonstrator. The trial was funded through the Scottish Government's "Demonstrating Digital" programme, with support from Microsoft and Spectrum Bridge.

The project aimed to enable co-existence data gathering as part of the progression to defining full TVWS regulations, gauge stakeholder interest, demonstrate the data rate capabilities of WSDs, and validate the framework of spectrum allocation through a geolocation database.

The installed network was designed to function either as a P2MP topology or a collection of individual P2P links. Four client stations, referred to as *EAR* units, were installed at locations around the campus: three on top of nearby university buildings and one in a communal garden area.

Each client unit connected over TVWS to a single basestation unit, referred to as a *CAR* unit, which was installed on the roof of a central building with a wired connection to the university network.

The established topology can be seen in Figure A.2, with the basestaion unit in black, and the different client stations across campus. A segmented line represents a LoS connection to node, while a solid line indicates LoS is not possible.

A combination of antenna configurations were used in the network, as requirements varied for each installation. At the basestation a high gain, wide beamwidth sector antenna was selected to ensure adequate coverage. Distances covered by the network ranged from 150 to 400 metres with varying LoS conditions.

A combination of antenna configurations were used in the network. Both the Rottenrow Gardens and Sir William Duncan sites used low-gain, omni-directional antennae due to the reduced distance from the basestation, and are highlighted in red. A moderate gain, wide beamwidth sector antenna was used in the Graham Hills site, shown in green. Finally, a high-gain directed log-periodic antenna was selected for the Curran Building installation, shown in blue, to compensate for the distance and topology. The installation on the Curran Building was located furthest away, with no direct LoS to the basestation.

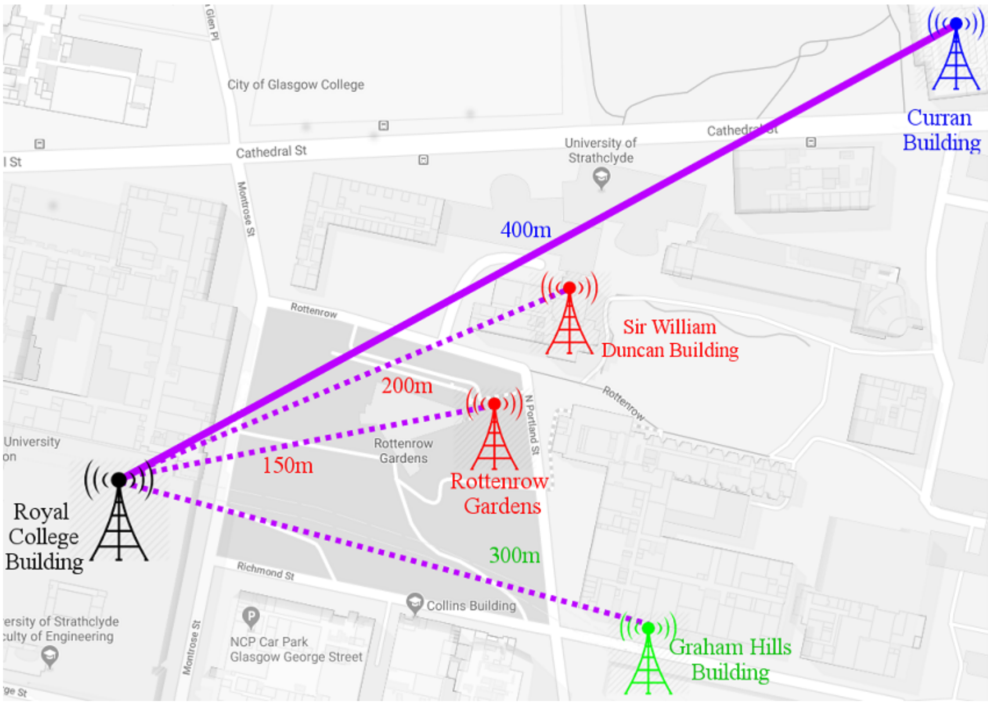


Figure A.2: Network diagram for the Glasgow TVWS trial.

Implemented antenna heights were varied to ensure that the received signal strength was sufficient to maintain the throughput and latency required. These parameters were verified through simulation of the P2P links prior to installation using the RadioMobile program [216]. Simulation results showing the basestation coverage profile is shown in Figure A.3.

