TV White Spaces for Railway Wireless Applications

BY

Mohamed Mahmoud Mohamed Soliman Samra

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Birmingham Centre for Rail Research and Education

Department of Electronic, Electrical and Systems Engineering

College of Engineering and Physical Sciences

University of Birmingham

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Abstract

Train-to-ground communication is one of the most crucial features of modern railway systems. The extensive use of emerging wireless technologies helps to achieve the rail industry vision of implementing intelligent trains, having a customised experience for travelling passengers, and running trains closer together. The Global System for Mobile Communications-Railway (GSM-R) is an international wireless communications standard introduced for train-to-ground communications in mainline railways. However, GSM-R currently suffers from severe interference and capacity problems that impede the consideration of this technology for emerging rail applications.

The prospect of opportunistic access to an inefficiently utilised frequency spectrum, known as TV White Spaces (TVWS), that exploits desirable railway propagation characteristics is proposed to solve the spectrum scarcity problem. In order to provide full protection for spectrum Primary Users (PUs), The IEEE 802.22 standard sets strict policies for mobile platforms. This research proposes a handover procedure and channel access scheme that maintain seamless connectivity for various railway wireless applications in the mobility-restrictive TVWS. The suitability of the approach is tested through its application in Remote Condition Monitoring (RCM) systems whose telecommunication requirements can tolerate the uncertainty in the TVWS spectrum availability. The method is applicable to other rail applications if special considerations are given to the specific application requirements.

Prior knowledge of the train's trajectory enables the method to pre-select a list channels that last for long distances, which minimises unnecessary control messages overhead. The newly proposed method indicates an improvement of 37.8% in the channel utilisation distance, as the train can have an uninterrupted connection for an average consecutive distance of 1.188 km using the new scheme compared with an average of 0.862 km for the IEEE 802.22 standard. Besides that, for the same data rate, an extra 6.5% of maintenance data can be transmitted using the new approach if compared with the IEEE 802.22 standard under various spectrum availability. The results also reflect 0% probability of channel collision under all spectrum availability, due to the first-come-first-served spectrum access adopted, and 0% probability of overall network blocking at spectrum availability that is ($\geq$ 30%). Finally, the new method does not cause any interference to the surrounding PUs and enables better transmission power for the spectrum Secondary Users (SUs) that can reach up to 42.2 dBm under different channel availability, which directly improves the overall network throughput.

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Publications

Prior to completing this thesis, one peer-reviewed journal paper was submitted, and three conference papers were published. Currently, a second journal paper that depends mainly on the work undertaken in Chapter 7 is under preparation.

Contributing Publications

Portions of my previous publications are reproduced within the body of this thesis in Chapters 3, 4, 5, and 6.

1. Samra, Mohamed, Lei Chen, Clive Roberts, Costas Constantinou, and Anil Shukla, "Assessing the Usage Feasibility of TV White Spaces for Rail Remote Condition Monitoring", *4th IET Colloquium on Antennas, Wireless and Electromagnetics*, Glasgow, UK, May 2016, pp. 1–21.

2. Samra, Mohamed, Lei Chen, Clive Roberts, Costas Constantinou, and Anil Shukla, "Assessing the Usage Feasibility of TV White Spaces for Railway Communication Applications", *IEEE International Conference on Intelligent Rail Transportation (ICIRT)*, Birmingham, UK, August 2016, pp. 1–6.

3. Samra, Mohamed, Lei Chen, Clive Roberts, Costas Constantinou, and Anil Shukla, "Handover Scheme for Seamless Connectivity of Cross-City Trains in TV White space", *6th IET Colloquium on Antennas, Wireless and Electromagnetics*, Bristol, UK, May 2018.

4. Samra, Mohamed, Lei Chen, Clive Roberts, Costas Constantinou, and Anil Shukla, "TV White Spaces Handover Scheme for Enabling Unattended Track Geometry Monitoring from In-Service Trains", *IEEE Transactions on Intelligent Transportation Systems*, doi: 10.1109/TITS.2019.2963876.

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List of Acronyms

AAA	Authentication, Authorisation, and Accounting
ACLR	Adjacent Channel Leakage Ratio
ACS	Adjacent Channel Selectivity
AP	Access Point
BCRRE	Birmingham Centre for Railway Research and Education
BRaSS	Birmingham Railway Simulation Suite
BS	Base Station
CBTC	Communications-based Train Control
CCTV	Closed-Circuit Television
CPE	Customer Premises Equipment
DCI	Delay Compensation Interval
DRM	Database Resource Manager
DSA	Dynamic Spectrum Access
DTT	Digital Terrestrial Television
ECO	European Communications Office
EIRP	Effective Isotropic Radiated Power
EOT	End of Transmission
ETCS	European Train Control System
FCC	Federal Communications Commission
GPS	Global Positioning System
GSM-R	Global System for Mobile Communications-Railway
GVA	Gross Value Added
HS2	High Speed 2
HS3	High Speed 3
ICT	Information and Communications Technology

ILR Interfering Link Receiver

ILT Interfering Link Transmitter

IP Internet Protocol

ITM Irregular Terrain Model

LTE Long Term Evolution

M2M Machine to Machine Communications

MAC Medium Access Control

MIMO Multiple-Input Multiple-Output

Ofcom Office of Communications

PMSE Programme Making and Special Events

PU Primary User

QoS Quality of Service

RCM Remote Condition Monitoring

REM Radio Environment Maps

RF Radio Frequency

RFID Radio-Frequency Identification

RSSB Rail Safety and Standards Board

RSSI Received Signal Strength Indicator

SINR Signal-to-Interference-plus-Noise Ratio

SU Secondary User

TVWS TV White Spaces

UHF Ultra High Frequency

UKPM UK Planning Model

UMTS Universal Mobile Telecommunications Service

UTGMS Unattended Track Geometry Measurement System

VHF Very High Frequency

VLR Victim Link Receiver

VLT	Victim Link Transmitter
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Networks
WRAN	Wireless Regional Area Network
WSDB	White Space Database
WSN	Wireless Sensor Networks

Dedicated to my parents.

Chapter 1

Introduction

1.1 Background

Rail transport is considered the most efficient mode for medium and short travel distances that brings great economic, social and environmental benefits (Dincer *et al.*, 2015). Railway-related activities within the UK contribute up to £36.4 billion of Gross Value Added (GVA) to the national economy and are associated with nearly 600,000 jobs (Oxford Economics, 2018). Besides, the industry reduces CO_2 emissions in Great Britain by up to 7.4 m tonnes, valued at £430 million annually (Oxera, 2014).

Information and Communications Technology (ICT) represents a strategic asset to the railway industry and a focal point for its evolution. In the past, telephone lines were deployed along railway routes to ease railway operations. Currently, ICT is in use all around us, from contactless payment, e-ticketing, video surveillance, and automated assets inspection to providing entertainment for the on-board passengers. Keeping an eye on emerging technologies helps to shape future solutions by tackling the existing rail industry challenges with more reliability and efficiency (Arup, 2014).

Train-to-ground communication is one of the most crucial features of modern railway systems. A large set of applications is enabled through the extensive use of wireless technologies. For example, transmission of the train position, direction, and speed to a ground central unit underpins an efficient train control system that contributes to overall network safety and capacity. Moreover, a train communicating the train/track health information to a central unit helps to initiate critical maintenance decisions. Last but not least, maintaining a high-quality communication link between the train and ground helps to provide on-board passengers with a reliable broadband connection. Unfortunately, the wireless systems currently deployed experience technical difficulties that limit their ability to meet the continuously developing industry requirements (Sun *et al.*, 2013).

1.2 Problem Statement

The Global System for Mobile Communications-Railway (GSM-R) is an international wireless communications standard introduced for train-to-ground communications in mainline railways. It is mainly being used in Levels 2 and 3 of the European Train Control System (ETCS) to maximise the network capacity while keeping a safe braking distance between in-service trains. GSM-R also delivers additional features such as group calls, voice broadcast, location-based connections, and emergency calls that would enable the development of future applications. However, the introduction of recent technologies, namely Long Term Evolution (LTE) and Universal Mobile Telecommunications Service (UMTS), in adjacent frequency bands has disrupted railway operations in 400 GSM-R stations around Europe. Besides, the utilised circuit-switching paradigm limits the capability of GSM-R to support bandwidth-demanding applications (Lindström, 2012).

Similarly, Wireless Local Area Networks (WLAN) are being used in metropolitan railways to transfer data between trains and ground in Communications-based Train Control (CBTC) systems. WLAN has a strong anti-interference and anti-multipath capacity because of its use of spread spectrum and RAKE receiver technology. Nevertheless, due to the limited coverage range of WLAN Access Points (APs), difficulty in dealing with frequent handovers, and severe Doppler frequency shift problems at high speed, it is not feasible to apply off-the-shelf WLAN technologies in mainline railway systems (Sun *et al.*, 2013).

With the increasing demand for a more reliable, secure, and seamless high data rate connectivity, it has become a necessity to investigate various emerging wireless technologies for mainline train-to-ground communications. LTE and 5G have been discussed in many papers due to the high throughput provided for fast-moving trains. LTE is able to provide 100 Mbps of downlink transmission rate with 20 MHz channel bandwidth (Guan *et al.*, 2011). On the other hand, the underutilised 5G millimetre wave (mmWave) band at 24–28 GHz can provide a 10 Gbps data rate for trains moving with a speed above 400 km/h (Kim and Kim, 2013). Yet, the cost of deploying an LTE/5G network in the countryside between large cities is quite high due to high cost of the dedicated spectrum.

Meanwhile, the switch-over from analogue to digital terrestrial TV has freed up valuable radio spectrum, known as TV White Spaces (TVWS). These frequencies fall within the range of 470-790 MHz and primarily being used by the Digital Terrestrial Television (DTT) and Programme Making and Special Events (PMSE) users. Any low-power secondary device can access this band on an opportunistic basis if full protection is ensured for the spectrum Primary Users (PUs). A TVWS system offers desirable railway propagation characteristics. In comparison with recent technologies such as LTE and 5G, the relatively lower frequencies of TVWS makes the propagating signal: less prone to both Doppler shift and path loss in high-speed lines, has higher penetration capabilities in typical rail environments such as tunnels, and able to cover wider areas with fewer Base Stations (BSs) (Saeed and Shellhammer, 2011). TVWS was designed initially to provide broadband access to stationary devices in rural areas. Consequently, the TVWS standards impose a set of restrictive mobility policies on Secondary Users (SUs) to prevent any possible interference with the spectrum PUs. For instance, the SU needs to comply with a set of operations for every mobility beyond the specified threshold. In the UK, this mobility threshold is defined as 100 m X 100 m geographic square, known as a "pixel". If a train is travelling at a speed of 100 km/h, a network update will be required every 3.6 seconds. This time interval tends to be shorter for trains travelling at higher speeds.

In the study that follows, a railway-tailored approach is proposed that would enable a TVWS system for various railway applications. The research takes into account the dynamic characteristics of the railway environment including signal propagation and the train mobility model including possible delays and the separation distance between in-service trains. TVWS is demonstrated to be able to fulfil the requirements of the railway telecommunications network as an SU while providing the spectrum PU with full protection from any undesirable interference. The thesis provides useful insights for railway industry stakeholders by paving the road for a reliable and economic wireless communication network for mainline railways.

1.3 Purpose of the Research

The purpose of this research is to develop a handover procedure and channel access scheme that maintain seamless connectivity for various railway wireless applications in the mobility-restrictive TVWS. The suitability of the approach is tested through its application in Remote Condition Monitoring (RCM) systems whose telecommunication requirements can tolerate the uncertainty in the TVWS spectrum availability. The method is applicable to other rail applications if special considerations are given to the specific application requirements.

Rail is a good example to test the suitability of TVWS for other transportation modes as they have similar mobility characteristics. However, as the train moves along a fixed track with a preset timetable, it is easier to predict its position in time. Moreover, train-to-ground communication is an active area of research due to its central role in enabling key applications for the industry. Within the UK, the introduction of projects such as High Speed 2 (HS2), High Speed 3 (HS3), and Crossrail indicates the urgent need for an efficient and economic wireless communication system.

A secondary purpose of this research is to investigate how wireless signals propagate in a mainline railway environment, identifying the factors that could affect this process. Accurate modelling of the spectrum enables several approaches to be developed for mobile platforms to operate seamlessly in the restrictive TV band. Moreover, other researchers could refer to the stated methodology to propose various handover schemes for emerging wireless technologies in the rail context.

1.4 Research Objectives

The main aims of this thesis are:

- To develop a method that maintains seamless connectivity for various railway applications in the mobility-restrictive TVWS band.
- To demonstrate the suitability of the method with an example of application in RCM systems.

In order to meet these aims, first, the requirements of pivotal railway wireless applications must be identified. Then, the TVWS framework and approaches to ease its mobility restrictions must be reviewed from both regulatory and technical standards perspectives. The third objective includes designing a generic method that enables a seamless and reliable connection. Finally, the method's performance will be quantified when applied to RCM systems, and the results obtained will be compared with the existing IEEE standard. The research objectives are given in Table 1.1, alongside the related research questions and the chapters that cover these objectives.

1.5 Hypotheses

A communication system that experiences seamless connectivity in the TVWS will offer an alternative technology that fulfils requirements of railway pivotal wireless applications. Quantifying the TVWS-enabled network performance for train-to-ground communications will allow conclusions to be drawn on: which approaches can be adopted to tackle mobility restrictions in the TVWS band; would these approaches be affected by rail-specific mobility factors such as the separation distance between moving trains; and what in-depth experimentation should be undertaken to evaluate the performance of these approaches.

The previously stated three pivotal questions within this hypothesis are tested further by the following sub-hypotheses that relate to the case study of RCM:

- Do the solutions offered for RCM systems differ for other rail applications?
- Can these differences be used to guide tailored development for pivotal industry applications to share the TV spectrum?
- What are the further experiments that the results would inform?

TABLE 1.1: Research objectives and related research questions of this thesis

Objective		Research Question		Chapter
1.	To analyse the main railway wireless applications and identify their telecommunications requirements	a.	What are the telecommunications requirements of main railway applications?	2
2.	To understand the regulated TVWS framework and the restrictions on mobile platforms	b.	What are the TVWS limitations on mobile platforms and methods to tackle them?	3
3.	To develop a railway-generic method for seamless connectivity	c.	How do the propagation models and train mobility affect generation of the spectrum availability map?	4
		d.	How to consider the possible trains' delay and coexistence into the developed method?	
4.	To demonstrate the suitability of the handover and channel assignment scheme, through application to a case study	e.	What is the best railway application that would fit the current development stage of TVWS?	5
		f.	How would the method perform in a small rail network if compared with the IEEE 802.22 standard?	6
		g.	What are the mobility factors that would affect scalability of the proposed method?	7
		h.	What is the suitability of the method for other rail applications?	8
		i.	How can the method be used in the future?	8

1.6 Thesis Structure

This section describes the thesis chapter organisation and how the research objectives and questions are addressed.

Chapters 2 and 3 are literature review chapters that satisfy the first two research objectives 1 and 2, respectively. Chapter 2 provides background information on the various railway wireless applications, identifying the telecommunications requirements of the pivotal applications, the development of which will bring great economic and operational value to the whole rail industry. Chapter 3 presents the TVWS regulated framework and investigates methods to tackle mobility restrictions in the TV band. Both chapters will address research questions a and b, stated in Table 1.1.

Chapter 4 gives a brief overview of spectrum availability map generation, identifying the factors that affect the process. The chapter then proposes a generic handover procedure and channel access scheme that achieve the third research objective and answers research questions c and d in detail. Chapter 5 discusses the current development stage of TVWS and justifies the selection of RCM systems for the case study, that addresses research question e.

In Chapter 6, the proposed method is applied to railway RCM systems, and the results obtained are compared to the IEEE 802.22 standard. A medium-scale network is later introduced in Chapter 7 to analyse the rail-specific mobility factors and their impact on scalability of the proposed method. These two chapters answer research questions f and g.

Chapter 8 concludes the thesis by discussing the research implications, key results, and future work. The chapter also discusses how the method can be modified to address other railway wireless applications. That addresses research questions h and i.

Chapter 2

Requirements Analysis of Railway Wireless Applications

2.1 Introduction

Applications and demand for mobile communications in the railway industry are rapidly growing and will continue to grow in the future to meet the industry's 'four C' challenges (Carbon, Cost, Customer, and Capacity). With the current limitations of the GSM-R system, significant research has been undertaken to adopt a successor technology for train-to-ground communications in mainline railways. Therefore, capturing a technology-independent set of applications requirements is crucial to evaluate the performance of TVWS for various railway applications.

The Rail Safety and Standards Board (RSSB, 2012) has divided the railway wireless applications into four categories as follows:

- **Operational – Safety-Critical:** Applications with high safety importance as any failure can lead directly to damage being caused or not prevented to rail passengers or personnel. Examples of this category include train control systems, staff communications, and level crossings.
- **Operational – Safety-Related:** Failure of these applications is not classified as critical but can still affect the safe running of railway operations.

Automatic train operations, surveillance cameras, and possession management are all examples of this category.

- **Operational – Non-Safety-Related:** The breakdown of these applications will affect normal rail operations that are not safety-related. Examples in this category include intelligent condition monitoring, driver advisory, and passenger counting.
- **Retail:** These applications focus on passenger leisure and retail opportunities. Passenger entertainment, e-ticketing, and on-board catering belong to this category.

The main aim of this chapter is to identify network requirements of pivotal applications, the development of which will bring great economic and operational value to the whole rail industry. In this thesis, signalling systems will represent safety-critical/related applications, while RCM and on-board broadband systems will represent non-safety and retail applications, respectively. These applications have received attention in the literature and fall within the scope of this research due to their high dependency on train-to-ground communications.

This chapter follows the RSSB T964 report (2012), and the user requirements specifications of Future Railway Mobile Communication System (FRMCS) introduced by (UIC, 2018) to define each application and list its telecommunication requirements in terms of geographical coverage and continuity, operational speed, and reliability. Geographical coverage represents the need for the communication network to be available at specific locations that include the rail line, station, and yard. Under this requirement, the frequency of use will reflect the duration at which each application is used at the predetermined locations in a certain operational mode (e.g. normal, degraded, emergency). Additionally, the coverage continuity sets the application need for a continuous connection under the available coverage. The operational speed determines the speed at which the communication system will be travelling and remains operational. Finally, the communication system reliability represents the ability to tolerate a transient link failure (e.g. interference) to achieve a given Quality of Service (QoS).

Besides, the chapter captures additional communications attributes for each application that include data rate, latency, setup time, priority, content type, and symmetry, as stated in the X2Rail-1 User & System Requirements (Telecommunications) (2018). Table 2.1 defines each of these attributes.

TABLE 2.1: Definition of additional communications attributes

Attribute	Definition
Data Rate	The transmission speed at which the system transfers a certain amount of data in a given time interval
Latency	The end-to-end transport delay between involved communications entities
Setup Time	The time needed to establish a communication session between the system stakeholders
Priority	Level of priority required for a specific application
Content Type	The type of transmitted content including the direction of the data flow (i.e. bi-directional data, unidirectional voice)
Symmetry	The ratio between the uplink (UL) and downlink (DL) traffic. The uplink traffic refers to the data transfer from "mobile to infrastructure", while the downlink traffic indicates the opposite flow from "infrastructure to mobile"

2.2 Signalling Systems

As the train moves on fixed rails with relatively high speed, it is hard to apply the brakes directly before any possible obstacle. It is the duty of the train control system to ensure a safe and efficient flow of trains through the rail network. When an incident interrupts normal rail operations, the control system activates either a backup timetable or the emergency mode. From that, the rail network will overcome the delay caused and return to normal operations.

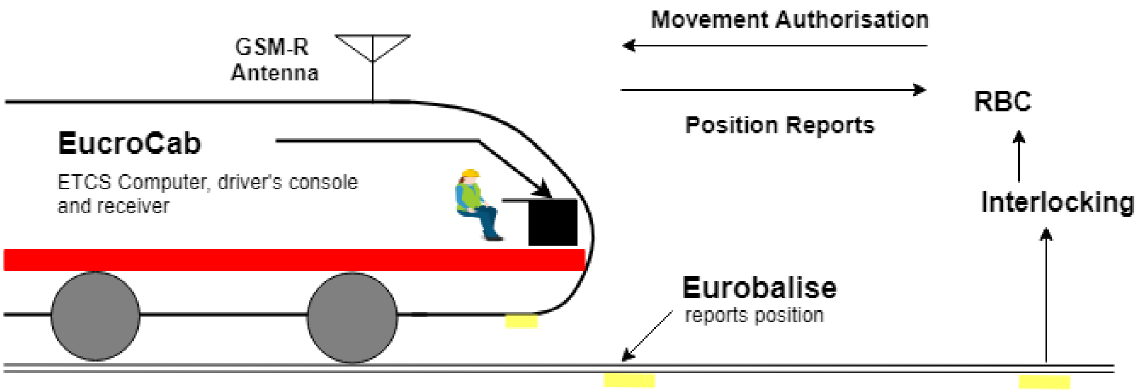

Figure 2.1: Schematic diagram of ETCS Level 2 main components

By utilising modern communication technology-based signalling systems, such as ETCS in mainline railways, instead of the traditional track circuit-based systems, information such as a train's location, speed, and movement authorisation can be transmitted more smoothly and efficiently. There are three levels specified within the ETCS (levels 1 to 3). ETCS L2 is the latest standardised level that enables a set of functions through the deployed system components demonstrated in Figure 2.1. For instance, the Eurobalise sub-system is responsible for detecting the train location using the on-board transmission module and the track-mounted balise. On the other hand, GSM-R ensures continuous transmission between the on-board equipment and the control centre to transmit the train location and receive the movement authority accordingly. Finally, the received movement authority (i.e. operating speed and next braking point) is displayed to the driver through the Driver Machine Interface (DMI).

Another application of the signalling system is to enable staff communications. Staff can also approve train movements and confirm the successful reception of these authorisations. This thesis considers signalling systems due to their importance to daily rail operations and the current GSM-R limitations. In 2011, railway operations in Germany registered 252 interference incidents compared with only 58 incidents in 2006. The number of incidents is expected to increase as more LTE and UMTS stations are expected (Lindström, 2012; UIC, 2014a).

Finding an alternative to the GSM-R system is an active area of research. For instance, Sniady and Soler (2014) evaluated the performance of LTE for railway signalling and its ability to fulfil ETCS requirements for transmission delay and data integrity performance. Another low-power signalling system that depends on the ZigBee protocol for data transmission and Radio-Frequency Identification (RFID) for train localisation was introduced by Samra *et al.* (2016). Besides that, Aguado *et al.* (2008) designed a signalling system that is based on the Worldwide Interoperability for Microwave Access (WiMAX) telecommunication architecture.

However, the cost of LTE and WiMAX network deployment in rural areas between the main cities may prevent the adoption of these technologies. Also, the limited bandwidth offered by the ZigBee protocol is not sufficient for staff voice communication which leaves this area open to research and further investigation. The next subsections will detail the technology-independent technical requirements of the signalling system.

2.2.1 Coverage Continuity and Geography

Pointing to the safety significance of the signalling system, it is crucial that the communication network must be available continuously in all the regions where the train passes by. Table 2.2 demonstrates the signalling system usage frequency at different locations in various operational modes, as stated in (UIC, 2018). The shown values indicate that the signalling system is active between 15 minutes per user per hour for the data transmission, and up to continuous usage at all times, regardless of the location and the mode of operation. Similarly, the high

TABLE 2.2: Frequency of use for the signalling system

Mode of Operation	Station	Yard	Line
Normal	High	High	High
Degraded	High	High	High
Emergency	High	High	High

frequency of use for voice transmission indicates more than 5 calls per user per hour (on average) (UIC, 2018).

2.2.2 Reliability

High network reliability is most needed as any link failure would lead to serious consequences, starting from disturbance caused to the rail operations and even raising the likelihood of train collisions. A lot of factors can affect the network reliability, including potential interference with adjacent technologies, or the limited capacity of the communication network that can cause a connection request to be dropped or queued.

2.2.3 Operational Speed

The application must ensure the delivery of safety information, movement authorities, and traffic management data without loss or delay at low, medium, and high speeds.

TABLE 2.3: Communications attributes values for the signalling system

Attribute	Value
Data Rate	64 kbps
Latency	10 - 100 ms
Setup Time	< 1 second
Priority	High
Content Type	Bi-directional data
Symmetry (UL/DL)	50/50

2.2.4 Additional Communications Attributes

The additional communications attributes for the signalling system is defined in the EIRENE Project System Requirements Specifications (UIC, 2014b). For instance, the latency is only valid if 95% of the total delays are less than 0.5 s, however, the typical latency value for the signalling system is between 10 - 100 ms (UIC, 2018). Besides, the typical time for the connection setup is less than 1 s. Finally, the data rate requirements are highly dependent on the ETCS level utilised and also on whether staff voice communication is provided or not. The ETCS sets a minimum data rate requirement of 2.4 kbps (Aguado *et al.*, 2008), while the RSSB (2012) recommends a data rate of 64 kbps to support a single voice channel to be used by each train throughout the whole journey. Table 2.3 lists the values of the communications attributes for the signalling system.

2.3 On-Board Broadband Systems

In 2016, the Department for Transport segmented the train travel market into 57% of trips made for commuting (including trips for education), 33% for leisure, and 10% for business travel (Oxera, 2014). The common aspect of these segments is that people want to stay connected continuously throughout the whole journey for different reasons. Some like to watch videos, make calls, or browse the Internet while the rest prefer to work on the train. Providing reliable on-board broadband will not only increase overall passenger satisfaction but also bring a huge economic value to the rail industry. With the usage of mobile communications, the speed of on-board retailing will be increased by enabling more efficient payment verification processes (RSSB, 2012).

There are a lot of technical solutions that have been introduced over the years to provide seamless broadband connectivity. These solutions range from the usage of existing mobile networks, dedicated track-side networks, satellite networks, or a mixture of all (Lannoo *et al.*, 2007). For instance, Icomera (2016) developed a broadband system that utilises cellular technology for the uplink, satellite technology for the downlink, and in-carriage Wi-Fi APs to provide Internet for on-board passengers (Masson *et al.*, 2015). Figure 2.2 represents the architecture of this concept.

A thorough search of the relevant literature yielded the result that an ideal unified communications solution does not exist. The technology choice depends hugely on the services offered, the train type, and the environment through which the train travels (Lannoo *et al.*, 2007). This section will list the requirements of various applications that are enabled through the on-board broadband.

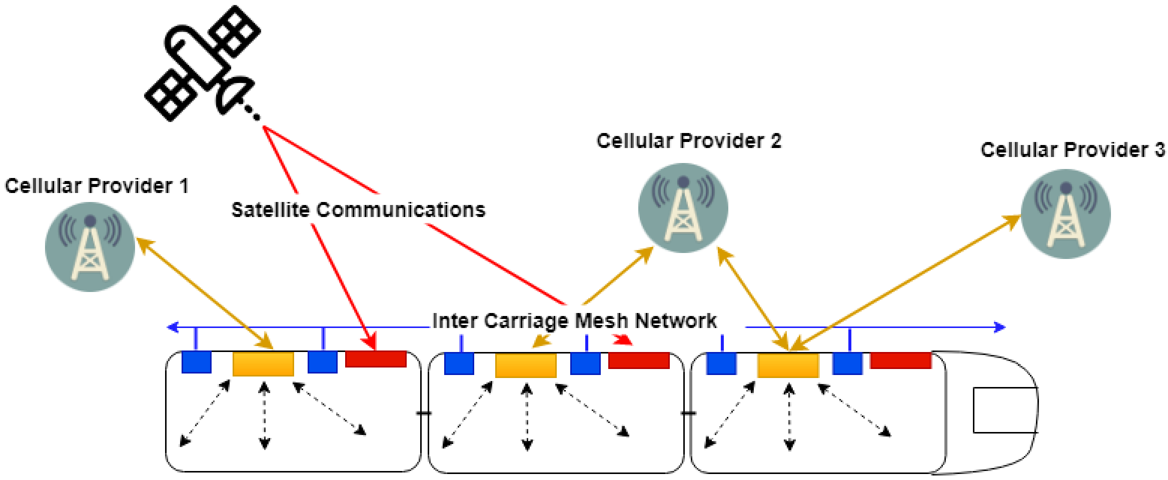

Figure 2.2: A multi-mode radio system that provides Internet for on-board passengers

2.3.1 Coverage Continuity and Geography

Ideally, the on-board broadband should be available throughout the whole rail network. However, coverage continuity is not a must for the entire set of applications enabled. For instance, streaming applications can tolerate discontinuity by buffering the media until the connection is made available again, providing that the coverage gaps do not last for long. Retail and normal Internet surfing applications can work around the problem if areas with poor coverage are known. On the other hand, real-time applications (e.g. voice calls) require continuous coverage to avoid an unacceptable level of dropped calls (RSSB, 2012; UIC, 2018). Table 2.4 shows high usage of the on-board broadband system in rail lines and stations in all modes of operation (X2Rail-1 Project, 2018). High usage frequency for data applications indicates an activity for at least 15 minutes per user per hour, while for voice applications it denotes an average activity of 5 calls per user per hour (UIC, 2018).

TABLE 2.4: Frequency of use for the on-board broadband system

Mode of Operation	Station	Yard	Line
Normal	High	n/a	High
Degraded	High	n/a	High
Emergency	High	n/a	High

2.3.2 Reliability

Due to the nature of on-board broadband systems, the reliability level is set to normal (X2Rail-1 Project, 2018). The link failure will not affect rail operations safety. However, the broadband provided must ensure an acceptable Quality of Service (QoS) for the various sub-applications requirements.

2.3.3 Operational Speed

Across the four sub-applications: Internet surfing, audio, video, and live TV, there is a need to provide seamless connectivity at various line speeds.

2.3.4 Additional Communications Attributes

First, the RSSB (2010) sets the minimum required data rate per train to 2256 kbps for standard Internet usage and 4512 kbps for high-speed connectivity. In the case of loading the data from an internal media server through Wi-Fi APs, the data rate required by then will be 200 kbps for video entertainment and 2000 kbps for live TV (RSSB, 2012). However, (UIC, 2018) sets the data rate for wireless internet (real-time and non-real time) for on-board passengers to be 5000 kbps at least.

TABLE 2.5: Communications attributes values for the on-board broadband system

Attribute	Value
Data Rate	$\geq$ 5000 kbps
Latency	10 - 100 ms (Real-time Connection) 100 - 500 ms (Non-real Time Connection)
Setup Time	1 - 3 seconds
Priority	Normal (Real-time Connection) Low (Non-real Time Connection)
Content Type	Bi-directional data
Symmetry (UL/DL)	50/50 (Real-time Connection) 20/80 (Non-real Time Connection)

On the other hand, the latency of the on-board broadband system is highly dependent on the sub-application nature, and if a real-time connection is required or not. Table 2.5 lists the values of the communications attributes for the on-board broadband system, as captured from (X2Rail-1 Project, 2018).

2.4 Remote Condition Monitoring Systems

Monitoring the track condition manually is an expensive and inefficient process due to the size of the rail network that extends approximately up to 150,966 km in the USA, 67,278 km in China, and 16,257 km in the UK (The World Bank, 2019). RCM systems represent the transition from manual infrastructure monitoring towards deploying intelligent devices that report to the control centres on the infrastructure's health, status, and condition of vital parameters to predict component degradation in the long and short term.

In a conventional maintenance system, the cost of breakdowns can be minimised by increasing the maintenance frequency that comes at a high cost (Tucker and

Hall, 2014). On the other hand, the main aspiration of RCM systems is to find an optimum point of minimal maintenance frequency that would lead to a lower number of system breakdowns. Automated maintenance will maximise the network capacity by enabling non-disruptive inspections. There are different paradigms of RCM systems stated in the literature. Tucker and Hall (2014) present them as follows:

- **Train Monitoring Infrastructure:** Infrastructure condition data are collected from train-mounted sensors, where one sensor can monitor large sections of infrastructure as the train travels around different routes. The collected data can either be stored on board or transmitted to the control centre for further analysis. A full-duplex communication link is desirable for this application to enable sending of requests from the control centre for specific measurement procedures. The Unattended Track Geometry Measurement System (UTGMS) is an example of this paradigm and it is being used to give detailed measurements of the track's vertical, lateral, twist, and gauge variation.

- **Infrastructure Monitoring Trains:** Track-side monitoring systems are an efficient way to monitor the train condition as a large number of trains passes by the same point repeatedly. The measured data will be transmitted from this fixed infrastructure point to the control centre for processing. Examples of this category include hot axle bearing detection, wheel impact load detection, and acoustic axle bearing monitoring.

- **Infrastructure Self-monitoring:** This category is identical to the case of 'Train Self-monitoring', as both make use of Wireless Sensor Networks (WSN). In the first category, the deployed sensors monitor the railway infrastructure such as bridges, rail tracks, track beds, and track equipment. In the second category, the sensors monitor the health of various vehicle

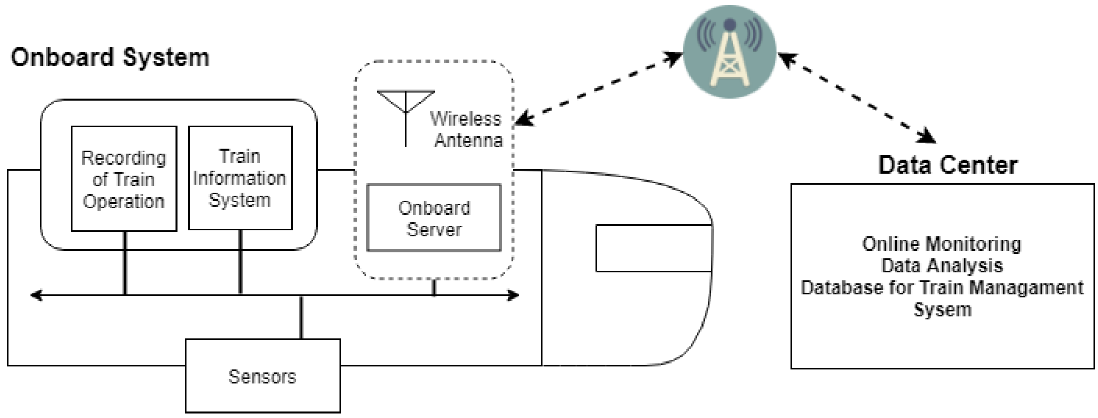

Figure 2.3: Block diagram of the online train-monitoring-infrastructure system

parts such as chassis, bogies, wheels, and wagons.

'Train Monitoring Infrastructure' and 'Train Self-monitoring' are in the scope of this thesis as they are highly dependent on mobile train-to-ground communications. Currently in the UK, Network Rail utilises a dedicated fleet of infrastructure measurement trains equipped with complex sensors such as lasers, ultrasonic probes, and high-speed cameras integrated with accurate positioning systems to collect asset-related data to tight measurement tolerances (Network Rail Infrastructure Ltd, 2015). Other experiments took place in Japan by utilising axle box accelerometers on high-speed trains (Yazawa and Takeshita, 2002). Deutsche Bahn (DB) in Germany also has a similar experience of running two trains with accelerometers on board (Erhard *et al.*, 2009).

Many systems have adopted the approach of storing the data into on-board hard disks for further analysis. However, local data storage restricts the information collected from different runs to being collated and processed jointly (Weston *et al.*, 2015). In addition, a full-duplex communication system will enable a fully automated system where real-time maintenance requests can be sent from the control centre to in-service trains. Ito *et al.* (2018) proposed a conceptual block diagram for the online monitoring system, reproduced in Figure 2.3.

In the literature, many systems have utilised various wireless technologies to enable a fully automated maintenance process. A system measuring the vertical rail profile on the channel tunnel rail link between London and Paris adopted the GSM-R standard to transmit the faults spotted to a central server (King, 2004). The competition to prioritise the signalling systems data and interference with neighbourhood technologies (Samra *et al.*, 2016) are all limitations of the GSM-R technology. With the possibility of RCM systems requiring a real-time video transmission of non-critical infrastructure, the GSM-R will suffer providing the required data rate. The upcoming section identifies the main technology-independent telecommunications requirements needed for the data offloading in RCM systems.

2.4.1 Coverage Continuity and Geography

The RCM backbone network should cover all the routes where passenger and freight trains would travel. Coverage continuity is desired for this application, especially if the system involves the transmission of a real-time video of the infrastructure. As the coverage continuity can be tolerated for this application, as the transmitted data is non-critical for non-critical infrastructure, the value of the coverage continuity can be set to normal (RSSB, 2012). The RCM system can deploy methods to store the dropped packets in areas of discontinuity, and re-transmit them as soon as the communication link is made available again.

Table 2.6 shows the frequency of use for the RCM system under various modes of operation. Under all of the given scenarios, the data transmission indicates a medium activity that lasts less than 15 minutes per user per hour. On the other hand, video transmission denotes a higher activity that lasts for at least 15 minutes per user per hour (UIC, 2018).

TABLE 2.6: Frequency of use for the RCM system

Mode of Operation	Station	Yard	Line
Normal	Medium (Data) High (Video)	Medium (Data) High (Video)	Medium (Data) High (Video)
Degraded	Medium (Data) High (Video)	Medium (Data) High (Video)	Medium (Data) High (Video)
Emergency	Medium (Data) High (Video)	Medium (Data) High (Video)	Medium (Data) High (Video)

2.4.2 Reliability

Network reliability should be sufficient to ensure the delivery of enough reports to the remote control centres. Link failure can be tolerated within RCM systems as the data can be re-transmitted when a good connection is made available. However, the communication network must have the ability to prioritise failure alarms over non-critical condition reporting data.

2.4.3 Operational Speed

The backbone telecommunication system must ensure the delivery of maintenance reports at various line speeds.

2.4.4 Additional Communications Attributes

The RCM surveying process generates enormous volumes of data that can reach up to 1.3 petabytes for only four weeks of infrastructure measurements (Network Rail Infrastructure Ltd, 2015). Núñez *et al.* (2014) stated that six inertial sensors generate around 180 megabytes of data in 16 hours of operation. The practical way of dealing with such enormous volumes of data is to process them on board and transmit only the necessary information (i.e. exception reporting). The data

TABLE 2.7: Communications attributes values for the RCM system

Attribute	Value
Data Rate	20 kbps (Data) 400 - 5000 kbps (Real-time video)
Latency	100 - 500 ms (Data) 10 - 100 ms (Real-time video)
Setup Time	1 - 3 seconds
Priority	Normal
Content Type	Unidirectional data
Symmetry (UL/DL)	100/0

rate required for RCM systems is dependent on the efficiency of the on-board data processing.

The RSSB sets the required data rate for each train to 20 kbps while setting a data rate of 1072 kbps for each track-side equipment. However, more bandwidth will be required, especially with the expected need for transmitting live video of the track (RSSB, 2012). (UIC, 2018) assumes a data rate between 400 - 5000 kbps for the live video transmission. Table 2.7 lists the values of the communications attributes for the RCM system, as captured from (X2Rail-1 Project, 2018).

2.5 Chapter Summary

The main aim of this chapter was to discuss the communication requirements of the pivotal applications, the development of which will bring great economic and operational value to the whole rail industry. In short, signalling systems require universal and continuous coverage with a highly reliable communication link that supports various line speeds and a low data rate. Besides, the signalling system requires low latency and short setup time with 50/50 symmetry between the uplink and the downlink traffic. The frequency of use for the signalling system is high at all locations under all modes of operation.

On the other hand, the on-board broadband system requires a high level of coverage in terms of continuity and geography for real-time sub-applications, while the demand downgrades to normal for non-real time sub-applications. The frequency of use for the on-board broadband system is high at rail lines and stations. The link reliability is set to normal due to the non-critical nature of the application. Additionally, the backbone network for this application must ensure a high data rate at various line speeds.

Finally, RCM systems require continuous coverage to be available at all locations, especially with the potential existence of live video transmission. However, this requirement is set to normal as the RCM system can tolerate a certain level of communication discontinuity. This requires ensuring the discontinuity duration does not exceed a defined threshold to achieve a desired QoS. The RCM system should adopt methods to store the dropped packets and re-transmit them as soon as the communication link is made available again. Besides, at all locations and under various modes of operation, the frequency of use for the RCM system is medium for the data transmission and high for the video transmission. The link reliability required for RCM systems should be sufficient to provide enough maintenance reports with the ability to prioritise failure alarms. At last, the backbone network, at various line speeds, should provide 20 kbps data rate for data transmission and (400 - 5000 kbps) for video transmission.

The chapter also states the various alternative wireless communication systems proposed in the literature for each application, focusing on their limitations. The next chapter will discuss the TVWS concept, detailing different spectrum access approaches and restrictions on the mobile platforms. The suitability of TVWS for the applications mentioned within this chapter will be analysed and discussed in Chapter 5.

Chapter 3

TVWS Framework and Mobility Challenges

3.1 Introduction

The usable radio spectrum for any given application is a scarce resource due to various application-specific constraints that are not limited to mobility model, size of antennas, coverage demands for particular terrain, and coexistence with other services. Developments of applications such as Big Data, Machine to Machine Communications (M2M), and Smart Cities increase the demand for sufficient spectrum to be available for wireless communication networks. Innovative and better use of the existing spectrum is needed to fulfil this demand. The approach of assigning an exclusive part of the spectrum to a service will no longer be the main way of operating. TVWS is an emerging model of the Dynamic Spectrum Access (DSA) approach that enables flexible sharing of the spectrum between various users. Each user can be assigned a channel that can be used by other users when being vacant. In other words, a particular frequency may thus move from broadcasting to M2M to telephony over a short time span (Department for Culture, Media & Sport, 2014).

The concept of DSA is very appealing due to train mobility from one location to another. That means there is no crucial need for an exclusive frequency to be assigned to the moving train. In addition, the TVWS offers desirable propagation characteristics in the railway context. A system deployed within UHF and VHF bands is resilient to path loss and long-term fading and can offer high penetration capabilities for large coverage ranges. However, restrictions are set upon mobile platforms to provide enough protection for other spectrum users.

First, this chapter focuses on explaining the TVWS framework from technical and regulatory perspectives. Identification of relevant limitations to the railway context then follows. Finally, the chapter presents various cases of using TVWS while reviewing the research undertaken so far to tackle the mobility limitations.

3.2 TVWS Concept and Framework

TVWS refers to the inefficiently utilised spectrum chunks in the frequency band between 470 and 790 MHz [1]. This TV band is originally allocated for Digital Terrestrial Television (DTT) broadcasting and Programme Making and Special Events (PMSE). After the switch-over from analogue to digital TV broadcasting, most of the channels are currently not being used for DTT. With a total of 32 channels, each 8 MHz wide, reserved for DTT in the UK, only six of these channels are required to receive the six TV multiplexes at any given location. Also, Office of Communications (Ofcom) has dedicated one channel (i.e. channel 38) as the main band to meet the assignments demand of PMSE equipment, including radio microphones and audio devices. However, Ofcom acknowledges that the PMSE assignments can take place in any of the other vacant bands of the TV spectrum.

