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Assessing the Usage Feasibility of TV White Spaces for Railway Communication Applications

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***Abstract*— Since telecommunications represent a strategic asset for the railway industry and a focal point for its evolution, it is important to consider emerging standards and technologies responding to the rapidly growing demand for mobile communication solutions in the railway domain. The prospect of opportunistic access to an inefficiently utilized frequency spectrum, known as TV whitespaces, was mainly proposed to solve the spectrum scarcity problem with desirable railway propagation characteristics. This research investigates the requirements of various railway communication applications against TV whitespaces characteristics, considering Rail Remote Condition Monitoring as an initial case study. The main objective is to specify and enhance the QoS parameters for the spectrum secondary users (rail network) in terms of throughput, availability, reliability and performance at speed while ensuring full protection for the spectrum primary users. A simulation scenario using BRaVE and OMNET++ was introduced for a train moving at maximum speed of 80 Km per hour between Selly-Oak and University Station, Birmingham, United Kingdom. Initial results indicate that TV White Spaces system can deliver average throughput of 1.47 Mbps per train. Coverage radius of 12 Km combined with perfectly aligned directional antenna in rural areas can ensure full protection for TV users while allowing higher transmission power for the rail TVWS network.**

Keywords*— *Dynamic Spectrum Access, TV White Spaces, Railway Telecommunications, Remote Condition Monitoring, OMNETT++, SEAMCAT.

I. INTRODUCTION

Now more than ever, railway operations are becoming increasingly automated through Information and Communication Technology. Enhancement of passenger experience, maintaining certain safety levels and reduction of operational costs all represent the main features of modern railway systems [1]. The rail telecommunication industry is in a phase of expansion due to the development of new applications while tackling challenges of the existing ones [2].
GSM-R is defined as the international wireless communications standard for railway communication. It is mainly being used to transmit data between trains and railway regulation centres within level 2 and 3 of ETCS (European Train Control System). Besides, GSM-R was planned to provide further services and applications for mobile communications in the railway domain [3] [4]. However, introduction of recent technologies such as LTE and UMTS in the adjacent frequency bands caused interference to GSM-R network which affected the rail operations in 400 locations around Europe [5].

The GSM-R narrow band and the utilized circuit switched transmission paradigm, make it hard to consider GSM-R for any future expansion either for railway signaling system that supports larger network capacity or for enabling additional rail applications [5].

Of these additional applications, providing affordable and low-latency on-board broadband as an alternative to the existing satellite-based backhaul has represented a priority for the literature in [6]. At the same time, various stakeholders in the rail industry have shown interest in enabling a Remote Condition Monitoring framework through the intensive use of recent communication technologies [7].

There are several mobile communication technologies that have shown great potential to fulfil the current industrial needs. Of these technologies, LTE can provide a promising performance in terms of a high data rate and suitability for safety-critical applications due to the available traffic prioritization features, its performance at high speed, and wide coverage [8] [9].

The switch-over from analogue to digital terrestrial TV has freed up highly valuable radio frequencies, which are known as TV White spaces (TVWS). These frequencies can be used by low-power secondary devices on an opportunistic basis provided that full protection is ensured for system primary users (e.g. TV users and Program Making and Special Events).

A deployed system in TV VHF/UHF frequencies can offer competitive performance to the other proposed technologies, as the low-frequency signal is subjected to lower path loss and higher penetration capabilities while covering wider areas with less base stations [10]. However, the spectrum regulator does not ensure a certain QoS for TVWS secondary systems, as connection can be immediately terminated if any interference is caused to the spectrum primary users.

This research is concerned with quantifying the TVWS network performance and its ability to meet different rail applications requirements in terms of coverage, reliability, availability, capacity, performance at high speed. The research will consider Remote Condition Monitoring (RCM) as an initial feasibility use-case due to its technical flexibility and strategic value. RCM data transmission can occur at any time-place depending on the best available network performance, which suits the current development stage of TVWS. Enabling RCM will contribute to the 5 strategic outcomes of the rail industry: Safety, Customer, Cost, Carbon and Capacity [7].