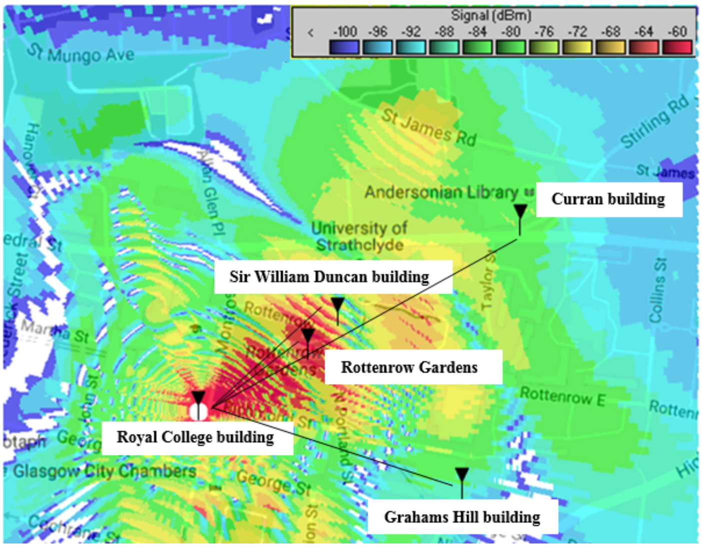


Figure A.3: Results of signal strength simulations, effectively showing network coverage.

As expected, installations at the Curran and Graham Hills buildings are in areas of weaker reception, but still achieve sufficient signal levels for operation. By varying the transmit power, receiver gain, and antenna gain at each site, the signal strength received at all sites could be maintained between the range -55 to -75 dBm.

The network was established with two urban use case demonstrations. A public-facing external Wi-Fi access point (AP) was installed in the communal garden, with backhaul connectivity provided by the TVWS link. In addition, IP cameras were installed at each of the client locations to provide real-time video streams from across the network. These applications, both with relatively high throughput and low latency requirements, enabled performance assessment of the client and basestation units provided by 6Harmonics [89].

This project helped validate the operation of TVWS and shared spectrum in an urban environment. As with the Bute trial, the implemented WSDs were able to co-exist with neighbouring DTT transmissions. Early network implementation was carried out under a non-operational development licence, as the database qualification process had not been completed by Ofcom. By the project conclusion, the pilot network was coordinated by a database provided by Spectrum Bridge, Inc.

Following completion of the network, Ofcom performed several measurements to assess the co-existence between TVWS traffic and the incumbent transmissions, and to validate the communication between WSD and the Spectrum Bridge database. Ofcom noted that there were no reported cases of interference caused by the pilot.

Appendix B

Further Technical Resources

B.1 3GPP Dynamic Spectrum Sharing (DSS)

During the development of the 5G NR standard, as part of Release 15, 3GPP introduced the Dynamic Spectrum Sharing (DSS) technology to facilitate a cost-effective method for 5G NR coverage in existing LTE spectrum. Although similar in terminology, and conceptually also about improvements in spectral efficiency, DSS is quite different from the DSA techniques discussed throughout the rest of this thesis.

DSS is based on the concept that NR signals are transmitted within the unused LTE sub-frames, as shown in Figure B.1. To maintain LTE operation and QoS, it is important to ensure that essential channels are not impacted, such as those for reference signal synchronisation and downlink measurement.

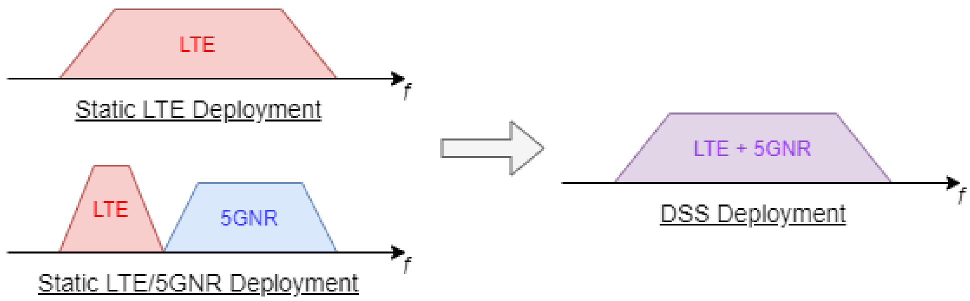


Figure B.1: DSS enables spectral coexistence of LTE and 5G NR deployments.

DSS is intended to be a backwards compatible technology, taking advantage of the similarity of the NR and LTE PHY layers with regards to subcarrier spacing and time domain structure. However, there are important fundamental differences between the two that are leveraged to provide DSS functionality.