Figure 3.1 reproduced from (Ofcom, 2015) highlights the channels needed for 6 TV multiplexes and the dedicated channel for PMSE assignments in London. The figure also represents white squares (i.e. empty chunks) where any spectrum

[1] These frequencies are specific for Europe and the UK, but the concept is still the same for other countries utilising different TV bands.

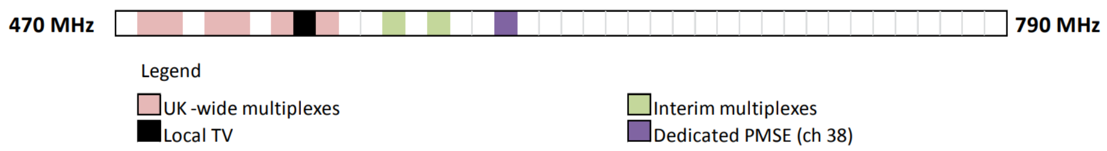

Figure 3.1: Available White Space spectrum in London (Ofcom, 2015)

SU can operate in accordance with specific technical parameters to ensure full protection for the spectrum PUs (i.e. DTT and PMSE).

Conventionally, each SU must perform independent spectrum sensing to detect vacant channels within the band (Jones *et al.*, 2007). There are many spectrum sensing methods mentioned in the literature that include energy detection, compressed sensing, waveform-based sensing, and pattern recognition–based sensing (Han *et al.*, 2017b). However, spectrum regulators such as Ofcom in the UK and the Federal Communications Commission (FCC) in the USA have adopted a database access approach that is believed to be more accurate, while spectrum sensing has been regulated as an optional technology (FCC, 2010).

The database holds information about spectrum availability and is used for assigning each SU with valid operational parameters for each 100 m x 100 m geographic square ('pixel'). To perform this task efficiently, the database deploys an interference algorithm on different data sets obtained from the spectrum regulator.

For instance, Ofcom with the usage of the UK Planning Model (UKPM) provides each qualified database with information on the existence of DTT (i.e. first category of PUs) operating in the band. This first data set is referred to as 'DTT Coexistence Data'. Another set of data is the 'Unscheduled Adjustments Data' which presents revised power limits that are valid temporarily within a specific area on an ad-hoc basis. Data about the second PU category (i.e. PMSE) operating in channel 38 and the services above and below the band are provided

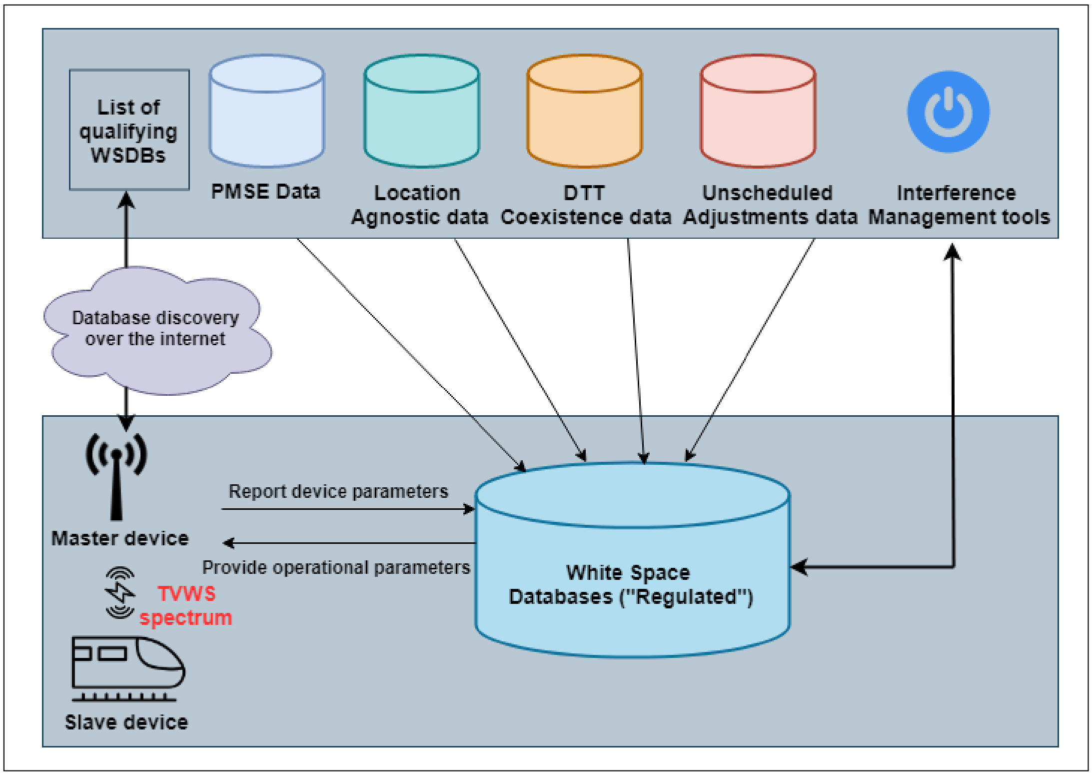

Figure 3.2: Framework for authorised use of the TVWS spectrum

through 'Location Agnostic Data'. The location uncertainty of these users is behind the term's name. The licensed PMSE use in the band (other than channel 38) is referred to as 'PMSE Data'. Figure 3.2, reproduced from Ofcom (2015), shows graphically the information entities and exchange needed to calculate valid operational parameters for each pixel.

Figure 3.2 also shows the process needed to be fully functional in the TVWS spectrum from a regulatory perspective. A master device that may act as a BS or an AP needs to download a list of the qualified databases (i.e. Database Discovery) and communicate its technical parameters to a single database to obtain the operational parameters. The master device needs to download an updated list of the qualified databases every 24 hours to be in line with the ETSI Harmonised Standard (ETSI, 2014). The operational parameters retrieved from the database will include the available frequencies to be used by the master device and the allowed transmission power for each frequency. A master device must update these parameters regularly to prevent any possible interference to the spectrum PU.

If a master device is part of a network comprising slave devices, then it will request operational parameters from the database for its slaves. To join the TVWS network, a slave device should initially listen to the master's broadcast of these parameters and decode them before starting the transmission anywhere within the coverage area of the master. These parameters tend to be restrictive as they are based on 'vanilla' calculations, where the slave's location, its leakage, and selectivity factors are not considered. A slave device can continue operating with these generic parameters or report its device parameters and location for enhanced and less restrictive parameters (Ofcom, 2015).

Aiming to provide a comprehensive understanding of the TVWS framework and the technical factors that restrict the SU mobility, the next section discusses various technical standards that conform to the regulators' database-centred approach.

3.3 Technology Standardisation

Many standards have been proposed for accessing the TVWS band. For instance, a few vendors consider LTE and 5G as their air interface to share the TV bands, as stated by Surampudi and Mohanty (2011) and Khalil *et al.* (2017). There is a growing interest in vacating the 600 MHz spectrum band to make it available for LTE and 5G technologies (Qualcomm Technologies, 2017). Holland *et al.* (2018) investigated TVWS spectrum sharing to realise the 5G capacity requirements in rural environments to enable various case studies that are not limited to tourism, agriculture, rural broadband, and unmanned aircraft systems. On the other hand, Baig *et al.* (2017) proposed a TVWS-compliant cellular network architecture which is built on top of the LTE stack.

However, most of the innovative Radio Frequency (RF) techniques being discussed for LTE and 5G, such as Multiple-Input Multiple-Output (MIMO) antennas, the concept of small cells to promote spectrum reuse, and beamforming in large bandwidth channels, are all techniques that need further development for the relatively low TV frequencies. Also, LTE and 5G technologies do not deploy any mechanism to avoid unplanned PU appearance or communicating with regulated white space databases that assign communication channels based on the SU's geographic location, which will lead to vital collisions and performance degradation in TVWS (Baig *et al.*, 2017).

Nevertheless, there are two standards specifically designed for the TVWS access, namely IEEE 802.11af and IEEE 802.22. The former can also be referred to as White-Fi or Super Wi-Fi as it allows WLAN operation in the TV spectrum. The coverage range of this standard can only reach up to 1 km which makes it ideal for indoor networks. On the other hand, the IEEE 802.22 standard referred to as Wireless Regional Area Network (WRAN) has a complete set of cognitive properties that enable network operation within coverage ranges of 30 km, if no special scheduling is considered (Lekomtcev and Maršálek, 2012).

This research focuses on the IEEE 802.22 standard as it is believed to be a better fit for the outdoor environment. The standard introduces a more complete set of features that would enable application of the methodology proposed in the next chapter to a larger context that is independent of the spectrum regulator of each country. As the standard is being used to demonstrate the suitability of the method for railway applications, other technology standards, namely LTE and 5G, can adopt the proposed methodology to share the spectrum specifically for rail applications, once these technologies are well developed to access the TV bands. The next subsection will briefly discuss the assignment of operational parameters under the IEEE 802.22 standard, aiming to build a full understanding of the mobility challenges in the TV bands.

3.3.1 Assignment of Operational Parameters in IEEE 802.22

The process of accessing the TVWS spectrum in the IEEE 802.22 standard is quite similar to the regulatory perspective discussed previously. After installation of the master device (i.e. AP), each AP must locate itself and select a database from a list of authorised databases held on the regulator's website. Once the database is selected and acknowledged with the AP device parameters and location, the database will inform each AP of the operational parameters such as frequencies and power that each slave device (i.e. Customer Premises Equipment (CPE)) would be allowed to use within the coverage area of this AP (IEEE 802.22 Working Group, 2011). Figure 3.3 shows the full procedure for master device initialisation.

On the other hand, the CPE initialisation procedure is summarised into three main steps (Wang *et al.*, 2017):

1. **Channel Scanning:** CPE is required to sweep TV channels to discover any WRAN services that may be present and decode the transmitted generic operational parameters. If the CPE is geolocated, it will acquire the downstream and upstream parameters from the selected WRAN service. Then, if channels N and $N \pm 1$ pass the sensing and timing requirements, the AP and CPE will perform the initial ranging. By then, the CPE will be able to transmit its basic capabilities.

2. **Authentication Process:** This the second phase where the Authentication, Authorisation, and Accounting (AAA) server authenticates execution of the CPE key exchange.

3. **Registration Process:** The registration procedure includes the exchange and verification of the CPE location and the configuration of CPE operational parameters (i.e. Internet Protocol (IP) address version to be used). By the end of this stage, the CPE will be fully operational and is required to report its channel usage to the serving AP.

Figure 3.4 shows the CPE full initialisation procedure that will be reflected in the WRAN simulation in Chapter 6. After understanding the procedure of TVWS spectrum access, the next section will focus on identifying the limitations defined by the spectrum regulators and the IEEE technical standard on the mobile platforms accessing the spectrum.

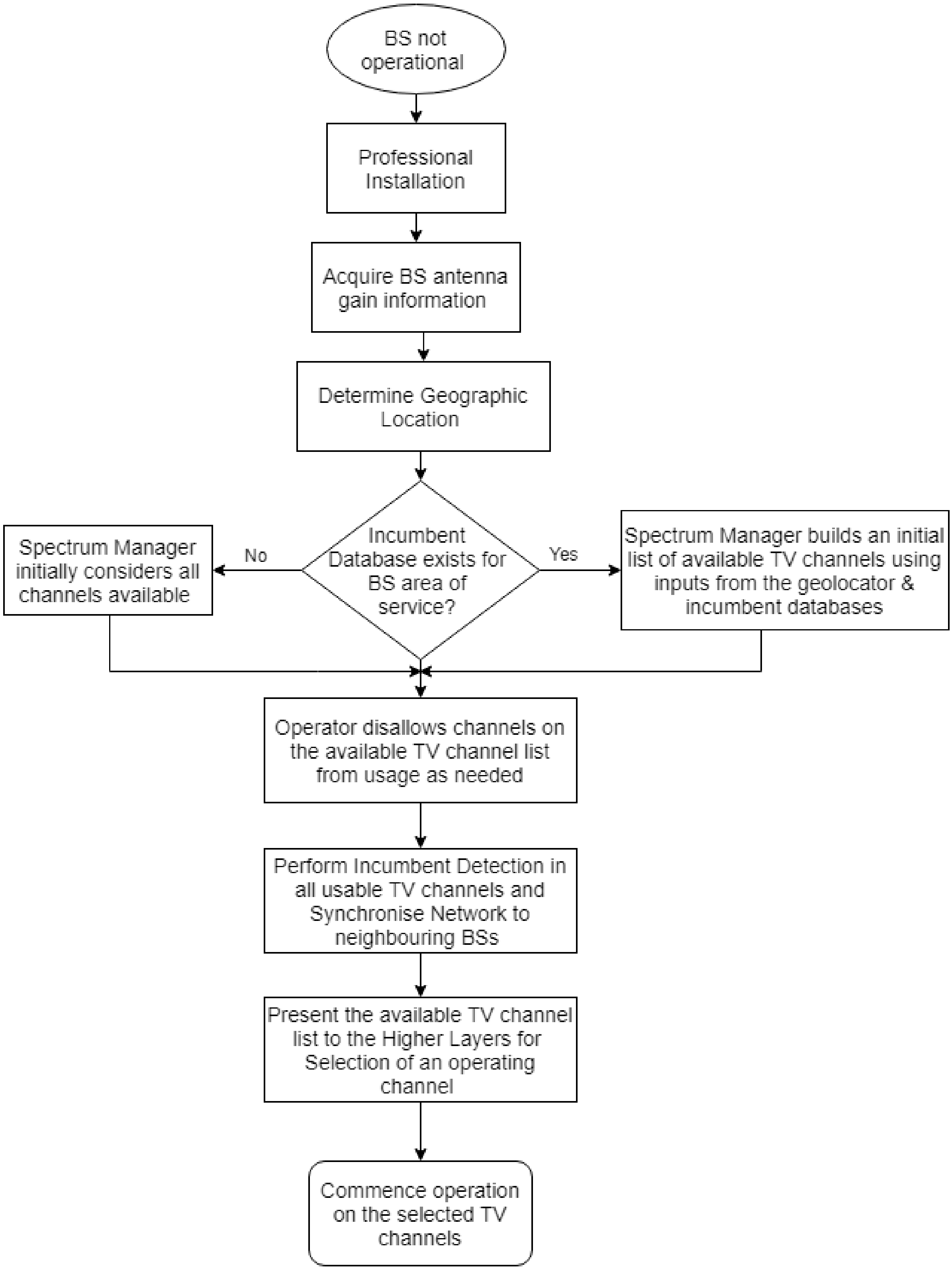

Figure 3.3: Master device initialisation procedure (IEEE 802.22 Working Group, 2011)

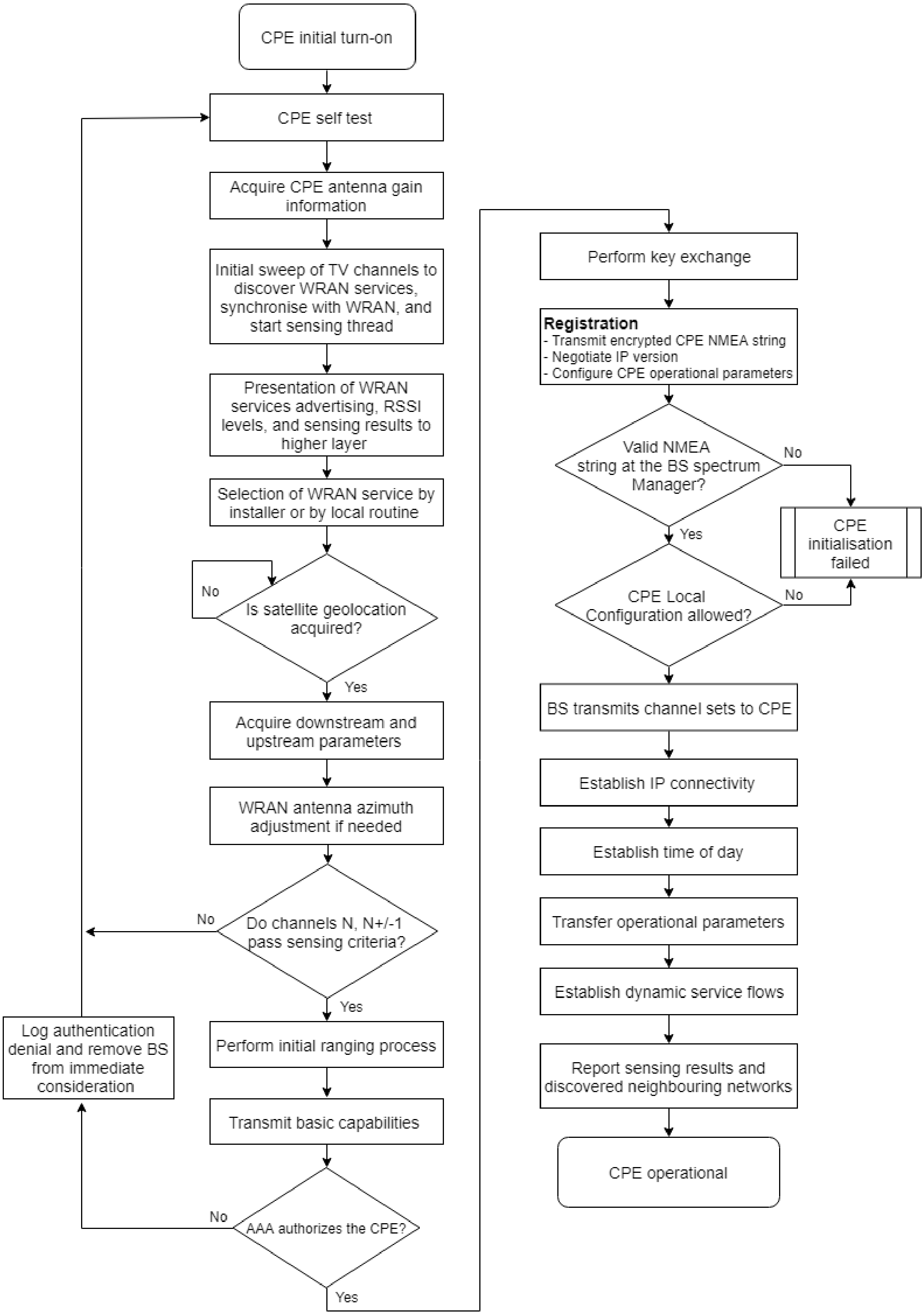

Figure 3.4: Slave device initialisation procedure (IEEE 802.22 Working Group, 2011)

3.4 Challenges of Mobile Platforms in TVWS

TVWS spectrum access has been designed to allow the operation of SUs in accordance with specific technical parameters that ensure full protection for the PUs. To achieve this vision, there has been a set of restrictive policies on mobile SUs. This section will detail these limitations, focusing on the ones relevant to the railway context.

3.4.1 Allowed Transmission Power

The fact that the TVWS band is unlicensed will create spectrum-sharing issues in the future as various networks will coexist and possibly interfere with each other. To prevent that and to provide enough protection for the spectrum PUs, regulators such as Ofcom and FCC force mobile platforms to transmit at a maximum Effective Isotropic Radiated Power (EIRP) of 100 mW compared with the 4 W allowed for stationary devices (FCC, 2010; Ofcom, 2015). The low transmission power will have a direct impact on the throughput which the SU network can provide (Hessar and Roy, 2015).

3.4.2 Spatial and Temporal Limitations

When the operational parameters get assigned to a CPE, they become valid only within a certain radius that is defined as the Location Validity, L_{val}. For a movement outside this location, the CPE is required to perform a specific action based on the mobility type. Table 3.1 lists all the spatial limitations set by the IEEE 802.22 standard that assumes a mobility threshold of $\pm$ 25 m. However, in this research, the Ofcom mobility threshold of $\pm$ 100 m will be used instead.

TABLE 3.1: IEEE 802.22 standard spatial restrictions

Mobility Type	**Required Action**
CPE moves outside the coverage area of one AP to another (intercell handover).	CPE must terminate its normal operation with the serving AP and shut down, start the whole spectrum access process again from channel scanning, got authenticated until CPE is fully registered with the new AP.
CPE moves above the mobility threshold of $\pm$ 100 m, and the current operating channel is **STILL** available (intracell handover).	CPE must update its transmission power and re-register to the network through the same AP.
CPE moves above the mobility threshold of $\pm$ 100 m, and the current operating channel is **NOT** available (intracell handover).	CPE starts the process by scanning the channels and gets registered with the same AP on the newly available channel.
CPE moves above the mobility threshold of $\pm$ 100 m, and **NO** channels are available.	CPE must terminate its normal operation with the serving AP and shut down. Then, CPE can start the process of channel scanning and registration with the same AP when a channel becomes available.

In addition to the spatial limitations, the assigned parameters are restricted by time limits known as Time Validity Start ($T_{ValStart}$) and Time Validity End (T_{ValEnd}) (Ofcom, 2015). It is important to consider that these parameters are sufficient to cover various scenarios of the train mobility model.

3.4.3 Database Interoperability

The regulator supports the operation of multiple databases for the same coverage area. It is believed to drive innovation and give the end users greater choice as each database operator will seek to provide tailored services for a specific market segment. Ofcom (2015) believes there is a need to subdivide the databases into regional, national, and international databases, each with distinct authority and interoperability enabled between them (Mwangoka *et al.*, 2011).

Cross-border trains may suffer from a lack of database interoperability as multiple systems will need to be adapted. However, within this thesis, the algorithm developed in Chapter 4 can be deployed using a single database that is tailored for railway operations within the same country.

3.5 Review of TVWS Use Cases for Mobile Platforms

Several researchers have studied the feasibility of TVWS for various applications. Enabling Broadband in rural areas that lack infrastructure is one of the most common use cases. In South Africa, a TVWS network was used to provide Broadband Internet to five schools that had never a connection before (Masonta *et al.*, 2015). Similar experiments also took place on the West coast of Scotland (McGuire *et al.*, 2012), in Malawi (Mikeka *et al.*, 2014), and in Zambia (Zennaro *et al.*, 2013). Most of these studies focused on analysing the

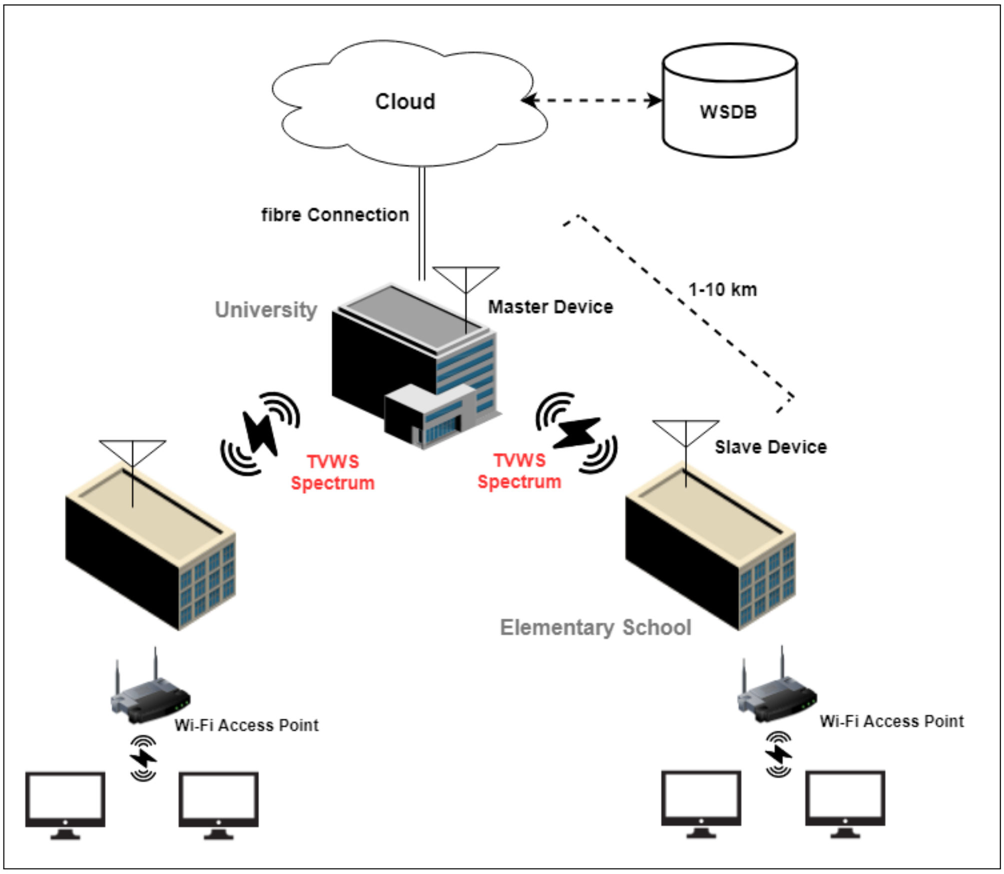

Figure 3.5: TVWS architecture to provide Internet broadband for various schools

performance of TVWS networks in terms of spectrum availability, throughput, latency, and path loss. Figure 3.5, reproduced from Lysko *et al.* (2014), shows a typical TVWS architecture that provides a broadband connection for schools in South Africa.

Other studies have focused on exploring TVWS characteristics and the capability of channel aggregation in indoor environments to support high bandwidth communication. For instance, Holland *et al.* (2016) investigated the possibility of aggregation in TVWS, either over contiguous channels achieved by a single radio or through non-contiguous channels by using multiple radios deployed on the White Space device. The study successfully aggregated the maximum possible number of channels of the utilised devices (four channels), which delivers an excellent percentage of the theoretical maximum capacity.

Furthermore, Ying *et al.* (2013) proposed a system called White-space Indoor Spectrum EnhanceR (WISER), that accurately identifies vacant TV channels for indoor networking, taking into consideration the built environment without the need for spectrum sensing by SUs and without causing any interference to the spectrum PUs. On the other hand, Kawade and Nekovee (2009) evaluated the performance of TVWS for different bands including 5 and 2.4 GHz, to test the potential offloading capabilities at various frequencies. Another case study by Bedogni *et al.* (2013) investigated the validity of TVWS for M2M, namely for smart metering applications.

Most of the previously mentioned cases indicate that a TVWS-enabled network can provide reasonable performance for stationary devices. However, in the literature, less attention has been given to the use of TVWS for mobile platforms due to the mobility restrictions mentioned in the previous section. Aiming to tackle these challenges, Lee *et al.* (2012) proposed a handover scheme for the IEEE 802.22 standard. In this study, each CPE located within an overlapping region with other BSs must report the signal quality to its serving station, aiming to build a map of all the neighbouring BSs. Then, it is the role of the serving BS to select the target BS based on the distance and QoS which does not comply with the current regulated framework.

Wang *et al.* (2017) presented another handover approach that depends on minimising the time needed for the authentication procedure. The process typically takes around 50 ms due to public cryptography operations and latency of information exchange between the CPE and the AAA server. When the CPE moves from one cell to another, authentication will not be required. However, the SU must perform the time-consuming channel scanning and network registration processes for every pixel crossing.

The patent by Lee and Jeong (2014) proposes a location-based handover concept for multiple vehicles, where the database assigns operating channels to the moving vehicles based on its planned trajectory. However, in the proposed architecture, the CPE tends to keep the channel list locally, which can cause unintended interference to the PUs as the list might become outdated over a relatively short time span. A train moving at a speed of 320 km/h under a 5 km access point coverage area will need a list update every 55.8 s for the intercell handover and every 1.125 s for the intracell handover, if the mobility threshold in Table 3.1 is applied. In addition, a similar concept introduced by LG Electronics details the handover process for CPE movement from one AP to another and from one enabler (i.e. database) to another (Kim *et al.*, 2015). However, this study did not cover CPE mobility restrictions under the same AP.

Furthermore, other TVWS channel access schemes for vehicular communication systems have been proposed by Chen *et al.* (2014), Han *et al.* (2017a), Kremo and Altintas (2013), and Kumar *et al.* (2017). These models have mainly focused on vehicle-related challenges that are not limited to prediction of the vehicle's trajectory and selection of the AP which provides the best signal at the new vehicle's location. The research conducted by Achtzehn *et al.* (2014) is one of the few published works that has proposed the utilisation of TVWS in the railway context. However, the proposed framework assumes a single operational channel throughout the whole journey which does not comply with the regulators' database-assisted framework.

Unfortunately, the reviewed approaches are not comprehensive either because they do not follow the TVWS database-assisted framework, or because they do not consider all the mobility scenarios including intercell and intracell movements stated in Table 3.1. To the best of the author's knowledge, no railway-focused research that considers all the standard and regulatory limitations has been yet presented. Channel access in the rail context is a unique and challenging procedure due to the fast-changing environment and the specific characteristics of the railway mobility model.

3.6 Chapter Summary

This chapter discusses the concept of accessing TV bands from regulatory and technical perspectives and reviews different approaches that tried to tackle the limitations of mobile platforms operating in the band. Unfortunately, most of the focus to date has been given either to stationary or vehicular networks which have different features from the railway context. There is a need for a generic handover and channel access scheme that will enable seamless connectivity for the pivotal wireless applications mentioned in Chapter 2. The approach must consider the railway propagation characteristics to build a sophisticated spectrum availability map. In addition, the train's mobility model including variable operating speeds, possible delays, and the coexistence of various trains within the same area must be considered. The next chapter discusses these issues in more detail.

Chapter 4

TVWS Seamless Connectivity Approach for Railway Applications

4.1 Introduction

The previous chapter focuses on the challenges that would face any mobile platform operating in TVWS. As the train's transmission power is set to a maximum of 100 mW, the overall network throughput becomes limited as a result of degradation in the received Signal-to-Interference-plus-Noise Ratio (SINR), as modelled by Hessar and Roy (2015). In addition, a mobile platform needs to sweep the area for new channels when moving from the coverage area of one AP to another and from one pixel to another. Unnecessary channel switches and overhead control messages increase the probability of service interruption and hence decrease the overall network QoS.

Given the fact that a train travels on fixed rails, it is easy to predict the train's trajectory under normal operating conditions. Having this in mind, the process of pre-assigning the communication channels for the whole journey sounds appealing to avoid unnecessary service interruptions. However, this approach is highly dependent on the knowledge of spectrum availability in all the areas where the train travels.

This chapter starts with modelling the spectrum availability, taking into account the operational characteristics of PUs and SUs. The output of this procedure will be a matrix that represents the channel availability at each relevant pixel. Afterwards, a novel greedy algorithm is introduced to assign operational channels to trains on a first-come-first-served basis. For each train, the algorithm tends to select the channels whose assignment lasts for the longest distance, to minimise unnecessary control messages and link interruptions. The algorithm considers train speed, possible delays, and the coexistence of trains within the same area. Finally, the chapter proposes a generic handover procedure that follows the previously mentioned channel assignment scheme, with details given for the handover preparation, decision, and execution along with the formatting of the broadcast packets.

4.2 Generation of Spectrum Availability Map

The available TVWS channels within a certain area are highly dependent on multiple factors including the PU protection contour, the behaviour of time-varying propagation models, and the SU allowed transmission power. The more precisely these factors are modelled, the fewer spectrum resources are wasted, and the better protection is guaranteed for the PUs (e.g. TV receivers). In this section, an overview of spectrum availability map generation is presented, and the factors that significantly affect the outcomes are introduced.

4.2.1 PU Overall Protection Region

The TV spectrum is mainly used by two categories of PUs, the Digital Terrestrial Television (DTT) and the Programme Making and Special Events (PMSE). Wireless microphones and audio devices are examples of PMSE users. According to (Ofcom, 2015), by default, PMSE users are assigned channel 38 for

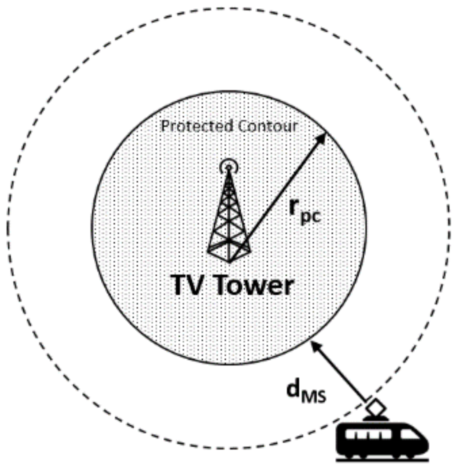

Figure 4.1: Primary user overall protection region that consists of a primary protection area of radius r_{pc} and an additional protection distance d_{MS}

their operations. "Location Agnostic Data" in the previous chapter at Figure 3.2, represents this scenario. However, for the licensed PMSE that operates in bands other than the default channel 38, Ofcom represents them in the "PMSE data" set. This data set has a dynamic nature as it dramatically changes based on the operational time and location of each PMSE.

This thesis assumes that PMSE information is retrieved solely from the "Location Agnostic Data", where all the PMSE are assigned to operate on channel 38. This channel is flagged as occupied for any simulated SUs throughout this research. Hence, this section focuses on defining the overall protection region depending only on the transmission characteristics of the Digital Terrestrial Television, defined in this thesis as the first category of PUs.

For every licensed TV station, the regulator defines a protection contour which is intended to be an interference-free zone. The protection contour is dependent on the station's effective radiated power and the antenna height above average terrain. As shown in Figure 4.1, r_{pc} represents the coverage radius of the TV transmitter protection contour. Any SU can only exist beyond these primary protected cells (Hessar and Roy, 2015).

The protection contour radius r_{pc} is defined as the maximum distance where the received signal power P_r (in dBm) drops to a minimum threshold Δ, which is a function of the station type (either analogue or digital), the operational frequency, and the propagation loss model. Typical values of Δ for various TV services can be found in (Hessar and Roy, 2015, Table 6). P_r can thus be expressed mathematically as (Rappaport, 1996):

$$P_r = \Delta = P_t + G_t + G_r - L_{TV}(r_{pc}), \tag{4.1}$$

where P_t is the PU transmitter power in dBm, G_t is the TV transmitter antenna gain, G_r is the TV receiver gain, and $L_{TV}(.)$ is the path loss model for TV signals as a function of distance to the transmitter.

Furthermore, an additional separation distance d_{MS} is added to the protection contour r_{pc}, aiming to provide extra protection for the spectrum PUs. It is highly dependent on the SU operational parameters and the application's nature. For instance, fixed TVWS devices with higher transmission power are forced to be further away from the TV transmitter than mobile TVWS devices that transmit at lower power. The additional distance d_{MS} is defined as the distance at which the interference ratio at the TV receiver (i.e. the PU) is less than or equal to a desired threshold γ_o.

$$P_{sec} + G_{sec} - L_{sec}(d_{MS}) - x_{dB} + G_r \leq \Delta - \gamma_o, \tag{4.2}$$

where P_{sec} is the SU transmission power, G_{sec} is the SU transmitter antenna gain, G_r is the PU receiver antenna gain, x_{dB} is the propagation-loss shadowing factor, and $L_{sec}(.)$ is the path loss model for the SU transmitter. From both Equations (4.1) and (4.2), the overall protection region for each PU transmitter will have a radius that is given by

$$L_{TV}^{-1}(P_t + G_t + G_r - \Delta) + L_{sec}^{-1}(P_{sec} + G_{sec} - x_{dB} + G_r - \Delta + \gamma_o). \tag{4.3}$$

Equation 4.3 shows that the overall protection area for each TV station is highly dependent on accurate modelling of the path loss for both the primary and secondary systems. In addition, it can be deduced that the SU allowed transmission power, P_{sec}, plays an important role in estimating the additional separation distance, d_{MS}, which as a result will affect the overall spectrum availability. In the next sections, the estimation of P_{sec} and propagation path loss modelling are discussed in detail.

4.2.2 SU Allowed Transmission Power

According to (Ofcom, 2015), the SU allowed transmission power P_{sec} (in Watt) is a function of the coupling gain G, the protection ratio r, and the maximum permitted nuisance power Z, and can be expressed as:

$$P_{sec} = \frac{Z}{r \times G}. \tag{4.4}$$

On the other hand, the coupling gain G is defined as the ratio of the SU signal power (i.e. interferer) received at a TV receiver over the power radiated originally by the SU transmitter. The coupling Gain G in dB is also defined by Ofcom (2015) as

$$G = G_{prop} + g + G_{Ins} + G_{BP} + G_B, \tag{4.5}$$

where G_{prop} is the propagation gain which is a function of the SU and PU antenna heights above the ground (rather than sea level) as well as the PU frequency; g is the TV receiver antenna angular discrimination that identifies the angle-dependent gain of a directional antenna; G_{Ins} is the installation gain, which represents the net gain of a TV receiver antenna gain including the cable loss; G_{BP} is the building penetration gain; and G_B represents the body gain.

On the other hand, the protection ratio r defined in Equation (4.4) represents the ratio of the received wanted TV signal power to the received unwanted SU interferer power at the point of failure of the TV receiver. It is a function of the SU Adjacent Channel Leakage Ratio (ACLR), as well as the Adjacent Channel Selectivity (ACS) of the TV receiver. The ACLR of the SU is characterised by five emission classes which are consistent with the harmonised standard EN 301 598. On the other hand, the ACS characterises the overall behaviour of the receiver in response to the adjacent channel interferer, including the receiver's response to large fluctuations in the interferer's power. Both the ACLR and ACS are functions of the frequency separation Δf between the SU channel and PU channel. Ofcom (2015) provides different calculations for low and high protection ratios for different device classes, considering different values of channel separation and received median wanted DTT signal power.

Finally, the maximum permitted nuisance power Z in Equation (4.4) relates to the maximum amount of unwanted SU power that a TV receiver can tolerate. Its value depends on the quality of DTT coverage, as described by the UKPM. The maximum permitted nuisance power Z will be calculated for every populated 100 m $\times$ 100 m geographic square (pixel) in the UK. Detailed calculations of Z can be found in Ofcom (2015).

4.2.3 Propagation Path Loss Model for PUs and SUs

The identification of each PU protection area along with the number of channels available for SUs to communicate, are highly dependent on the accurate modelling of path loss, as indicated in Equation 4.3. This section discusses the propagation path loss models for both PUs and SUs.

The literature has proposed various path loss models that mainly depend on the antenna height, frequency range, and operational environment. The Longley–Rice model (Longley and Rice, 1968), also known as the Irregular Terrain Model (ITM), is used to estimate the TV coverage for TV towers that have high antennas (up to 400 m) and a large coverage radius (up to 100 km), as stated by Hessar and Roy (2015), Kasampalis *et al.* (2015), and Lazaridis *et al.* (2015). The model is an empirical parametric model that derives the median path loss and variability from extensive sets of measurements. The total path loss for a given distance r_{pc} can be expressed as

$$L(r_{pc}) = A_{ref} + 20\, log_{10}\Big(\frac{4\pi \times r_{pc} \times f}{c}\Big), \tag{4.6}$$

where c is the speed of light, r_{pc} is the distance between the PU transmitter and receiver, f is the operating frequency, and A_{ref} is the median attenuation relative to a free space signal observed from similar paths at various atmospheric conditions. For a simpler Longley–Rice version that suits TVWS capacity calculations, Hessar and Roy (2015) considered three main contributions to calculate A_{ref}, referring to the line-of-sight element (A_{el}), diffraction (A_{ed}), and scatter (A_{es}) mechanisms as

$$A_{ref} = \begin{cases} max[0, A_{el} + K_1 r_{pc} + K_2 \ln(r_{pc}/d_{Ls})] & \mathrm{r}_{pc} \le d_{Ls} \\ A_{ed} + m_d.r_{pc} & \mathrm{d}_{LS} \le r_{pc} \le d_x \\ A_{es} + m_s.r_{pc} & \mathrm{d}_x \le r_{pc} \end{cases} \tag{4.7}$$

The coefficients A_{el}, K_1, K_2, A_{ed}, m_d, A_{es}, and m_s, and the distance d_x are calculated using the ITM algorithms. The line-of-sight distance d_{LS} can be obtained from Hessar and Roy (2015),

$$d_{LS} = \sqrt{\frac{2 \times h_{g,T_x}}{\gamma_e}} + \sqrt{\frac{2 \times h_{g,R_x}}{\gamma_e}}, \tag{4.8}$$

where h_{g,T_x} and h_{g,R_x} are the transmitter/receiver effective heights above the ground, and γ_e is a constant characterising the Earth's curvature. From Equation (4.1), the value of the desired path loss $L_{TV}(.)$ can be obtained for the TV transmission. Hence, by substituting this path loss value into Equation (4.6), r_{pc} can be obtained.

On the other hand, the SU operational parameters vary dramatically in terms of the antenna height and coverage area. Ofcom utilises the Extended Hata propagation model issued by the European Communications Office (ECO, 2016) to determine path loss in TVWS networks. For outdoor-outdoor propagation model, SEAMCAT calculates the propagation loss between SU transmitter and receiver as

$$f_{propage}(f, h_1, h_2, d_{MS}, env) = L(d_{MS}) + T(\sigma), \tag{4.9}$$

where f is the operating frequency (MHz); h_1 is the transmitter antenna height above the ground (m); h_2 is the receiver antenna height above the ground (m); d_{MS} is the distance between the SU transmitter and receiver (km); env is the general environment attenuation (dB); L is the median path loss (dB); and $T(\sigma)$ is the variation in path loss (dB) that is achieved by applying the log-normal distribution. The relative standard deviation σ for different distances and propagation modes can be found in (ECO, 2016, Table 80). Additionally, values of the median path loss L for various distances, environments, and operating frequencies can be obtained from (ECO, 2016, Table 79).

The desired path loss for the SU can be calculated from Equation (4.2), and by substituting the obtained path loss into the relevant Equation in (ECO, 2016, Table 79), the additional separation distance d_{MS} can be calculated. Referring to Figure 4.1, the protection contour r_{pc} and the additional separation distance d_{MS} defines the overall protection area A for each PU transmitter. The percentage of channels available for SUs operations in a given area with multiple PU transmitters can be expressed as (Hessar and Roy, 2015):

$$P = 1 - \frac{\sum_{j=1}^{N} A_{co}(j) + \sum_{k=1}^{M} A_{adj}(k) - \sum_i \sum_j A_p(i,j)}{A}, \tag{4.10}$$

where $A_{co}(j)$ is the co-channel protection area for transmitter $j \in \{1 : N\}$, $A_{adj}(k)$ is the adjacent channel protection area for transmitter $k \in \{1 : M\}$, and A_p is the overlap between the adjacent and co-channel protection areas. The number of available channels within a specific area is a function of the SU required transmission power, besides the TV transmitters service type and regional distribution. According to (Hessar and Roy, 2015), the population density is another factor that impacts the percentage of available TVWS channels. This research considers varying global channel availability to cover all the factors mentioned above.

4.3 Location-based Handover Scheme

Following the availability of TVWS channels modelled in the previous section, this section discusses a novel handover scheme. The scheme aims to minimise the number of channel handovers and unnecessary overhead control messages based on knowledge of the train's trajectory and the spectrum availability managed by the TVWS database. This approach strives to improve the SU network throughput, lower the handover frequency to reduce the probability of service interruption and hence increase the overall QoS of the SU network. Besides that, the handover latency in this approach is expected to be minimised as there is no time consumed searching for new operational channels in each pixel. Therefore, extra protection will be provided to the PUs by minimising the probability of co-channel interference.