Different physical-layer approaches such as directional antenna and various spectrum access methodologies including VANET will be applied to minimize the interference probability with the spectrum primary users. That would result in enhancing the rail communication network performance as the communication link will be less prone to termination and higher transmission power would be allowed. Customized Physical / MAC solution is expected to be provided by the end of this research enabling TVWS-based RCM system.

Part II of this paper will analyze the requirements of various mobile railway communication applications along with the potential technologies that have been proposed to meet these requirements. The main features of the TVWS system and its ability to meet rail needs are introduced in Part III. This part also states the RCM requirements in detail, including possible network topologies. Part IV describes the RCM simulation process using OMNET++, BRaVE and SEAMCAT, and discusses the indications of the obtained results. Part V will summarize the work done, including recommendations on the required enhancements and future work plan.

II. Requirements Analysis of Railway Communication Applications

Capturing the user requirements of rail mobile communications is considered to be the first step towards developing innovative solutions and business cases. It is hard to predict the future requirements accurately; however, the current requirements give a sufficient indicator towards areas of growth and development. The author in [11] represents the requirements in a series of applications which are either in current use or are expected to be in use in the future, and their development is subject to the intensive usage of mobile communications. The applications are categorized into four main groups as follows:

Operational – Safety Critical – Any failure in these applications can directly lead to damage being caused, or not prevented. Examples of this category can include: Train Control, Staff Communications and Track-Side Safety.

Operational - Safety Related– Failure of these applications has the potential to affect the safe running of the railway operations. Automatic Train Operation, CCTV and Possession management are all examples of this category.

Operational – Non Safety Related – The failure of these applications will affect normal rail operations but not safety related operations. Examples of this category can include: Intelligent Condition Monitoring, Driver Advisory and Passenger Counting.

Retail – These applications are more concerned with passenger leisure and use of available retail opportunities. Passenger Entertainment, Ticketing/ Revenue Collection and On-board Catering are all examples of this category.

Each category has been evaluated in the context of GB mainline rail according to four key requirements: Coverage, Reliability, Performance at Speed and Capacity. Safety-critical and safety-related applications demand the highest reliability, availability, and performance at speed. The coverage requirements need continuous and near universal coverage along the whole rail network with a lower required data rate [11].

On the other hand, non-safety related applications can have their communication service at discrete coverage. This offers a great economical approach, as bandwidth is only needed at certain locations of the network. Performance at high speed is not required, as data can be transferred when the train is about to stop at a station or depot. This brings with it, for some applications, a medium need for reliability and availability, as the railway service will continue to operate normally even if the communication service is lost [11].

Analysis of retail requirements showed low demand for reliability and dependability, as passengers' data are not critical for rail operations. However, the service must be provided continuously over large areas of the rail network at operational line speeds. The retail category also requires the highest data rate due to passengers' multimedia applications [11].

Reference [8] has assessed various technology options based upon their ability to fulfil the various category requirements. From a technical perspective, LTE, WiMAX, satellite and 3G showed great potential due to their high data rates. However, LTE and WiMAX can be considered the main competitors due to their high profile and ability to fulfill the requirements of large railway applications number. Traffic prioritization features, wide network coverage and performance at high speed are all features of LTE that make it a perfect candidate for safety-critical systems.

On the other hand, mobile WiMAX has been known with its flexibility and better Quality of Service for nearly 3 million subscribers around the world. WiMAX can provide high throughput that can reach up to 32 Mbps. However, there are still questions regarding the industry ecosystem and the network wide-area coverage [8].

TV Whitespaces can offer competitive performance to LTE and WiMAX as its low-frequency signal is subjected to less path loss and has higher penetration capabilities. In addition, a TVWS system can be deployed in lower cost as less base stations are needed to cover a certain area. The next section will demonstrate the main concept and characteristics of TVWS, showing how an enabled system in these bands can provide competitive advantages.

III. TVWS TECHNICAL CHARACTERISTICS

A. TVWS Concept and Regulator's Proposed Framework

The TVWS refers to the inefficiently utilized spectrum chunks in the frequency band between 470-790 MHz . The TV band was originally allocated for use by Digital Terrestrial Television (DTT) broadcasting and Programme Making and Special Events (PMSE). After the TV analogue to digital switchover, most of the channels are now not used for DTT transmission at any given location. In the United Kingdom, only 6 out of 32 channels are being used to receive DTT services, as shown in Figure 1. The white squares represent the channels that could potentially accommodate secondary low-power devices. The spectrum secondary users would operate in accordance with specific technical parameters to ensure full protection for the band primary users [9].