In LTE, all channels are statically assigned in the time-frequency domain. The NR physical layer allows flexible deployment for reference signals, data, and control channels. This dynamic configuration minimises the chance of collision between the two technologies, and enables spectral coexistence, however there is still a significant amount of coordination required. This is predominantly carried out through designations in the LTE Cell Specific Reference Signal (CRS), which provide stable and consistent tracking reference signals to the UE.

The other notable attribute of DSS implementation is to accommodate the 5G NR reference signals within transmitted subframes in a manner that avoids impacting the NR downlink measurements and synchronisation. This means ensuring that the 5G NR Synchronisation Signal Block (SSB) and Demodulation Reference Signal (DRMS) are placed in appropriate time-frequencies away from any collision with LTE signals. The DMRS is only transmitted in combination with 5G NR data, which minimises impact on LTE capacity.

There are three main methods to implement DSS into the network, each with distinct advantages and disadvantages for network operators: using Multimedia Broadcast Single Frequency Network (MBSFN) frames, using CRS rate-matching patterns, and using mini-slot scheduling in URLLC applications. All of these implementation strategies come with scheduling complexity in the PHY layer.

In any of the DSS implementation options, the transmission of either control channel or data channel can be dynamically configured for both LTE and 5G, depending on the capacity requirements at a given point in time.

Although this deployment flexibility is highly desirable, it is for the network operator to determine the value relative to the additional scheduling complexity. In addition, there are concerns about the additional DSS-induced overheads impacting the efficiency of both the LTE and 5G NR carriers. However, as a further trade-off, the ability to deploy multiple RATs simultaneously on the same network infrastructure reduces the CAPEX and provides an evolutionary path to full 5G deployment without switching off existing LTE services.

B.2 TVWS Operating Standards

This section will briefly overview both the IEEE 802.22 and 802.11af standards, which support methods of TVWS spectrum sharing through implementations of geolocation database requests and cognitive sensing techniques.

B.2.1 IEEE 802.22

The IEEE 802.22 standard, published in 2011, defines MAC and PHY layer specifications for wireless regional area network (WRAN) operation in the frequency range of 56-806 MHz. The intended topology is cellular P2MP, with a single basestation connected to CPE units within an operating cell.

As a WRAN, the maximum achievable coverage area is relatively large compared to a Wireless LAN WLAN standard, such as those in the IEEE 802.11 family, even though they are intended for use in similar applications. For IEEE 802.22 implementations, typical distances between basestation and CPE are in the range of 17-33 km, but up to 100 km is supported [217], while a WLAN is better optimized for distances of up to 1 km, as discussed later in this appendix.

The MAC and PHY layer were both designed to fully accommodate spectrum sharing. The standard adopts an OFDMA scheme using TDD, enabling the fast channel adaptation needed for operation in shared spectrum, and supports Quadrature Phase Shift Keying (QPSK), 16 QAM or 64-QAM modulation schemes. Bandwidths of 6, 7 or 8 MHz can be implemented. Contiguous channel bonding is supported to improve achievable bandwidth and performance, similar to the carrier aggregation techniques used in LTE systems [218]. With channel bonding the combined system must be in spectrally adjacent channels, while carrier aggregation allows for the use of non-contiguous spectrum, potentially in different operating bands to form larger bandwidths [219].

The basestation and CPE are capable of performing cognitive sensing both in-band, i.e. in the current channel being used by the device, and out-band, i.e. in the remaining channels. These sensing processes occur during transmission breaks and determine local Incumbent information that is then fed back to the basestation. While carrying out this process could impact the achievable QoS, techniques such as Dynamic Frequency Hopping (DFH) can be used to mitigate the effects [220].

Two methods of spectrum sensing are implemented. *Fast*, or blind, sensing typically involves an energy detection method not particular to any signal properties [221]. The outcome of fast sensing is used to determine if further information is required. In that case, *Fine*, also referred to as feature or signal-specific, sensing is used, which leads to a higher success rate in determining channel occupation but is slower and requires the use of prior information [217].

Each CPE feeds back its sensing data to the basestation, which combines it with data from the geolocation database to determine spectrum information for the whole network and adjust operating channels accordingly. To ensure Incumbent protection, the basestation cannot continually broadcast pilot signals. Unused channels are initially identified by the database. These channels are then used to transmit superframes, which are defined structures containing a Superframe Control Header (SCH), and potentially multiple data frames. At the initialisation stage, the CPE must first determine any channel occupancy through sensing before scanning the vacant frequencies for superframes and the information contained within the SCH regarding establishing connection to the basestation.

B.2.2 IEEE 802.11af

The operations for the use of TVWS frequencies as a WLAN are detailed in IEEE 802.11af, which defines an updated MAC and PHY layer modifications.