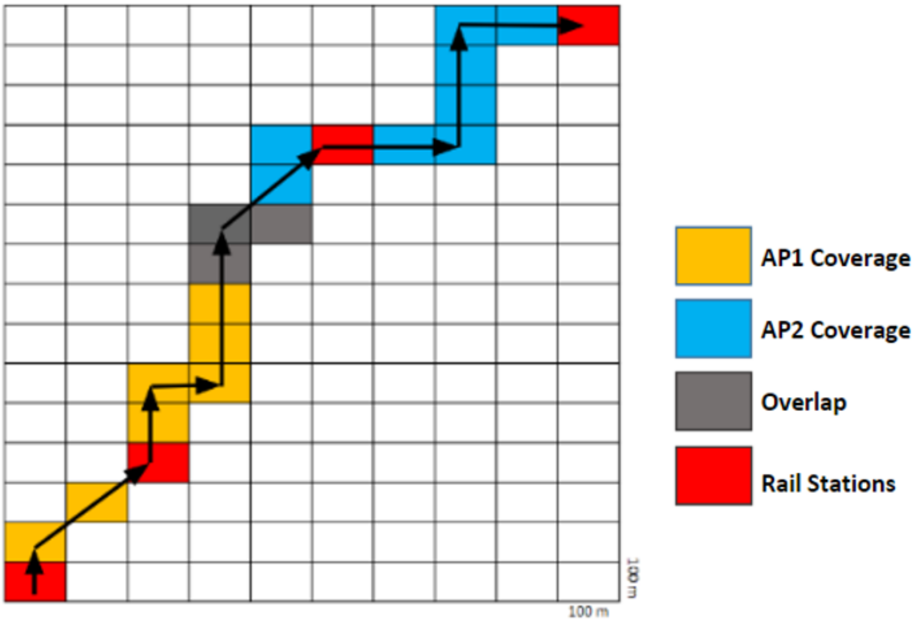

Figure 4.2: The database decodes the train's trajectory by loading the scheduled timetable and locating the relevant pixels and the coverage of each AP along the path

The handover procedure proposed in this section consists of four main stages, namely: handover preparation, handover decision, handover execution, and handover completion; these are discussed next.

4.3.1 Handover Preparation

The network association procedure in IEEE 802.22 consists of 3 main steps. First, the train needs to sweep TV channels to discover WRAN services in the area. Then, once found, the AAA server commences the authentication process. Finally, the train can register with the network and make its initial transmission with the serving AP (IEEE 802.22 Working Group, 2011). The first broadcast operational parameters (i.e. frequency and allowed transmission power) from the serving AP tend to be restrictive as the train is assumed to be anywhere within the AP coverage area (Ofcom, 2015). For enhanced operational parameters, the train has to report its exact geolocation.

In the proposed scheme, the train needs to report its planned trajectory $T(l,s)$ to the database through the first associated AP. By then, the database can decode the received trajectory to obtain the train's speed s at any location l. Transmitting the prospective locations will ease the process of locating the relevant pixels j, in addition to determining the AP coverage, the overlapping coverage pixels, and the location of railway stations. Figure 4.2 presents an example of how the database would locate the relevant pixels based on the information obtained from the train's trajectory.

Afterwards, the database constructs an empty 2D matrix $MAP[N][j]$, where each row represents a channel $C \in N$ (total number of channels) and each column represents a pixel j. In other words, each matrix element represents the availability of each channel per pixel, as shown in Figure 4.3. Then, the database considers the train's radio emission class, allowed transmission power, and the path loss model utilised, to estimate the protection contour for each PU transmitter $\in$ PUs $[M]$, where M is the total number of transmitters. Finally, using (Equation (4.10)), the database estimates the global channel availability P within the impacted area to populate the generated matrix $MAP[N][j]$. An available channel is represented by 1 in the matrix $MAP[N][j]$, whereas 0 indicates channel inaccessibility within a specific pixel.

The global channel availability indicates the number of 1's represented in the matrix $MAP[N][j]$. For a matrix size of (10 pixels X 10 channels), the 50% channel availability is represented by fifty 1's randomly distributed in $MAP[N][j]$. To overcome the impact of random allocation of available channels, this thesis considers running a single experiment multiple times to calculate the error bars for each graph as an indication of uncertainty in the obtained results.

Direction of Accumulation ←

Channel / Distance	Pixel 1	Pixel 2	Pixel 3	Pixel 4	Pixel 5	Pixel 6	Pixel 7	Pixel 8	Pixel 9	Pixel 10	Pixel 11	Pixel 12	Pixel 13
Ch1	1	1	0	0	0	0	1	0	0	1	1	1	1
Ch2	0	1	0	0	1	0	0	1	0	1	1	1	0
Ch 3	1	0	1	0	0	1	0	0	1	1	1	1	0
Ch 4	0	1	0	1	0	1	1	0	0	0	1	1	1
Ch 5	0	0	0	0	1	0	0	0	1	1	0	0	0
Ch 6	1	1	1	0	1	0	1	0	1	1	0	0	0
Ch 7	0	0	0	0	1	0	0	0	0	0	0	0	0
**													
Ch 40	1	1	0	0	0	0	0	0	1	1	0	1	1

AP 1 Coverage (Pixels 1–7) | Overlap (Pixels 8–10) | AP 2 Coverage (Pixels 11–13)

Figure 4.3: Matrix availability map for 40% spectrum availability

4.3.1.1 Greedy Algorithm for Operational Channel Assignment

After filling the matrix $MAP[N][j]$, the database will accumulate the channels available in consecutive pixels. Starting from the very last pixel in the train's journey, if the channel is available in the last two pixels, then these are added together and, if not, the process skips to the next pixel. This process is repeated for the whole list of available channels. The resultant matrix will represent the continuous distance over which an individual channel can be used without interruption. Figure 4.4 demonstrates the resultant matrix before the greedy algorithm is applied. The main objective of the greedy algorithm is to find the minimal set of resources (i.e. channels) that cover the problem needs (i.e. all relevant pixels). Minimising the number of utilised channels will reduce the unnecessary signalling and channel handovers, which will enhance the link reliability and potentially increase the size of transmitted data. This problem is a typical optimisation problem, known as the minimum set cover.

Channel / Distance	Pixel 1	Pixel 2	Pixel 3	Pixel 4	Pixel 5	Pixel 6	Pixel 7	Pixel 8	Pixel 9	Pixel 10	Pixel 11	Pixel 12	Pixel 13
Ch1	2	1	0	0	0	0	1	0	0	4	3	2	1
Ch2	0	1	0	0	1	0	0	1	0	3	2	1	0
Ch 3	1	0	1	0	0	1	0	0	4	3	2	1	0
Ch 4	0	1	0	1	0	2	1	0	0	0	3	2	1
Ch 5	0	0	0	0	1	0	0	0	2	1	0	0	0
Ch 6	3	2	1	0	1	0	1	0	2	1	0	0	0
Ch 7	0	0	0	0	1	0	0	0	0	0	0	0	0
**													
Ch 40	2	1	0	0	0	0	0	0	2	1	0	2	1

AP 1 Coverage | Overlap | AP 2 Coverage

Figure 4.4: Operational channel list after spectrum availability accumulation

To define the problem mathematically, let $J = \{j_1, j_2, ...j_m\}$ be a set of m pixels and $C_1, C_2, ...C_N$ be subsets of J (i.e each $C_i \subseteq J$). In other words, each channel C_i covers a subset of relevant pixels in J. Assume that every item in J appears in some set (i.e. $\bigcup_i C_i = J$). A set cover of J with C is a set $I \subseteq \{1, 2, 3, ...N\}$ such that $\bigcup_{i \in I} C_i = J$. The solution for this problem is a set cover I of minimum size. The objective of the proposed greedy algorithm is to select the minimum set of channels $C = \{C_1, C_2, ...C_N\}$ that covers all the relevant pixels in J.

Algorithm 1 demonstrates a pseudo-code of the proposed algorithm. All the channels are assumed to have equal operational characteristics. In other words, the current algorithm only considers the factor of channel availability to score each channel in $MAP[N][j]$, without reflecting any other advantages that might result from channel-specific characteristics. The output of this algorithm is a list of operational and backup channels to be used at each pixel located on the train path. A single channel can be used for multiple consecutive pixels, referred to as the channel allowed distance limit.

Algorithm 1 : Greedy algorithm for operational channel selection

Input: T(l,s), PUs[M] ▷ **Train's Trajectory, PUs Vector**

Output: C[j], D[j] ▷ **operating channels, utilisation distance**

function MAPGENERATION(T(l,s),PUs[M])
    Select j $\in l$ ▷ pixels relevant to the journey
    Initialise MAP[$N * j$] = 0 ▷ Global Availability Matrix
    $\forall$ PU $\in$ M calculate $r_p \leftarrow r_p \perp \Gamma$ ▷ Γ is a set of network parameters
    $P \leftarrow M_{adj}$, $M_{co} \in$ M ▷ estimate global availability
    MAP[$N * j$] $\leftarrow$ populate relevant pixels with 1's
    ConsecutiveAvailability(MAP[N] [j])
end function
function CONSECUTIVEAVAILABILITY(MAP[N] [j])
    for each Channel C $\leq$ N **do** ▷ for each row/channel
        for each pixel j **do** ▷ starting from last pixel/column
            if MAP[N] [j] !=0 and MAP[N] [j-1] !=0 **then**
                MAP[N] [j-1] += MAP[N] [j] ▷ build accumulative availability map
            else
                MAP[N] [j] = MAP[N] [j]
            end if
        end for
    end for
    ChannelsSelection(MAP[N] [j])
end function
function CHANNELSSELECTION(MAP[N] [j])
    while count $\leq$ j **do**
        C $\leftarrow$ index of maximum N
        D $\leftarrow$ maximum N
        count $\leftarrow$ count + D ▷ select next channel
    end while
end function

Performance Analysis of The Greedy Algorithm

This subsection focuses on bounding the optimal solution for the defined problem, and showing that the proposed greedy algorithm is a $O(log\ n)$-approximation of optimal.

The presented approach gives significant importance to the current state of the channels list, acknowledging that the channel availability can change in short time interval due to unforeseen circumstances such as the appearance of a PMSE user. Hence, the algorithm selects the channel that covers the maximum number of consecutive pixels, starting from the first pixel of the journey. Referring to Figure 4.4, the algorithm picks C_6 as it covers the maximum consecutive pixels of 3 from j_1 to j_3. Afterwards, the algorithm iterates to find the second channel that covers the maximum number of pixels, which is C_4. The final generated channel list of the proposed algorithm for this example will be $C_6, C_4, C_2, C_4, C_2, C_3, C_1$.

In general, for the pixels range $J = \{j_1, j_2, ...j_m\}$, only the elements $j_1, j_2, ..., j_{i-1}$ can be covered at the first iteration, and the elements $j_i, j_{i+1}, ..., j_m$ remains uncovered. To cover the remaining $(m - i + 1)$ elements, the optimal solution (OPT) needs at least $\frac{(m-i+1)}{c(i)}$ sets, where $c(i)$ represents the maximum number of consecutive pixels that a single channel can cover in the each iteration. The iteration starts from the first pixel left uncovered by the previous channel. Hence, OPT can be expressed as:

$$OPT \geq \frac{(m - i + 1)}{c(i)}$$

The cost of covering each pixel can be defined as $cost(j_m) = 1/c(i)$. For instance, referring to Figure 4.4, the cost of covering the first pixel j_1 is $cost(j_1)$, and its value equals $1/3$ as C_6 covers the first 3 consecutive pixels. In this way, the cost of covering all the new elements for the same set is 1. In general, if I is the final channel list (i.e. set cover) generated by the greedy algorithm, the main objective of the algorithm is to minimise the size of I as much as possible. I can be expressed as:

$$
\begin{aligned}
|I| &= \sum_{j=1}^{m} cost(j_m) \\
&\leq \sum_{j=1}^{m} \frac{1}{c(i)} \\
&\leq \sum_{j=1}^{m} \frac{OPT}{(m-i+1)} \\
&\leq OPT \sum_{z=1}^{m} \frac{1}{z} \\
&\leq OPT(\ln m + O(1))
\end{aligned}
$$

In the previous equation, the second and third steps represent direct substitutions for $cost(j_m)$ and $c(i)$ based on the relations discussed earlier. Besides, there was a variable change where $z = (m - i + 1)$ in the fourth step. The harmonic series in the fourth step can also be bounded by $(\ln m + O(1))$. For a fixed number of channels N, the set cover produced by the greedy algorithm is at most $O(\log m)$ times optimal. In other words, the approximation ratio grows slowly as the number of pixels m increases. This approximation might not be ideal, but it is a start for the development of more advanced algorithms.

Database Consideration of Additional Factors

Besides the greedy algorithm application, the database also takes into account the variable train speed to determine the time validity for each channel. Reserved channels will have a flag of 2 in the original availability $MAP[N][j]$ (instead of 0 for unavailable and 1 for available channels), to indicate that these channels are reserved for use at specific times. That will help other SUs to access these channels at the times when the train is not there yet. When a SU requests a channel list, the database first needs to decide on the availability of these reserved channels considering the trajectory of the requested SU. The database then transforms the availability flag of these channels from 2 to either 1 or 0, based on the conflict with the preceding bookings. Finally, the database applies the greedy algorithm discussed earlier. The database procedure to decide on the reserved channels will be detailed in Chapter 7, see Figure 7.14.

Passenger actions, infrastructure faults, and severe weather condition are all reasons for train delay. A train delay can cause unintended interference to PUs and SUs operating on the same channel initially assigned for the in-service train. The proposed algorithm tends to assign a Delay Compensation Interval (DCI) to the channel's time validity to accommodate any possible train delays with the main aim of preventing any potential unintended interference. According to Network Rail (2019), only 67.87% of trains arrive on time while 86.45% arrive 3 minutes late, 92.72% arrive within 5 minutes, and 97.38% arrive within 10 minutes of the scheduled time. Chapter 7 of this thesis investigates the TVWS network performance for different DCI values.

At the final stage of handover preparation, the database broadcasts a packet to each relevant AP as shown in Figure 4.5. The packet contains the train's ID, operational channels to be used under the coverage of each particular AP, time validity of each channel, handover locations, handover mode (e.g. intercell or intracell), and the next AP's ID in case of intercell handover.

The initially associated AP will forward the first operational channel to the train and will only trigger the handover when the train moves beyond the channel allowed distance limit D. This limit refers to the distance where a single channel can be used consecutively. Figure 4.6 shows the packet that is initially transmitted from the serving AP to the moving train. The approach tends to keep track of the

	Train ID	Channel List	Time Validity	Handover Locations	Handover Mode	Next AP ID
Packet to AP1		Channel 1	10:00 - 10:05	Edge of Pixel 2	0	NA
		Channel 3	10:03 -10:07	Edge of Pixel 3	0	NA
		Channel 4	10:05 - 10:08	Edge of Pixel 4	0	NA
		Channel 2	10:06 - 10:10	Edge of Pixel 5	0	NA
		Channel 4	10:09 - 10:25	Edge of Pixel 7	1	**AP2**
Packet to AP2		Channel 4	10:20 - 10:40	NA	NA	NA

Obtained from Speed Profile that has been first transmitted (+/- DCI%)

Figure 4.5: Packet broadcast from the White Space database to relevant APs

AP ID	Channel Number	Allowed EIRP	Backup Channel	Allowed EIRP
	Channel 1	100mW	Channel 15	50mW

Figure 4.6: Explanatory formatting of the packet broadcast from AP to each train

operational channel list on the network side (e.g. database and APs) and not at the user equipment end (e.g. the train), as this eases the process of updating the list in case of the sudden appearance of PMSE devices or any interference caused to an existing PU. In such cases, the database will regenerate a new operational channel list and only update the affected APs along the way.

4.3.2 Handover Decision

After receiving the first assigned operational channel, the train keeps transmitting periodic packets that indicate its exact satellite-determined geolocation and the Received Signal Strength Indicator (RSSI) as another index of the train location and link quality. Figure 4.7 shows the format of the packet transmitted from the moving train to the serving AP. As the train moves under the coverage of

Train ID	Location	Operating Channel	Transmission Power	RSSI

Figure 4.7: Explanatory formatting of the packet broadcast from the moving train to the serving AP

a particular AP, the AP will observe the train crossing an individual pixel, and accordingly the AP will notify the database to release the assigned channel for the previous pixel. When the train approaches the allowed distance limit of a channel D, a new channel needs to be assigned, which is defined as an intracell handover shown in Figure 4.8. The current serving AP will trigger the handover process, and that is explained in the next subsection.

Similarly, the serving AP will initiate the handover when the train approaches the border of the current AP and its RSSI drops under a certain threshold as shown in Figure 4.9. In both cases, the current AP triggers the handover based on the packet received initially from the database. The packet indicates the handover locations precisely and obtains information regarding the handover mode, which means identifying whether the train is moving into a new AP coverage or staying under the current AP coverage.

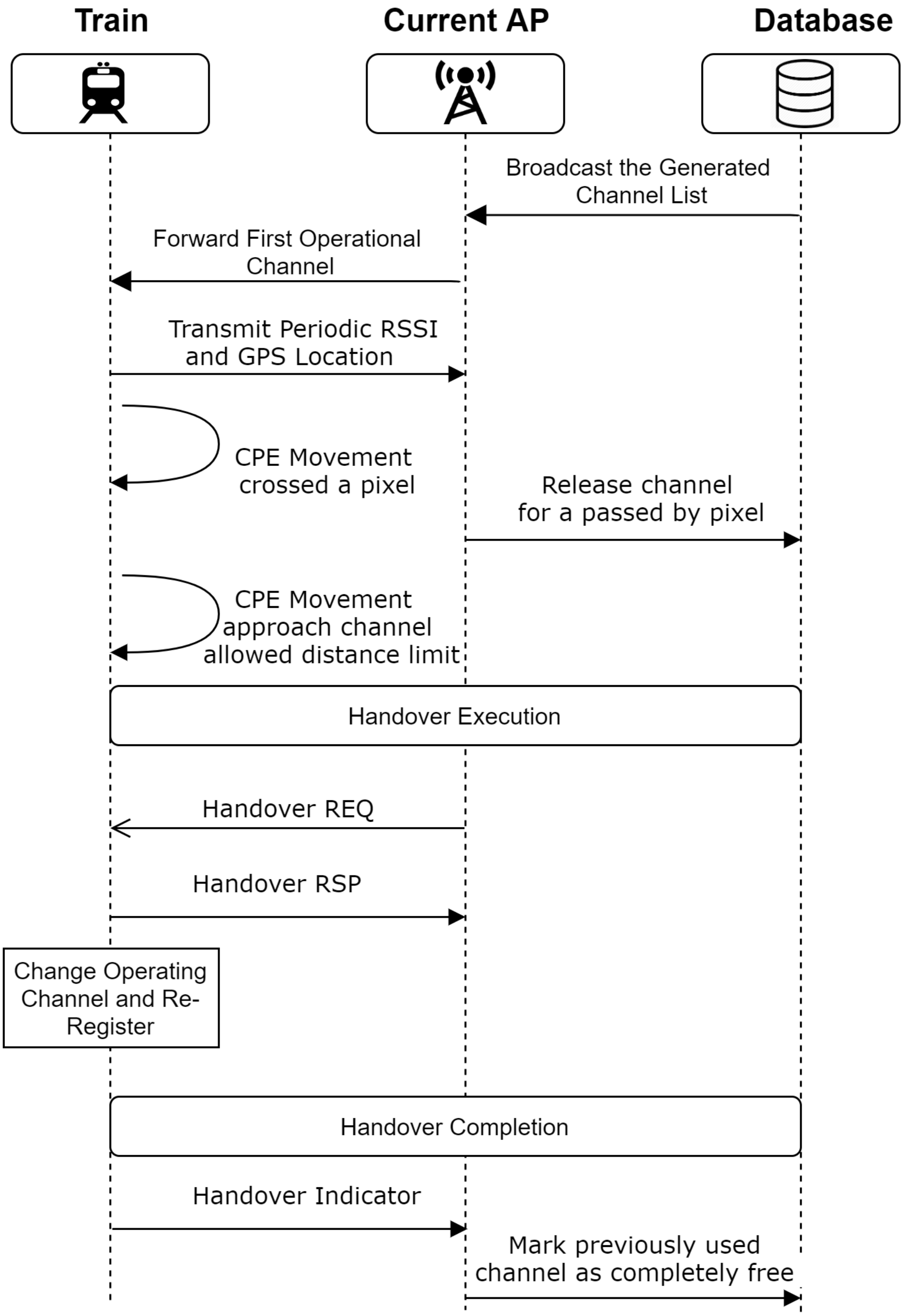

Figure 4.8: Proposed handover procedure under the coverage of the same AP (intracell handover)

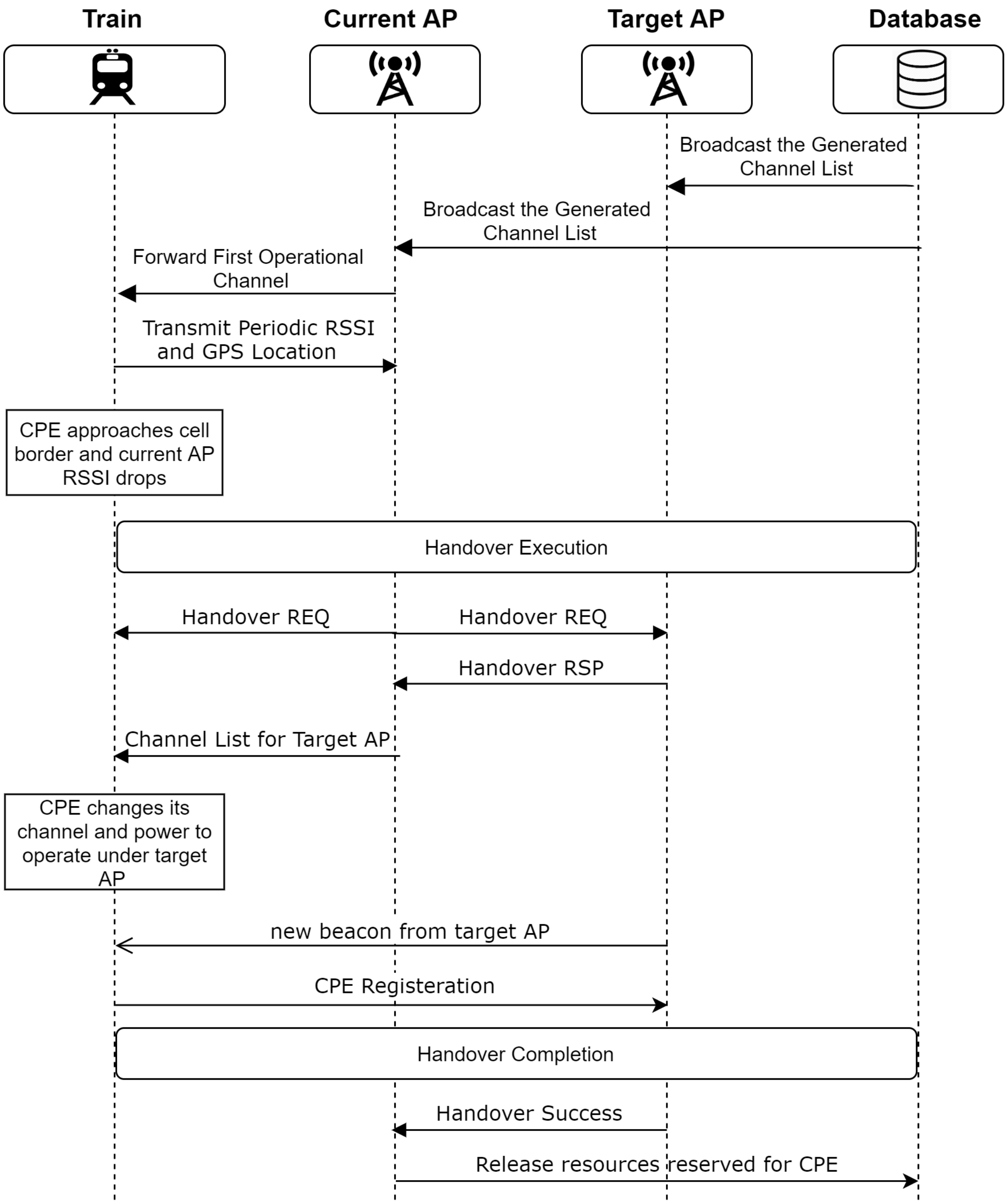

Figure 4.9: Proposed handover procedure for the transition from one AP to another (intercell handover)

4.3.3 Handover Execution and Completion

In the case of the intracell handover shown in Figure 4.8, the current AP will send a handover request (REQ) packet to the train, reporting the new operating channel and the new allowed transmission power. Afterwards, the train has to confirm receipt of these new parameters by sending a Handover response (RSP) packet. As an indication of channel switching success, the train will send a handover indicator packet to the serving AP. Finally, the database will mark the previously utilised channel as completely free and it can be used for transmission by other SUs. This process repeats until the train approaches the border of the current AP that triggers the intercell handover.

By then, the current AP will send a handover REQ to the train and the target AP. If a handover RSP packet is received, the current AP will forward a specific operating channel to the train (i.e. backward handover). Afterwards, the train changes its operational parameters and re-registers to the network under the new AP. When the train is successfully associated with a new AP, the AP will send a handover success packet to the old AP that releases all the resources reserved for the train at the old AP. The train does not break its connection with the old AP until successfully associated with the new AP (i.e. performs a soft handover), as shown in Figure 4.9.

The sudden appearance of a PU on one of the pre-assigned channels can cause the handover procedure to fail. In this case, the train will first attempt to switch the communication to one of the backup channels previously received by the serving AP. If that is not successful, the train will have to completely cease the connection and report its geolocation to the database so a new list can be generated and broadcast. In this solution, the database follows the spectrum regulatory framework and acts as a central unit that assigns and updates the list of operational and backup channels.

4.4 Chapter Summary

This chapter proposes a novel channel assignment scheme to be executed by the TVWS database. The scheme is based on the knowledge of a train's trajectory and the modelled spectrum availability. A greedy algorithm is introduced to produce a set of operational channels that are available for long distances, to minimise unnecessary control messages and service interruptions and to enhance the QoS of the SU network. Advance knowledge of the operational channels results in a changed network procedure to decide and execute a handover. The chapter presents the process needed when the train executes both intracell and intercell handover, detailing the exchanged packets' format.

The proposed handover procedure and channel assignment scheme are designed to be generic, meaning they can be utilised for any of the railway wireless applications mentioned in Chapter 2. However, a case study is needed to accurately evaluate the performance of the proposed methodology. The next chapter gives background regarding application of the methodology to railway RCM systems, quantifying the overall network performance in terms of coverage, reliability, data rate, and performance at line speed.

Chapter 5

Application to Remote Condition Monitoring: Background

5.1 Introduction

In the previous chapter, aspects such as path loss, transmission power, and co-channel and adjacent channel interference were taken into consideration, to build an accurate model of the PU protection areas and predict the probability of spectrum availability. By using the train's planned trajectory, a generic greedy algorithm was implemented as part of the handover preparation process to pre-select the channels that last for the longest travel distance, aiming to minimise unnecessary signalling and channel switching.

The main objectives of this chapter are to identify the most appropriate railway wireless application for a case study and to justify the reasons for this choice. First, the chapter states the TVWS characteristics that correspond to the wireless applications' requirements mentioned in Chapter 2. These characteristics include the expected TVWS performance in terms of geographical coverage, connection reliability, performance at high speed, data rate, latency, and setup time. Selection of a suitable application for the case study helps to evaluate the TVWS performance and identify the limitations that might exist for other railway applications.

5.2 TVWS Characteristics

5.2.1 Geographical Coverage

There is a strong dependence between the choice of an operating frequency and potential coverage radius. As the TVWS system operates at a relatively low frequency compared to LTE and 5G, it is expected to provide better coverage and penetration capability in tunnels, buildings, and cuttings, using fewer BSs. However, the use of TVWS is not guaranteed to provide continuous coverage along the track through the whole train journey. The availability of TVWS channels is a function of population density. Areas with a higher population have fewer channels available to operate. Figure 5.1 by Hessar and Roy (2015) indicates the total number of channels available for different population densities in the USA. There is a noticeable drop when the population density approaches 1000 (per square mile) as that represents the transition from rural to semi-urban areas.

Besides PU density and characteristics, the SU's mobility, transmission power, transmission class, and geographic location have a great impact on the availability of TVWS channels. Ofcom (2015) specifies the available channels for different scenarios and locations. For instance, Figure 5.2 shows the available channels for a mobile SU with a 1.5 m antenna transmitting at various powers of 10, 13, 16, 20, and 23 dBm. From the figure, it is noticeable that fewer channels become available as the transmission power increases.

From the preceding discussion, it is clear that the availability of TVWS channels is dependent on both SU and PU characteristics. Ideally, White Spaces will be available in all rail network locations, especially in the rural areas where most trains travel between cities using the main line. On the other hand, transmission

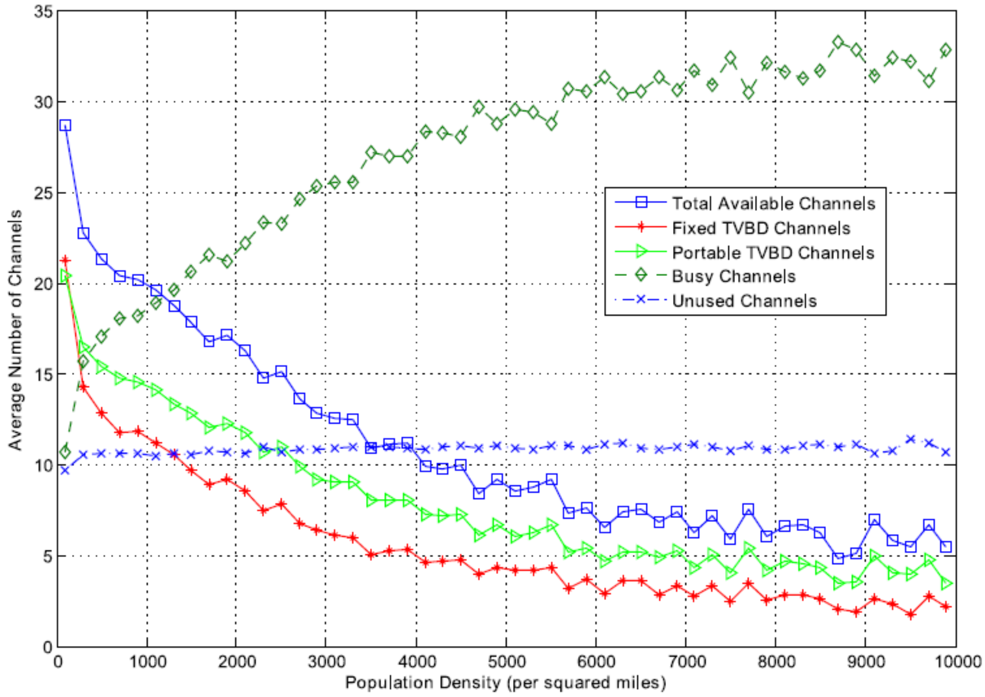

Figure 5.1: Available TVWS channels for different population densities in the USA (Hessar and Roy, 2015)

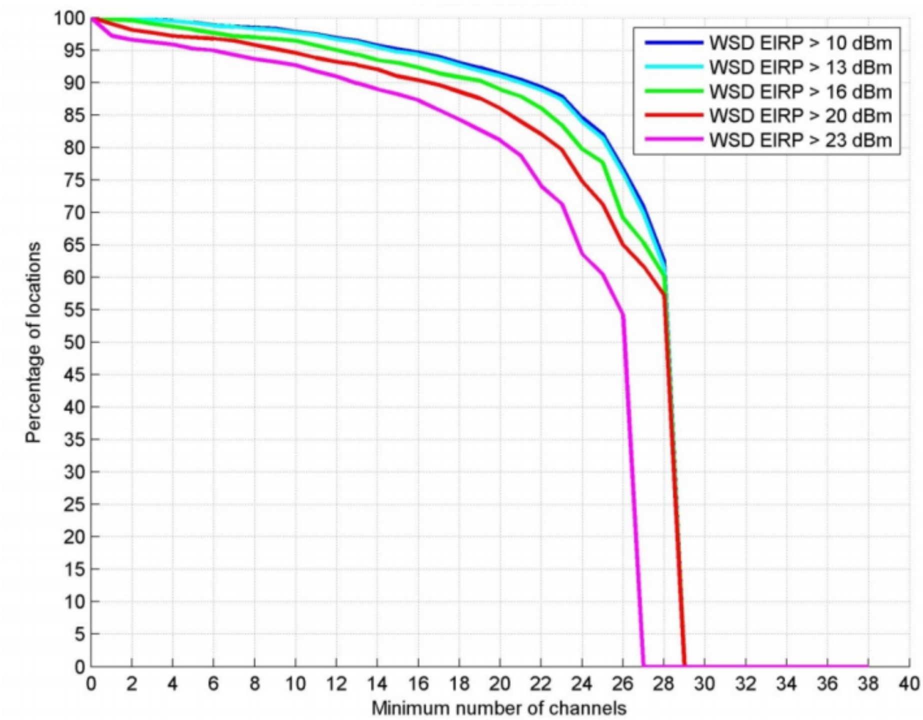

Figure 5.2: TVWS spectrum availability in central London (Ofcom, 2015)

continuity is not guaranteed unless the requirement of having high transmission power is tolerated.

5.2.2 Reliability

Spectrum regulators in the UK and USA currently adopt a database-oriented framework to assign free TVWS channels to SUs, depending on the user's location and device characteristics. The framework aims to provide full protection to the spectrum's PUs. Gavrilovska *et al.* (2014) claimed that the database-oriented approach is not accurate enough, as it only considers fixed propagation models to determine spectrum availability without taking into consideration dynamic real-life changes.

Consequently, the operational parameters (i.e. frequency and transmission power) assigned to an SU might be inaccurate and could cause interference to nearby PUs. There are ongoing trials to enhance the accuracy of the regulator's database framework by using Radio Environment Maps (REM) that would provide more accurate and local channel propagation information (Gavrilovska *et al.*, 2014). The combination of spectrum sensing and database access was proposed by the IEEE 802.22 Working Group (2011) to overcome the shortage of each approach if applied individually.

Additionally, the fact that PUs always have priority over SUs affects TVWS network reliability. An SU must cease its connection within a specific time interval if it exceeds the allowed operational parameters or in the case of sudden PMSE appearance. To sum it up, the reliability of a TVWS network is not guaranteed because of the deployed database approach and the priority given to spectrum PUs.

5.2.3 Performance at High Speed

Doppler shift represents one of the challenges adversely affecting wireless communications to high-speed platforms. The shift is defined as the frequency change Δf due to the relative movement between transmitter and receiver. It is a function of the carrier frequency f_o, the velocity of waves in the medium c, and the relative velocity magnitude between transmitter and receiver Δv (Gothard and Rosen, 2010).

$$\Delta f = \frac{\Delta v}{c} \times f_o \tag{5.1}$$

Due to multipath propagation, Doppler shifts between different signal components introduce Doppler spread into the received signal, which means the received signal has a larger bandwidth than that of the transmitted signal. Doppler spread is used to measure the spectral broadening caused by the time rate of the change of the mobile radio channel (Wang, 2015). Coherence time T_C is inversely proportional to the Doppler spread, and it is widely used to characterise the time duration over which the channel impulse is invariant and to quantify the similarity of the channel response at different times (Shankar, 2002). Since fading depends on whether signal components add constructively or destructively, channels with a large Doppler spread have a very short coherence time T_c and are more prone to distortion to be caused on the receiver side. As the TVWS system operates at a relatively lower frequency compared to LTE and 5G, the system is more resilient to high mobility as the induced Doppler shift/spread is smaller and thus the received signal experiences less distortion.

5.2.4 Data Rate

Wireless technologies that operate at higher frequencies can offer wider bandwidth that directly improves the overall network throughput. For instance, the channel bandwidth offered by LTE is 20 MHz compared with only 6 or 8 MHz offered by TVWS, depending on the standard utilised. However, for high availability of TVWS channels, the database can assign multiple contiguous channels to the SU based on its communicated requirements. According to the IEEE 802.22 standard, a single TVWS channel can provide a data rate of nearly 5 Mbps when physical mode 5 is adopted (IEEE 802.22 Working Group, 2011).

5.2.5 Latency and Setup Time

According to the IEEE 802.22 standard, the setup time is the duration needed by the user to transmit control information to the network, before a full operation is established under a given channel. The default value of the setup time is 2 s (IEEE 802.22 Working Group, 2011).

On the other hand, the network joining latency is the duration that the user needs to wait after determining the start of the next IEEE 802.22 frame. The latency value depends on the followed sensing type and duration. For the IEEE 802.22 standard, the mean latency for is 88 ms (IEEE 802.22 Working Group, 2011).

5.3 Why Remote Condition Monitoring?

To ease the decision-making process, the applications' requirements defined in Chapter 2 have been summarised in Table 5.1. The table highlights each cell based on the ability of a TVWS system to meet this requirement. The red colour indicates a "hard-to-meet′ requirement, while the green colour indicates a "possible-to-meet" requirement. The not highlighted cells are not decisive in the application selection process. This section analyses each of these requirements from a TVWS perspective to select an application for the initial case study.

Signalling Systems: Based on the shown requirements, signalling systems require universal and continuous coverage with a highly reliable communication link to be available under various modes of operation. However, the previous discussion of this chapter indicates that the TVWS availability is not guaranteed, as it is highly dependent on multiple factors including population density, and PU and SU technical characteristics. As the railway communication network would act as the TVWS spectrum SU, providing a reliable connection continuously along the whole track will be challenging. Also, the setup time offered by the TVWS standard does not satisfy the signalling system requirement. Under the current state of TVWS development, the critical nature of this application does not make it the best candidate for the preliminary case study.

On-board Broadband Systems: This application requires a high level of coverage in terms of continuity and geography for real-time sub-applications, while the demand downgrades to normal for non-real time sub-applications. The uncertainty in the TVWS spectrum would work for the non-real time sensitive applications if some approaches are adopted. For instance, locations where the bandwidth is highly available, can be utilised to buffer some of the on-demand media. However, this solution will not be viable for real-time applications such as live TV and voice communications. Besides, the small channel bandwidth (i.e. 6 or 8 MHz) offered by TVWS and the restricted transmission power on mobile platforms will limit the overall network throughput. Assignment of multiple contiguous channels to the same user is not

TABLE 5.1: Summary of pivotal application requirements

Applications \ Requirements	Coverage Availability	Coverage Continuity	Link Reliability	Data Rate	Latency	Setup Time	Operational Speed (km/h)	Content Type	Symmetry (UL/DL)
Signalling System	High	High	High	64 kbps	10 - 100 ms	< 1 s	0 - 500	Bi-directional data	50/50
On-board Broadband System (Real Time)	High	High	Normal	$\geq$ 5000 kbps	10 - 100 ms	1 - 3 s	0 - 500	Bi-directional data	50/50
On-board Broadband System (Non-real Time)	Normal	Normal	Normal	$\geq$ 5000 kbps	100 - 500 ms	1 - 3 s	0 - 500	Bi-directional data	20/80
RCM System (Data)	Normal	Normal	Normal	20 kbps	100 - 500 ms	1 - 3 s	0 - 500	Unidirectional Data	100/0
RCM System (Video)	Normal	Normal	Normal	400 - 5000 kbps	10 - 100 ms	1 - 3 s	0 - 500	Unidirectional Data	100/0

guaranteed as it is a function of channel availability at different locations. For this reason, the on-board broadband system is not considered for the initial case study of this research.

Remote Condition Monitoring System: This application requires continuous coverage to be available at all locations, especially with the potential existence of live video transmission. However, this requirement is set to normal as the RCM system can tolerate a certain level of communication discontinuity that achieves the desired QoS. By adopting methods to store the dropped packets and re-transmit them as soon as the communication link is made available again, the RCM system can operate efficiently under the uncertainty of the TVWS spectrum. Besides, the data rate needed for the RCM system can be met using a single TVWS channel. Finally, the latency and setup time offered by the IEEE 802.22 standard satisfies the RCM system requirements.

For the previous reasons, The RCM system represents the best candidate for a preliminary case study that will help to evaluate the TVWS performance in a dynamic railway context while quantifying the challenges that might exist for the other safety-critical and retail applications. The results will pave the road to develop methods to tackle these challenges and enable efficient and economic train-to-ground communication for the rail industry.

To achieve this vision, of various paradigms, this thesis focuses on the 'Train Monitoring Infrastructure' paradigm as it exhibits similar features to the railway wireless applications mentioned previously. Figure 5.3 describes the block diagram of the various system components considered for the initial case study. The case study focuses on transmitting the collected maintenance data using a TVWS network from the on-board server to a remote centre for online monitoring and live data analysis. The Global Positioning System (GPS) aims to locate the train accurately and report the geographic location to the TVWS

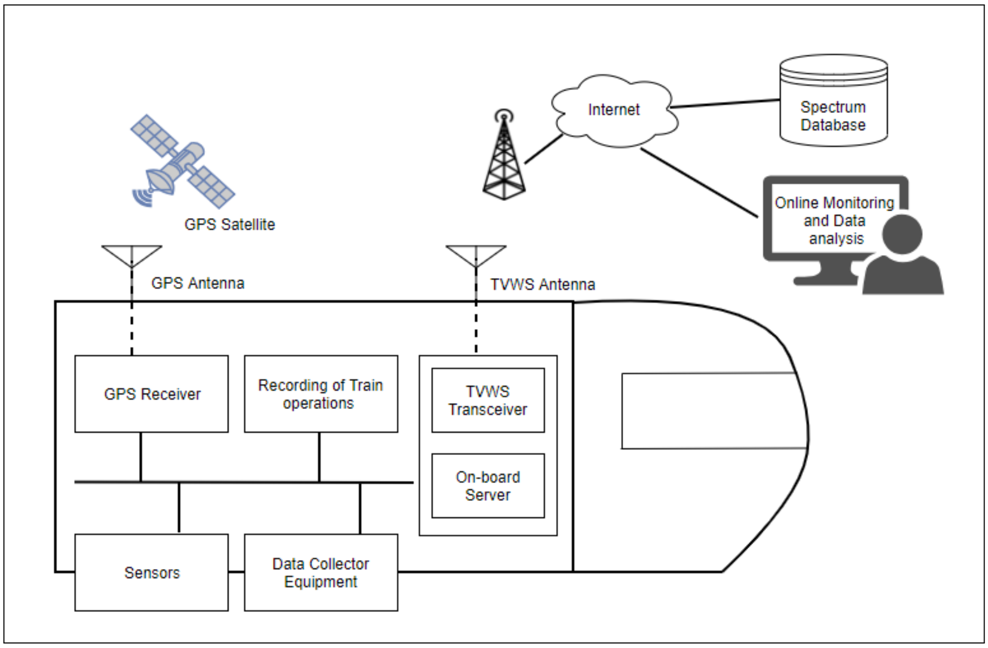

Figure 5.3: Main components of the RCM system considered for the initial case study

spectrum database. Also, GPS is needed to link the measured maintenance data with their relevant position.