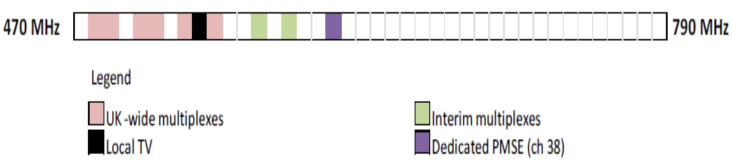

Figure 1: Illustration of White Space spectrum in London [9]

To effectively reuse the TVWS spectrum without causing any harmful interference to the primary licensed users, spectrum regulators adopted a database-assisted TVWS network architecture [9] [10]. In the architecture shown in Figure 2, unlicensed white space devices (WSDs) obtain the TV channel information from a certified geolocation database residing in the cloud. This approach came as an alternative to the local spectrum sensing technique used in traditional dynamic spectrum sharing systems. The geolocation database updates its data periodically to keep WSDs updated with the existing TV licensees and their channel occupations [10]. The architecture is based on cognitive radio as enabler technology without considering the used standard.

Different trials have been carried out to utilize the TV white space spectrum through adaption of existing technologies such as Wi-Fi and LTE. On the other hand, building a new flexible standard that can best suit the nature of TVWS was the main focus of the IEEE 802.22 work group. The author in [11] introduced White-Fi, the first Wi-Fi like system built on top of the UHF white spaces spectrum providing technical solutions to overcome the spatial variations, temporal variations and fragmentation of the TVWS spectrum.

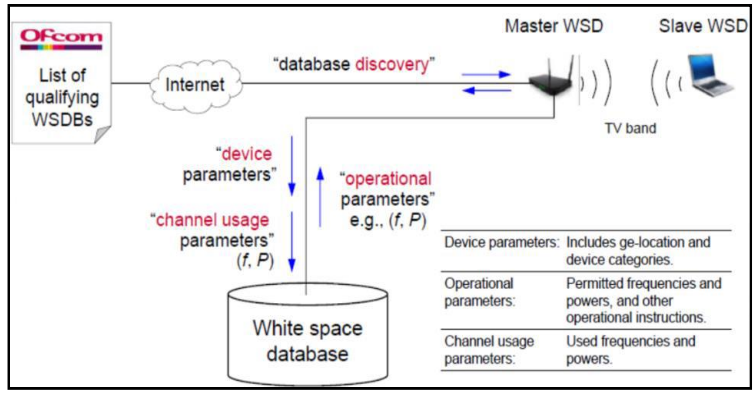

Figure 2: A database-assisted TVWS network architecture [9].

Moreover, LTE operating in TV white spaces was introduced in [12] as a good solution due to the wider coverage that can be achieved. A great deal of literature, including [13] and [14], focused on the introduction of cognitive radio in the TV white space spectrum, highlighting the system's main functions along with the future research challenges that need further development.

B. TVWS Evaluaiton in Railway Context

In this section a TVWS enabled system will be assessed for its ability to meet various rail applications requirements including: Coverage, Reliability, Availability, Performance at Speed and Data rate. The evaluation process will also consider external factors such as interoperability, commercial availability and regulator policies. The main aim of this evaluation is to highlight the main advantages of a TVWS system over other potential technologies, and recommend a development roadmap for intensive TVWS usage in the railway environment.

a. Coverage

Figure 3 shows the relation between the frequency and the possible coverage area. With usage of higher frequency, a small coverage area will be presented. The spectrum above 1 GHz can cover smaller areas with the ability to provide large volumes of traffic per user, which satisfies the user requirements of high bandwidth. On the other hand, the spectrum below 1 GHz can cover wider areas with better signal penetration through walls and tunnels.

TVWS is allocated in the frequency band between 430 – 790 MHz, while LTE operates in various bands including the 800 MHz band, the 1800 MHz band and the 2600 MHz band. Consequently, the TVWS system can achieve optimal coverage using fewer base stations as it operates in lower frequency bands.