The implemented Television Very High Throughput (TVHT) PHY layer is OFDM based, and supports multiple modulation schemes from Binary Phase Shift Keying (BPSK) up to 256-QAM [218]. It is extremely similar to the IEEE 802.11ac implementation, down-clocked to support channel bandwidths of 6, 7 or 8 MHz in accordance with local regulations. These design similarities were intentional, as it would aid manufacturers of chipsets in the adaptation of their existing products [217].

Unlike IEEE 802.22, which is a cell-based architecture, IEEE 802.11af networks comprise multiple stations (STA), or nodes. The IEEE 802.11af nodes are categorised as either Access Points (APs), which bridge connection to a wired network that is typically Internet enabled, or clients, devices seeking access to the wired connection. Each AP might be connected to multiple client nodes, collectively referred to as its Basic Service Set (BSS), and is responsible for routing traffic to each of them [217].

The standard allows for up to four spatial streams and simultaneous operation in up to four TVWS channels for connection between a client and an AP, which can be completed in multiple different ways [219]. Devices can choose to operate in a single channel or in two non-adjacent channels. Alternatively, bonding can be applied to two or four adjacent channels to form a single contiguous channel. Finally, a device can use two non-contiguous pairs of bonded channels.

Overall, the standard allows for up to 35.6 Mbps per spatial stream per 8 MHz channel. Therefore, with four bonded channels and four spatial steams, the maximum theoretical peak data rate is 568.9 Mbps [217].

MAC layer functionality is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), as is common within the 802.11 standards family. When a device wants to transmit, it will first listen to the desired operating channel for a set time. If there is contention, the device will wait a random amount of time before trying again. If the channel is available, transmission will begin on pre-determined slot boundaries. When a device is transmitting, it cannot simultaneously listen for others. If two devices end up operating in the same channel, a collision will occur and the resulting interference will likely cause reception of the signals to fail [217].

Transmission slot boundaries and the time spent listening to channels are dependent on a number of factors. One of these is the propagation delay of the signal, i.e. the time taken for a transmission to reach the defined furthest away receiver. For IEEE 802.11af, the default propagation time allows for a maximum distance of roughly 900 m, giving an AP BSS an operating range of 450m. This propagation delay, combined with the CSMA/CA based scheduler, exacerbates the well known *hidden node problem* [217].

B.3 Overview of Underlying Technologies

Section B.3 provides context for some of the underlying technologies that are fundamental to both the TVWS and CBRS spectrum access frameworks. This includes the JavaScript Object Notation (JSON) data format, for creation and transmission of data objects containing parametrised information, and the Hypertext Transfer Protocol (HTTP) methods, for data exchange.

B.3.1 JavaScript Object Notation (JSON)

JSON is a standard file format that uses an object notation syntax to allow for data exchange in a human readable fashion [222]. While primarily intended as a data serialisation and exchange mechanism, JSON has increasingly been used as a configuration language. An example of such usage in this project is within the parameter files used to control the Amarisoft software, discussed in Chapters 4, 5, and 6.

In JSON, data objects are written as a collection of name-value pairs. Each object contains at least one field name, or key, which is unique to the containing object. Every field name has a corresponding value, which could be any of the supported data types.

The basic types are signed decimal numbers, Unicode strings, boolean, ordered lists or arrays, and the null value. Associated values can also be objects themselves, and it is common to see multiple layers of nested structures. This creates a very flexible system for data representation.

However, while JSON implementation enables creation of standard frameworks for data representation, it is possible that the same dataset could be represented in multiple valid ways. Therefore, the design will vary depending on the application and intended role of the data structure. This also means that the efficient exchange of information will require pre-arrangement between the JSON source and the recipient to ensure equivalent syntax and data types are used or expected.