5.4 Chapter Summary

This chapter reviews various TVWS characteristics against the application requirements set out in Chapter 2 to select the most suitable application for a preliminary case study. A TVWS system, with the existing spectrum uncertainty, would still be able to satisfy the communication requirements of the RCM application, whose studying will help to evaluate TVWS performance in a dynamic railway context, identifying challenges that might emerge for other railway applications. The chapter also outlines the scope and initial structure of the proposed system that is implemented and validated in the next two chapters.

Chapter 6

Application to Remote Condition Monitoring: Implementation

6.1 Introduction

This chapter focuses on simulating a TVWS-enabled RCM system. The case study includes two trains offloading their track maintenance data to a remote control centre. Train and track environments considered within this research are presented first. Then, the parameters of the railway network as an SU are introduced. Finally, the work done on the simulation environment integration and development is discussed, demonstrating some validation and initial results to highlight the fidelity of the simulation environment and to indicate the performance of the SU network. Figure 6.1 shows the typical architecture of the simulated TVWS network considered in this case study.

6.2 Train and Track Environment

The case study within this chapter simulates two trains dwelling at Selly Oak, University, and New Street stations in Birmingham, UK. Both trains are British Rail Class 323 trains having a maximum speed of 144 km/h, length of 20 m per carriage, and each consisting of three carriages. There is no tunnel environment considered in this study. Although the train speed can reach up to 144 km/h, the infrastructure has a speed limit of 85 km/h.

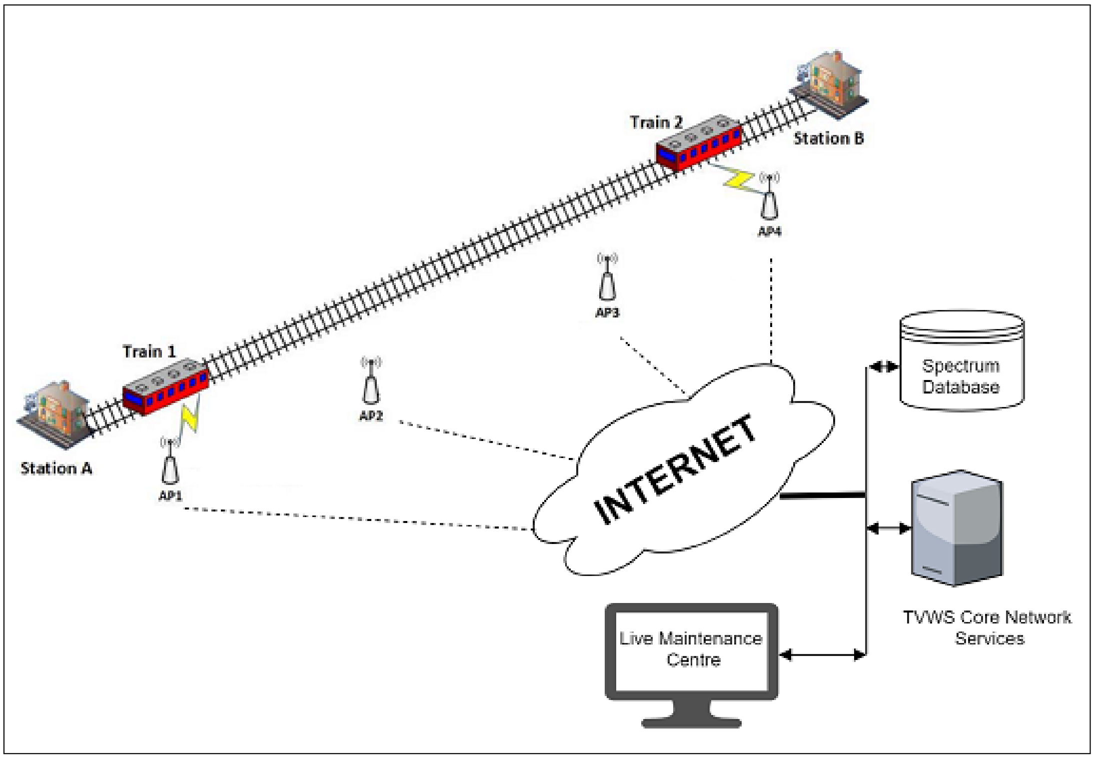

Figure 6.1: Envisioned TVWS network architecture for predictive maintenance systems

Figure 6.2 shows the speed profile of both trains. There is a time gap between the two trains even they start the journey at the same location but at different simulation times. As shown in the figure, each train starts with a maximum allowed speed of 85 km/h and decelerates to 0 km/h to dwell at the previously mentioned three stations Selly Oak, University, and New Street stations at different timings. The parameters defined in this section are fed into the railway simulator introduced in Section 6.4.1.

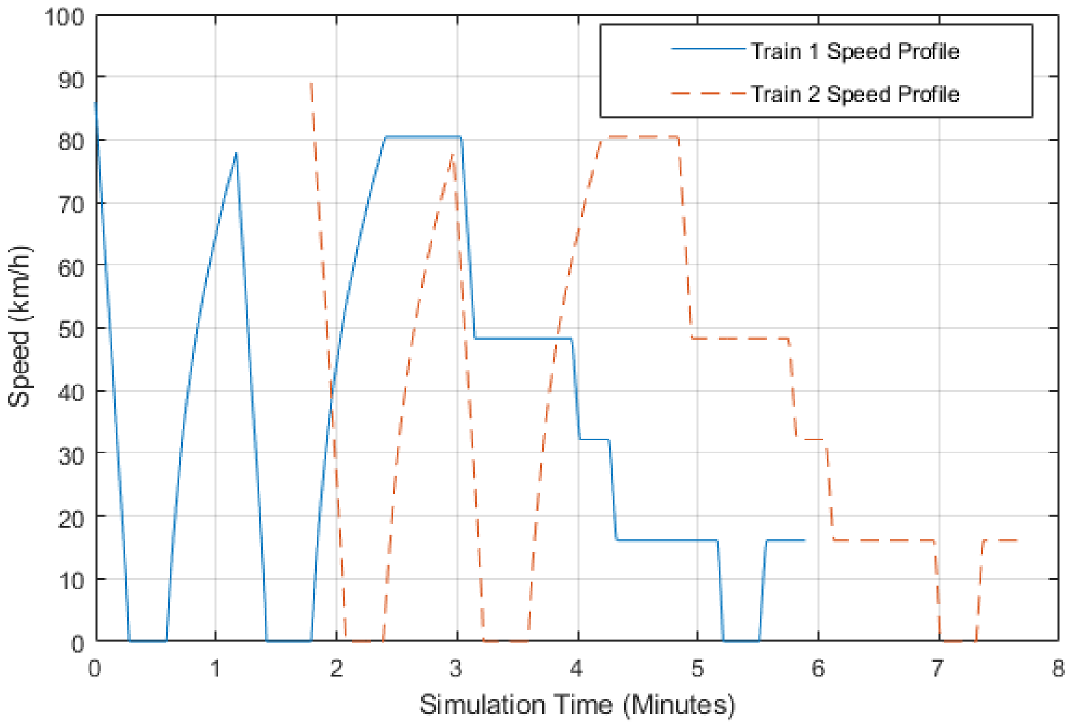

Figure 6.2: Speed profile for the two simulated trains with the second train starting 114 seconds (1.9 minutes) after the first train start

6.3 Network and Simulation Parameters

All of the SU network parameters considered within this case study are stated in Table 6.1. The values of all parameters are excerpted from the IEEE 802.22 standard (IEEE 802.22 Working Group, 2011) and are fed into the network simulator introduced in Section 6.4.2. Spectrum Regulators in various countries use different channel bandwidth for the Digital Terrestrial Television. For instance, FCC in the USA adopts a 6 MHz bandwidth, while Ofcom in the UK defines the channel bandwidth as 8 MHz. Since the IEEE 802.22 standard considers both figures, this thesis considers a channel bandwidth of 6 MHz for both the PUs and SUs to provide a solution that suits the regulations in all countries.

The simulated rail line is covered with three partially overlapping AP coverage areas. Each AP has a coverage radius of 1.5 km, and each train attempts to transmit 370 Megabytes of data acquired during a total journey time of 7.6 minutes. The transmitted data represents the track-health data along with video transmission of the infrastructure. Varied population densities (e.g. number of PUs) are introduced to represent rural, suburban, and urban areas.

The global channel availability in this thesis; modelled in Equation 4.10, considers the technical characteristics of DTT users. Besides, this thesis excludes SU operation on channel 38 to represent PMSE operations on this channel. To simulate other licensed PMSE users operating on channels other than channel 38, two PMSE users are included in this simulation under the coverage area of AP1. The two users always have a link priority over the train as an SU. For instance, in the case of co-channel assignment, the train will have to cease a connection on the same channel to prevent interference. Both users operate on a 40% duty cycle basis that starts after an idle time of 3.6 seconds from the simulation start.

In this case study, the two PMSE users are assigned private channels that the SUs cannot operate on. In other words, the existence of these PMSE users does not affect the simulation results from the SU perspective, as the SU connectivity depends only on the global channel availability mentioned above. The main objective of including these PMSE users is to highlight the existence of this software capability, which might lead to further research that might consider the technical characteristics of wireless microphones and audio devices operating in channels other than channel 38 to define the TVWS spectrum availability.

In terms of the computing environment, the simulation was run on a computer that has an i7 3.60 GHz CPU and 12 GB of RAM, and it took 770 seconds to complete the journey of the two introduced trains.

TABLE 6.1: Railway communications network parameters

Parameter Name	Value	Parameter Name	Value
Probe Request	300 ms	Modulation Type	QPSK
Probe Response	300 ms	Coding Rate	1/2
CBC_REQ	5 ms	Channel Bandwidth	6 MHz
CBC_RSP	5 ms	Receiver Sensitivity	−103 dBm/100 kHz
AUTH_REQ	25 ms	Data Rate	5 Mbps
AUTH_RSP	25 ms	Frequency Range	470 – 790 MHz
REG_REQ	160 ms	Noise Floor	−110 dBm
REG_RSP	160 ms	Multiple Access	OFDMA
Sensing Duration	44 ms	Duplexing Mode	TDD
Antenna Gain	6 dBi	Tx Power	20 dBm
Tx Antenna Height	3 m	Rx Antenna Height	38 m

6.4 Integration of Network and Railway Simulators

Extensive development has been carried out to create a comprehensive simulation environment that enables comparison between the performance of the proposed method and the conventional IEEE 802.22 standard. Wen *et al.* (2015) have integrated two separate simulators, the Birmingham Railway Simulation Suite (BRaSS) and OMNET++ to create a co-simulation environment spanning railway operations and wireless communications. As this simulation environment is adopted in this research, the features of BRaSS and OMNET++, as well as their integration, are introduced in the upcoming subsections.

6.4.1 Railway Simulator

BRaSS is a microscopic railway simulator developed by the Birmingham Centre for Railway Research and Education (BCRRE), and it can simulate all the basic

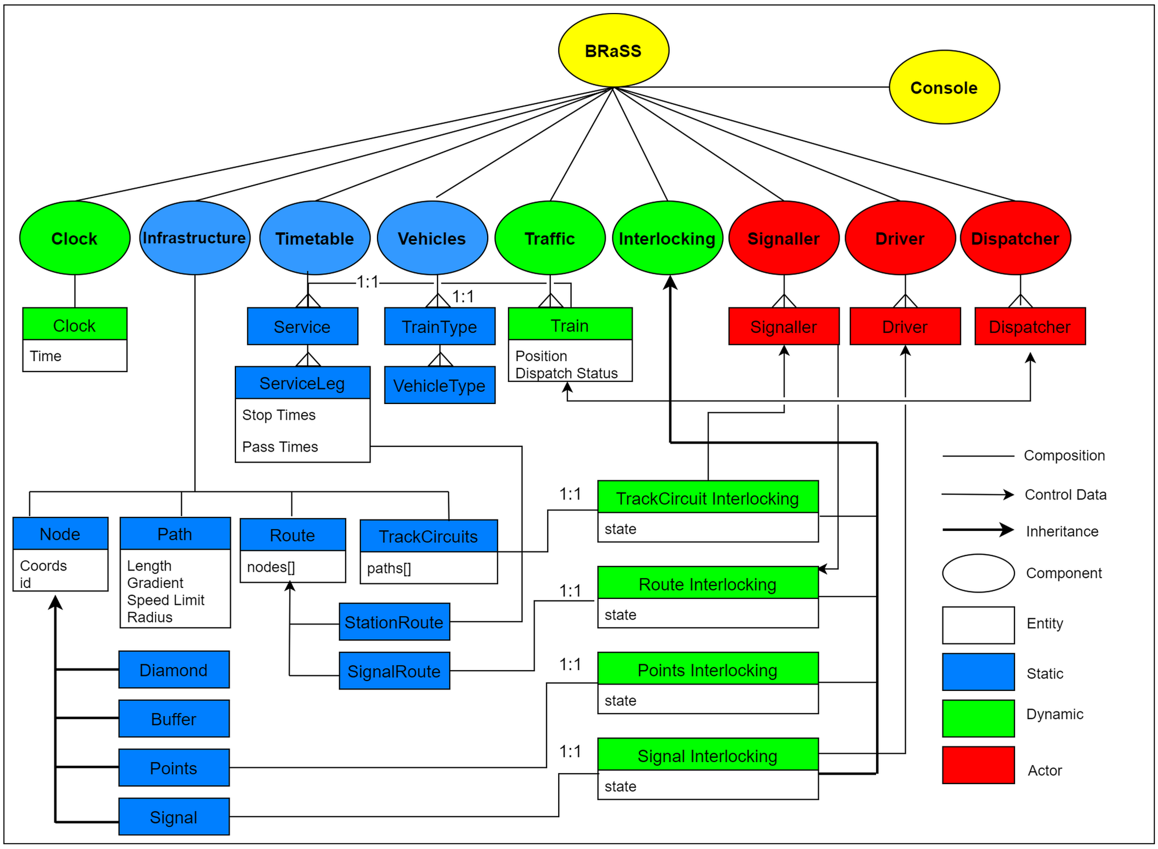

Figure 6.3: BRaSS main components and entities

functions of railway control and management. Through a number of panels, the user can set realistic scenarios by configuring parameters, including the traffic setup, vehicle type and specification, infrastructure data, and interlocking arrangements. Figure 6.3 shows the main components and entities included in BRaSS. Static components represent the elements of the railway network that do not change state during railway operation such as the vehicle type and infrastructure properties. On the other hand, dynamic components represent elements that change their state during railway operation such as a change in the train's location. Actor components represent elements of decision-making in the railway, such as the train driver. Figure 6.4 shows a snapshot of railway operations configured in BRaSS for this case study. Appendix A details how BRaSS was used and configured to serve the rail scenarios built of this research.

6.4.2 Network Simulator

To simulate a realistic wireless communications scenario in railway operations, OMNET++ was incorporated. OMNeT++ is a discrete event modular simulator developed by András Varga and OpenSim Ltd (2017) for simulating propagation models and path loss, as well as the operation of digital communication protocols corresponding to different network layers, such as IEEE 802.11 and Ethernet network IEEE 802.3 protocols. An exhaustive search of the existing OMNET++ protocol library confirmed the absence of any model for the database-oriented IEEE 802.22 standard. The crSimulator framework proposed by Khan *et al.* (2013) was determined to be a good starting point to build such a simulation that permitted the addition of essential compound modules in OMNET++.

The setup of the wireless communications network considered for this case study is shown in Figure 6.5. The wireless network consists of various compound modules used to define APs, PMSEs, moving trains, radio medium, external simulator interface (i.e. extSim), and the global spectrum database (i.e. mobilityDatabase). Each of these compound modules consists of sub-modules. For instance, the compound module that represents a moving train in this case study is shown in Figure 6.6. The node includes sub-modules that represent the functions of the application layer (i.e. appLayer), network layer (i.e. netLayer), MAC layer (i.e. macLayer), physical layer (i.e. phyLayer), Signalling and Communication Link (SCL), spectrum sensing (i.e. specSensor), mobility module (i.e. regMobility), and local Database Resource Manager (DRM).

The mobility module is responsible for monitoring the train's movement and identifying if the train has crossed a pixel boundary and then initiates the intracell handover. In addition, the module triggers the intercell handover

Figure 6.4: BRaSS demonstrates two trains running from Selly Oak towards New Street station

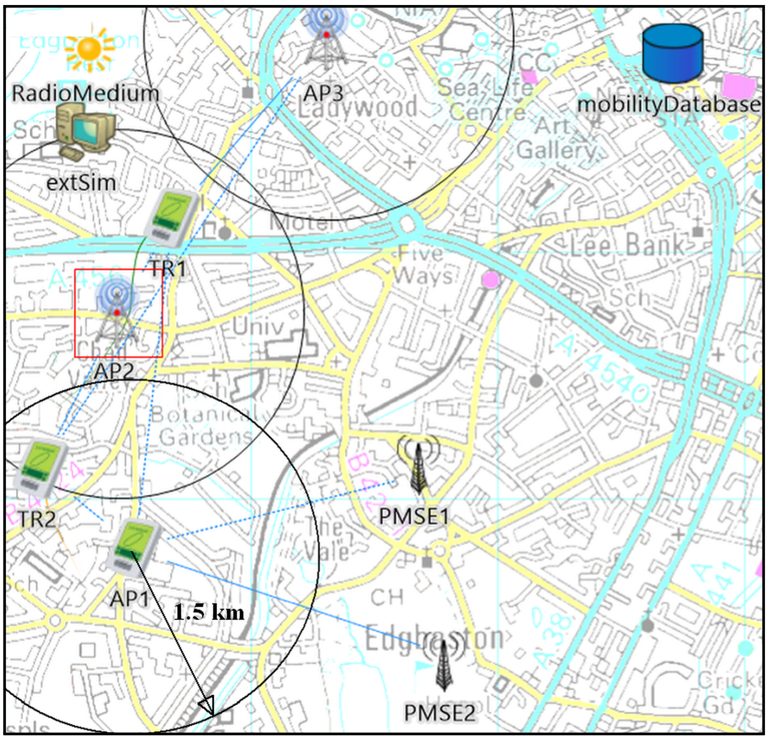

Figure 6.5: OMNET++ shows the simulated wireless network that consists of 3 APs, 2 trains, and 2 PMSE users operating within the coverage area of AP1

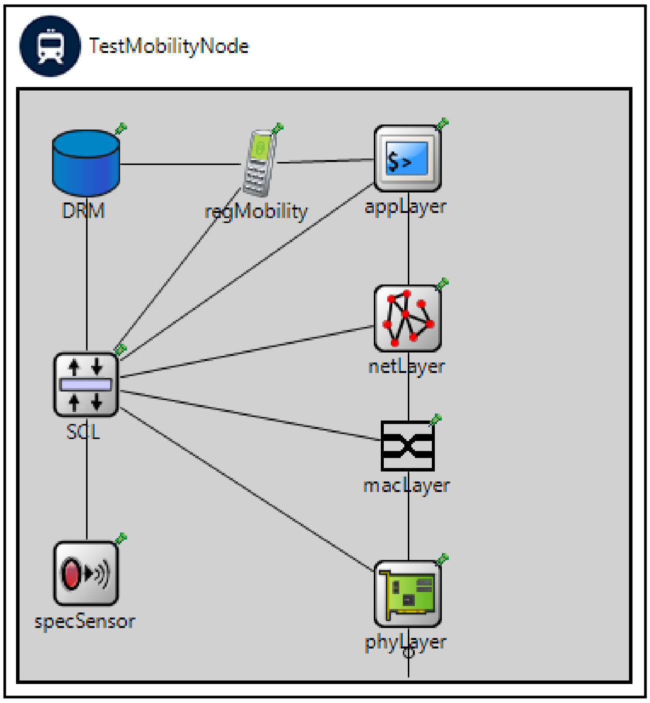

Figure 6.6: Sub-modules that constitute the train compound module

procedure when the train transits from the coverage of one AP to another. On the other hand, the database module holds a local version of the channels to be used by this train at each pixel. Appendix B details the functionality of each module included in this study.

6.4.3 Data Flow in Integrated Simulation Environment

Within the integrated simulation environment, BRaSS updates OMNET++ with a periodic packet that contains the train's ID, current speed, a time stamp, and the current coordinates of the train. The reported speed profile of the train complies with the initial configurations set by the user for a specific rail scenario. Once OMNET++ receives the packet, an acknowledgement message is sent back to BRaSS to indicate successful reception. OMNET++ handles the received packet through the external simulator interface (i.e. extSim), as shown in Figure

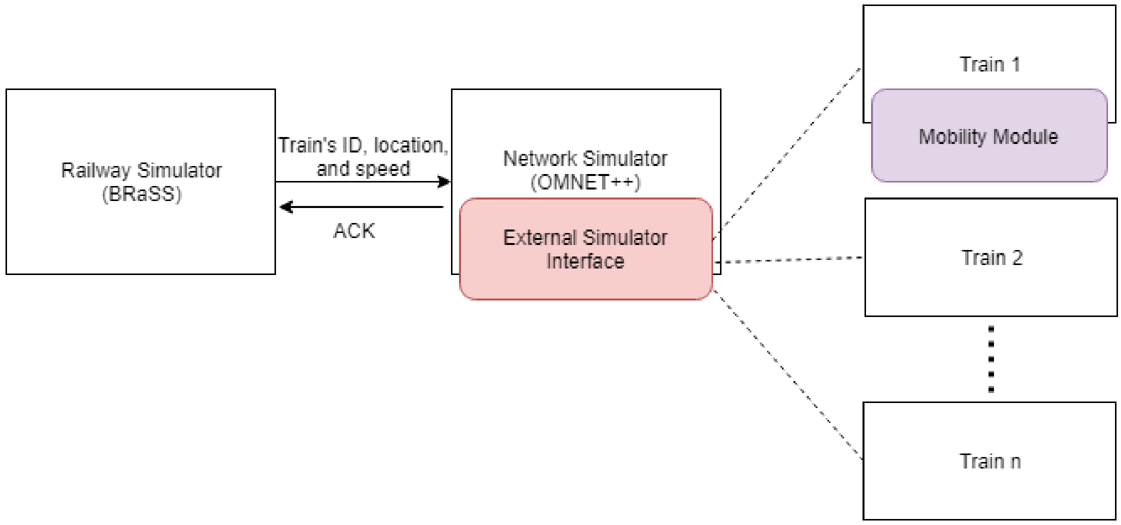

Figure 6.7: External simulator interface between BRaSS and OMNET++

6.7. The module routes the packet to each relevant train which updates its position in the OMNET++ environment accordingly.

6.5 Quantifying Interference Through SEAMCAT

To determine the possible interference caused by the railway communication network to a residential TV receiver (i.e. PU), independent simulations have been carried out using SEAMCAT (ECO, 2016). This is a Monte Carlo simulation tool that allows statistical modelling of interference scenarios between systems operating in overlapping or adjacent frequency bands. Within the tool, to imitate the predefined scenario, a TV broadcasting link was defined as a victim system (e.g. PU) whereas the railway communication link was defined as an interfering system (e.g. SU). Appendix C gives more details on SEAMCAT and how it was configured to achieve the interference calculations of this thesis.

Figure 6.8 shows the green-coloured Victim Link Transmitter (VLT) positioned at (0,0) coordinates while the blue-coloured Victim Link Receiver (VLR) is

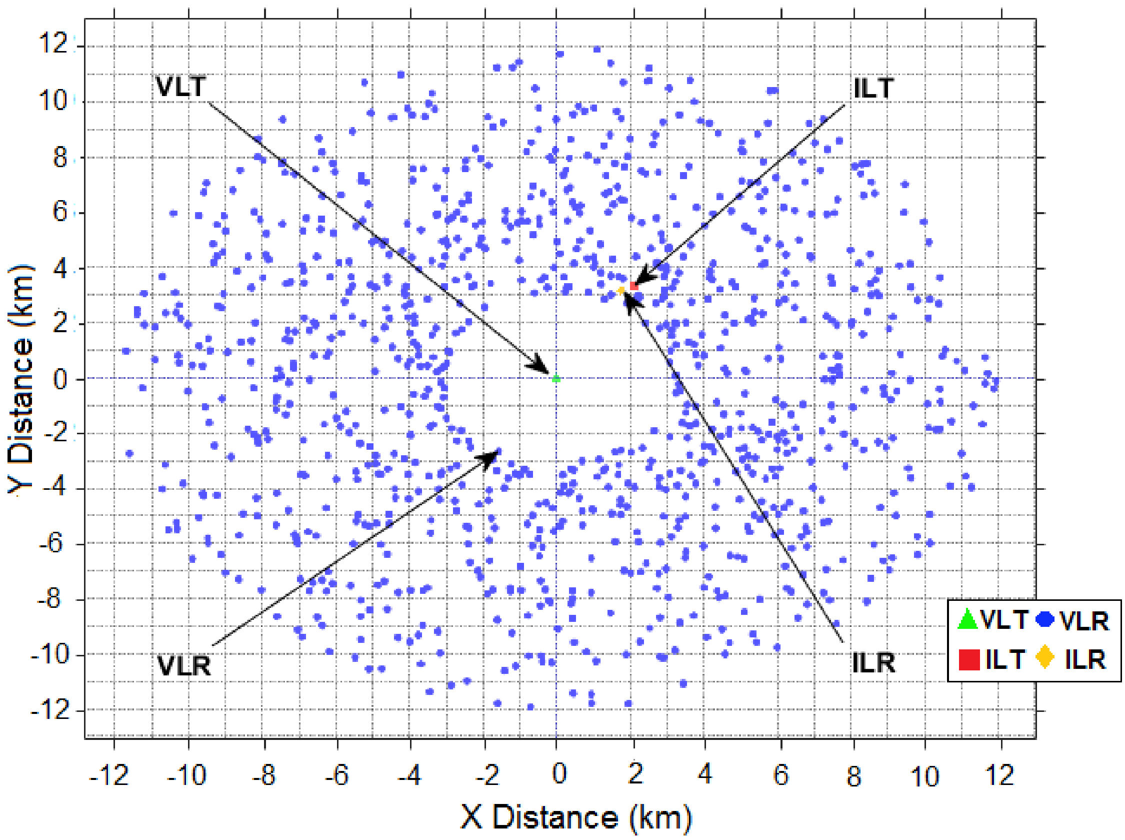

Figure 6.8: Interference scenario at 20% channel availability. The TV transmitter is located at (0,0) while TV receivers are distributed according to channel availability. The transmitting train (ILT) is shown in red while the associated AP (ILR) is in yellow

randomly distributed around the VLT. The maximum separation distance $(r_{pc} + d_{MS})$ corresponds to the VLT coverage radius and is assumed to be 12 km in this interference simulation. The operating frequency distribution of the TV broadcasting system corresponds to the percentages of channel availability (i.e. variable frequency separation Δf represents different spectrum availability). Table 6.2 states all the TV broadcasting system parameters used for the interference calculations.

On the other hand, the red-coloured Interfering Link Transmitter (ILT) represents the moving train while the yellow-coloured Interfering Link Receiver (ILR) represents the currently associated AP. The train and the AP locations are obtained from the OMNET++ mobility module mentioned previously. The

TABLE 6.2: TV broadcasting network parameters

Parameter Name	**Value**	**Parameter Name**	**Value**
Tx Antenna Height	50 m	Tx Antenna Gain	8.25 dBi
Rx Antenna Height	10 m	Rx Antenna Gain	6 dBi
Emission Power	63 dBm	Noise Floor	–110 dBm
Tx Coverage Radius	12 km	Sensitivity	–103 dBm

operational channel list of the railway network is selected either by the IEEE 802.22 standard or the newly proposed approach.

To compare the interference performance of both the IEEE 802.22 standard and the newly proposed approach, this research has considered calculating the interference probability for varying power supplied to the interfering transmitter (i.e. a moving train). It is a function of the desired Received Signal Strength ($dRSS$) and the interfering Received Signal Strength ($iRSS$). Using the unwanted $iRSS$ protection mode in SEAMCAT, if the calculated carrier-to-interference ratio C/I is above the protection criteria, the probability of interference calculated by SEAMCAT will be equal to 0%. The protection ratio within this experiment was set to 19 dB to follow the protection ratios for DTT services in the VHF/UHF bands proposed by the BT Series Broadcasting Service (2013). Carrier-to-interference ratio C/I equals $\frac{dRSS}{iRSS_{unwanted}}$, where $iRSS_{unwanted}$ is defined as the unwanted interfering power received at the VLR side, and $dRSS$ is the desired received signal strength at the VLR side.

According to ECO (2016), $dRSS$ can be defined as

$$dRSS = P_{VLT}^{output} - PL_{VLT \to VLR} + G_{VLR \to VLT} + G_{VLT \to VLR}, \tag{6.1}$$

where P_{VLT}^{output} is the power supplied to the VLT antenna, $PL_{VLT \to VLR}$ is the path loss between the VLT and the VLR, $G_{VLR \to VLT}$ is the VLR antenna gain in the direction of the VLT, and $G_{VLT \to VLR}$ is the VLT antenna gain in the direction of

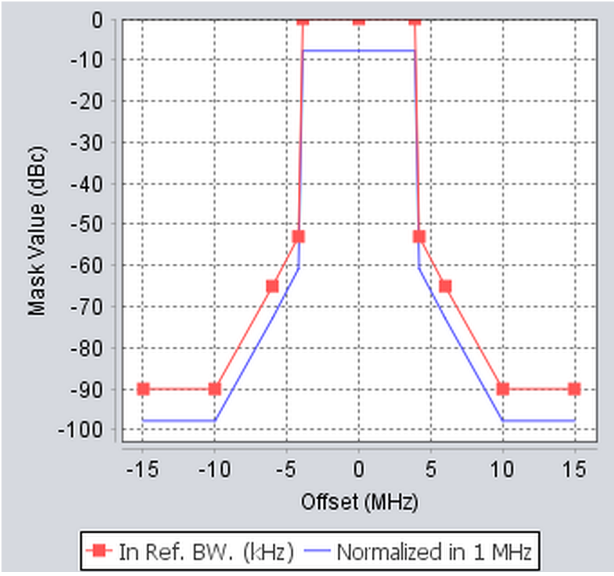

Figure 6.9: Emission mask utilised for the moving train. The red mask represents the defined reference bandwidth while the blue mask is normalised to 1 MHz measurement bandwidth

the VLR. On the other hand, $iRSS_{unwanted}$ for each interfering link can be obtained from

$$iRSS_{unwanted} = emission_{ILT}(f_{ILT} - f_{VLR}) + g_{ILT}^{PC} - PL_{ILT \to VLR} - G_{ILT \to VLR} + G_{VLR \to ILT} \tag{6.2}$$

where $emission_{ILT}(f_{ILT} - f_{VLR})$ is the relative emission mask as a function of the ILT frequency f_{ILT} and the VLR frequency f_{VLR}. The emission mask defined for the moving train in this case study is shown in Figure 6.9. g_{ILT}^{PC} is power control gain for the ILT, $PL_{ILT \to VLR}$ is the path loss between the ILT and the VLR, $G_{ILT \to VLR}$ is the ILT antenna gain towards the VLR, and $G_{VLR \to ILT}$ is the VLR antenna gain in the direction of the ILT.

6.6 Simulation Validation

Various validation results are shown in this section to demonstrate the fidelity of the presented simulation environment. The results include locations for both intracell and intercell handovers, the RSSI chart, and the control messages needed to complete the handover process for each protocol. As the train reports its location periodically, it becomes an easy task for the simulation environment to detect the locations where a handover is required. Similarly, the simulation environment can recognise the time when the train moves from the coverage of one AP to another. According to the IEEE 802.22 standard, intracell handover is needed at every pixel (i.e. a 100 m x 100 m square) where an operational parameters update is required, while intercell handover is needed when the train changes the associated AP.

Figure 6.10 shows the handover locations for a train travelling between Selly Oak and New Street stations and utilising the IEEE 802.22 standard. Fifty-three intracell handovers are present for a travel distance of 5 km. In addition, two intercell handovers were needed between the three deployed APs. These handovers correspond to the spatial restrictions set by the IEEE 802.22 standard, stated in Chapter 3 in Table 3.1.

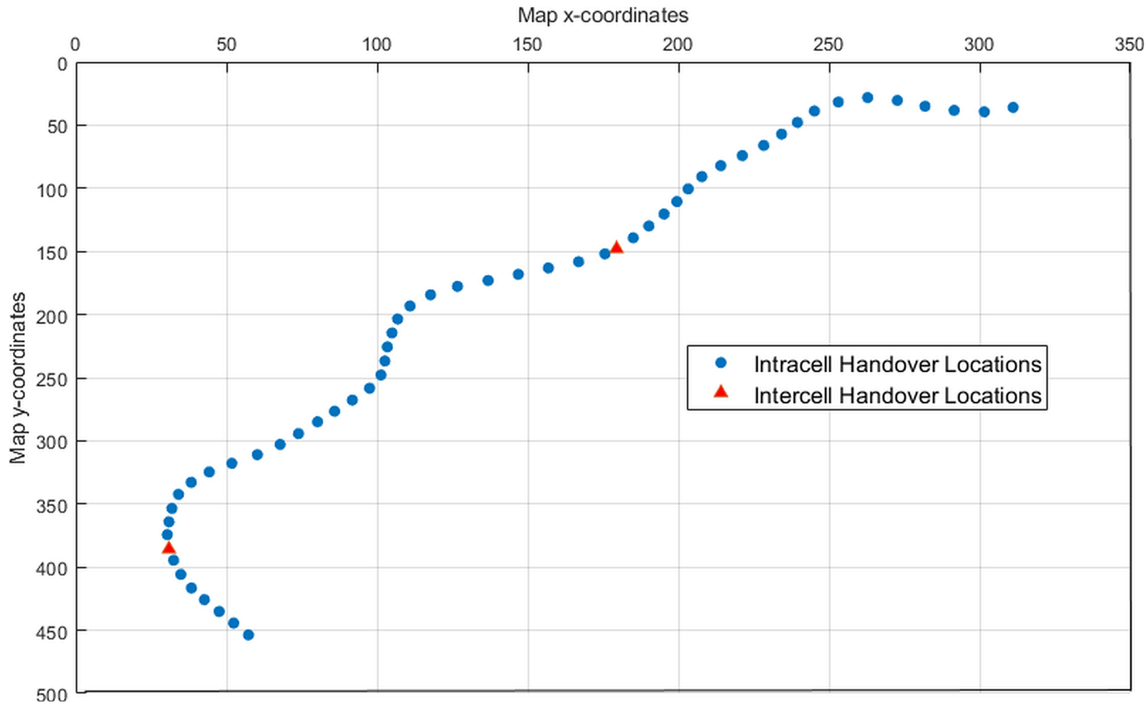

Figure 6.10: Handover locations under the IEEE 802.22 standard. The intracell handovers (blue) take place under the coverage of the same AP before the execution of intercell handover (red) that represents the transition to the coverage of a new AP

Figure 6.11 is another indicator of intercell handover. The graph shows the signal quality received at the first train from three APs at different simulation times. The signal drops when the train moves away from AP1 in the direction of AP2 and executes the first handover at t = 61.14 seconds (1.019 minutes) and the second handover to AP3 at t = 185.94 seconds (3.099 minutes) from the simulation start, as shown in the figure.

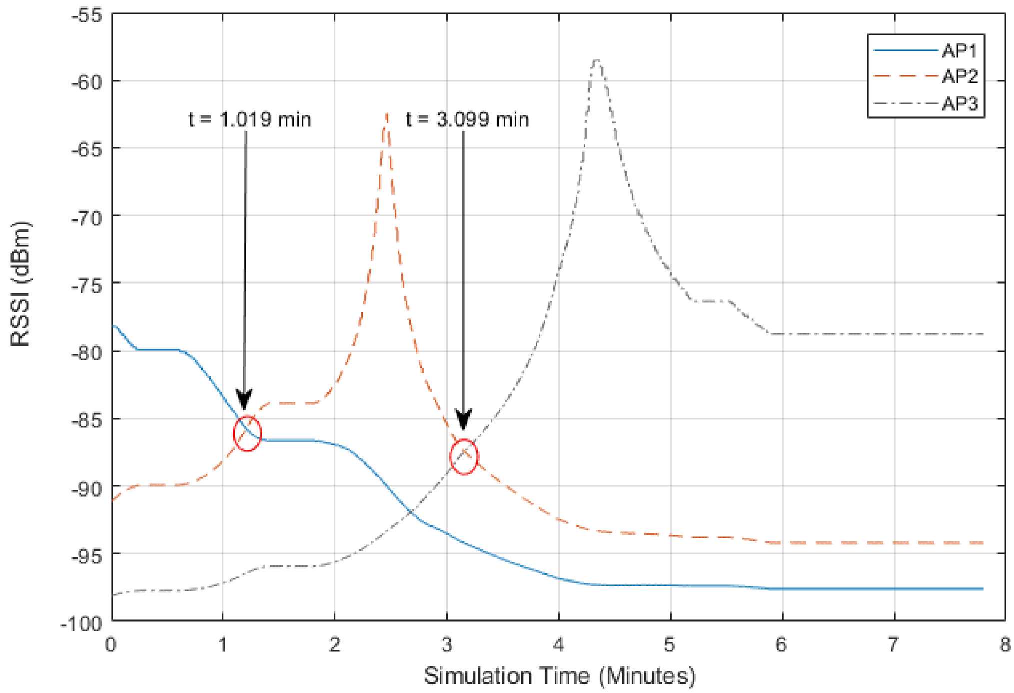

Figure 6.11: RSSI measured throughout the whole experiment that confirms the intercell handover between APs

In addition, Figures 6.12 and 6.13 show the control messages exchanged when a handover is triggered. In the IEEE 802.22 standard, when the train crosses a single pixel, it must end its transmission by sending an End of Transmission (EOT) message then search for an available channel in the new pixel. Once found, the train sends a registration request packet (REG_REQ) and waits for the AP confirmation (REG_RSP) before starting to transmit the data again, as shown in Figure 6.12. This process is repeated every 100 m in case of the IEEE 802.22 standard; however, in the newly proposed handover scheme, this process is only needed when the channel allowed utilisation distance, defined as D in Algorithm 1, expires. By then, the train needs to consult the serving AP to obtain a new operating channel, as shown in Figure 4.8.

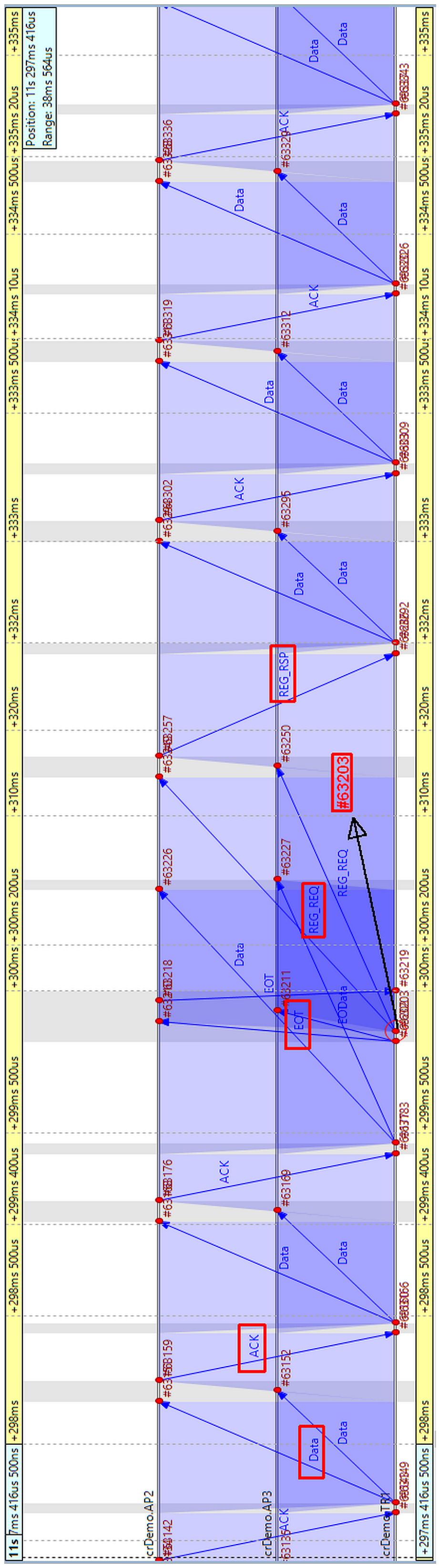

Figure 6.12: Control Messages for Intracell Handover using IEEE 802.22. The train ends its transmission by sending an EOT message searching for a new available channel, and registers to the new channel by sending a REG_REQ message at event (#63203)

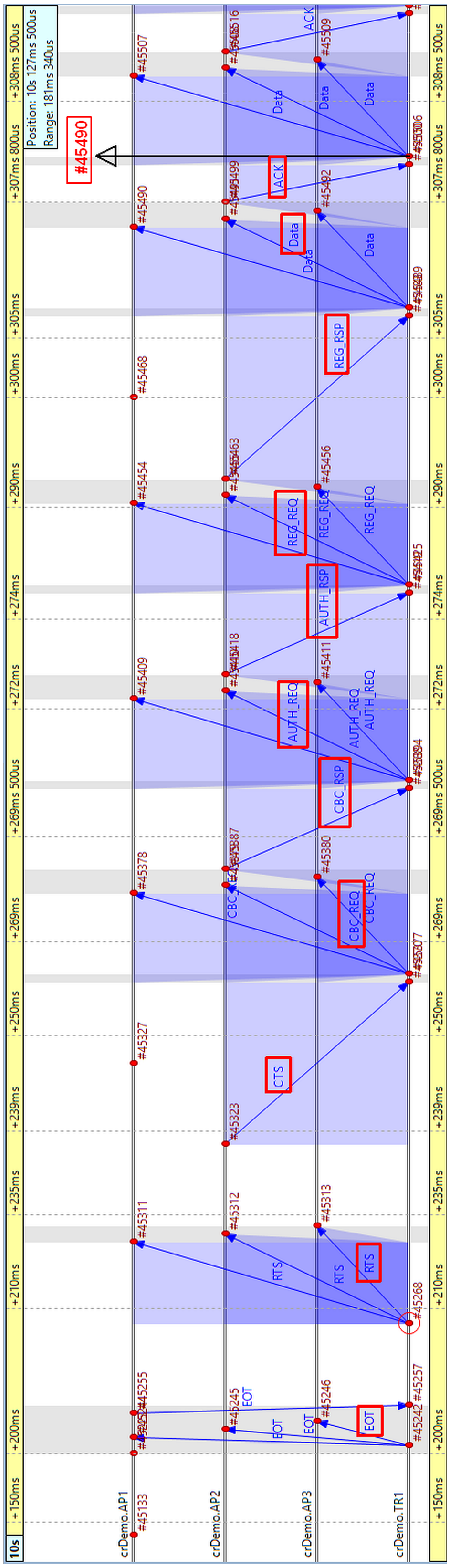

Figure 6.13: Control Messages for Intercell Handover using IEEE 802.22. The train ends its transmission with the old AP by sending an EOT message, and then sends an initialisation request (RTS) to get back to normal transmission with the new AP at event (#45490)

Similarly, for the IEEE 802.22 intercell handover, when RSSI drops under a certain threshold and the train approaches the border of the current serving AP, the train must cease its transmission and listen for beacons from the new AP, if any. Once found, the train sends a probe request (RTS), waiting for AP confirmation (CTS), then the train is able to send its basic capabilities (CBC_REQ), and get authenticated (AUTH_REQ) with the network before getting registered with the network and being able to send data normally, as shown in Figure 6.13. In the case of the newly proposed handover scheme, this process is only needed at T_0 when the train initially joins the network. Afterwards, a seamless intercell handover is executed, as the new channel will be reported through the old AP so that no time will be consumed in searching for new beacons or in the repetition of the authentication process, as detailed in Figure 4.9.