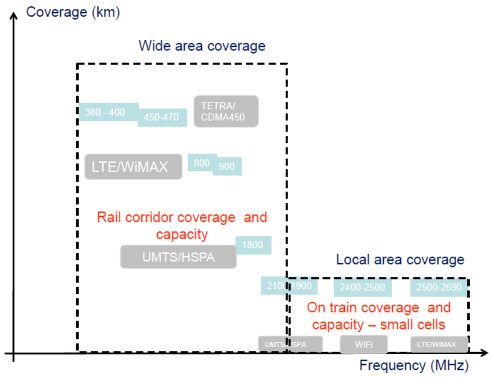

Figure 3: Relation between Coverage (Km) and Frequency (MHz) [5].

b. Capacity

In terms of delivering more capacity, spectrum at higher frequencies can support wider bandwidths and thus higher data throughput and capacity compared to lower frequencies. According to IEEE 802.22, the channel bandwidth is 6 MHz compared to 20 MHz in LTE. This indicates that LTE can provide higher throughput than a TVWS system if only one channel is assigned to the secondary spectrum user (i.e. worst-case scenario). The regulator's database can assign more than one channel based on the nature of the application.

c. Availability

According to [15], TVWS channels are reduced significantly as population density approaches 1000 per sq. mile, which represents the transition from rural to sub-urban areas. Figure 4 indicates that more TVWS channels are available in rural areas (i.e. to the left of the blue line which represents the total available channels) with less obtainable channels in urban areas. As a result, more restrictions will be applied to secondary system transmission power in urban areas in order to protect the band primary users.

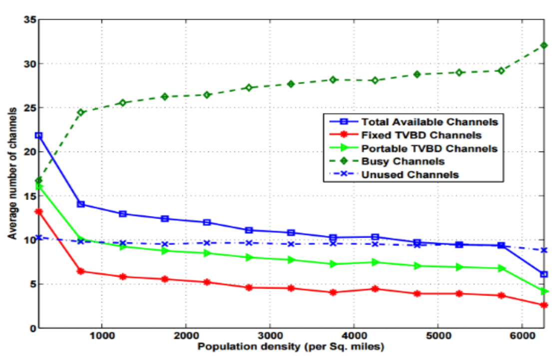

Figure 4: TVWS availability versus Population Density [15]

Figure 5 shows the relationship between allowed transmission power and the number of available channels within Central London. This indicates that 20 channels will be available in 5% of locations for transmission power greater than 35 dBm, while 20 channels will be available at 100% of locations for transmission power greater than 13 dBm and less than 16 dBm. Hence, urban areas represent a bad candidate for a TVWS system with high data rate requirements in comparison with suburban and rural areas, as less contiguous channels are available, and there is a lower allowed transmission power for secondary users.

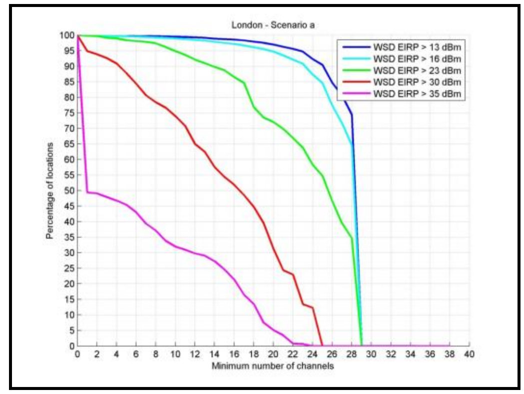

Figure 5: TVWS Availability versus Allowed Transmission Power in Central London [9]

d. Reliability

In reference to the regulator's framework, the TVWS system is fully dependent on the geolocation database to access the available spectrum chunks. However, the author in [16] proved that the proposed framework does not provide enough protection for the primary users, as the in-use database is being built using fixed propagation models. Consequently, the QoS of the secondary system will be greatly affected, as the communication link will be ceased immediately if any interference is caused to primary users due to inaccurately provided operational parameters (e.g. frequency and allowed transmission power).

e. Performance at High Speed

Doppler shift is defined as the frequency change due to the relative movement between transmitter and receiver. In other words, the frequency perceived by the receiver differs from the one that was originally emitted. The shift mainly depends on the velocity of mobile and carrier frequency fc. The Doppler shift is minimised while using lower carrier frequency. The TVWS system is proven to provide higher resilience to mobility.

f. External Influences

One of the most important requirements for rail safety applications is the system interoperability between different countries. Although TVWS is available for operation in Europe, research is still undergoing to provide Database-to-Database coordination and interoperability [17] [18].