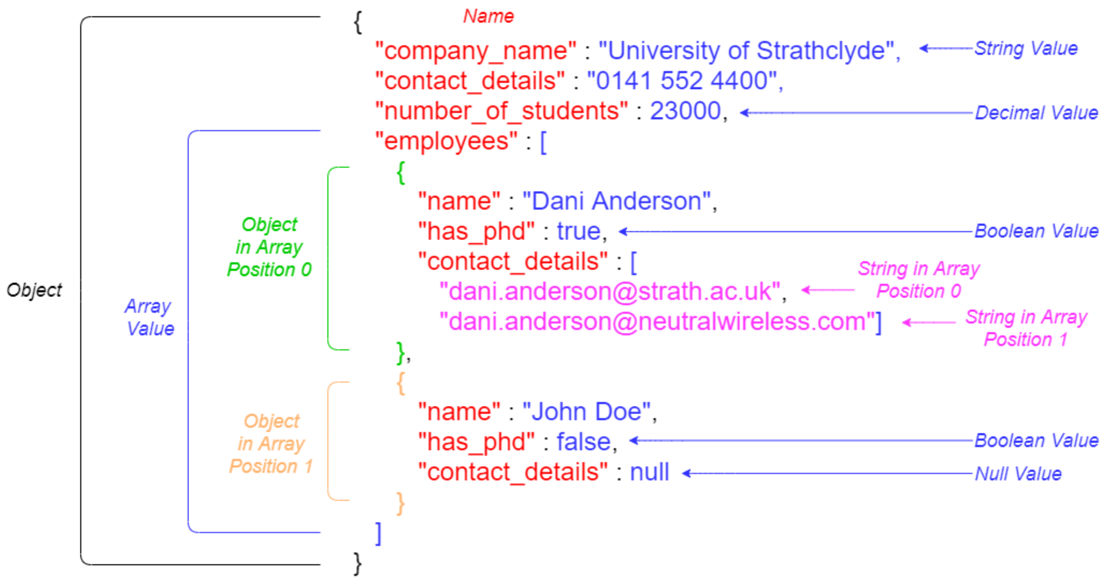


Figure B.2: An example of a JSON structure with four named fields

JSON is comparable to eXtensible Markup Language (XML), which can also be used to describe data structures and objects. The main difference between the two is that JSON does not have a dedicated parser. This influences how values are stored and addressed, which can impact the speed of data processing. One valuable asset long associated with XML implementations is the concept of an XML Schema (XSD). An equivalent feature, based on the same concepts, was later implemented in the standard JSON libraries, referred to as JSON Schema.

A schema file describes and defines the possible structure and parameter types of a second JSON format source file, referred to as the data *instance*. The schema itself is written in JSON and is used to validate data prior to transmission, or after reception, and is commonly implemented in Application Programming Interfaces (APIs) that use JSON.

In this way, it is simple to describe the data structure and enable automated validation of data against it. However, there will be certain relationships or validation criteria outside of the capabilities of schema representation.

Validation strategies for sufficiently complex data structures will therefore likely involve multiple stages. The first would operate using the schema, with a second performing semantic verification. In the latter case, this would likely require a more general purpose programming language.

B.3.2 HTTP Methods

HTTP is an application layer protocol that is designed to enable request-response communication between clients and servers.

A number of request methods, sometimes referred to as HTTP verbs, are defined in the protocol as shown in Table B.1, which indicate what action is intended to be performed on a specified resource.

HTTP Method	**Description of Method**
GET	Requests a representation of the specified resource. Should only retrieve data.
HEAD	Requests a representation of the specified resource. Identical to the GET request, but without the response body.
POST	Used to submit an entity to the specified resource, often causing a change in state on the server.
PUT	Replaces all current representations of the target resource with the request payload.
DELETE	Requests the target to delete the target resource.
CONNECT	Establishes a TCP/IP tunnel to the server identified by the resource.
OPTIONS	Requests the target resource for a list of supported HTTP methods.
TRACE	Requests a message loop-back of the received request within the response body.
PATCH	Apply a partial update to a specified resource.

Table B.1: Summary of HTTP Methods.

The Status-Code element in a server response is a 3-digit integer that indicates how a server has reacted to a specific HTTP request. The first digit defines the class of response, with five defined categories, as shown in Table B.2. These codes are extensible and HTTP-based applications are not required to have understanding of all the registered status codes. The desired response, in most request cases, is a *200 OK* message indicating that the operation has succeeded.

Status Code	**Description of Response**
Informational Responses (100–199)	Request has been received. Process is continuing.
Successful Responses (200–299)	Action was successfully received, understood, and accepted by server.
Redirects (300–399)	Further action must be taken to complete the request.
Client Errors (400–499)	Request contains incorrect syntax or cannot be completed by the server.
Server Errors (500–599)	Server failed to fulfil a request with apparently valid syntax.

Table B.2: Summary of HTTP Response Codes.

The applications discussed throughout Chapters 4 and 5 only make use of a further subset of the available HTTP methods.

One such example of this is a GET request, one of the most commonly implemented methods in APIs and websites, which is used to retrieve data from a web server according to provided specifying parameters. In context of Dynamic Spectrum implementations, this method is used by a WSD or CBSD to communicate with its respective WSDB or SAS, using the defined messaging structure.

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