6.7 Simulation Results

In this section, the newly proposed handover scheme is compared to the conventional IEEE 802.22 standard in terms of the number of initialisation and registration requests, total transmitted data size, total number of utilised channels, consecutive channel utilisation distance (i.e. continuity of transmission), channels collision rate, and interference probability. These factors should be representative of the network coverage, reliability, data rate, and operational speed requirements mentioned in Chapter 2.

6.7.1 Number of Registration and Full Initialisation Requests

The full initialisation process under the IEEE 802.22 standard includes channel scanning, the authentication process, the registration process, and establishing IP connectivity. A train following the IEEE standard needs to follow the initialisation process under three main scenarios: when the train initially joins the TVWS network, when the train executes an intercell handover, and finally when the train moves from a pixel with no available channels to a new pixel where at least one channel becomes available. As the yellow bars in Figure 6.14 show, for spectrum availability that is ($\geq$ 30%), the train would only encounter the first two conditions to perform the full initialisation process (total requests = 3). However, in the event of low channel availability (i.e. 10% and 20%), the train will execute more initialisation requests (12 and 6 requests respectively) arising from the third case above.

Similarly, the IEEE 802.22 standard tends to send registration requests every time the train moves from one pixel to another under the coverage of the same AP given that there is an available channel in the new pixel. For medium and high channel availability ($\geq$ 30%), in blue in the bar chart in Figure 6.14, the train sends 53 re-registration requests which nearly correspond to the existing 54 pixels in the simulation. For lower availability (< 30%), there tend to be fewer registration requests as more initialisation requests take place.

On the other hand, under the newly proposed handover scheme, the full initialisation process is only needed when the train initially joins the network or when a train ceases a connection and reconnects again due to sudden PU appearance. Figure 6.14 shows that the full initialisation process (purple bars) is independent of the probability of channel availability. The number of full initialisation requests is constant at only one request, assuming accurate

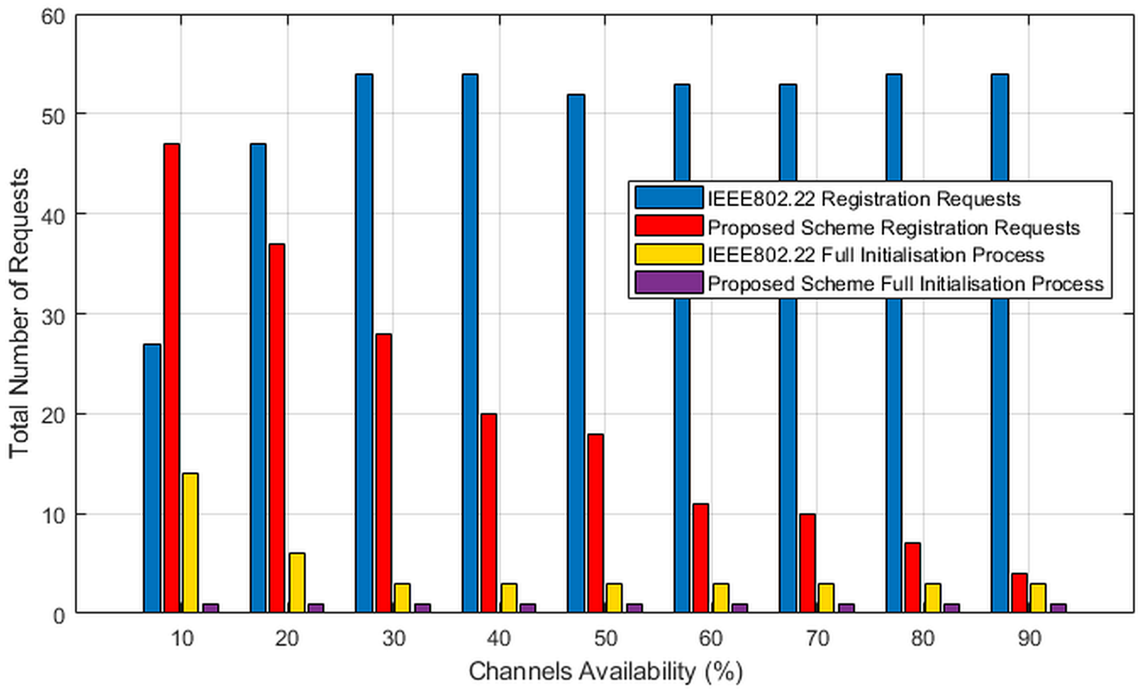

Figure 6.14: Total number of full initialisation and registration requests for the IEEE standard and the newly proposed method under various channel availability

modelling of the spectrum availability map and that no sudden PU appearance will take place. The PUs in this case study were assigned two private channels that the SUs cannot operate on.

The registration procedure is needed under the new approach when the allowed channel distance limit expires and the train needs to switch into another operational channel, or when the train moves under the coverage of the same AP from one pixel with no available channels to another pixel with at least one available channel. In the latter case, the scheme will notify the respective AP with areas where channels are not available. The train does not need to be disassociated from the network totally and will be able to re-register to the network when a new channel becomes available. In addition, the registration procedure is also needed when the train moves from the coverage of one AP to another.

The red bars in Figure 6.14 shows that channel switching is relatively high under low spectrum availability (< 30%). It is challenging to assign the same channel for long track lengths. When the channel availability increases ($\geq$ 30%), fewer channel changes are needed. The number of requests can reach up to 48 for 10% channel availability, 38 for 20% availability, and 28 for 30% availability. For higher channel availability, the number of requests keeps reducing until it reaches only three registration requests at 100% spectrum availability.

6.7.2 Transmitted Data Size

Sending a single registration request takes around 320 µs, whereas the full initialisation request takes around 1.024 s. The outcome of minimising these unnecessary requests is to have a direct impact on increasing the amount of transmitted data. Figure 6.15 shows that under any spectrum availability, the new approach provides better performance than the IEEE 802.22 standard. For low channel availability ($\leq$ 40%), an average of 12 megabytes of extra data was transmitted, as assigning the same channel for consecutive pixels was challenging. However, for higher spectrum availability (> 40%), an extra 27 megabytes of data was transmitted, which represents a 8% improvement in the amount of data transmitted using the new scheme. For a 5.8-minute journey for the first train and under various spectrum availability, the new scheme has improved the overall transmitted data size by 6.56% if compared to the IEEE 802.22 standard. Better performance is expected for longer journeys. The potential additional data transmission demonstrates a resilient RCM system to the unsecured continuous coverage under the TVWS spectrum. In the case of queued maintenance data or video, the train can offload more data using the developed approach compared with the IEEE 802.22 standard.

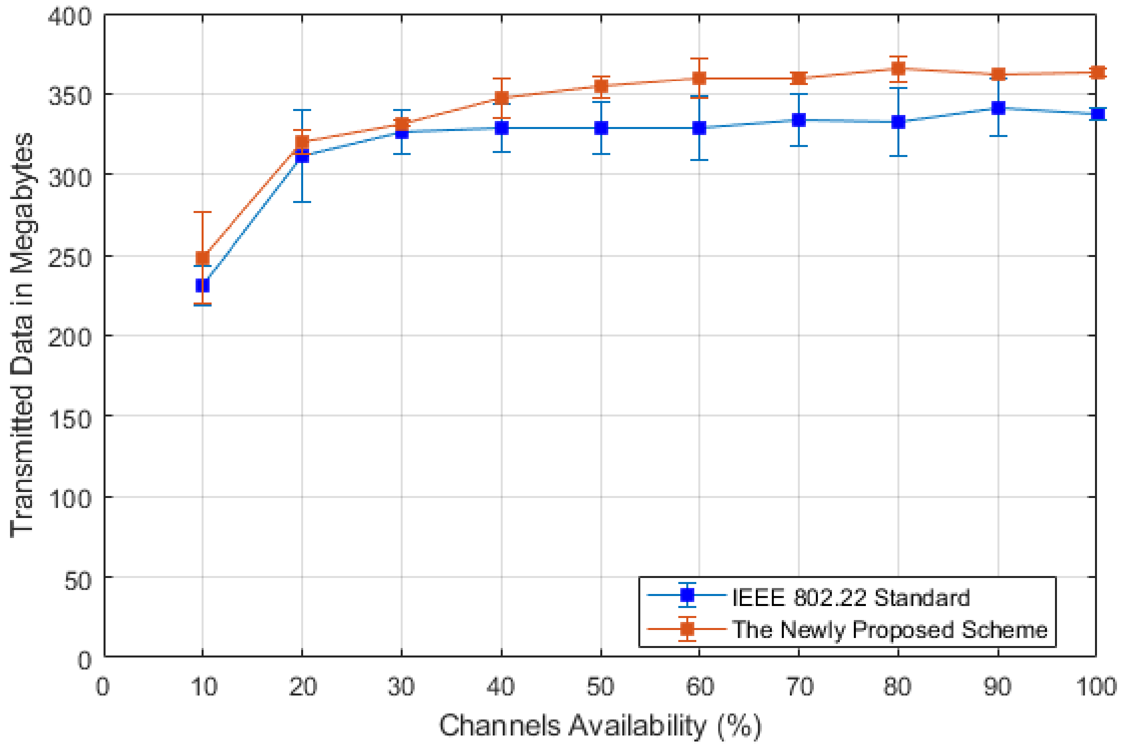

Figure 6.15: Size of transmitted data for the IEEE standard and the newly proposed scheme under various channel availability

6.7.3 Channel Collision Rate

Another factor to consider is the channel collision rate that can be defined as selection of the same channels within the same pixel by two different SUs (i.e. trains). In the presented case study, the two trains follow each other with a time gap of nearly 114 seconds as shown in Figure 6.2. The figure indicates the time when both trains started the journey and their speed profile moving from one pixel to another. The gap between the two trains prevents any existence of channel collision, as both trains tend to select the exact same channel list except in the case of PMSE appearance which forces the train to cease the connection and search for a new channel. Chapter 7 of this thesis quantifies the probability of channel collision for various channel access schemes on a larger simulated rail network.

6.7.4 Consecutive Channel Utilisation Distance

Figure 6.16 shows the average consecutive distance where one channel can be used under different channel availability for both the IEEE 802.22 standard and the newly proposed method. The plots tend to be similar at the beginning and start to diverge at a spectrum availability that is ($\geq$ 30%). Utilising the new approach enables the usage of one channel for an average of 11.88 pixels under various spectrum availability compared with 8.62 pixels for the IEEE 802.22 standard. As each pixel represents movement of 100 m in this case study, this result indicates a channel utilisation distance of 1.188 km using the new scheme and only 0.862 km for the IEEE 802.22 standard, which represents a 37.8% improvement. Using the same channel over long distances is an indicator of transmission continuity required for the real-time video transmission in some RCM systems.

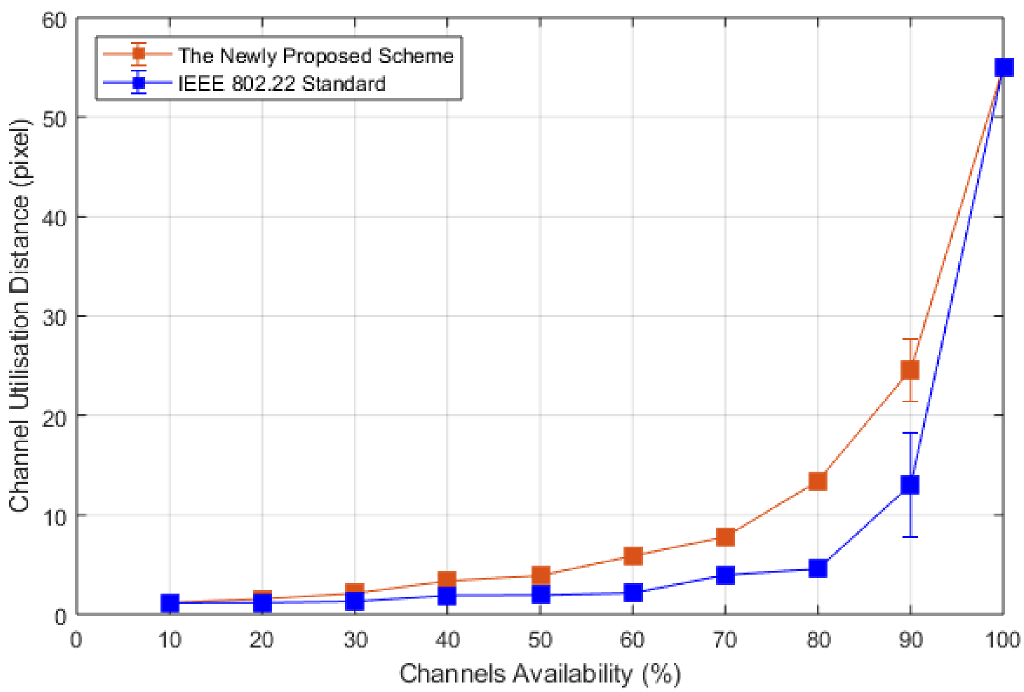

Figure 6.16: Channel utilisation distance for both the IEEE 802.22 standard and the newly proposed scheme

6.7.5 Interference Probability and Allowed Transmission Power

Co-channel interference is the cross-talk from two different transmitters using the same frequency. The interference occurs when the C/I drops under the 19 dB protection contour. For each pixel, C/I was calculated for both the IEEE 802.22 standard and the newly proposed scheme. Figure 6.17 indicates that both approaches provide nearly identical performance regarding PU interference. C/I was 50 for 10% spectrum availability and reached up to 100 for 100% availability, both results representing 0% interference caused to the PUs. According to the previous graph, the ILT (e.g. moving train) can operate using higher transmission powers while keeping a safe margin to the C/I critical limit.

Figure 6.18 shows the new allowed transmission power under various channel availability. The initial ILT transmission power used for this simulation was 20 dBm; however, by using the new scheme, the transmission power can be increased to 34 dBm for 10% channel availability and 45 dBm for 100%. Increasing the transmission power will enable the railway communication network to have a higher system throughput while providing full protection to the system PUs.

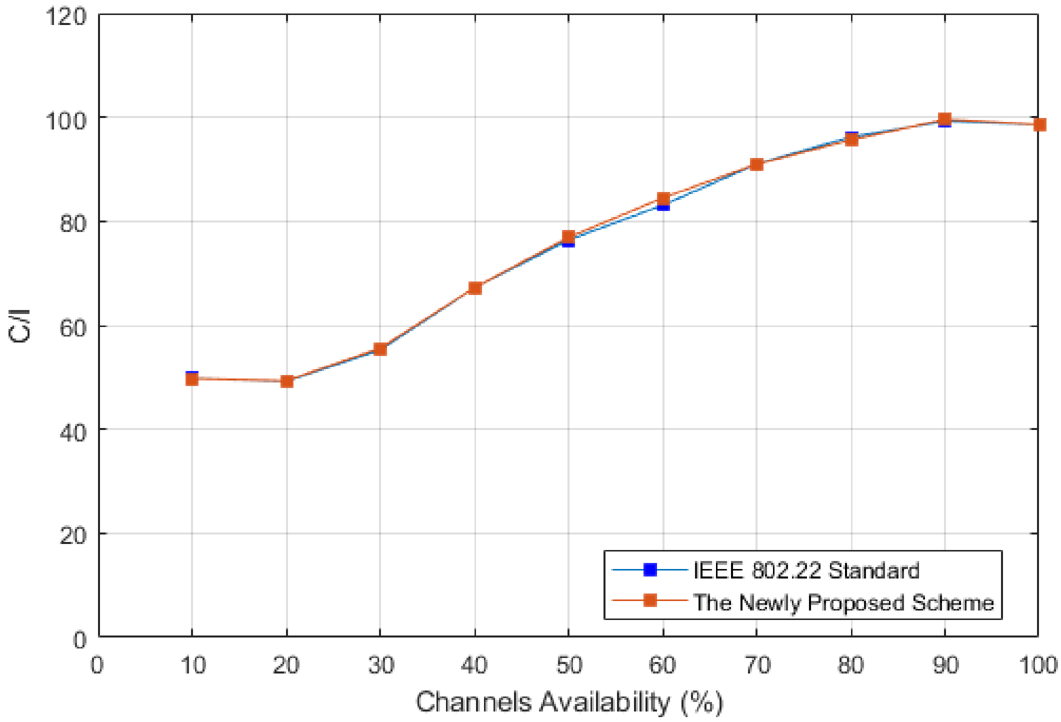

Figure 6.17: Measured C/I for varying channel availability using both the IEEE standard and the new scheme

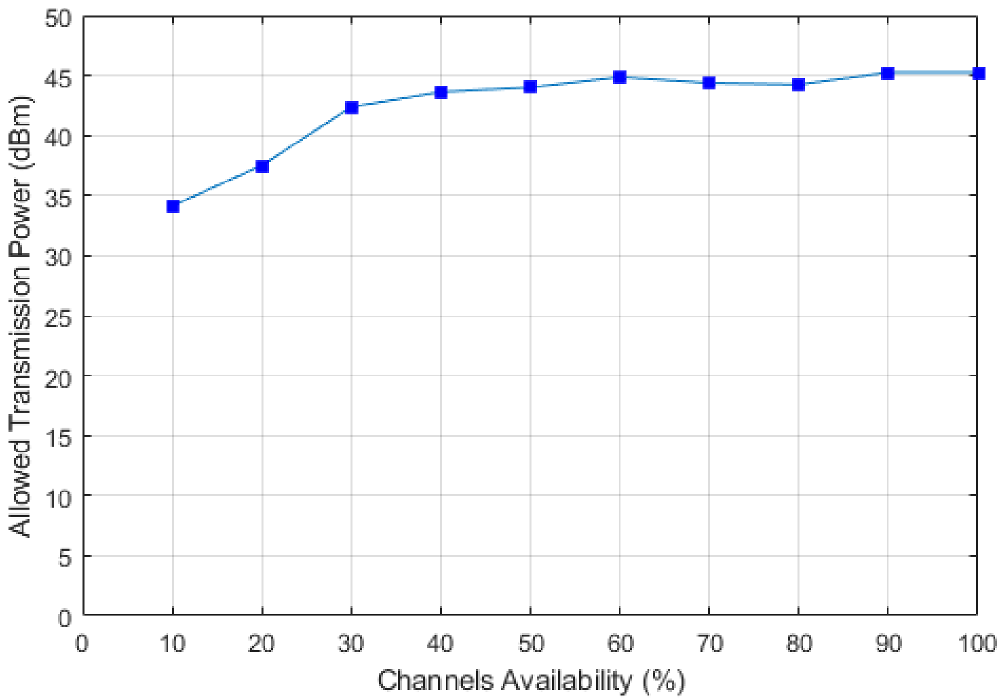

Figure 6.18: Allowed transmission power for a moving train (i.e. ILT) under the new scheme

6.8 Chapter Summary

This chapter focuses on evaluating the ability of the proposed scheme to meet the coverage, reliability, throughput, and line speed requirements of RCM systems. Although the greedy algorithm assumes equivalent features for each channel in terms of frequency and allowed transmission power, evaluating the algorithm and the proposed handover scheme gives valuable insights for the performance of mobile platforms operating in the TV bands.

The scheme is compared with the IEEE 802.22 standard whose results are considered as a benchmark. In terms of the coverage geography, both schemes do not have any impact on the spectrum availability at different locations. However, the database-centred approach and knowledge of the train's trajectory (i.e. location and speed) enable the new approach to account for areas with no available channels. Therefore, under low spectrum availability ($\leq 30\%$), the train only needs to disassociate temporarily from the network in areas with spectrum unavailability, and re-registers when a new channel becomes available. Besides that, at higher spectrum availability ($\geq 40\%$), the new approach takes advantage of prior knowledge of the spectrum availability to select channels that last for long distances, which minimises unnecessary control messages overhead. The total number of initialisation and registration requests represents a successful strategy for dealing with the variable coverage geography.

For coverage continuity, by utilising the new approach, a single channel can be used for an average consecutive distance of 1.188 km using the new scheme and only 0.862 km for the IEEE 802.22 standard under various levels of spectrum availability. Using the same channel over long distances is an indicator of transmission continuity required for the real-time video transmission in some RCM systems.

As the throughput was assumed to be fixed at 5 Mbps for this simulation, the size of transmitted data during the journey was measured. Under various spectrum availability, the new scheme allows the transmission of 6.56% more track-health data when compared with the IEEE 802.22 standard, due to the reduction of unnecessary registration and initialisation requests. The potential additional data transmission demonstrates a resilient RCM system to the unsecured continuous coverage in areas with low TVWS spectrum.

Both systems gave identical interference performance, causing no interference to the surrounding PUs (i.e. reliability measure). However, the new scheme enables better transmission power that can reach up to 42.2 dBm for SUs under different channel availability, which will have a direct impact on the total network throughput. For a more realistic scenario, the next chapter evaluates the proposed channel assignment scheme in a busier network in order to obtain a reasonable value of the DCI and to investigate the factors that affect the algorithm scalability.

Chapter 7

Impact of Train Mobility on TVWS Channel Access Policies

7.1 Introduction

The last chapter focused on evaluating the newly proposed scheme and comparing its performance with the IEEE 802.22 standard using a small-scale network of two trains. This chapter focuses on applying the proposed methodology on a medium-scale network to identify the factors that would influence the method's scalability. First, the chapter introduces different aspects of the train's mobility. Then, the chapter defines the simulation parameters used in the new case study that includes a network of 10 trains travelling between Bournville and New Street stations in Birmingham, UK. Next, various channel reservation policies and their relationship with the train's mobility model are evaluated. Finally, the chapter evaluates the performance of the proposed channel reservation policy in accommodating potential train delays and minimising the blocking probability of the TVWS network.

7.2 Train Mobility Model

As stated previously, UKPM holds spectrum information for each 100 m x 100 m geographic square (pixel). The coexistence of multiple trains within the same pixel and the separation distance between successive trains have a direct impact

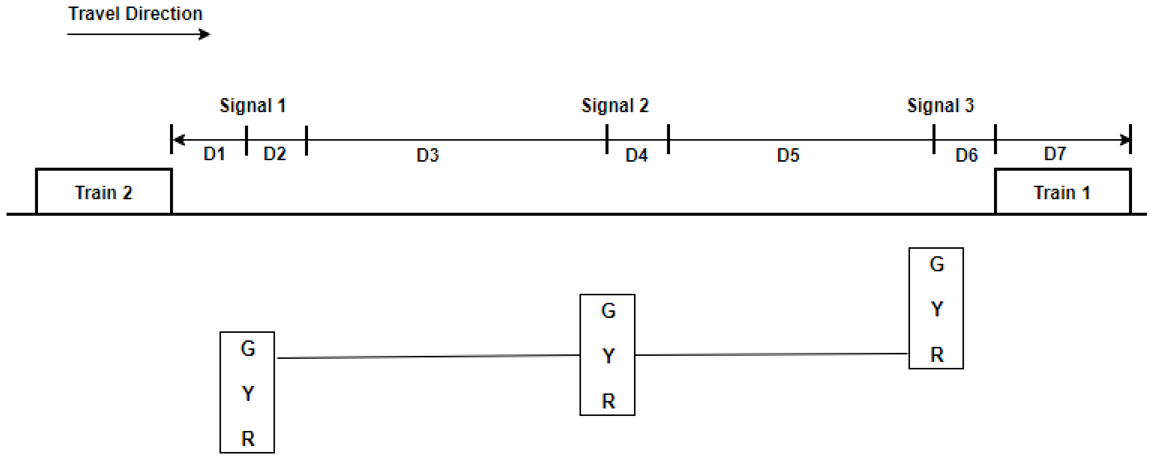

Figure 7.1: Headway calculations for fixed block signalling systems

on the performance of spectrum assignment strategies proposed in this chapter. This section discusses an essential aspect of train mobility known as the line headway before identifying the cases where two trains could coexist within the same pixel.

7.2.1 Headway Calculations

Trains travelling in the same direction are always separated by a safety distance that enables the second train to stop in case of emergency. The time needed to cover this distance, given that the second train is running under a clear signal, is defined as the line headway. The headway's numerical value is dependent on the signalling system deployed, which is discussed in the following subsections.

7.2.2 Fixed Block Signalling System

In a fixed block signalling system (e.g. ETCS Level 2), the network is divided into sections knows as blocks or sections. Two trains cannot occupy the same section of track at the same time. Line-side signals in traffic light form are one of the methods used to indicate the status of the block ahead. Three-aspect signalling is usually used for the mainline train service where two empty blocks exist between the moving trains, as shown in Figure 7.1. A green light (G) indicates the next section is clear, a yellow light (Y) means caution as the following signal will be Red (R), and that is where a stop is required. In the case of a three-aspect fixed block signalling system, the overall headway t can be expressed as follows:

$$t = \frac{D1 + (D2 + D3) + (D4 + D5) + D6 + D7}{v}, \tag{7.1}$$

where $D1$ is the distance between the second train and the first signal. This distance allows the driver to notice the signal ahead clearly. $(D2 + D3)$ and $(D4 + D5)$ are the block distances between signal 1 and signal 2, and signal 2 and signal 3, respectively. $(D4 + D5)$ is added to represent the braking distance needed by train 2 to stop by the red signal 3. $D6$ is the overlap distance between signal 3 and train 1, $D7$ is the length of the first train, and v is the speed of the second train.

7.2.3 Moving Block Signalling System

The main challenge of a fixed block signalling system is to size the block distances for optimum headway and maximum safety at the same time. On the other hand, the concept of moving block signalling systems (e.g. ETCS Level 3), shown in Figure 7.2, was introduced to enhance line capacity, especially with the advance of train detection mechanisms. Now, the track is being dealt with as a continuous guideway rather than being divided into smaller chunks. The overall headway t in a moving block signalling system can be expressed as follows:

$$t = \frac{D1 + D2 + D3 + D4}{v}, \tag{7.2}$$

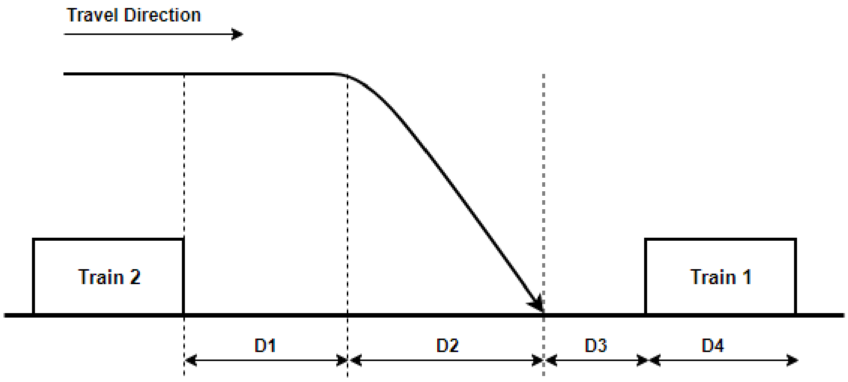

Figure 7.2: Headway calculations for moving block signalling systems

where $D1$ represents the safety separation distance between the moving trains, and is a function of the second train's speed. $D2$ is the braking distance of Train 2, while $D3$ is an additional safety margin. Finally, $D4$ represents the length of the first train. Unlike the fixed block signalling system, $D1$ and $D2$ are not static but rather depend on the train's speed and acceleration/deceleration class, which drastically enhances the overall line capacity.

Moreover, emerging signalling concepts such as the virtual coupling in ETCS Level 4 aim to improve the line capacity further by reducing the line headway to a minimum (Mitchell *et al.*, 2016). The approach depends on train-to-train communications where the braking points of the first train are continuously reported to the following train to act accordingly.

This case study considers a fixed block signalling system as a starting point to study the impact of headway on the TVWS channel booking policies presented in this chapter. The simulated network consists of nine trains travelling in the same direction and only one train is moving in the opposite direction, as shown in Figure 7.3. The figure also demonstrates the starting pixel of each train, dwelling time at on-route stations, and locations where each train intersects with others. The line headway between travelling trains is variable. It can be as low as 12 seconds between TR5 and TR6 while dwelling at New Street station, and it

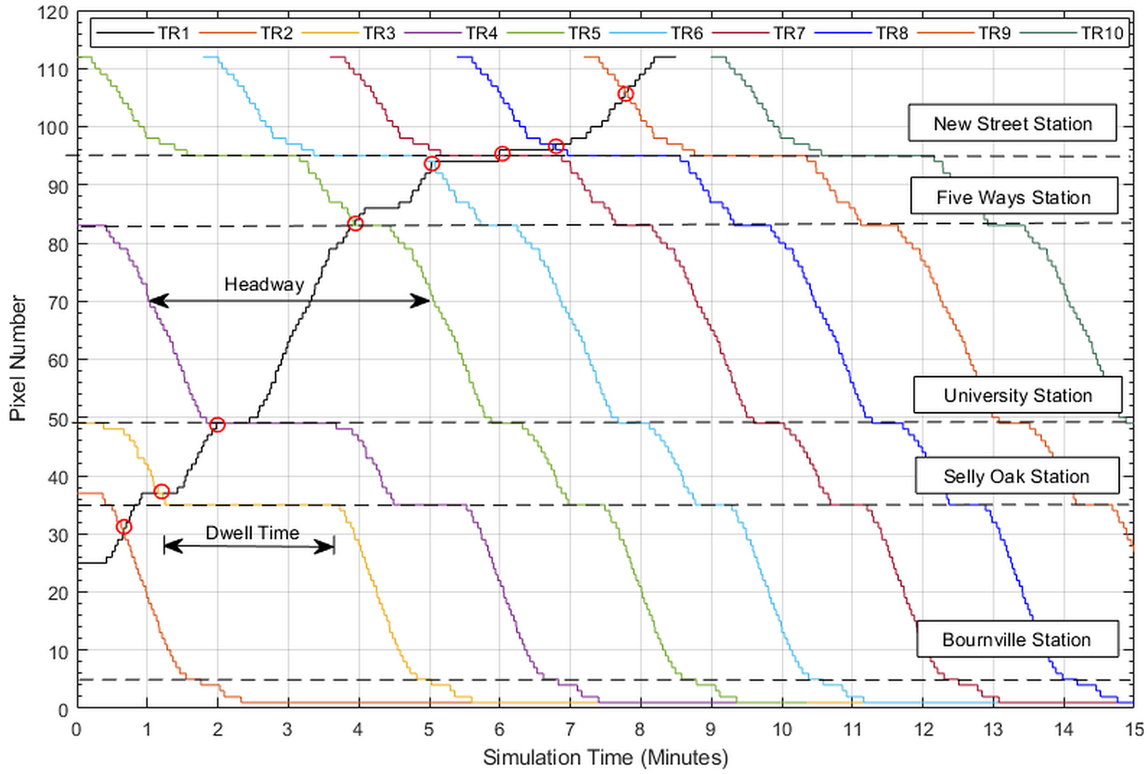

Figure 7.3: Location of simulated trains, expressed as a pixel number, at any given simulation time

can reach up to a maximum of 240 seconds between TR4 and TR5 from t = 86.34 seconds (1.439 minutes) to t = 327.6 seconds (5.46 minutes).

7.2.4 Coexistence of Trains in One Pixel

The second element to consider in the train mobility model is the probability of multiple trains to coexist within the same pixel. Co-located trains have a direct impact on the channel booking strategies, as a single channel can be assigned to multiple trains if asynchronous access to the database spectrum is adopted. The concept of asynchronous access and its consequences will be discussed later in this chapter.

In a railway context, pixel coexistence can occur under three main scenarios:

- In a double track environment, two trains travelling in opposite directions will intersect with each other within the same pixel.
- On busy routes, more than two parallel tracks can be used. In this case, multiple trains can coexist in the same pixel.
- Multiple trains travelling in the same direction can also coexist within the same pixel in if the train length and the safety distance between consecutive trains are minimised (i.e. Hyperloop-like scenario (Ross, 2015)).

As a starting point, the case study in this chapter simulates the first scenario where only one train (i.e. TR1) intersects with trains travelling in the opposite direction (i.e. TR2 -> TR10) in the red-highlighted points, as shown in Figure 7.3. This scenario limits the trains' interaction to thoroughly investigate the relationship between trains coexistence and the efficiency of channel booking policies before introducing the scalability factor into the equation.

The following sections of this chapter highlight the parameters used for this case study. Afterwards, the results obtained from this case study are compared with the results of the previous case study as a consistency check for the developed simulation environment. Finally, channel allocation policies are introduced and assessed in Section 7.6.

7.3 Train and Track Environment

This case study simulates 10 trains of British Rail Class 323 having a maximum speed of 144 km/h, length of 20 m per carriage, and each consisting of three carriages. Due to the infrastructure speed limitation, the trains' maximum speed is limited to 96 km/h. There is no tunnel environment considered in this case study. All the trains stop at New Street, Five Ways, University, Selly Oak, and

Bournville stations. Their dwelling times are determined by each train's mobility model, as shown in Figure 7.3.

7.4 Network and Simulation Parameters

All of the SU network parameters considered within this case study are identical to the parameters used in the case study of Chapter 6. The network parameters are taken from the IEEE 802.22 standard (IEEE 802.22 Working Group, 2011). However, as this case study simulates a bigger network, the rail line is being covered with four partially overlapping AP coverage areas of 1.5 km, as shown in Figure 7.4. TR1 attempts to transmit 520 megabytes of track-measured data within a total journey time of 8.5 minutes for TR1 and a total simulation time of 900 seconds for TR1 to finish its journey. The simulation was run on a computer that has an i7 3.60 GHz CPU and 12 GB of RAM, and it took 1860 seconds to complete the journey of the 10 introduced trains.

7.5 Validation Results

Validation results are shown in this section to check the consistency of the developed simulation environment before introducing TVWS channel booking strategies in the next section. The presented results are reflective of the TR1 performance that is independent of the channel booking policy applied. This section shows TR1's RSSI chart, the number of registration and initialisation requests, and the size of transmitted track data for the same train.

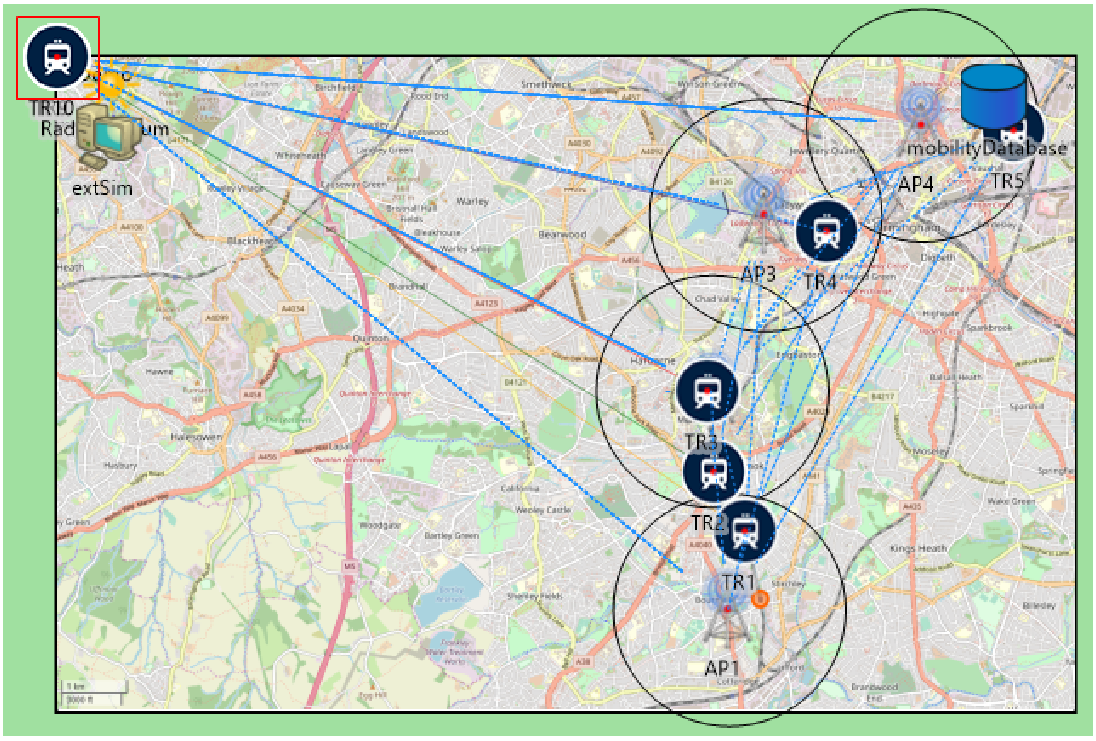

Figure 7.4: OMNET++ shows the simulated wireless network that consists of 4 APs and 10 trains, 5 of which start at the same time

7.5.1 RSSI from Deployed APs

Figure 7.5 is an indicator of the time when TR1 performs intercell handovers between the deployed APs. TR1 starts at the edge of AP1 and it executes the first handover at t = 41.94 seconds (0.699 minutes). Then, TR1 spends nearly 146.46 seconds (2.441 minutes) under the coverage of AP2, where RSSI reaches a maximum of −41 dbm. The second handover from AP2 to AP3 occurs at t = 188.4 seconds (3.14 minutes). Finally, TR1 executes the last handover to AP4 at t = 291.66 seconds (4.861 minutes) from the simulation start.

7.5.2 Number of Registration and Full Initialisation Requests

Under the scheme proposed in Chapter 4, the full initialisation process is only needed when the train initially joins the network or when a train ceases the

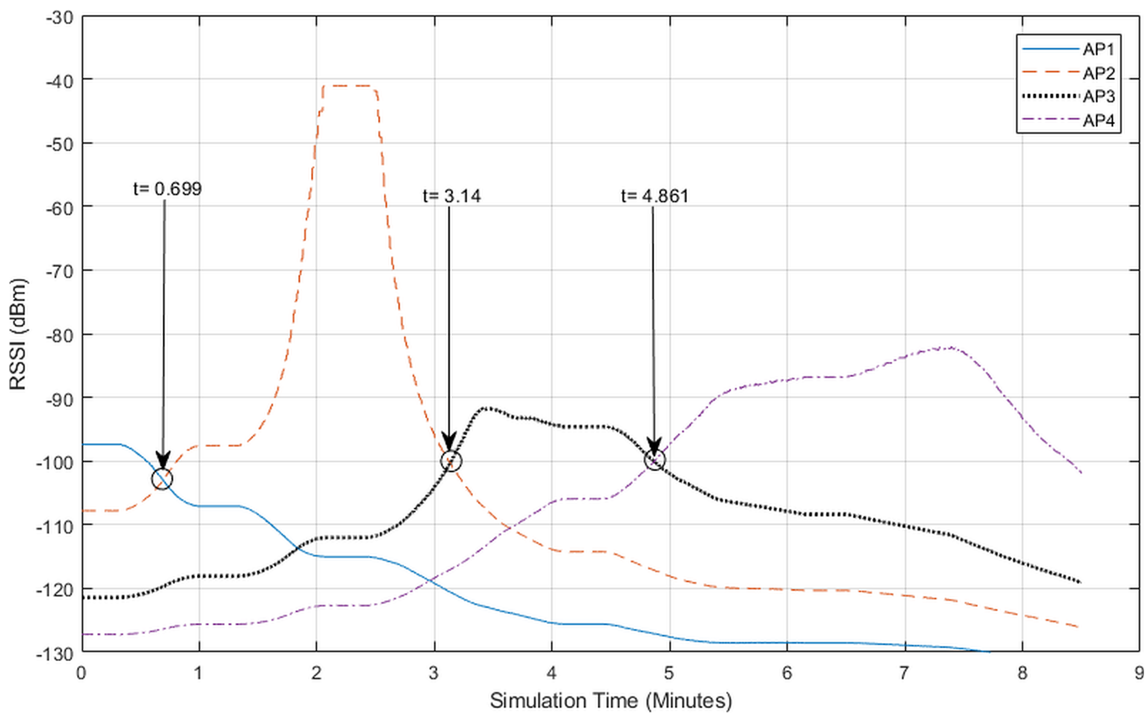

Figure 7.5: RSSI measured throughout the whole experiment that confirms the intercell handover between APs for TR1

connection and reconnects again due to sudden appearance of a PU. As there was no sudden PU appearance introduced in this case study, the red bars in Figure 7.6 indicates one full initialisation request under various channel availability as a result of TR1 initially joining the network.

The registration procedure is needed under the new approach when the allowed channel distance limit expires and the train needs to switch into a new operational channel under the coverage of the same AP. The registration procedure is also needed when the train moves from the coverage of one AP to another. The blue bars in Figure 7.6 indicate the number of registration requests needed in this case study under various channel availability. Channel switching is relatively high under low spectrum availability (< 30%) as it is challenging to assign the same channel for long track lengths. When the channel availability increases ($\geq$ 30%), fewer channel changes are needed. The number of requests decreases to reach 64 requests for 10% channel availability, 52 requests for 20%

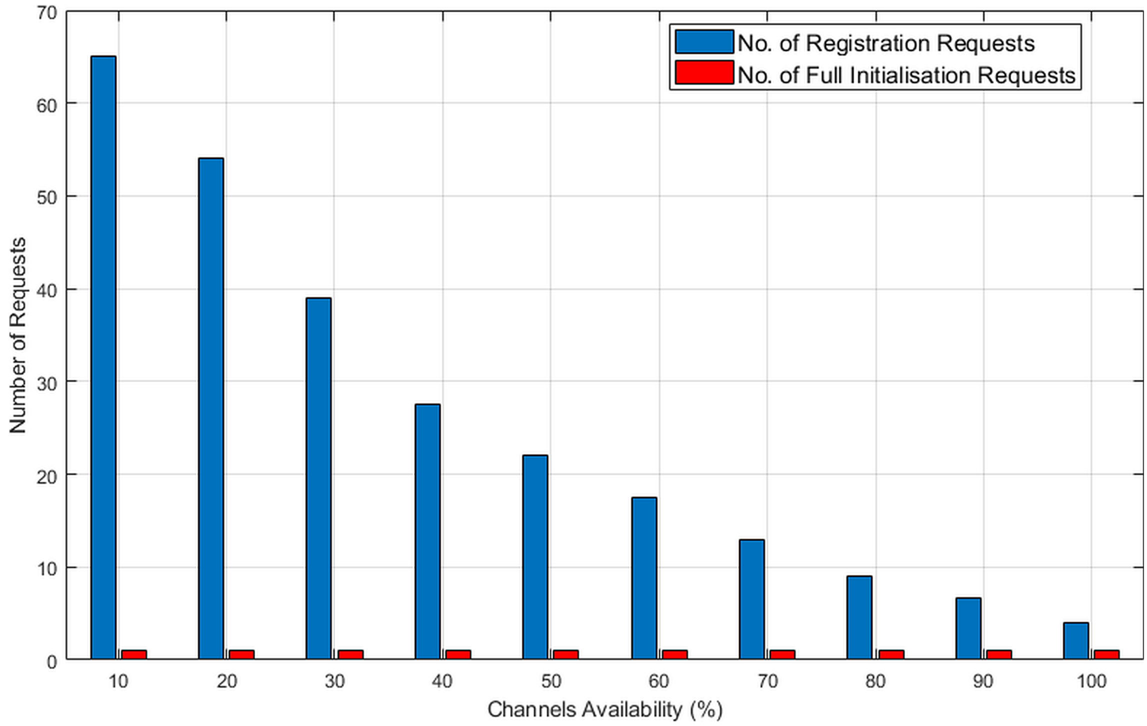

Figure 7.6: Total number of full initialisation and registration requests for TR1 under various channel availability

availability, and 39 requests for 30% availability. For higher channel availability, the number of requests keeps dropping until it reaches three requests for 100% spectrum availability.