Another factor to consider while evaluating a TVWS system is the availability of commercial off-the-shelf products. Carlson wireless is one of the rare products that are patented and certified from a regulator body. Use of commercial-off-the-shelf (COTS) products has the advantage of: cheaper cost, greater expansion, ease of design and maintenance, availability of spares and longer system life.

Regulatory policies are the last factor to consider in the evaluation process proposed in this paper. As TVWS services are non-protected from interference by primary users, techniques must be developed to ensure a certain threshold of QoS (e.g. usage of TV back-up channels for secondary users' migration when interference happens). It is also important that the regulator's standards for protection of primary users are not excessively restrictive and inflexible. Conversely, the regulator should work on increasing the chances for coexistence of DTT receivers with other technologies.

C. TVWS Evaluation Summary

From the previous section, we can conclude that a system operating in TV white spaces will give better performance than a LTE system in terms of: Coverage and Performance at High Speed. TVWS will give medium throughput performance, as this is dependent on channel availability from one location to another. Reliability needs validation to ensure that TVWS can provide certain level of QoS, however the fact that interoperability is still under development prevents TVWS from being applied in rail safety critical applications. The suitability of TVWS for different rail applications categories can be summarized as follows:

Safety Critical/Related Applications (e.g. Signaling System): TVWS at its current development stage does not represent the best candidate for these types of applications. This is because of a lack of accuracy in the regulator's database and insufficient protection for the secondary systems operating in TV bands. The unavailability of database interoperability also represents a challenge for trains travelling between different countries. However, there are ongoing trials to enhance the accuracy of the regulator's database framework by using Radio Environmental Maps (REM) that provide more accurate and local channel propagation information [16].

Non Safety Related Applications (e.g. Remote Condition Monitoring): This kind of application does not have restricted requirements, which perfectly suits the flexible nature of TVWS characteristics. There is no need to ensure that throughput must exceed a certain threshold and no harm if the connection is terminated, as ideally the data transmission can take place at any time-location where a suitable B.W. is available with minimal interference to the primary users.

Retail Applications (e.g. Passenger Leisure): The small channel bandwidth of TVWS proposed in the IEEE 802.22 standard can limit the system from providing throughput above a certain QoS threshold, as availability of multiple channels is dependent on service location. However, TVWS can provide universal coverage of a rail network at low cost. Retail applications require low reliability because of the nature of passenger data; however, it must be guaranteed that the number of ceased connections will not exceed a certain limit. Passenger retail rail applications have been the subject of many literatures.

In [19], the author proposed a LTE secondary system that operates in TV White Space frequencies providing on-board broadband to a moving train from Hamburg to Munich in Germany. The analysis showed that sustainable data rates beyond 20 Mbps per train can be achieved in all considered scenarios; however, the number of ceased connections as the main factor of QoS was not evaluated.

To the best of my knowledge, a TVWS system has not been simulated for either rail safety-related applications or non-safety related applications, such as RCM. The on-board broadband application proposed in [19] did not consider the strict regulator's policies on secondary system transmission power especially for mobile platforms [20]. Hence, the TVWS system will not have the advantage of wide coverage, as a dense network of base stations will be needed to achieve good performance while protecting TV primary users.

A simulator that takes into account the comprehensive technical parameters in addition to variables in the railway context is needed for a precise evaluation of a TVWS system. The simulation output will draw the future development map of the TVWS system for high speed trains and could represent a serious step towards mitigation of the regulator's policies guaranteeing a certain level of quality for the railway as a spectrum secondary user.

Considering Remote Condition Monitoring (RCM) as an example of a non-safety related application has its technical and strategic advantages. From the technical side, this category does not have strict QoS requirements regarding reliability or throughput, as transmission can occur at any time-place depending on the best available network performance which best suits the flexible nature of TVWS. In addition, as mentioned in [4], RCM will contribute to the 5 strategic outcomes Safety, Customer, Capacity, Carbon and Cost-Efficiency.