The journey duration of TR1 has increased in this case study to 8.5 minutes compared with a journey time of 5.8 minutes in the previous case study of Chapter 6, as shown in Figure 7.7. The longer journey duration allows TR1 to travel longer distances as it crosses 86 pixels in this case study compared with 54 pixels in the previous case study. The rise in the number of pixels crossed results in an increase in the total number of registration requests.

Besides that, the method used to determine the transition from one pixel to another in both case studies has been changed. In the previous case study, the train was assumed to follow a straight path where a pixel change only takes place every 100 m of movement. However, in this case study, for a more realistic

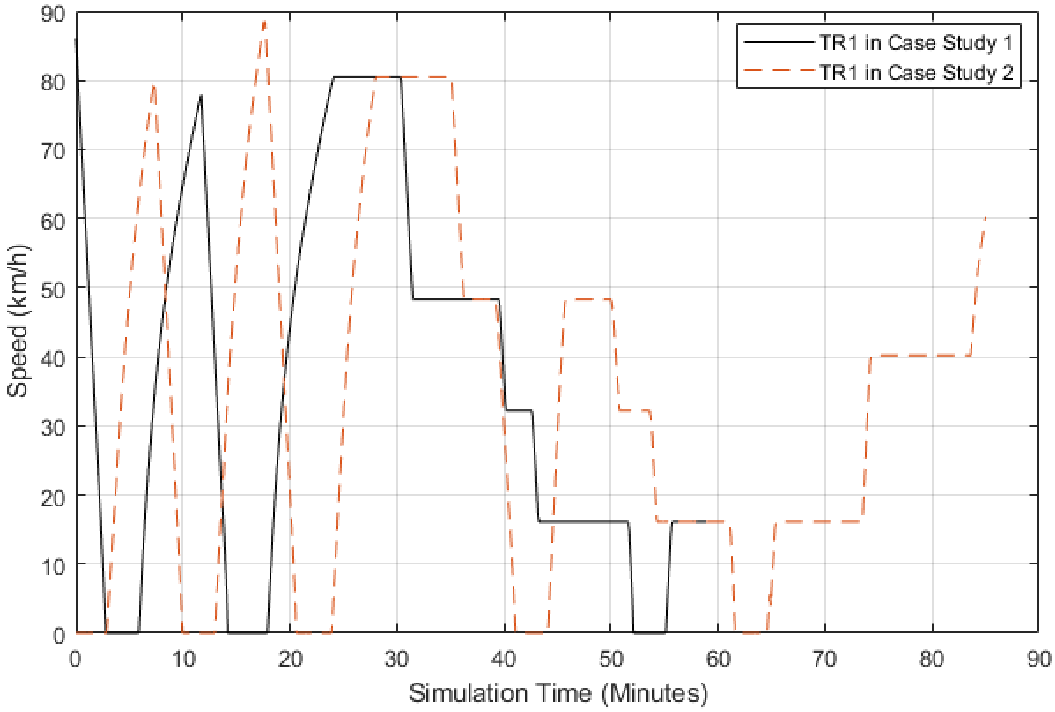

Figure 7.7: TR1's speed profile in both case studies

simulation, the whole area of impact was divided into pixels where the train does not have to complete 100 m of movement to transit from one pixel to another. Appendix B details the method that determines the pixel change for both case studies as part of the OMNET++ mobility module.

7.5.3 Transmitted Data size

The last parameter to consider in this section is the size of the track data transmitted by TR1. As indicated in Figure 7.7, The trajectory of TR1 in the two case studies is not identical. In the second case study, TR1 stops at four stations compared with only three stations in the first case study. In addition, TR1 starts the simulation in a stationary state in the second case study, which gives time to transmit more data in case a TVWS channel is available. All of these factors allow the transmission of more measured track data, as shown in Figure 7.8. For

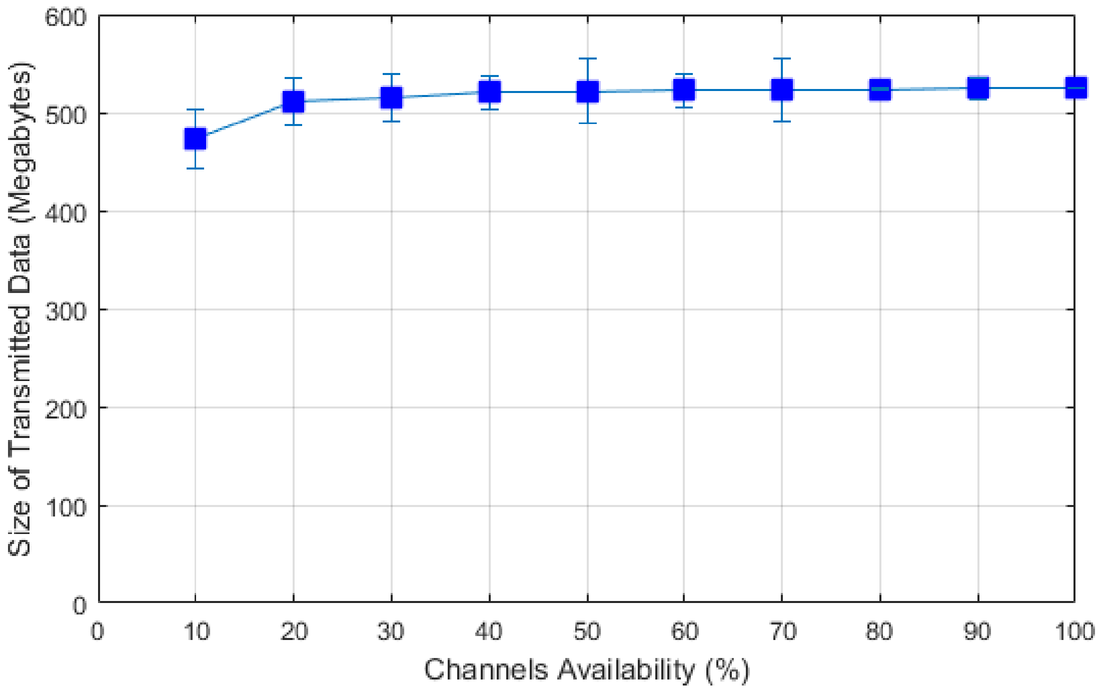

Figure 7.8: Size of transmitted data for TR1 in the second case study under various channel availability

a spectrum availability of 10%, the transmitted data size reaches 480 megabytes and keeps increasing until it reaches up to 520 megabytes for 100% spectrum availability. On the other hand, in the previous case study, the transmitted data size was 248 megabytes for 10% spectrum availability and 363 megabytes for 100% using the new proposed method.

7.6 Channel Allocation Policies

This section analyses the relationship between train mobility and various channel allocation schemes. First, asynchronous access to the spectrum database is presented, quantifying the induced probability of channel collision. Then, the section evaluates the blocking probability of synchronous access to the spectrum database, where a channel is booked for the train's whole journey and cannot be reused by other SUs. Finally, the section assesses the performance of the methodology proposed in Chapter 4, which accommodates possible train delays and enables TVWS channels to be reused by other SUs.

7.6.1 Asynchronous Access to the Spectrum Database

In this chapter, the simulation starts with five trains (TR1 -> TR5) which access the spectrum database at the same time from different starting pixels. As shown in Figure 7.3, the other five trains (TR6 -> TR10) join the network at a later simulation time and request a list of operating TVWS channels consecutively. The section aims to quantify the risk of channel collision between the first five trains, in case the spectrum database lacks access prioritisation.

A channel collision is defined as the situation when two or more trains attempt to access the same transmission channel at the same time. Referring to Figure 7.3, TR1 coexists with TR2, TR3, TR4, and TR5 in pixels 31, 37, 49, and 83, respectively. Figure 7.9 presents the probability of channel collision between the first five trains under various channel probability. Under low spectrum availability ($\leq$ 40%), the trains tend to select only the available operating channels which cause a collision probability of 90% at 10% channel availability. The collision probability drops to 55% at 40% spectrum availability. As more channels become available ($\geq$ 50%), the database tends to assign a single channel for each train as long as possible to minimise the channel switch. That results in reducing channel collision as each train adheres to its pre-selected channel list. With a different starting pixel for each train, the probability of channel collision drops to 45% for 50% channel availability and keeps dropping until it reaches 25% for 100% channel availability. Channel collision causes co-channel interference that directly affects the overall performance of the TVWS network.

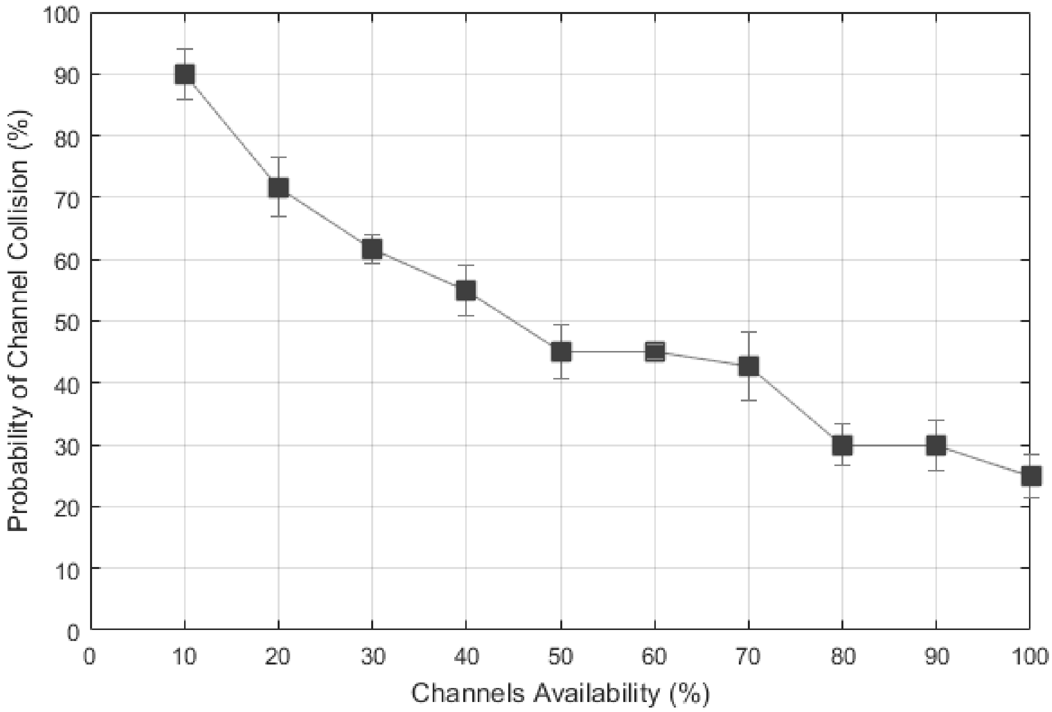

Figure 7.9: Probability of channel collision for asynchronous spectrum access under various channel availability

7.6.2 Synchronous Access to the Spectrum Database

In this section, the approach of prioritising database access on a first-come-first-served basis is presented. The case study consists of 10 trains, five of which start at the same time, (see Figure 7.3). The database access priority of the first five trains (TR1 -> TR5) is assumed initially as a proof of concept to be based on their number. In other words, TR1 has priority over TR2, TR2 has priority over TR3, and so on. In future work, the access prioritisation should consider other factors that include the safety nature of the deployed railway application. The succeeding trains (TR6 -> TR10) arrive at different time intervals, and that is when they gain access to the spectrum database. When a train accesses the database, the database is locked until an operational channel list is generated, and the channel availability map is updated. Then, the spectrum database is released and can be accessed by the next train on the list.

This section aims to evaluate the handover schemes proposed by Lee and Jeong (2014) and Kim *et al.* (2015). As the presented methods do not track the vehicle's location, the status of the assigned channels is not updated until the end of each train's journey. This section investigates the cost of this approach on the blocking probability of both the overall TVWS network and the last train accessing the spectrum database. Here, TR9 is considered as the last train instead of TR10, as it travels for a longer distance and its performance is more representative, (see Figure 7.3).

7.6.2.1 Blocking Probability

Iversen (2015) defines the blocking probability in telecommunication systems as the possibility that CPE will be denied the service due to lack of resources (e.g. channels). Consequently, user requests are either queued, in delay systems, or completely dropped in lost-call systems. This research considers a lost-call system that blocks connection attempts if all TVWS channels are in use. Erlang loss formula is usually used to estimate the blocking probability in large systems where users follow a similar calling patterns and an arrival rate that can be described by a Poisson distribution. The case study of this chapter does not represent a Poisson distribution as 5 out of 10 simulated trains start at the same time, and the interval between the remaining trains is not fixed, as shown in Figure 7.3.

Accordingly, this research defines the total blocking probability of the simulated system as the total number of incidents where the requests by the simulated in-service trains were denied service due to lack of TVWS channels at specific pixels.

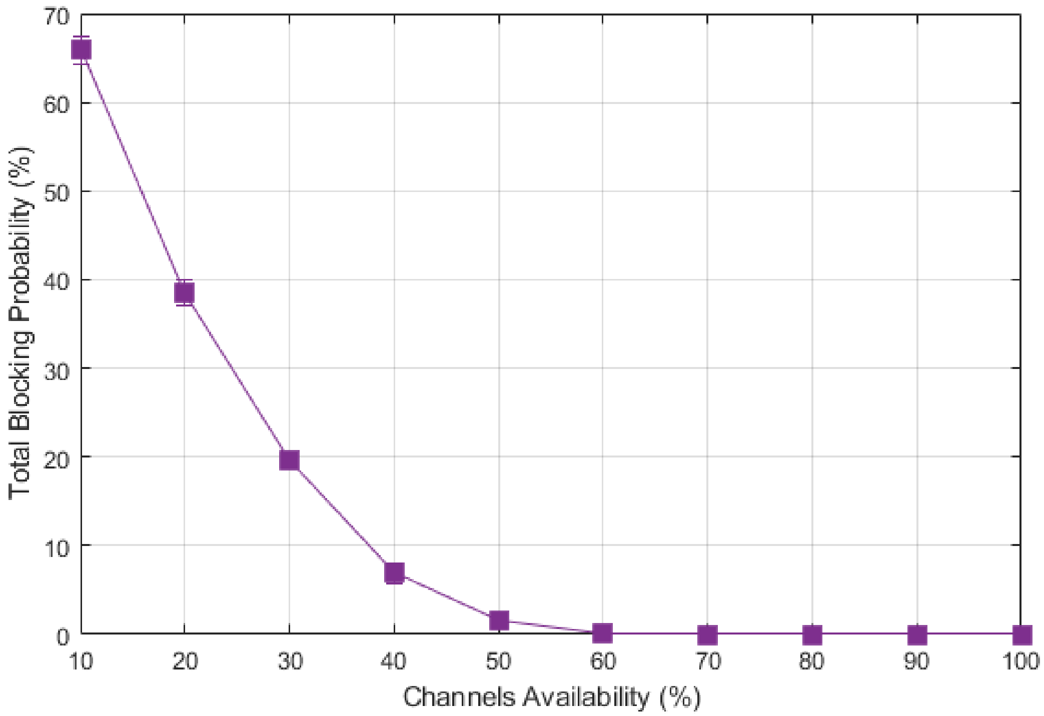

Figure 7.10: Blocking probability of a TVWS network under various channel availability

The total blocking probability, represented in Figure 7.10, can be expressed as:

$$\textit{Total Blocking Probability} = \frac{\sum_{i=1}^{j} M_i}{N}, \tag{7.3}$$

where M_i represents the number of requests where each train i was denied the service due to channel unavailability, j is the total number of simulated trains (e.g. 10 in this study), and N is the total number of requests handled by the white spaces database for all simulated trains. On the other hand, the blocking probability of TR9, in Figure 7.11, focuses on the grade of service provided for the 'last train' accessing the spectrum database on a first-come-first-served basis. TR9 blocking probability is the fraction between the number of blocked requests for TR9 and the total number of requests made by the same train.

In the proposed approach by Lee and Jeong (2014) and Kim *et al.* (2015), the

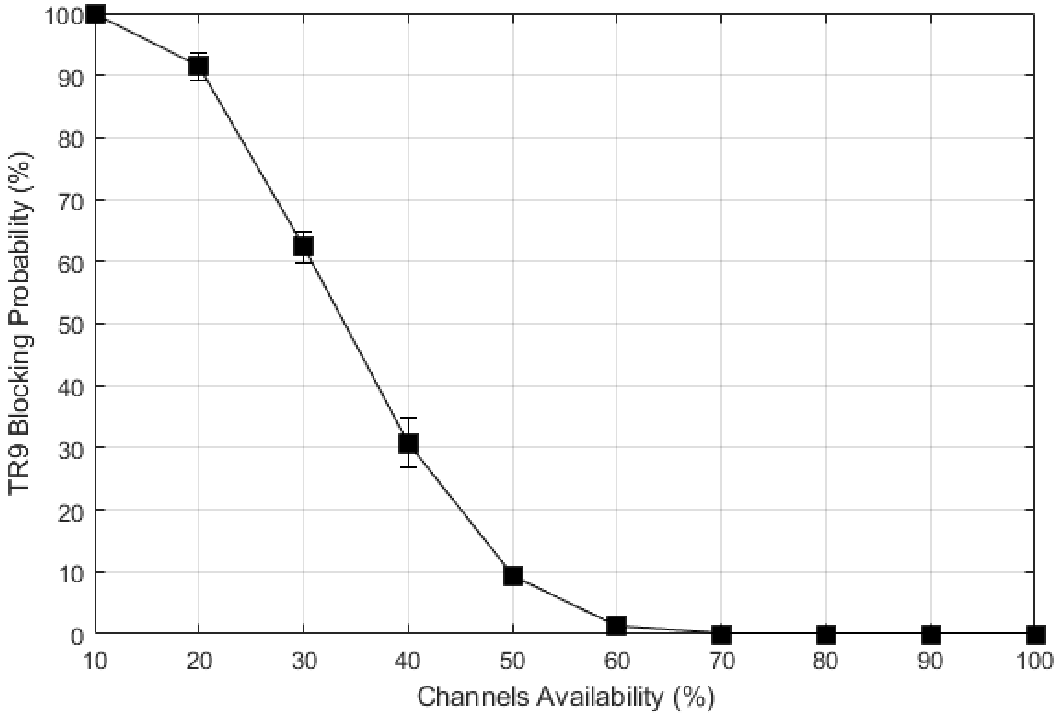

Figure 7.11: TR9 Blocking probability under various channel availability

blocking probability tends to be high at low spectrum availability, as the early-access trains book the only available channels leaving the consecutive trains with no channels available for communication. The blocking probability reaches 68% for 10% spectrum availability, and it drops to 0% when more spectrum becomes available ($\geq$ 60%), as shown in Figure 7.10. Figure 7.11 demonstrates the high blocking probability caused to TR9 when this approach is adopted. As TR9 requests the spectrum database after all trains, TR9 has access to fewer available TVWS channels. For instance, TR9 cannot communicate due to channel unavailability at spectrum availability of 10%. The blocking probability drops to 91% for 20% spectrum availability, as more channels are left unused by preceding trains. The blocking probability keeps dropping until it reaches 0% for channel availability that is ($\geq$ 60%).

The scheme presented in Chapter 4 has considered the tracking of each train's location to free the TVWS channels once the train crosses a certain pixel. As the TVWS channels are being selected at the start of each train's journey, any train delay will invalidate the generated channel list, and a newly updated list must be requested. The next section quantifies the blocking probability for the channel access scheme proposed in Chapter 4 that accounts for possible train delays.

7.7 Accommodating Train Delays

A train can be delayed for multiple reasons that include passenger actions, infrastructure faults, or severe weather conditions. Train punctuality was measured by Network Rail (2019) for the year 2018/2019. In 6,325,380 stations, only 67.87% of the trains arrived on time while 86.45% arrived 3 minutes late, 92.72% arrived within 5 minutes, 97.38% arrived within 10 minutes, 98.67% within 15 minutes, and 99.22% of the trains were delayed up to 20 minutes from the scheduled timetable. The indicated delays are measured at every recorded stations stops and not only at the final calling station for the service, as stated by the Office of Rail and Road (ORR, 2019).

To accommodate possible delays, the presented methodology adds a DCI to the channel's time validity, as shown in Figure 7.12. The check-out time, known as T_{ValEnd}, is extended to allow a late check-out that compensates for any delay caused within the pixel. Also, check-in time, known as $T_{ValStart}$, is extended so that the drivers can speed up to make up for the caused delay. The value of early check-in can be obtained from:

$$\text{Early Check-in} = \text{Original Check-in} - (\text{DCI} * \text{Channel's Time Validity}), \quad (7.4)$$

whereas late check-out can be calculated as follows:

$$\text{Late Check-out} = \text{Original Check-out} + (\text{DCI} * \text{Channel's Time Validity}) \quad (7.5)$$

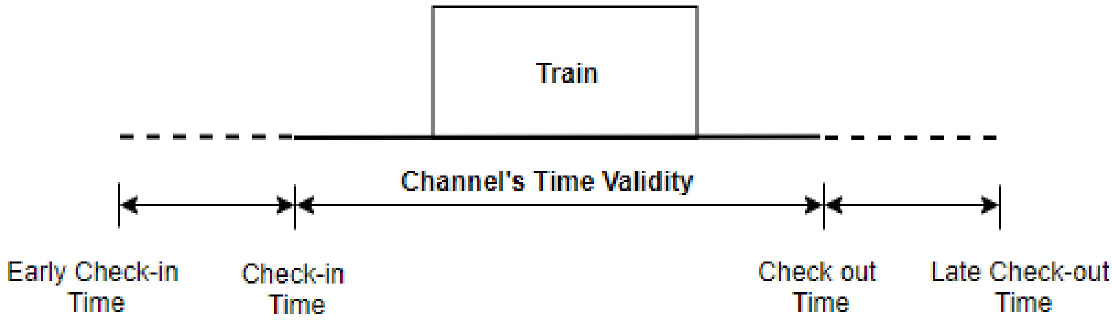

Figure 7.12: Extended time validity of a TVWS channel

This case study considers delays of 3, 5, 10, 15, and 20 minutes that were mentioned earlier to cover 99.22% of the trains commuting on the British rail network. The average duration of a train journey in the UK is 59 minutes, as stated by the Department for Transport (2017). For this value, the delay values can be translated into DCI of 5%, 9%, 17%, 28%, and 34%, respectively. The value of each delay results in a new DCI figure, which determines new early check-in and late check-out timings for each pixel. Figure 7.13 graphically represents the percentage of trains included by various DCI values.

As discussed in Chapter 4, when a train requests a new channel list, the database needs to decide on the availability of the channels pre-booked by the preceding trains. In other words, the database must convert all the 2s stored in the spectrum availability matrix $MAP[N][j]$ either to 1, if the TVWS channel would be available, and to 0 if the channel would not be available for the new train. At each corresponding pixel, the database compares the check-in and check-out times of the new train with the booking information of each pre-booked channel. In the case of no conflict, the database marks the channel as available for the new train, before applying the greedy algorithm to generate the operational channel list. Finally, the database updates its registry with the booking information of the recently reserved channels. Figure 7.14 summarises the

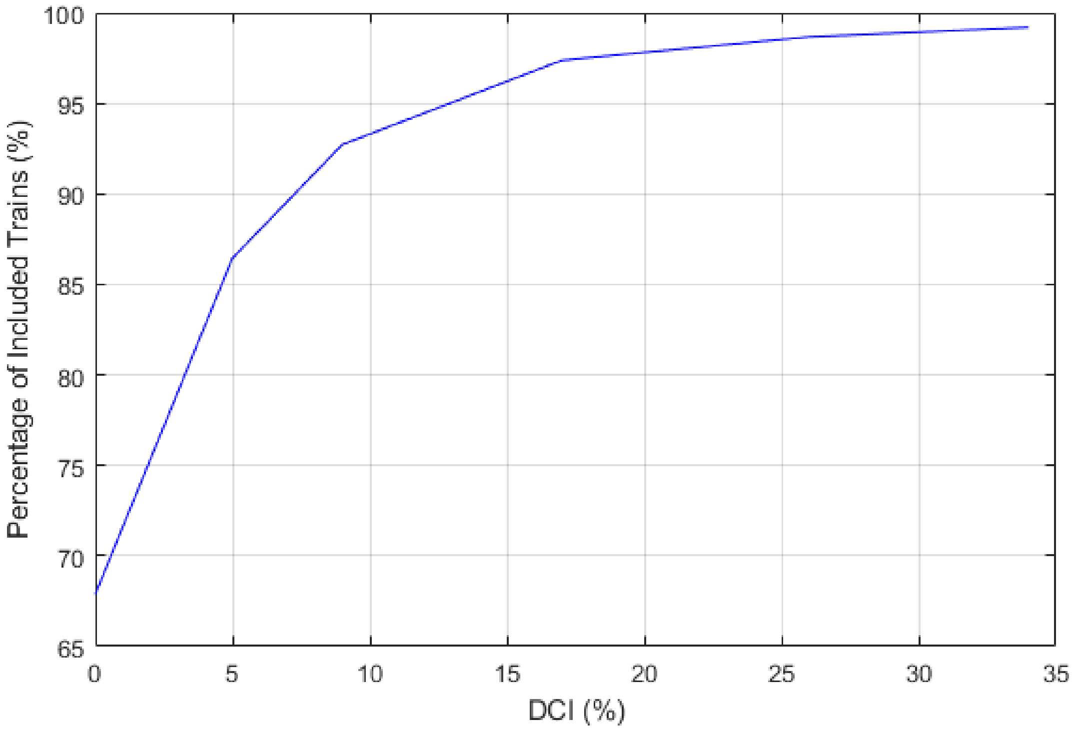

Figure 7.13: Percentage of trains included for various DCI values

database procedure to assign an operational channel list for a new train.

7.7.1 Blocking Probability

The availability of a single TVWS channel is a function of SU and PU technical parameters, as discussed in Chapter 4. However, extending the channel's time validity for a certain train impacts the spectrum available for succeeding trains. In this section, the relation between spectrum availability and the separation distance between in-service trains (i.e. line headway) is discussed.

Figure 7.15 demonstrates this relation for an example of two succeeding trains which follow the same route. As both trains will exist in the same pixel at different times, the database spectrum needs to follow the procedure in Figure 7.14 to decide if the same channel would be available for both trains. If the early

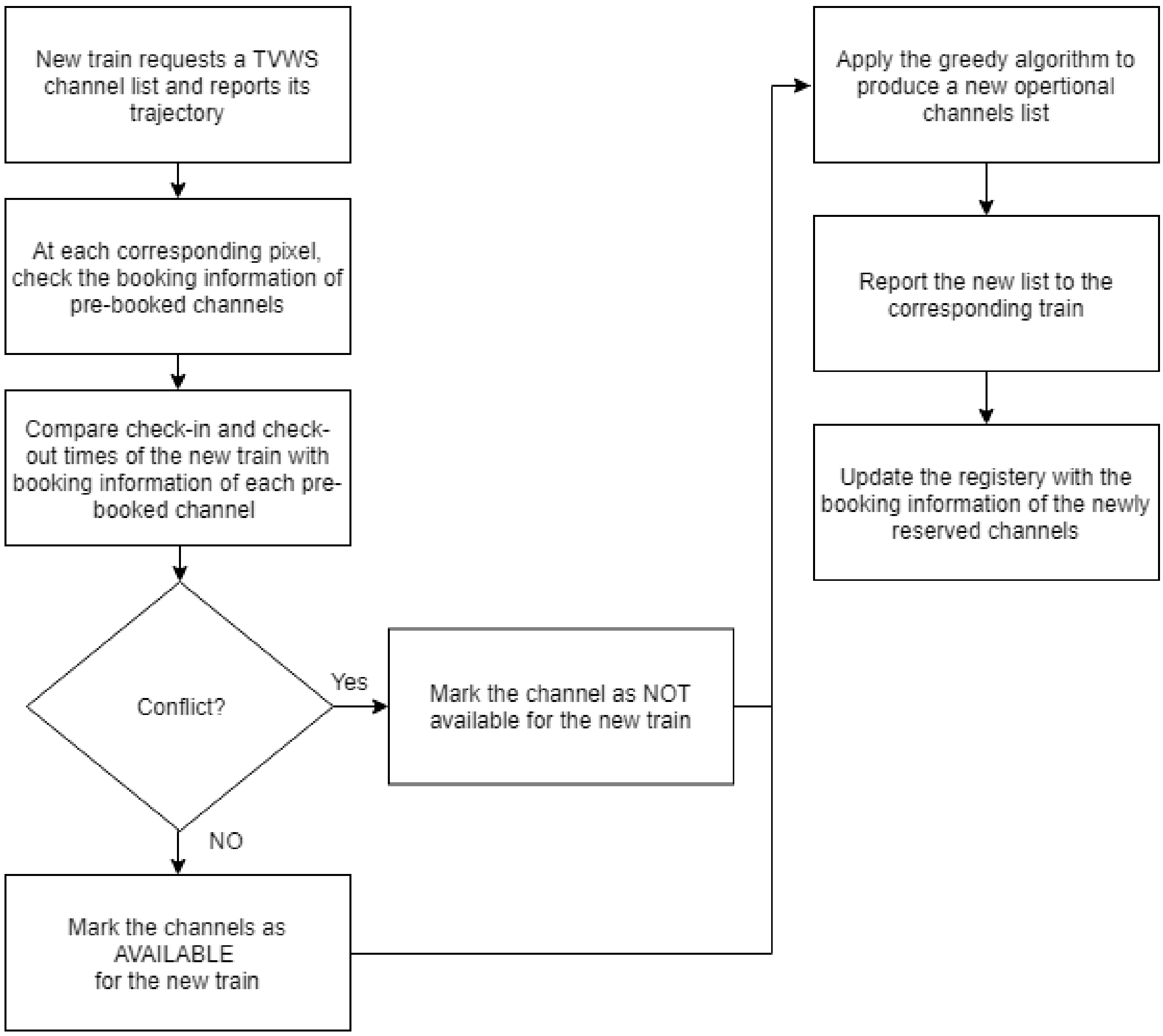

Figure 7.14: TVWS database procedure to generate an operational channel list

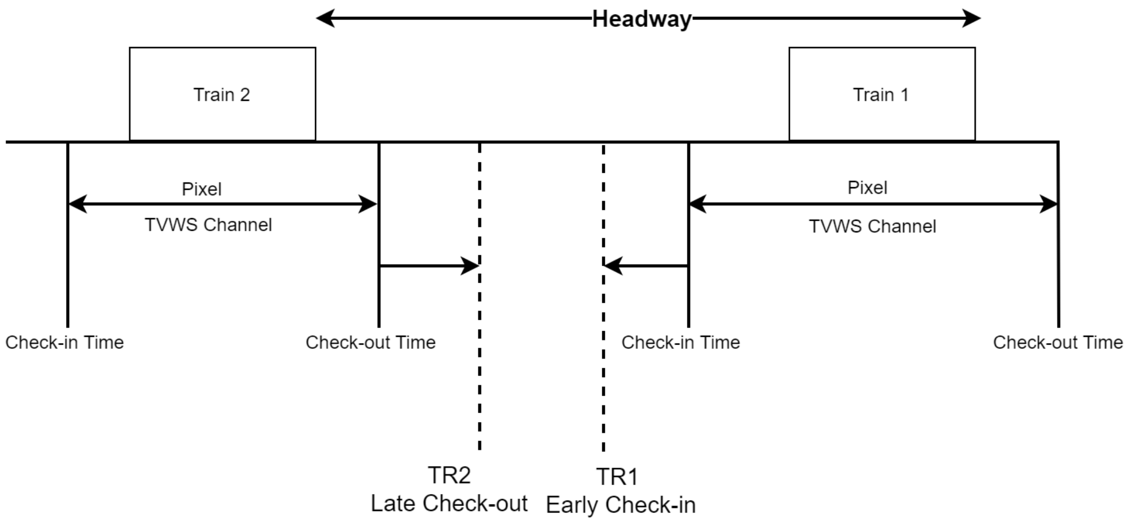

Figure 7.15: Relation between channel availability and line headway

check-in time of TR1 does not intersect with the TR2 late check-out time, the database will consider this TVWS channel as available for both trains. If any intersection happens, the database will mark this channel as unavailable for TR2 only.

The early check-in time and the late check-out time of both trains depend on the time each train spends in the pixel, and also on the value of DCI, as stated in Equations (7.4) and (7.5). In addition, the time separation between two succeeding trains, known as headway, plays a major role in determining the availability of a TVWS channel. If the headway value is large enough to prevent any time intersection, the blocking probability of the TVWS network can be improved drastically. Finally, the last mobility factor that influences spectrum availability is the coexistence of multiple trains within the same pixel. This scenario prevents the white spaces database from assigning the same TVWS channel for more than one train at the same time, which contributes to the rise of the overall network blocking probability. Figure 7.3 shows the time and place at which TR1 coexists with all other simulated trains.

To evaluate the performance of the proposed method, the network blocking probability is calculated for the DCI values discussed above. In addition, Figure 7.16 demonstrates the blocking probability for DCI = 0, which corresponds to a no-delay scenario. Increasing the DCI value to accommodate train delays raises the intersection probability between channel booking times under the headway values mentioned in Section 7.2. Under low spectrum availability of 10%, the blocking probability reaches 11.8% for DCI = 0%, 12% for DCI = 5%, 14% for DCI = 9%, 14.6% for DCI = 17%, 15.8% for DCI = 26%, and its maximum of 16.1% for DCI = 34%. The blocking probability drops as the channel availability improves until it equals 0% at spectrum availability that is ($\geq$ 30%).

The newly proposed approach, using the highest DCI value of 34%, gives better performance than the results indicated in Figure 7.10. Both approaches give an identical performance at spectrum availability that is ($\geq$ 60%), as the blocking probability reaches 0%. However, under lower spectrum availability (< 60%), the proposed scheme gives better performance. For example, the blocking probability drops from 68% to 16.1% for spectrum availability of 10%, from 39% to 2% for spectrum availability of 20%, from 20% to 0% for spectrum availability of 30%, from 8% to 0% for spectrum availability of 40%, and from 1% to 0% for spectrum availability of 50%.

Moreover, the TR9 blocking probability has drastically improved when compared with the previous approach, as indicated in Figure 7.17. For the highest DCI value, The blocking probability of TR9 drops from 100% to 23% for 10% spectrum availability, and from 90% to 3% for 20% spectrum availability. For spectrum availability that is ($\geq$ 30%), TR9 guarantees an available TVWS channel for each pixel on its planned trajectory.

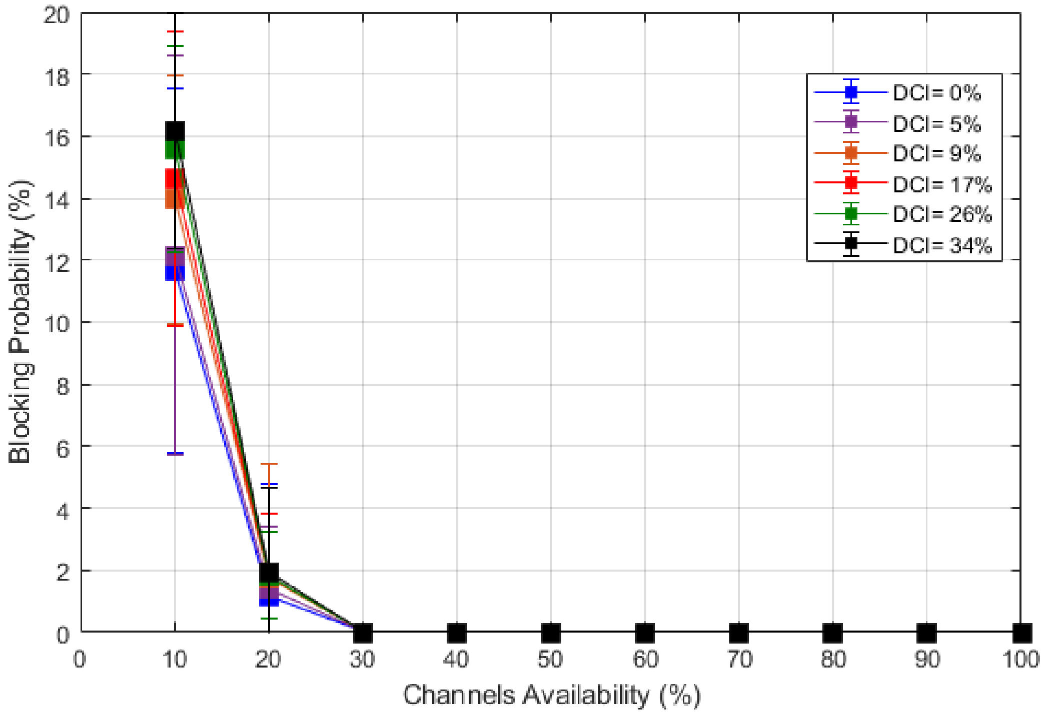

Figure 7.16: Network blocking probability for various DCI values under various channel availability

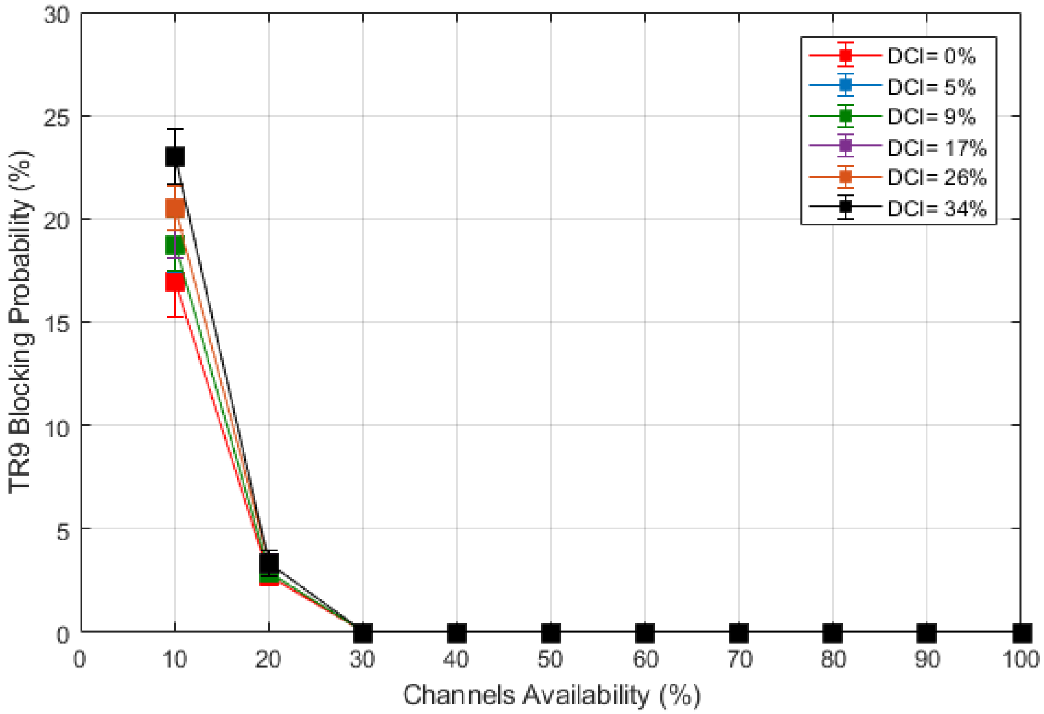

Figure 7.17: TR9 blocking probability for various DCI values under various channel availability

7.8 Chapter Summary

This chapter reviews the mobility factors that have an impact on various channel booking strategies. This gives valuable insights into how these strategies would perform in medium- and large-scale rail networks. Then, the chapter quantifies the channel collision probability when multiple trains access the database simultaneously without any coordination implemented.

Subsequently, the chapter considers synchronous access to the spectrum database following a first-come-first-served basis, while assessing two approaches through the presented case study. These two approaches include:

- A method that assigns a channel list to the train without updating the channel's status according to the train's location. In other words, each individual channel is being booked for the whole train journey, which has a direct impact on the TVWS network blocking probability.
- The proposed method that releases the reserved TVWS channel whenever the train crosses a specific pixel. The method also accommodates possible train delays for 99.22% of the trains operating on the British rail network.

In the next chapter, the conclusions that can be drawn from this research are given together with recommendations and suggestions for further work.

Chapter 8

Conclusions and Further Work

This chapter focuses on the research's key achievements, before providing recommendations and suggestions for further work. These are discussed in the following sections.

8.1 Key Achievements

The main aims of this research, as stated in Chapter 1 on page 5, are reported below:

- To develop a method that maintains seamless connectivity for various railway applications in the mobility-restrictive TV band.
- To demonstrate the suitability of the method with an example application in RCM systems.

The results obtained indicate that the method proposed in Chapter 4 is successful in providing seamless connectivity for various railway applications utilising TVWS. Prior knowledge of the train's trajectory enables the method to select channels that last for long distances, which minimises unnecessary control messages overhead. Chapter 6 addressed the second research objective by demonstrating the method's suitability with an example application in RCM systems whose communication network requirements can tolerate the uncertainty in the TVWS spectrum availability.

In more detail, this research compares the performance of the newly proposed method with the IEEE 802.22 standard, whose results are considered as a benchmark, in terms of coverage continuity and geography, link reliability, and amount of data transmitted.

In terms of the coverage geography, both schemes do not have any impact on the spectrum availability at different locations. However, the database-centred approach and knowledge of the train's trajectory (i.e. location and speed) enable the new approach to account for areas with no available channels. Therefore, under low spectrum availability ($\leq$ 30%), the train only needs to disassociate temporarily from the network in areas with spectrum unavailability, and re-registers when a new channel becomes available. Besides that, at higher spectrum availability ($\geq$ 40%), the new approach takes advantage of prior knowledge of the spectrum availability to select channels that last for long distances, which minimises unnecessary control messages overhead. The total number of initialisation and registration requests represents a successful strategy for dealing with the variable coverage geography.

For coverage continuity, under variable spectrum availability, the newly proposed method indicates an improvement of 37.8% in the channel utilisation distance, as the train can have an uninterrupted channel for an average consecutive distance of 1.188 km using the new scheme compared with an average of 0.862 km for the IEEE 802.22 standard. Using the same channel over long distances is an indicator of transmission continuity required for the real-time video transmission in some RCM systems.

In addition, the proposed scheme allows the transmission of 6.56% more on-board data when compared with the IEEE 802.22 standard, under various spectrum availability, due to the reduction of unnecessary registration and initialisation requests. The increase in the data capacity is beneficial to bandwidth-hungry applications such as on-board broadband systems. Besides, the potential additional data transmission demonstrates a resilient RCM system to the unwarranted continuous coverage under the TVWS spectrum.

This research also considers communication link reliability by quantifying the potential interference probability, the probability of channel collision between various SUs, and the TVWS network blocking probability. The IEEE 802.22 standard and the new method give identical interference performance, causing no interference to the surrounding PUs. However, the new scheme enables better transmission power that can reach up to 42.2 dBm for SUs under different channel availability, which has a direct impact on the total network throughput.

Besides that, the scheme prioritises spectrum access following a first-come-first-served approach to avoid any probability of channel collision, as presented in the case studies of Chapters 6 and 7. Finally, the approach accommodates potential train delays by adding a DCI to the channel validity time. Continuous monitoring of the train's geographic location enables the network to free the previously used channels and make them available for other in-service trains. The former policy contributes to minimising the overall network blocking probability that reaches 16% for the highest value of DCI at a spectrum availability of 10%. The probability later drops to 0% blocking probability at spectrum availability that is ($\geq$ 30%).

Moreover, the thesis hits other key achievements on the way to reaching the main objectives, and these are:

- The integration between BRaSS and OMNET++ was extended to obtain a comprehensive simulation environment that is able to simulate realistic telecommunications scenarios in the rail context. The key development contributions are:

    - The SEAMCAT tool was integrated to calculate the interference probability and the SU's allowed transmission power at each reported train's geographic location. This integration can be used to evaluate the interference performance of any wireless technology in the railway environment;
    - The crSimulator project in OMNET++ was developed to simulate spectrum access policies in the TV band, either using the IEEE 802.22 standard or any other approaches under development. That includes the implementation of a train localisation function and operations of a regulated White Space Database (WSDB);
- The research modelled the TVWS spectrum considering rail-specific factors that are not limited to the mobility model, PU and SU operational properties, and the time-varying propagation models.
- A WSDB dedicated to railway operations can adopt the proposed channel access policy with minor alteration to the entity roles of the IEEE 802.22 standard to support the presented handover scheme. These alterations include continuous reporting of the train location to the serving AP to trigger the handover procedure. Besides that, the AP should hold a whole channel list for each pixel located in the train's trajectory;

8.2 Recommendations

The recommendations of this thesis arise from addressing each of the sub-hypotheses that relate the method aims to the specific example of RCM. The discussion of these sub-hypotheses is listed below.

- Do the solutions offered for RCM systems differ for other rail applications?

The requirements analysis in Chapter 2 indicated that a single solution for all applications does not exist. For instance, signalling systems require universal and continuous coverage with a highly reliable communication link that supports various line speeds and a low data rate. Besides, the signalling system requires low latency and short setup time with 50/50 symmetry between the uplink and the downlink traffic. The frequency of use for the signalling system is high at all locations under all modes of operation. On the other hand, on-board broadband systems requires a high level of coverage in terms of continuity and geography for real-time sub-applications, while the demand downgrades to normal for non-real time sub-applications. The frequency of use for the on-board broadband system is high at rail lines and stations. The link reliability is set to normal due to the non-critical nature of the application. Additionally, the backbone network for this application must ensure a high data rate at various line speeds. Finally, RCM systems require continuous coverage to be available at all locations, especially with the potential existence of live video transmission. However, this requirement is set to normal as the RCM system can tolerate a certain level of communication discontinuity. This requires ensuring the discontinuity duration does not exceed a defined threshold to achieve a desired QoS. The link reliability required for RCM systems should be sufficient to provide enough maintenance reports with the ability to prioritise failure alarms. At last, the backbone network, at various line speeds, should provide 20 kbps data rate for data transmission and (400 - 5000 kbps) for video transmission. This conclusion leads to the next sub-hypothesis:

- Can these differences be used to guide tailored development for pivotal industry applications to share the TV spectrum?

The simple answer is yes. The handover procedure and the channel access scheme proposed in Chapter 4 are generic to ensure seamless connectivity for all railway wireless applications. However, the application of the method to RCM systems indicates the following recommendations for each application:

Signalling Systems:

The results showed that coverage geography and continuity vary from one place to another which does not fulfil the signalling systems requirements of continuous and universal coverage across the network. The method was successful at ensuring link reliability by causing 0% interference to PUs and preventing any probability of channel collision with other existing SUs by adopting a first-come-first-served approach. However, the network has an overall blocking probability of 15% for the highest DCI value.

Aiming to tackle the blocking probability, the WSDB can prioritise access to the TV band by taking into account the safety nature of the application. A train deploying a signalling system will be given access before trains running other less safety-critical applications. However, in large-scale rail networks where multiple trains deploy a signalling system, the network blocking probability might not be reduced from the 15% mentioned above. Another way to approach this is to adopt a dual-mode radio system so that a train can access any other available spectrum (e.g. 3G/LTE) as a 'gap-filler' to communicate in the areas where the TV band is not available.

On-board Broadband Systems:

This research has considered the assignment of a single TVWS channel in each pixel, which does not fulfil the capacity requirements of on-board broadband systems. Aiming to tackle this limitation, the method can achieve a higher bandwidth by assigning multiple contiguous channels in each pixel whenever available. Besides that, the approach can make use of the variable allowed transmission power, obtained in this thesis, to improve the overall network throughput.

Remote Condition Monitoring Systems:

This thesis shows that a TVWS network can fulfil the requirements of RCM systems in terms of reliability, operational speed, size of transmitted data, latency, and setup time. Also, the results indicated that a single channel can be used for an average consecutive distance of 1.188 km under the proposed approach. The connection continuity aims to fulfil the requirement of real-time video transmission in some RCM systems. However, the coverage continuity is not guaranteed under low channel availability that is $\leq$ 50%. Future research can develop approaches that tackle this spectrum challenge by storing and re-transmitting the dropped data/video packets as soon as the network is made available. The obtained performance should be validated against the QoS of existing RCM systems.

8.3 Further Work

This work has opened up a number of different research opportunities:

- As a dual-mode radio system can tackle the uncertainty within the TVWS spectrum availability as mentioned previously in the recommendation section; future research can focus on evaluating the TVWS performance and its ability to meet ETCS technical requirements for signalling systems in the areas where the TVWS spectrum is available. The work should consider quantifying the network performance in terms of handover latency, message delivery rate, and handover procedure duration.

- Another research opportunity arises from evaluating the ability of the TV spectrum to fulfil the bandwidth requirements of on-board broadband systems. The research can assess the overall network throughput when the WSDB assigns multiple contiguous channels, if available, to in-service trains with variable transmission power allowed at each pixel.

- The developed simulation environment can integrate real spectrum availability information from a regulated WSDB. This will enable evaluation of the approach in which a train deploying an RCM system can transmit collectively the measured track data at various areas where assigning multiple contiguous channels is possible. This approach must not degrade the overall system QoS, or negate the need for near real-time video transmission of the rail infrastructure. The WSDB will not assign other TVWS channels to the same train in areas with low spectrum availability, leaving these channels free for other SUs.

- One limitation of the proposed channel access scheme is selecting channels that last for long distances, which might not be of interest for all railway applications. Alternatively, the database can adopt a score function for each channel, taking into account the specific requirements of each application. For instance, the WSDB can give channels with low frequency a higher score when requested by signalling systems, as these channels provide a more reliable link due to the minimised Doppler shift/spread.

- The rail line between Bournville and New Street stations was introduced in this research to investigate the relation between TVWS channel allocation schemes and the train mobility model including the separation distance and the coexistence of multiple trains in the same pixel. However, the service frequency on this railway line is low; therefore, the number of train interactions is limited. As a possible extension to this work, a busier and larger network in a perturbed scenario could be used to test the proposed method.

- The IEEE 802.22 standard was selected initially to demonstrate the method's suitability. Nevertheless, It is worth investigating how other recent technology standards such as LTE and 5G can deploy the developed handover and channel access policy to provide seamless connectivity for in-service trains sharing the TV band using these standards.

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Appendix A

BRaSS Parameters Configuration

BRaSS is a microscopic rail simulator developed at Birmingham Centre for Railway Research and Education (BCRRE), which is able to simulate different aspects of the railway control and operations. This appendix focuses on providing more details on the simulator usage and configuration of the rail parameters defined within this research.

Getting Started

BRaSS can run either by double-clicking the "RunMe" launcher or from any available Java Integrated Development Environment. Figure A.1 shows the BRaSS launcher and multiple options that the user can select before running the simulation. Selecting DCS (OMNET) is key to enable the socket connection between BRaSS and OMNET++. The user also can select the desired network model as part of this step.

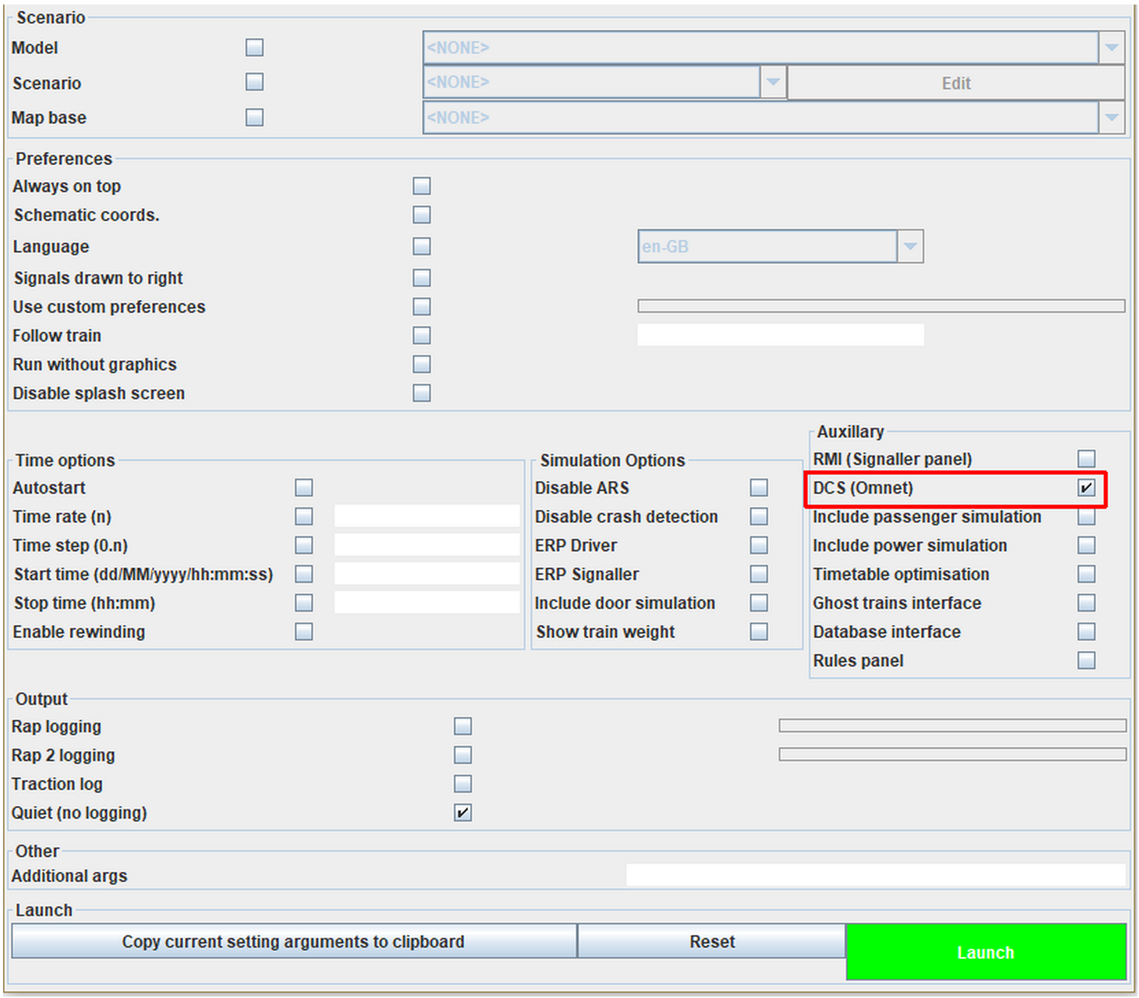


Figure A.1: BRaSS Launcher

If the network model was not selected, BRaSS will load an empty model with two main panels. Firstly, the graphical panel on the left shows a graphical representation of the network including infrastructure, signals and operational trains. This panel keeps updating when the simulation is running and can be used to trigger certain actions. Secondly, the information panel shows the state of the model data in a table format. This panel is updated as the simulation runs. Figure A.2 shows BRaSS graphical and information panels.

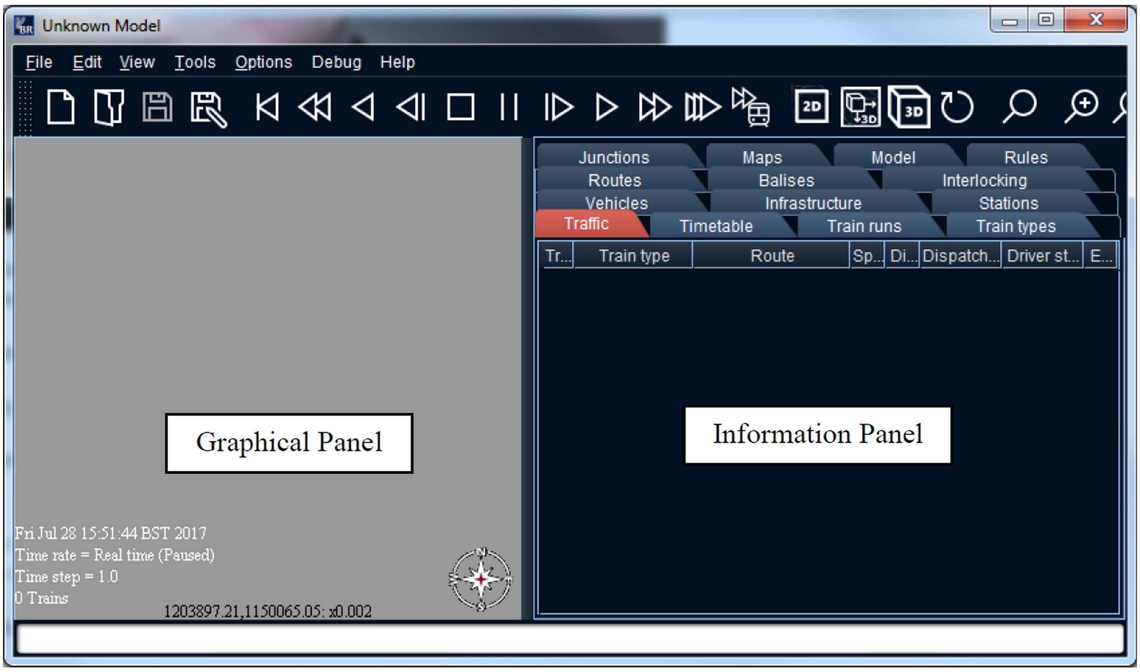


Figure A.2: BRaSS graphical and information panels

Loading a Model

BRaSS can be used to load an existing model or to create a new model. Models must have a file extension of KSM to be loaded into the simulator. In this research, two existing models were used to support case studies of Chapter 6 and Chapter 7. The first model is called "SO2BNS3", and it shows a rail network that contains two trains dwelling at Selly Oak, University, and New Street stations in Birmingham, UK. On the other hand, the name of the second model is "SO2BN5", and it contains a bigger network of 10 trains travelling between New Street, Five Ways, University, Selly Oak, and Bournville stations. Modelled trains are of British Rail Class 323 having a maximum speed of 144 km/h, length of 20 m per carriage, and each consisting of three carriages. The two case studies of this thesis did not consider any tunnel environment.

To load one of these two models, the user needs to select Load model from the file menu in the menu bar, as shown in Figure A.3. Then, the user needs to navigate to the data folder to select the desired model. Once selected, the network information will be populated to the graphical and graphical panels.

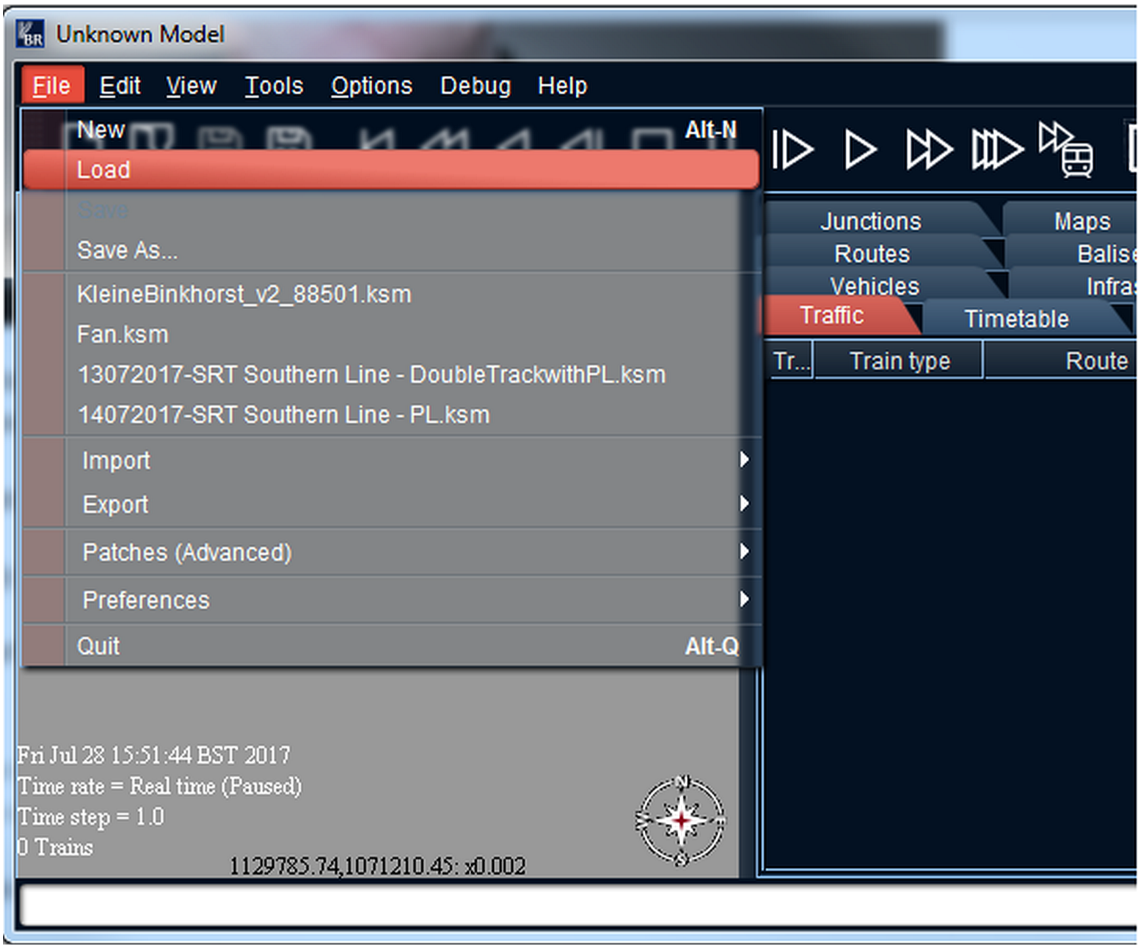


Figure A.3: Loading an existing model in BRaSS

Figure A.4: BRaSS model used in Chapter 6 case study

Figure A.4 shows the screen after loading the model used in Chapter 6. The graphical panel shows the name of each station, train ID and its current speed. The information panel (on the right) shows more details about the network in a table format where each tab represents a different data set. In addition to the Station tab shown in A.4, Figure A.5 features vehicle specifications in terms of class, max speed, car count, length, and weight. Each of these data fields can be altered to fit the requirements of each scenario. However, this research has used the previously mentioned models without any modification.

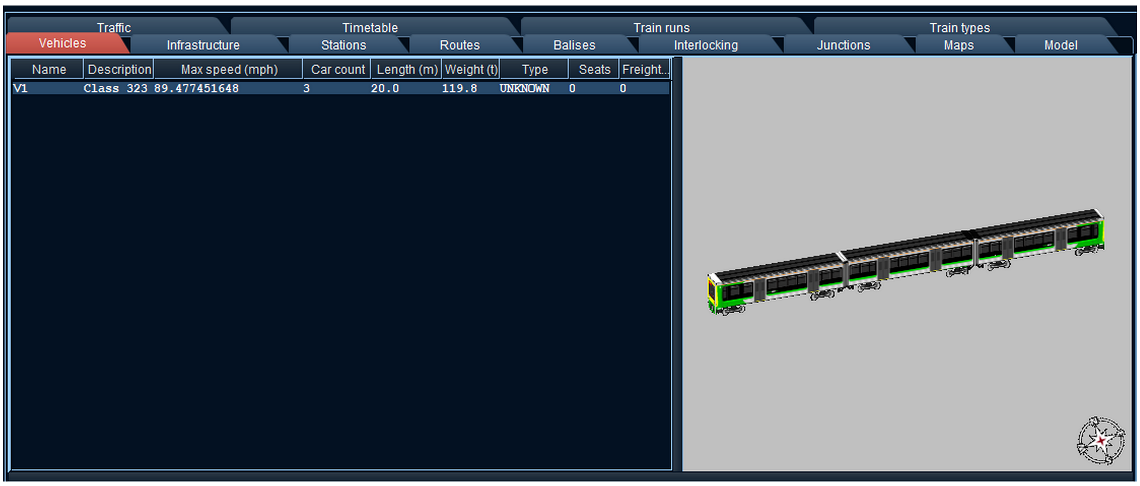
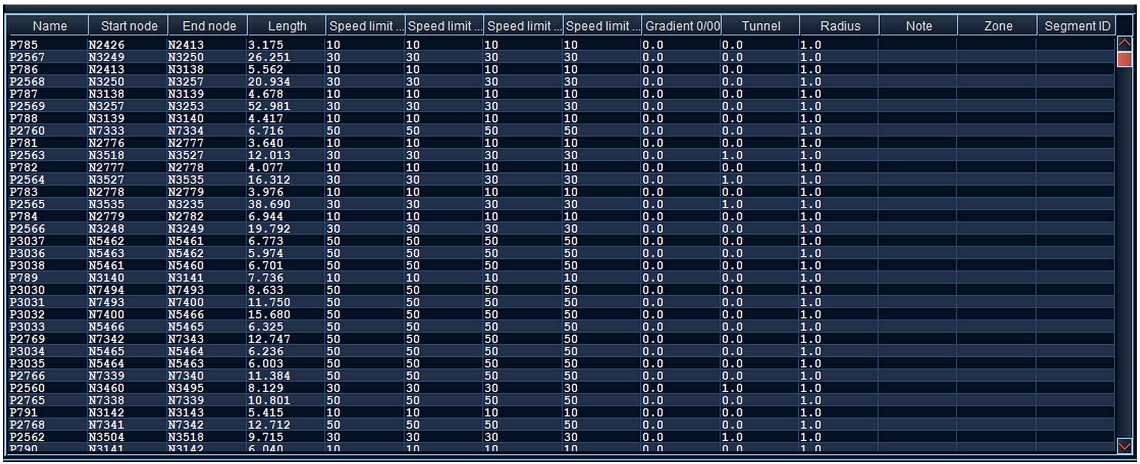


Figure A.5: Vehicles tab in BRaSS information panel

Similarly, Figure A.6 shows information about the infrastructure points; including existing speed limits, gradients, and any tunnel environment.



Name	Start node	End node	Length	Speed limit ...	Speed limit ...	Speed limit ...	Speed limit ...	Gradient 0/00	Tunnel	Radius	Note	Zone	Segment ID
P785	N2426	N2413	3.175	10	10	10	10	0.0	0.0	1.0			
P2567	N3249	N3250	26.251	30	30	30	30	0.0	0.0	1.0			
P786	N2413	N3138	5.562	10	10	10	10	0.0	0.0	1.0			
P2568	N3250	N3257	20.934	30	30	30	30	0.0	0.0	1.0			
P787	N3138	N3139	4.678	10	10	10	10	0.0	0.0	1.0			
P2569	N3257	N3253	52.981	30	30	30	30	0.0	0.0	1.0			
P788	N3139	N3140	4.417	10	10	10	10	0.0	0.0	1.0			
P2760	N7333	N7334	6.716	50	50	50	50	0.0	0.0	1.0			
P781	N2776	N2777	3.640	10	10	10	10	0.0	0.0	1.0			
P2563	N3518	N3527	12.013	30	30	30	30	0.0	1.0	1.0			
P782	N2777	N2778	4.077	10	10	10	10	0.0	0.0	1.0			
P2564	N3527	N3535	16.312	30	30	30	30	0.0	1.0	1.0			
P783	N2778	N2779	3.976	10	10	10	10	0.0	0.0	1.0			
P2565	N3535	N3235	38.690	30	30	30	30	0.0	1.0	1.0			
P784	N2779	N2782	6.944	10	10	10	10	0.0	0.0	1.0			
P2566	N3248	N3249	19.792	30	30	30	30	0.0	0.0	1.0			
P3037	N5462	N5461	6.773	50	50	50	50	0.0	0.0	1.0			
P3036	N5463	N5462	5.974	50	50	50	50	0.0	0.0	1.0			
P3038	N5461	N5460	6.701	50	50	50	50	0.0	0.0	1.0			
P789	N3140	N3141	7.736	10	10	10	10	0.0	0.0	1.0			
P3030	N7494	N7493	8.633	50	50	50	50	0.0	0.0	1.0			
P3031	N7493	N7400	11.750	50	50	50	50	0.0	0.0	1.0			
P3032	N7400	N5466	15.680	50	50	50	50	0.0	0.0	1.0			
P3033	N5466	N5465	6.325	50	50	50	50	0.0	0.0	1.0			
P2769	N7342	N7343	12.747	50	50	50	50	0.0	0.0	1.0			
P3034	N5465	N5464	6.236	50	50	50	50	0.0	0.0	1.0			
P3035	N5464	N5463	6.003	50	50	50	50	0.0	0.0	1.0			
P2766	N7339	N7340	11.384	50	50	50	50	0.0	0.0	1.0			
P2560	N3460	N3495	8.129	30	30	30	30	0.0	1.0	1.0			
P2765	N7338	N7339	10.801	50	50	50	50	0.0	0.0	1.0			
P791	N3142	N3143	5.415	10	10	10	10	0.0	0.0	1.0			
P2768	N7341	N7342	12.712	50	50	50	50	0.0	0.0	1.0			
P2562	N3504	N3518	9.715	30	30	30	30	0.0	1.0	1.0			
P790	N3141	N3142	6.040	10	10	10	10	0.0	0.0	1.0			

Figure A.6: Infrastructure tab in BRaSS information panel

Running a Simulation Scenario

Before starting the simulation, the user needs to make sure that the OMNET++ interface window is already launched. If not, OMNET++ interface can be opened from the Tools menu in the menu bar, as shown in Figure A.7.

Once the interface is loaded, the window will show current simulated trains along with the packet being sent from BRaSS to OMNET++, so that OMNET++ can update the mobility module of each train, as explained in Appendix B. The packet includes each train's ID, position, and speed, as shown in Figure A.8.

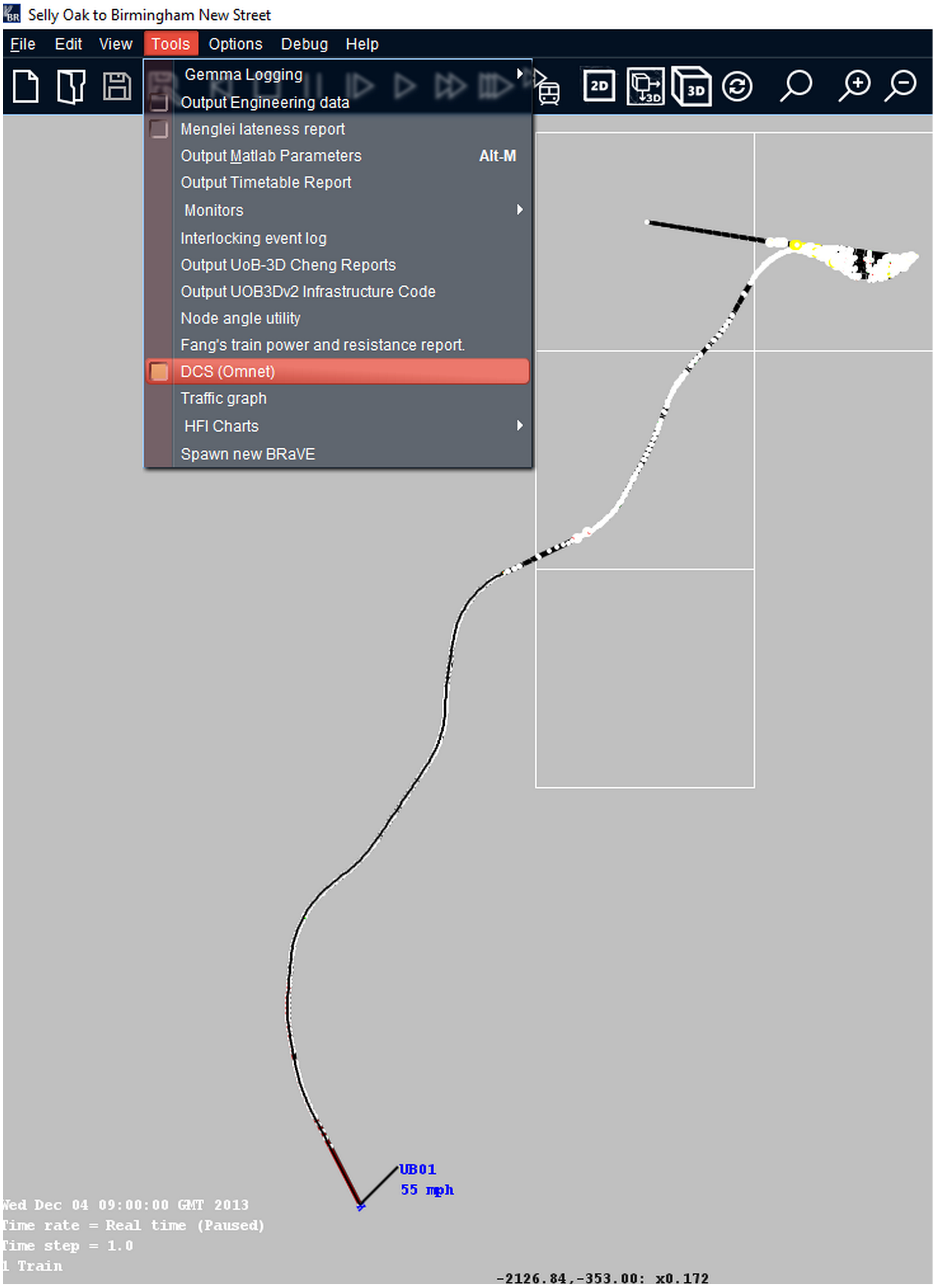


Figure A.7: Launching OMNET++ connection

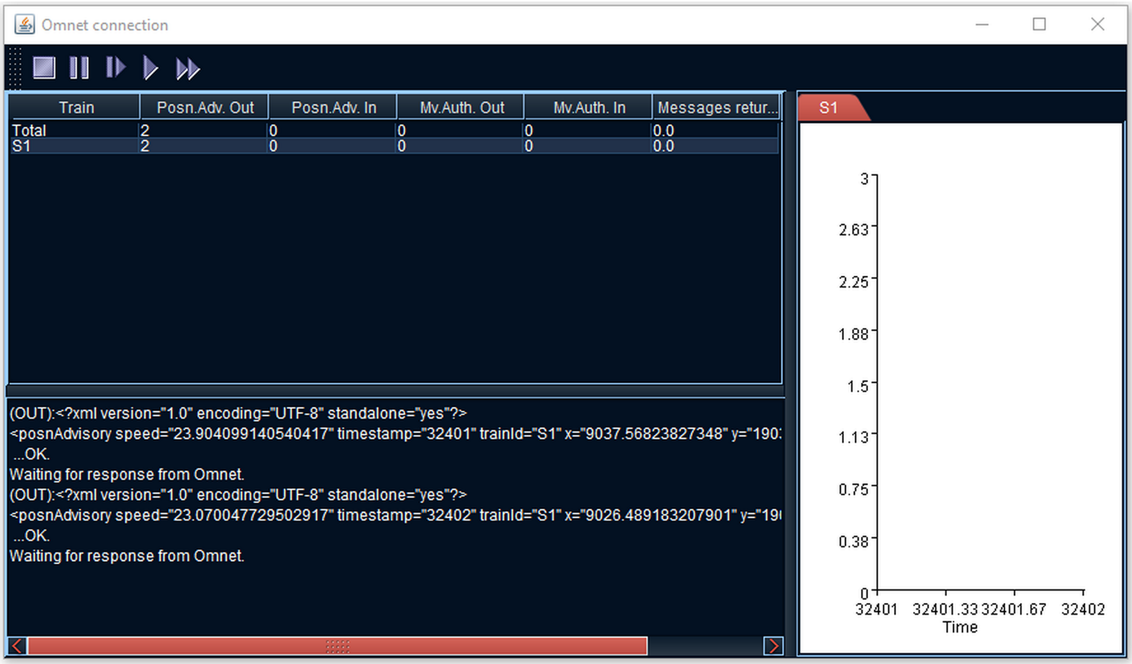


Figure A.8: Connection between BRaSS and OMNET++

Finally, the user can start the simulation by clicking the play button in OMNET++ connection window or from BRaSS main menu bar. By then, the simulation scenario configured in OMNET++ can start accordingly, as explained in Appendix B. More information about BRaSS can be found in the user guide provided with the software.

Appendix B

OMNET++ Module Functionality

This appendix states the functionality of modules used to define the wireless network in the case studies of Chapters 6 and 7. These modules are the external simulator interface, the radio medium module, the spectrum database module, the train module, and the AP module; these are discussed next.

External Simulator Interface

This module works as an interface between BRaSS and OMNET++. The module receives packets from BRaSS, processes them, and forwards them to the relevant train. At the initialisation stage, this module sets up a socket connection for the incoming and outgoing packets. Once a packet is received from BRaSS, the module first sends back an acknowledgement packet and starts the message processing procedure. By then, the module recognises the received train ID, geographic coordinates, and current speed. Based on the train ID, the module forwards the geographic coordinates to the mobility module of each relevant train. This process takes place every 0.01 s so that each train updates its location in OMNET++ according to the packet received from the railway simulator.

Radio Medium Module

The radio medium module models the shared physical medium where wireless communications take place. The module depends on several models, namely,

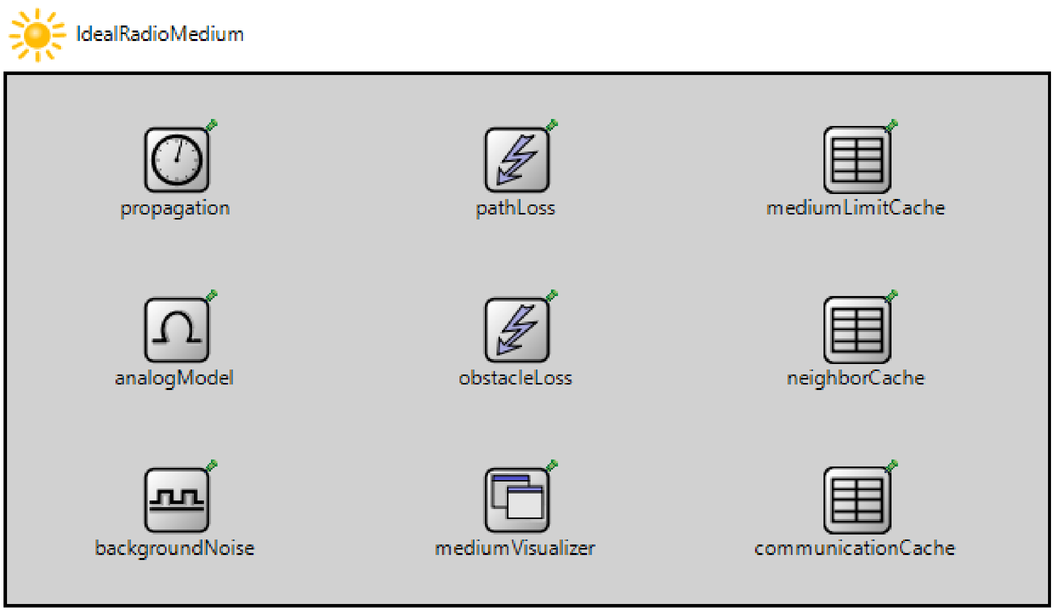


Figure B.1: Radio Medium compound module

the signal propagation model, the path loss model, the obstacle loss model, the background noise, and the signal analogue model, as shown in Figure B.1. Each of these models has a set of parameters that can be configured based on the simulated scenario.

PMSE Module

The PMSE module defines the PU activity pattern so that the simulation environment can evaluate the impact of sudden PU appearance on the algorithm presented in Chapter 4. At the initialisation stage, the module outlines the idle and activity times (i.e. duty cycle) of each PU. Then, the module sets the communication channels to be used by PUs throughout the simulation. Channel Numbers are either hard-coded or selected through a random function. When the PU starts its activity on the pre-selected channel, the module sends a broadcast message to the whole network. Every SU operating on the PU's assigned channel needs to cease its communication within a defined time interval. Finally, the PU stops its activity at the end of the activity duration.

Spectrum Database Module

The spectrum database module in OMNET++ simulates the operations of the regulated White Space Database (WSDB). The database module implements the spectrum access policy set by the IEEE 802.22 standard as well as the novel policy proposed in this research. This section details the development of this module.

Initialisation Stage

At this stage, the database sets the value of various parameters that include the number of channels, the overall spectrum availability, DCI, and the number of relevant pixels. The module utilises the number of relevant pixels as well as the number of channels to create a 2D matrix that has a size of [No of Channels * No of Pixels]. At the end of this stage, the module fills the 2D matrix with 1s based on the predefined percentage of spectrum availability.

Channel List Generated Using The IEEE 802.22 Standard

A train that is deploying the IEEE 802.22 standard requests the WSDB in each pixel to obtain a TVWS channel. First, the database checks the state of the channel assigned in the previous pixel and re-selects the same channel in the new pixel if it is available. In the case of channel unavailability, the database searches for any other available channel in the new pixel; once found, the database reports the channel number back to the train. If there are no available channels in the pixel, the database returns the value of 0. The simulation repeats this process for every pixel located on the train route.

Channel List Generated Using The Proposed Scheme

The main aim of this function is to generate a list of operational channels that is valid for the whole train journey. A train that is deploying the new access scheme requests the WSDB once at the start of the journey. First, the database identifies the train's starting pixel as well as the moving direction to create a sub-matrix that holds the spectrum availability information for the area where this specific train will travel. Then, the database considers the train's extended check-in and check-out times to decide on the channels that were booked by the preceding trains. The state of these channels is indicated by a value of 2 in the sub-matrix. Each booked channel is linked to another matrix that holds booking information for this channel. The database retrieves the booking information for each booked channel and compares it with the current train potential booking duration to decide if a channel would be available or not for this train. The database alters the state of the channel from 2 to 1 in the 2D sub-matrix if the channel would be available, and to 0 if the channel would not be available.

Once the sub-matrix is updated, the database applies the greedy algorithm proposed in Chapter 4. The algorithm accumulates the 1s starting from the last pixel located on the train route. Then, the algorithm selects the channels that last for the longest distances, as previously explained. Finally, the database returns a vector that holds the channels to be used along the whole train journey before updating the selected channel booking information. The same process is repeated to generate a list of backup channels for the same train.

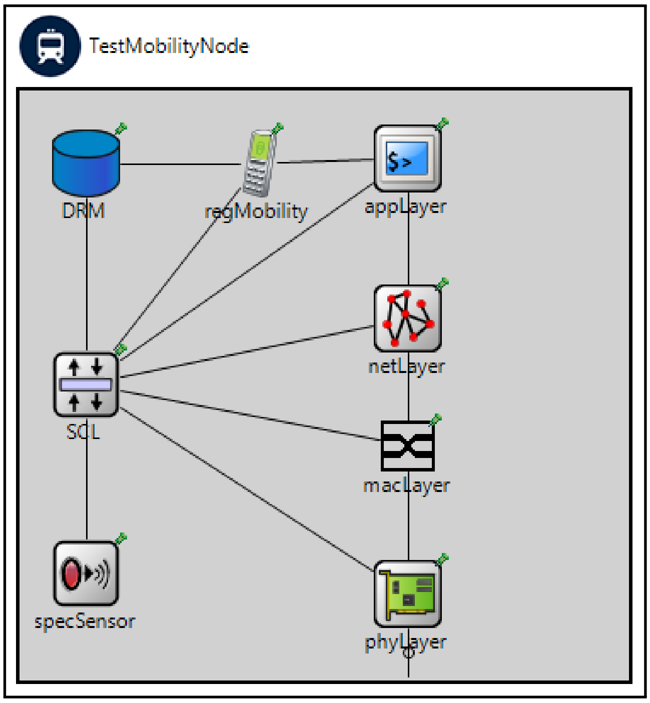


Figure B.2: Train compound module consisting of multiple sub-modules

Train Module

The train module consists of multiple sub-modules that are shown in Figure B.2. This section details the functionality of each of these modules.

Application Layer Module

The application layer module, named 'appLayer' in Figure B.2, enables the train to send the initialisation request RTS to the neighbouring AP when the train becomes operational in the simulation environment. The train sends the RTS request to the neighbouring AP address that can be identified from the network setup file. The application layer module recognises the neighbouring AP address from the network setup file. The RTS request is passed from the application layer to the physical layer through the Medium Access Control (MAC) layer. In addition, the module updates the destination node address when an intercell handover is triggered. Finally, the application layer is also responsible for a set of functions that include ending the simulation when all the data packets are successfully transmitted and re-sending the communication request when the transmission link fails.

Network Layer Module

The network layer module, named 'netLayer' in Figure B.2, acts as a mid-layer between the application layer and the MAC layer, as it forwards the messages from the upper layer to the lower layer or the opposite.

MAC Layer Module

The MAC layer is responsible for a wide range of functions. This section summarises the functions of the train's MAC layer. First, the module receives the RTS request from the application layer and sends a message to the spectrum sensing module to get the channel proposed by the local spectrum database (i.e. DRM). Then, the module will broadcast the RTS to the network through the physical layer.