D. Remote Condition Monitoring

Remote Condition Monitoring (RCM) represents the movement from manual infrastructure control and monitoring towards deploying intelligent devices that report on the infrastructure's health, status and condition of vital parameters to control centres. RCM can introduce improved infrastructure performance with lower probability of failures affecting the railway service. In a traditional system, the cost of breakdowns can be minimized through increasing the maintenance frequency, which comes at a high cost [21] [22]. The main objective of RCM is to find the optimum point where a minimal maintenance frequency can lead to a lower number of system breakdowns, as shown in Figure 6.

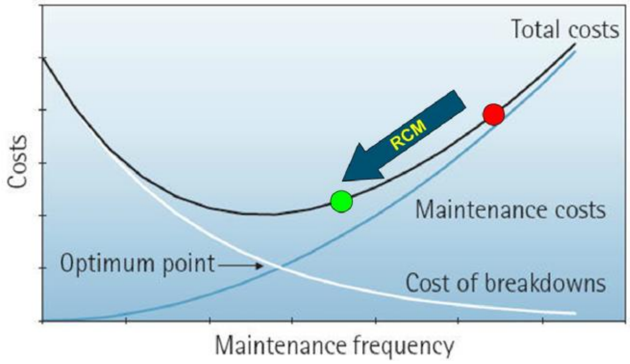

Figure 6: Effect of RCM on Reduction of maintenance cost.

At the present time, Network Rail [23] uses a fleet of infrastructure measurement trains that are 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. The data are initially stored on hard drives on-board the train then transferred to control centres where validation and distribution to customers can occur. The process generates enormous volumes of data that can reach up to 1.3 petabytes for only four weeks of infrastructure measurements.

It is an essential step to understand and consider detailed RCM requirements to ensure precise evaluation of the TVWS performance. The backbone network of RCM should cover all the routes where passenger and freight trains would travel. However, continuous coverage is not required, which gives the application a higher degree of flexibility, as there are no restrictions regarding the time and location where the transmission must happen. On the other hand, with the assumption of on-board data processing, the network must have the ability to prioritize failure alarms over non-critical condition reporting data.

TVWS system reliability should be sufficient to ensure delivery of enough reports to the remote control centres with communication link availability at all times and especially when the train service could be affected (e.g. traffic hours). It was assumed that only 20 Kbps is needed for each train and 1072 Kbps for each trackside device for condition and fault monitoring [2]. The real application would require higher throughput, however, data volumes were assumed to be minimized through techniques such as exception reporting.

According to [22], there are various communication network topologies to consider for RCM, which are presented as follows:

- **Train Monitoring Infrastructure:** Infrastructure condition data is collected from train-mounted sensors, where one sensor system can monitor large sections of infrastructure as a train moves around different routes. Data transmission takes place from the train to the base station and forwarded afterwards to the control centre. A full duplex communication link might be desirable to enable requests to be sent from the control centre for customised measurement procedures. Examples of this include Unattended Geometry Measurement Systems (UGMS), which give a detailed measurement of track vertical, lateral, twist, cross level and gauge variation.

- **Infrastructure Monitoring Trains:** Lineside monitoring systems can be an efficient way to monitor train condition as a large number of trains pass by a particular point on the network. Afterwards, the data need to be transmitted from a fixed infrastructure point to the control centre. Examples of this category include: hot axle bearing detection, wheel impact load detection and acoustic axle bearing monitoring, which provides alarm indications when a passing axle bearing reaches a predefined temperature.

- **Infrastructure Monitoring Infrastructure:** This category is identical to the case of "train monitors train", as both are enabled by the use of Wireless Sensor Networks (WSNs). The first category is used to monitor the railway infrastructure such as bridges, rail tracks, track beds, and track equipment while the second type is used for vehicle health monitoring such as chassis, bogies, wheels, and wagons.