The MAC layer is also responsible for handling the CTS message sent from the neighbouring AP to confirm successful reception of the RTS message. Afterwards, the MAC layer enables the train to exchange messages with the AP to complete the transmission of basic capabilities, the authentication process, and the registration procedure. Once the train is registered with the network, the MAC layer starts sending data packets to the physical layer to be broadcast to the associated AP. The MAC layer does not send a new data packet unless transmission of the previous packet was successful.

Finally, the module handles the sudden appearance of PUs. The MAC layer ceases the train's transmission and requests the spectrum sensing module to find the next proposed channel from the local DRM. The module also addresses the negative acknowledgement received from the requested AP. Once received, the train attempts to send a new RTS request to initiate the connection.

Physical Layer Module

The main function of the physical layer modules is to receive the messages from the upper layer (i.e. MAC layer) and broadcast these messages to the whole network. The physical layer also receives the messages from the outside world and routes them up to the MAC layer. Finally, the physical layer has a set of parameters that describes the physical device that is capable of transmitting and receiving signals on the medium. These parameters define the antenna model, the transmitter model, and the energy consumption model.

Spectrum Sensing Layer Module

The spectrum sensing module, named 'specSensor' in Figure B.2, keeps track of the channel state and provides this information for any modules requesting it. In this research, the spectrum sensing module informs the MAC layer with the channels proposed by the local DRM, and finally updates the channel state in the case of sudden PU appearance.

Signalling and Communication Module

This module acts as a central unit that connects all the modules together.

Local Spectrum Database Module

This local spectrum database module is named ‘DRM’ in Figure B.2. According to the design proposed in Chapter 4, the channel list generated from the global spectrum is broadcast to each relevant AP that is required to communicate operational channels individually to each train and triggers the proper action based on the train’s mobility and the spectrum access policy deployed. However, to ease the exchange of messages between the train and the AP, the DRM module is temporarily part of the train compound module. In other words, the train currently holds the local channel list and triggers the registration/full initialisation requests based on its mobility. This does not influence the results obtained in this thesis; however, migration of the DRM module to the AP side, as part of future work, will help to further evaluate the overall communication latency, and the number of hits for both the local and the global spectrum databases.

The DRM module implements the IEEE 802.22 spectrum access policy, the newly proposed method for TVWS access, and a method that prioritises the trains’ access to the TVWS database on a first-come-first-served basis. For the IEEE 802.22 standard, the module requests the global spectrum database in each pixel to obtain a valid communication channel. In addition, the module sends RTS initialisation requests when the train moves from a pixel with an unavailable channel to a pixel where a channel is available. Finally, the module sends a registration request when the train changes the operational channel while moving from one pixel to another under the coverage of the same AP (i.e. intracell handover).

Under the new scheme, the DRM module requests the global spectrum database only once to obtain a list of channels that is valid for the whole train journey. The

```
//setting the order at which each train accesses the global spectrum Database
if(trainName=="TR1"){ scheduleAt( omnetpp::simTime(), macTimer);}
if(trainName=="TR2"){ scheduleAt( omnetpp::simTime()+ 0.00001, macTimer);}
if(trainName=="TR3"){ scheduleAt( omnetpp::simTime()+ 0.00002, macTimer);}
if(trainName=="TR4"){ scheduleAt( omnetpp::simTime()+0.00003, macTimer);}
if(trainName=="TR5"){ scheduleAt( omnetpp::simTime()+0.00004, macTimer);}
if(trainName=="TR6"){ scheduleAt( omnetpp::simTime()+ 0.00005, macTimer);}
if(trainName=="TR7"){ scheduleAt( omnetpp::simTime()+ 0.00006, macTimer);}
if(trainName=="TR8"){ scheduleAt( omnetpp::simTime()+ 0.00007, macTimer);}
if(trainName=="TR9"){ scheduleAt( omnetpp::simTime()+ 0.00008, macTimer);}
if(trainName=="TR10"){ scheduleAt( omnetpp::simTime()+0.00009, macTimer);}
```

Figure B.3: Access prioritisation to the global spectrum database

module also sends registration requests to the network when the channel allowed distance expires (i.e. intracell handover) so that the train can register with the network using the newly assigned channel. Finally, the module prioritises access to the global spectrum database, as shown in Figure B.3. This process ensures that each train is being assigned with operational channels that will not cause any co-channel interference with other SUs.

Mobility Module

The mobility module, named 'regMobility' in Figure B.2, is responsible for receiving the coordinates from the external simulator interface module and updating the train location in OMNET++ accordingly. Another main function of the mobility module is to determine when the train has moved from one pixel to another. The pixel change function has developed from the case study of Chapter 6 to the case study of Chapter 7.

In Chapter 6, the mobility module decides on the pixel change when the train moves a distance of 100 m starting from the initial starting point, as shown in Figure B.4. When a pixel change occurs at a certain point, the mobility module considers this point as an initial point to decide on the next transition. However, this method is not accurate as the train does not travel in a straight line. An

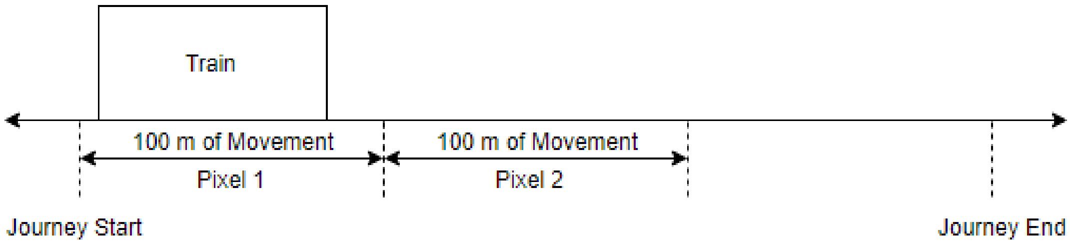


Figure B.4: Pixel change in the case study of Chapter 6

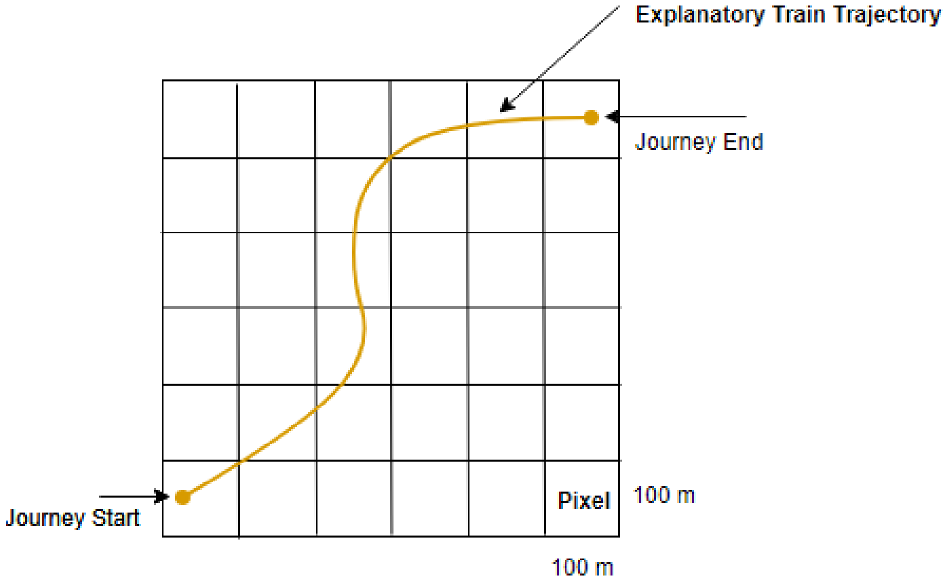


Figure B.5: Pixel change in the case study of Chapter 7

explanatory train trajectory is shown in Figure B.5. The train does not need to travel 100 m for a pixel change. In Chapter 7, the mobility module gives coordinates to each of the relevant pixels located on the train route to accurately identify the transition from one pixel to another. The new pixel number is reported to the local spectrum database (i.e. DRM module) to take proper action.

Furthermore, the mobility module triggers the intercell handover. As the module is aware of the train location, it continuously calculates the distance from APs included in the simulation to decide on the location where an intercell handover is required. By then, the mobility module disconnects with the current AP and sends the address of the target AP to the train's application layer module. The application layer module forwards the address to the train's MAC layer to register with the new AP. In the design proposed in Chapter 4, the AP initiates the intercell handover based on the reported train location. However, this function currently resides in the train's module for simplicity and will be moved to the AP module in future development.

AP Module

The AP module has the same architecture as the train compound module, excluding the mobility and local spectrum database modules. The MAC layer of the AP handles the train requests for the authentication and registration processes. In addition, the AP sends an acknowledgement message back to the train for each data packet received. In the future, the DRM module will be implemented to be on the AP side rather than being located at the train's end, to fully simulate the channel access scheme proposed in Chapter 4.

Appendix C

SEAMCAT Parameters Configuration

SEAMCAT is a software tool, developed within the context of the European Conference of Postal and Telecommunication administrations (CEPT), to enable the statistical modelling of different radio interference scenarios to evaluate the coexistence feasibility between wireless systems operating in overlapping or adjacent frequency bands.

SEAMCAT adopts the Monte Carlo approach as its statistical simulation methodology. This method offers flexibility as some parameters, in the radio communication system, can vary within a certain range to represent various interference scenarios. These parameters might include the antenna height, the transmission power, the operating frequencies, and the geographical positions of transmitters/ receivers.

SEAMCAT uses these distributions to generate random events. For instance, to calculate the interference probability, SEAMCAT stores the signal strength of the interfering and the desired signals for each event, to compare unwanted signals at the victim receiver with the selected interference criterion (e.g. C/I). Then, the software can calculate the interference probability at the victim receiver based on the generated values of each event. Each event can represent different geolocation of the interfering transmitter in relation to the victim receiver. Other simulation parameters can be left fixed to realise a certain equipment standard (e.g. standards by ETSI, 3GPP, and IEEE).

This appendix focuses on providing details on how the interference scenario and network parameters of this thesis are configured in SEAMCAT.

Getting Started

SEAMCAT is an open-source project developed in Java, and it can run on any operating system. The latest version is available from SEAMCAT website, and it is simply can be started by double-clicking the installed file. To create a new workspace or to load an existing one, the user needs to select File item in the menu bar. This appendix demonstrates the workspace produced to obtain the interference results within this research.

Figure C.1 presents the SEAMCAT interface when the pre-defined workspace is loaded. The screen shows two main groups of tabs, the first (part 1) displays the systems defined within the workspace, and the environment specified between these systems (scenario tab). In this research, there are two main radio systems presented, the TV broadcasting system acting as the spectrum PU, and the railway communication system as the SU. Besides, the second screen of the figure (part 2) defines the transmitter and receiver characteristics, along with their relative positioning and used propagation models for the selected system. The next section discusses the configuration of defined radio systems, before introducing the interference scenario set-up in the section that follows.

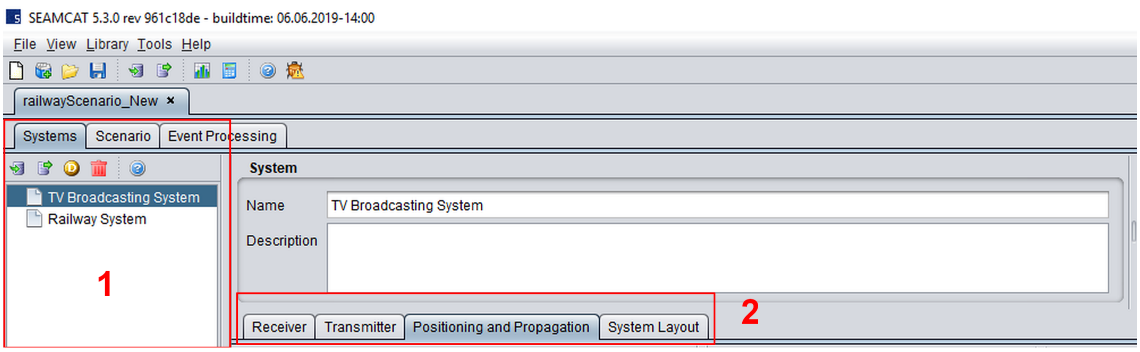


Figure C.1: SEAMCAT main screen

Radio System Configuration

First, the user can define a new receiver or load a standard one from the SEAMCAT library. The antenna radiation pattern, along with the antenna pointing, can be defined through this tab, as shown in Figure C.2.

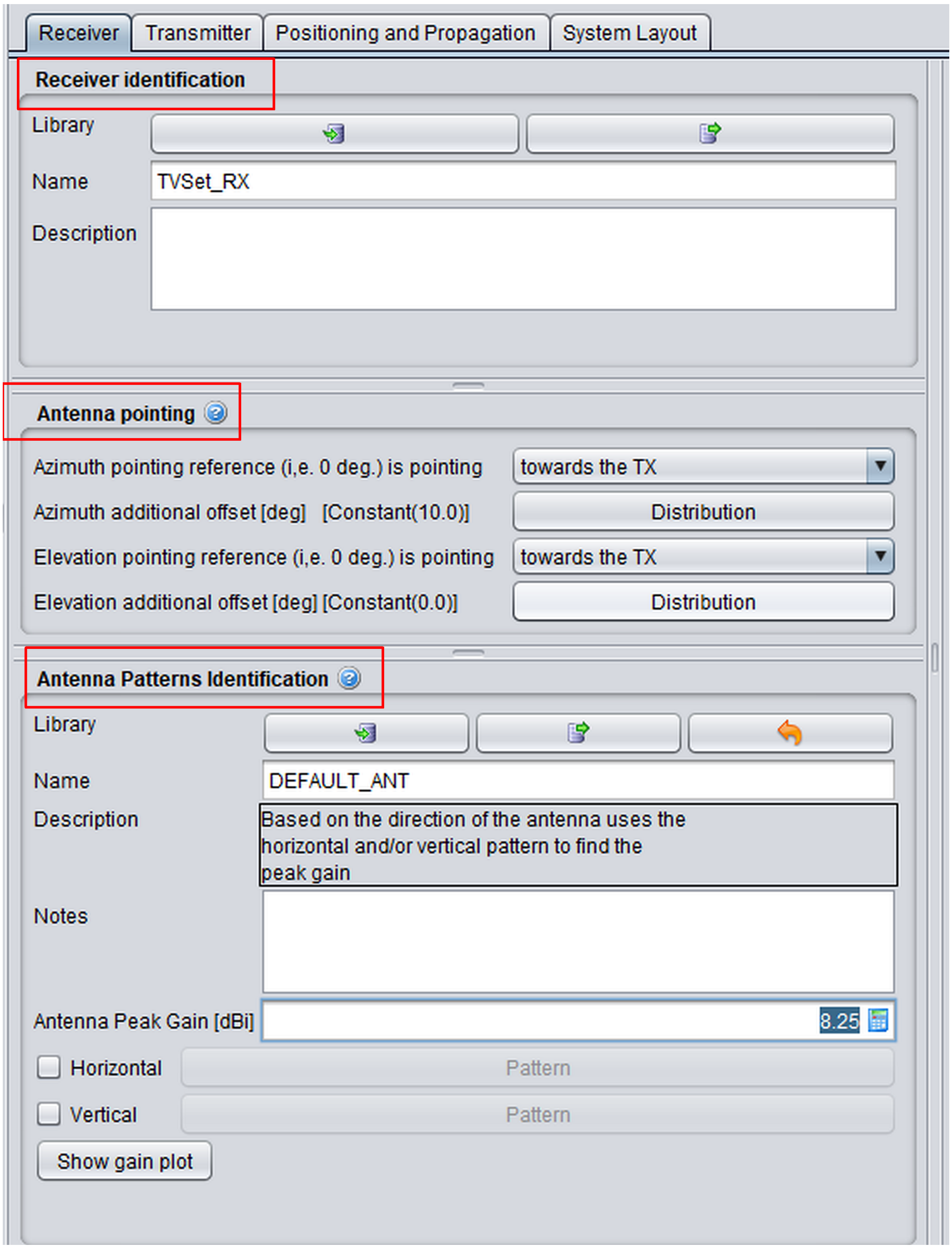


Figure C.2: Parameters configurations for each receiver's antenna

Besides, in the same tab, the user can define the reception characteristics which include the receiver sensitivity, noise power, noise figure, noise floor, and the receiver blocking mask, as shown in Figure C.3. The figure also demonstrates the concept of interference criteria used in calculating the interference probability. In this thesis, the values used to define the characteristics receiver of both systems, along with the used interference criteria, are detailed in Chapter 6.

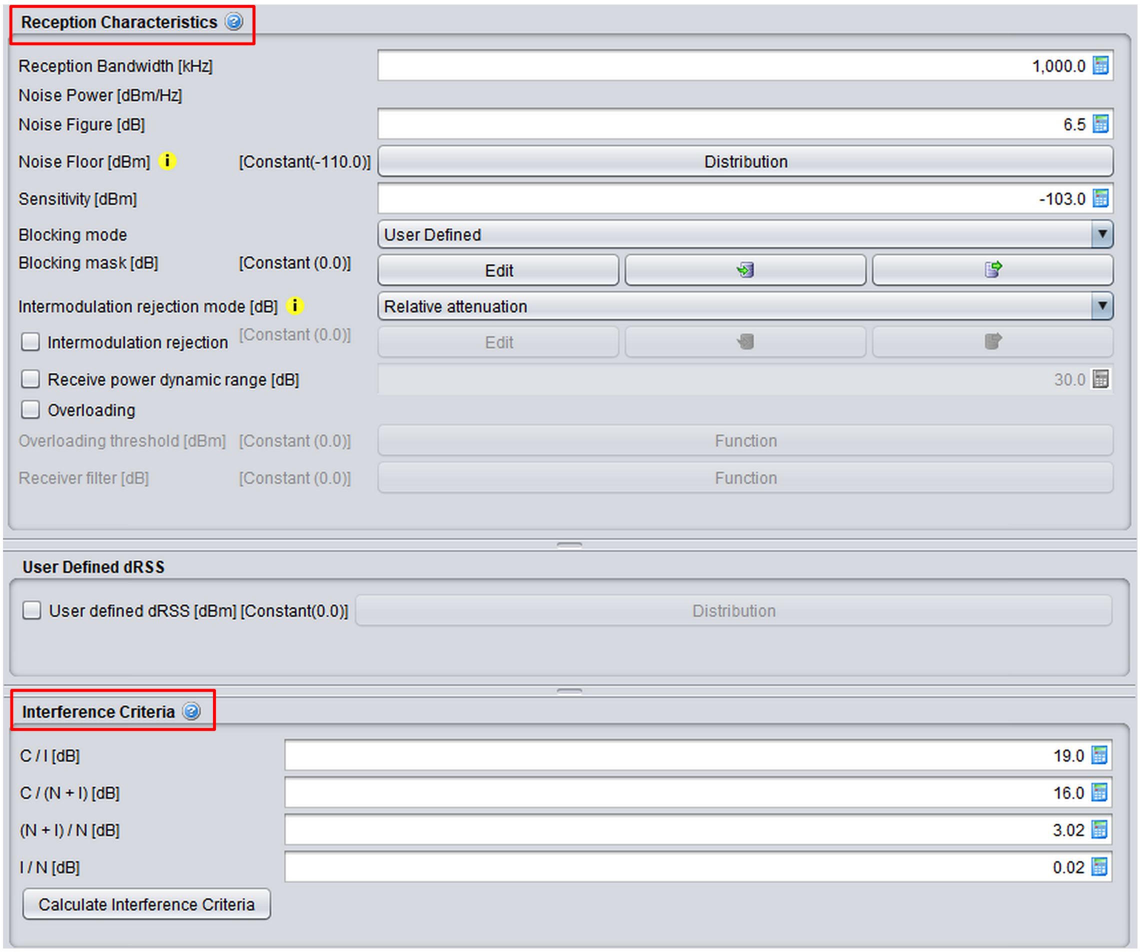


Figure C.3: Reception characteristics for each receiver

Similarly, when the user clicks on the transmitter tab, the antenna radiation pattern and the antenna pointing can be configured for each transmitter, as shown in Figure C.4.

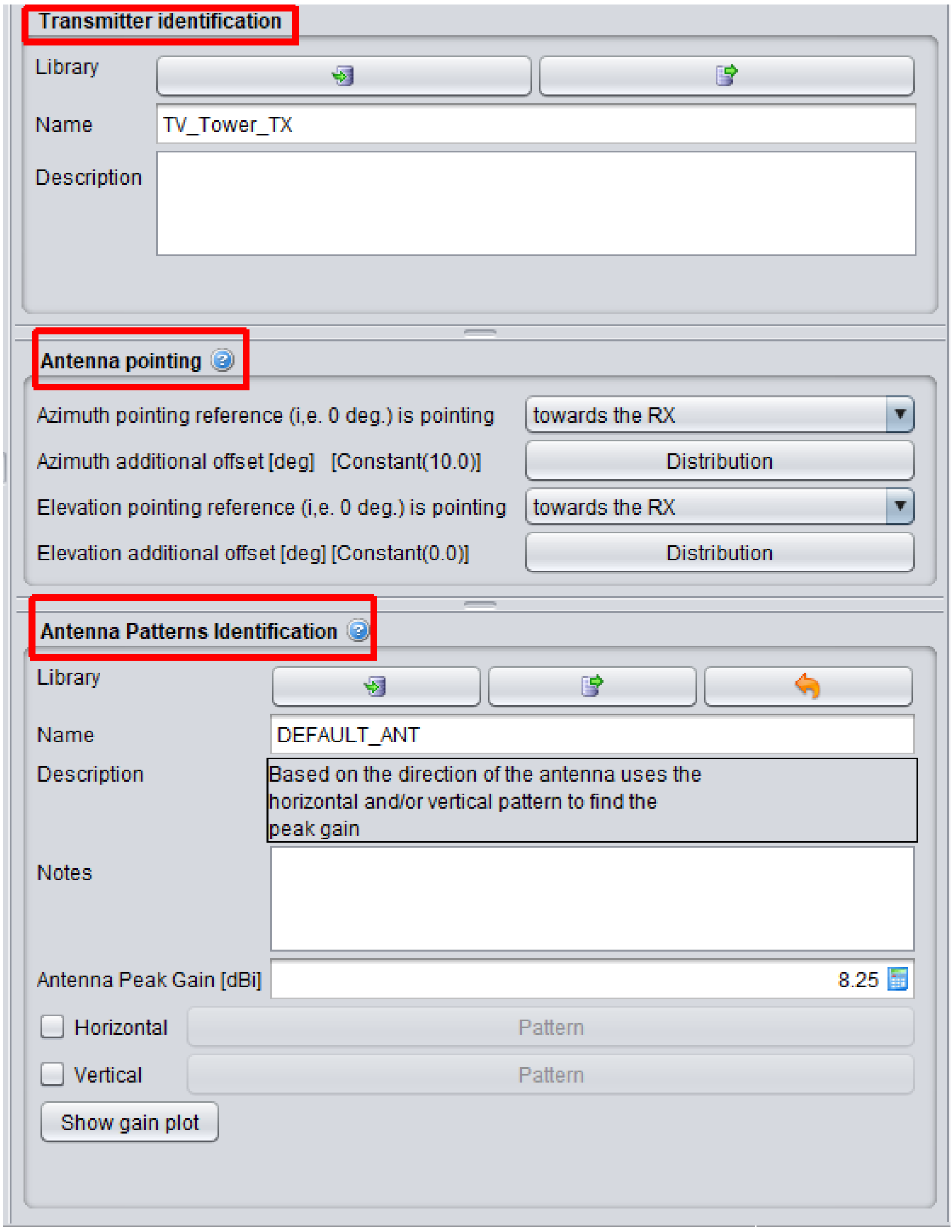


Figure C.4: Parameters configurations for each transmitter's antenna

Also, the emission mask can be defined under the emission characteristics demonstrated in Figure C.5. In this thesis, the values used to define the transmitter characteristics of both systems are detailed in Chapter 6.

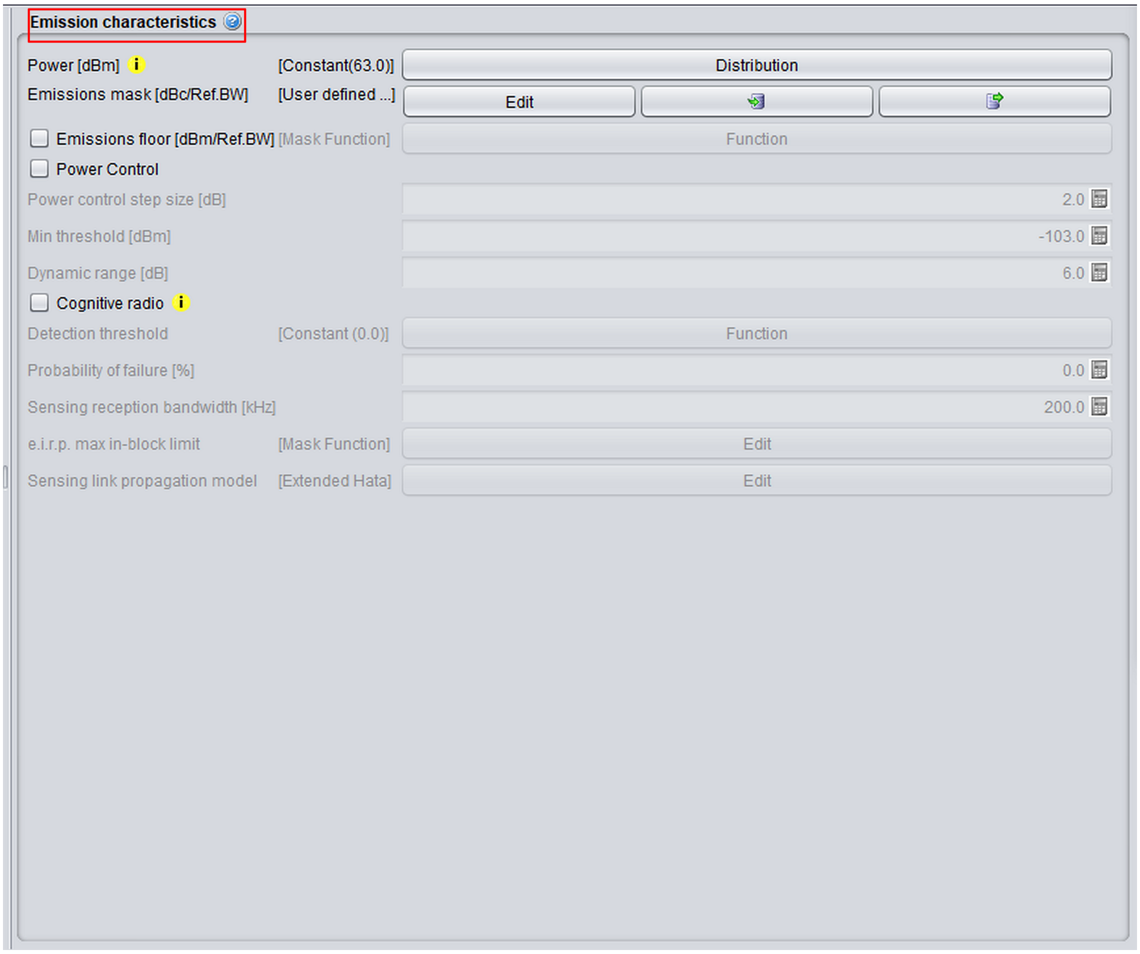


Figure C.5: Emission characteristics for each transmitter

The third tab of radio system configurations is for relative positioning and propagation models set-up. Through the tab, the user also can define the transmitter density and traffic. The receiver instance (i.e. VLR) can be located anywhere around the transmitter (i.e. VLT). The horizontal angle at which the receiver can exist is set through the path azimuth, while the path distance factor defines the path length between the transmitter and the receiver.

For the TV broadcasting system, the path azimuth is set to be between 0 and 360 deg, while the path distance has a maximum value which is equal to the transmitter coverage radius. For the railway system, the distance between the transmitting train (i.e. ILT) and the receiving AP (i.e ILR) are being extracted from the mobility module in OMNET++. Figure C.6 shows the parameters used to set-up the positioning between the transmitter and the receiver.

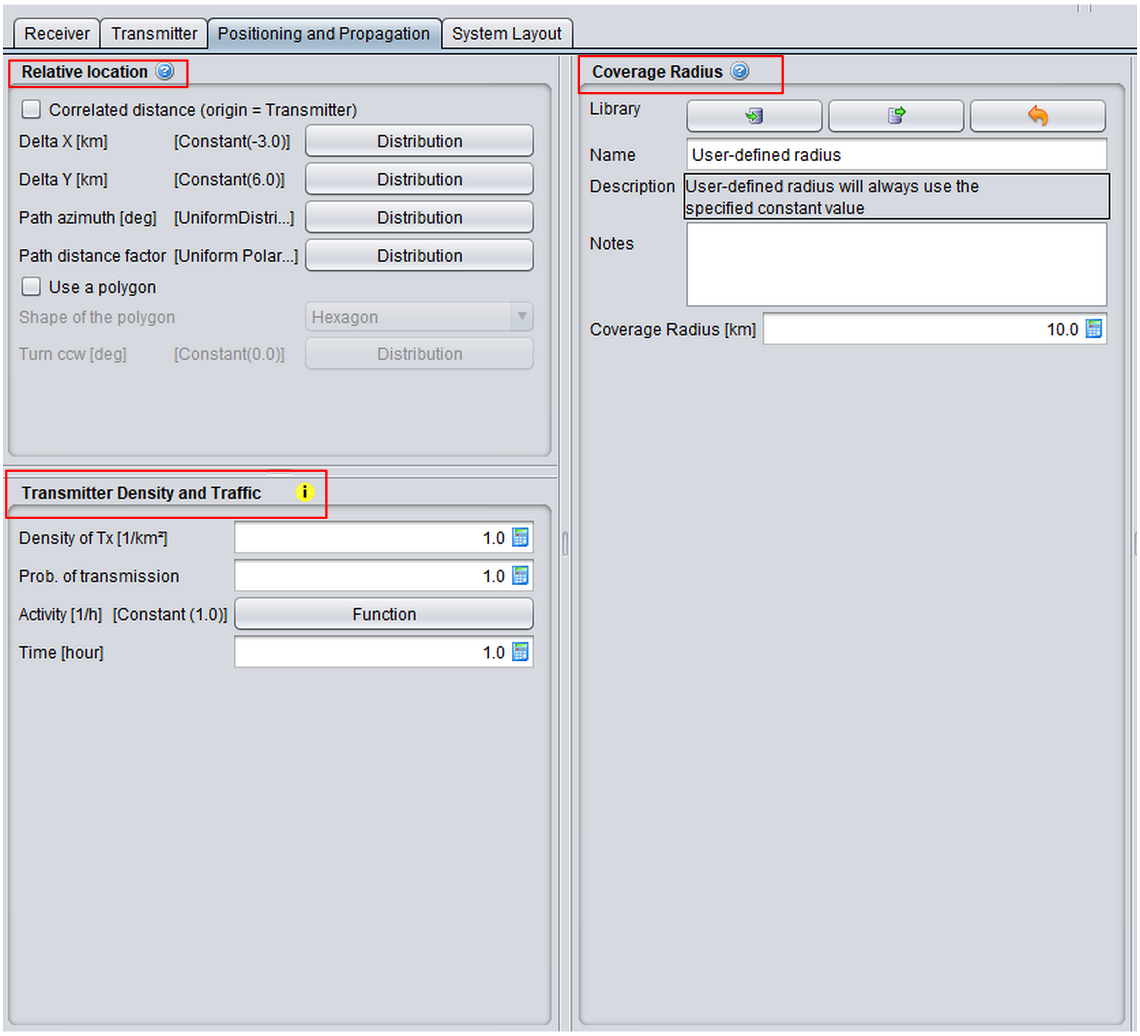


Figure C.6: Positioning set-up between transmitter and receiver

Finally, under the same tab, the user can define the propagation model between the transmitter and the receiver of the same system, as shown in Figure C.7. In this research, the SEAMCAT pre-defined Longley Rice is being used for the TV broadcasting system while Extended Hata is considered for the railway network, as mentioned in Chapter 6.

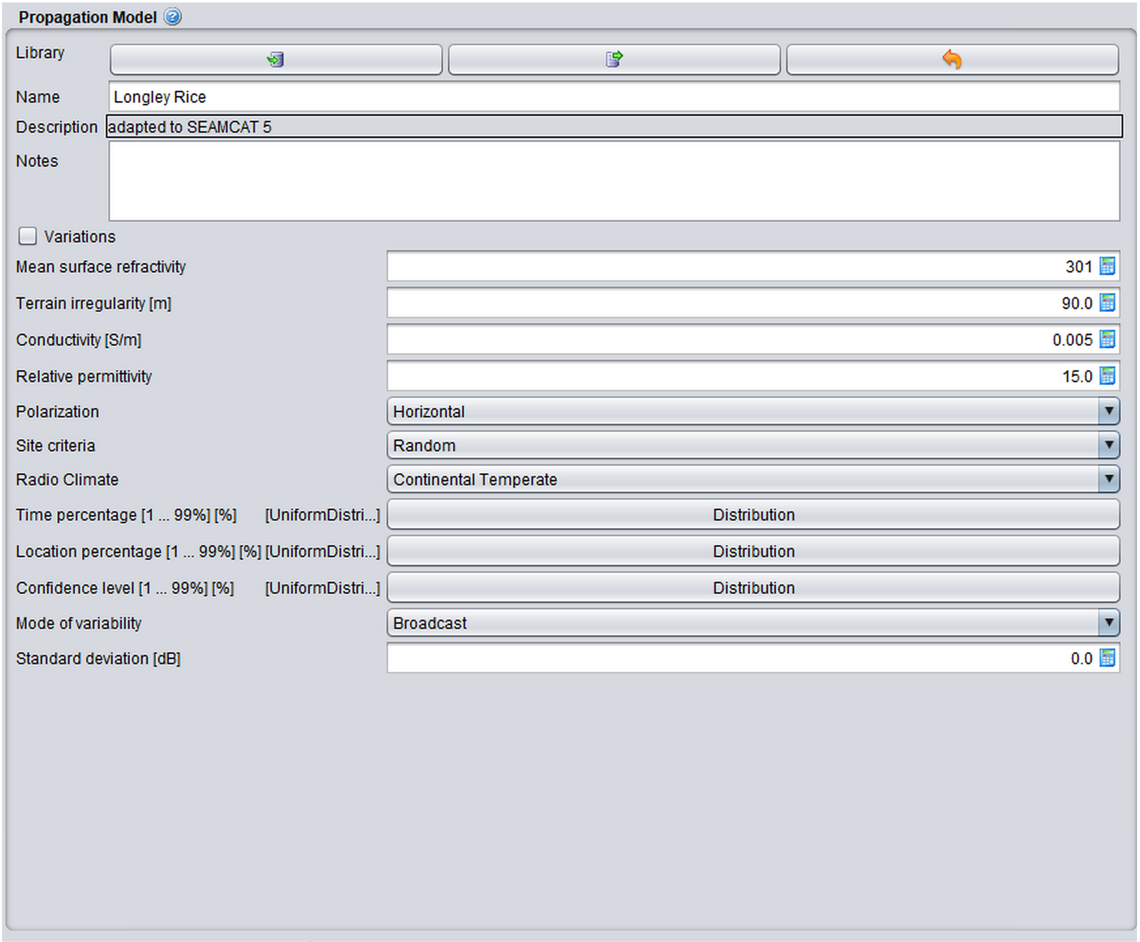


Figure C.7: Propagation model set-up between transmitter and receiver of the same radio system

Interference Scenario Definition

Referring to the scenario tab in Figure C.1 (part 1), the user can define radio systems that SEAMCAT will consider as the "victim" and "interfering", and the operating frequencies of each system. The second part defines the relative positioning between the two systems and the separation between ILT and VLT, as shown in Figure C.8. The separation distance reflects the protection contour modelled in Chapter 6.

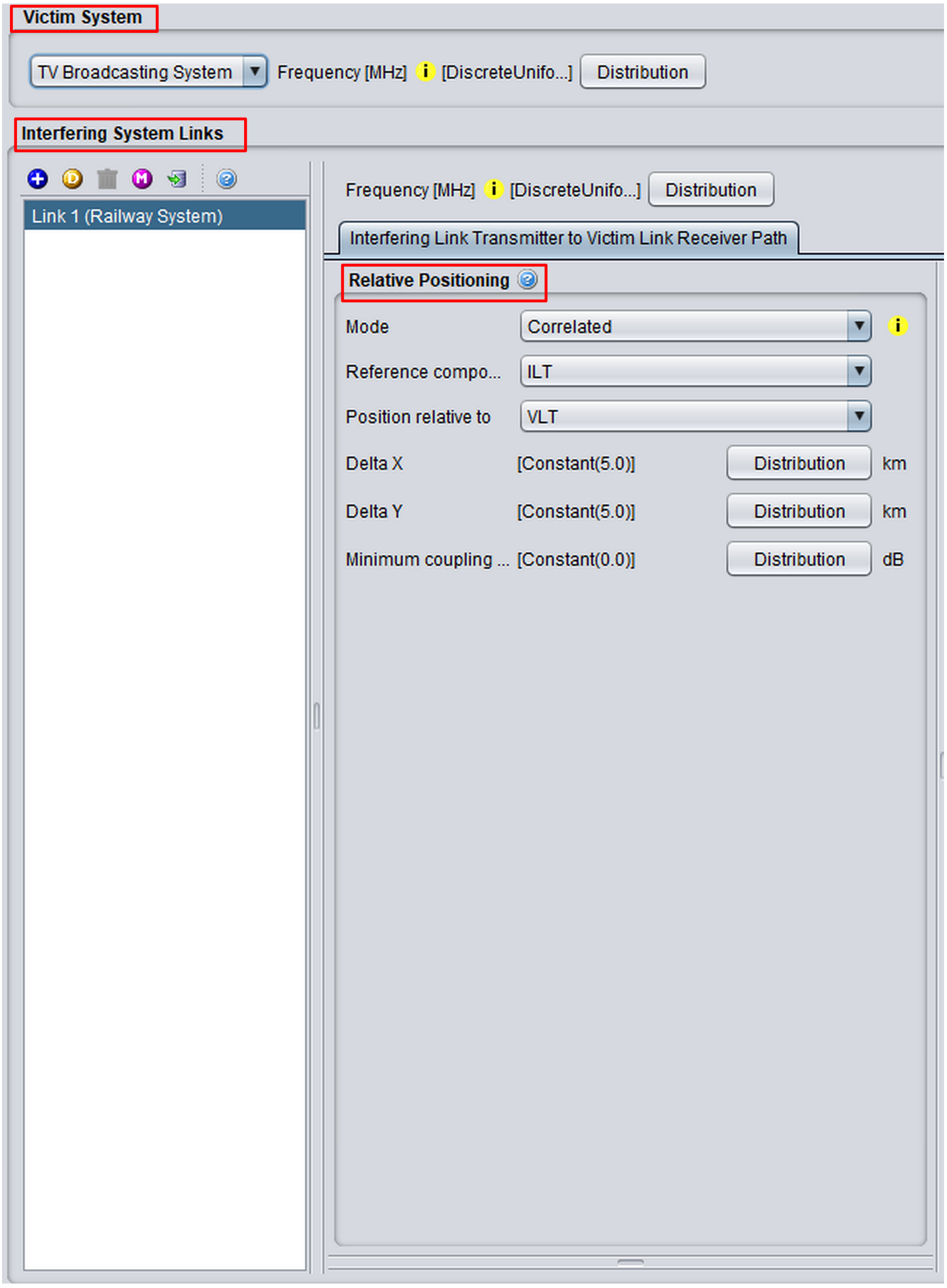


Figure C.8: Scenario definition in SEAMCAT

From the same panel, the user can specify the number of events to be generated by SEAMCAT to represent variable parameters mentioned above. Once selected, the user can click on the highlighted button of Figure C.9, to start the simulation and obtain results.

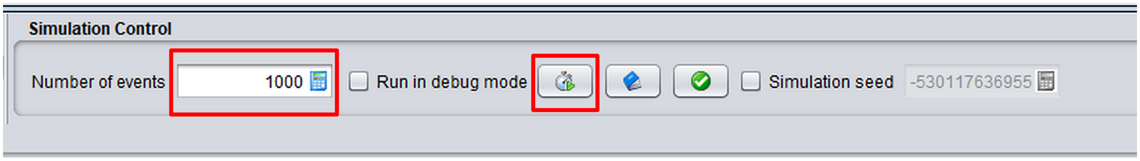


Figure C.9: SEAMCAT simulation start

The main result considered in this thesis is the interference calculation as it indicates the interference probability caused by the interfering system to the victim system. Also, the same result reflects the impact of increasing the interfering transmitted power on the victim receiver.

After user-selection of the translation parameters, Figure C.10 will appear. The figure shows the interference probability for each given interfering transmitted power, which reflects the potential safe raise in the interfering transmitted power without causing any interference to the victim system. More information about SEAMCAT parameters can be found in the handbook available online.

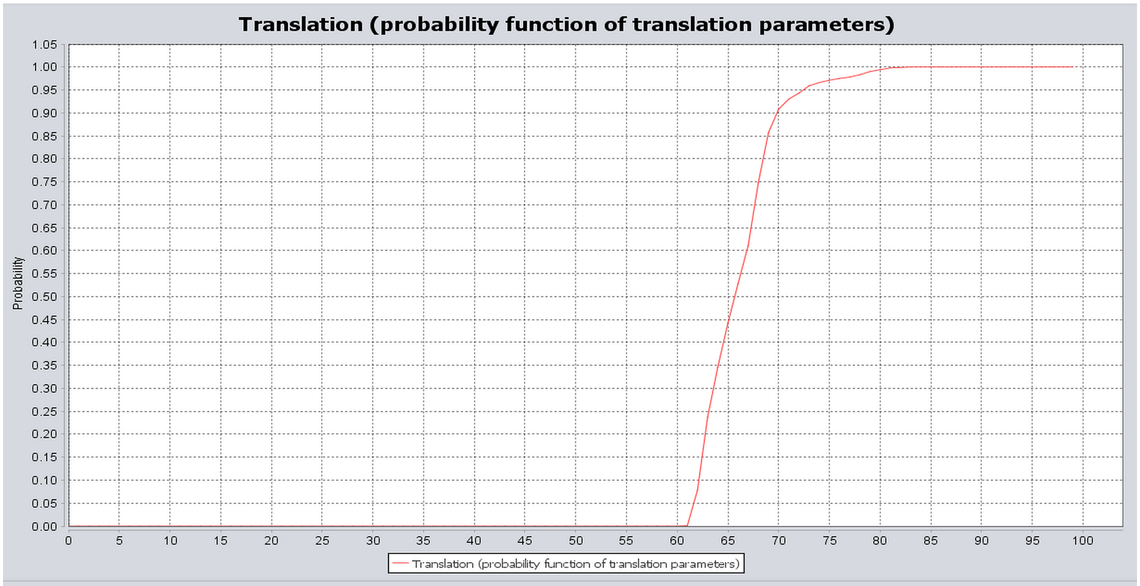


Figure C.10: Interference probability for various values of interfering transmitted power