IV. RCM SIMULATION

The scope of this research will focus on considering "Train Monitoring Infrastructure" as a feasibility validation case for TVWS usage in a railway context along with evaluating the system QoS factors including reliability, capacity and coverage range. This can be achieved through building a comprehensive simulator which takes into account most of the possible technical and external inputs which can affect the system performance, presented in correspondence to an OSI model, as shown in Figure 7.

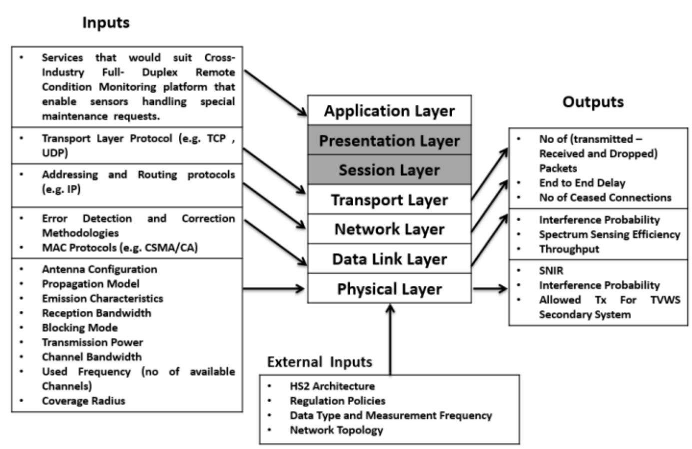

Figure 7: RCM Simulation Procedure

The specifications of DVB-T as the spectrum primary user and a TVWS system as a secondary user are listed below in

Table 1. Both systems are operating at the same frequency spectrum, 470-790 MHz. Channel allocation is the regulator's database responsibility, however, through this simulation the used channels will be assumed as a start [9] [15] [24] [25].

	Input Name	Primary System (DVB-T)	Secondary System (TVWS)
Physical Layer	Propagation Model	• Longley Rice Model	• Hata Model
	Coverage Radius	• ≈ 40 Km	• 15 Km (non-line of sight)
	Antenna height	• **Transmitter:** 51m • **Receiver:** 10 m	• **Fixed Devices:** 30m • **Portable Devices:** 3m
	Antenna Gain	• 8.25 dBi	• 6 dBi
	Modulation	• 64-QAM	• BPSK to 64-QAM
	Channel Bandwidth	• 8 MHz	• 6 MHz
	Topology	• Point to Multipoint	• Point to point and point to multi
	Transmission Power	• **Base Station Power:** 63 dBm	• **Fixed Devices:** 36 dBm (3.9 Watt) • **Portable Devices:** 20 dBm (0.1 Watt) • **Portable Devices in adjacent Channel:** 16 dBm
	Noise Floor	• -105 dB	• -105 dB
Data Link Layer	Multiple Access Protocols	OFDM	CSMA/CA
Transport Layer	Transport Protocol	Real-Time Transport Protocol (RTP)	TCP/UDP

Table 1: TVWS input parameters of Primary and Secondary Systems

There are many simulation environments that propose a framework where Cognitive Radio (CR) can be implemented. NS2, NS3 and OMNET++ are all examples of these simulators, however, the latest give better accuracy when simulating large networks with better CPU utilization [26] [27] [28] [29]. In addition, OMNET++ with its modular nature provides a more detailed definition of the physical layer parameters, including different propagation models and directional antenna implementation. However, the CR implementation of OMNET++ source code has not been published yet. Hence, a fixed frequency and transmission power will be initially used for this simulation.

The integration that took place at the Birmingham Centre for Railway Research and Education (BCREE) between OMNET++ and BRaVE (Birmingham Railway Virtual Environment) by Xinnan Lyu and David Kirkwood et al [30] simulating Wi-Fi as a communication network for a signaling system in CBTC, paved the road for the implementation of different wireless technologies in the railway environment.

A simulation scenario was built for a train moving at a maximum speed of 80 Km per hour between Selly-Oak and New-Street Station, Birmingham, United Kingdom and two base stations were used provide the needed coverage as shown in Figure 8. All the inputs stated in the previous table were used to simulate a TVWS based network, except for a Hata propagation model, as it is not yet available in OMNET++. As a result, a Constant Time propagation model was used instead. The modulation was chosen to be BPSK and UDP for the transport layer with packet size of 1000 Byte.

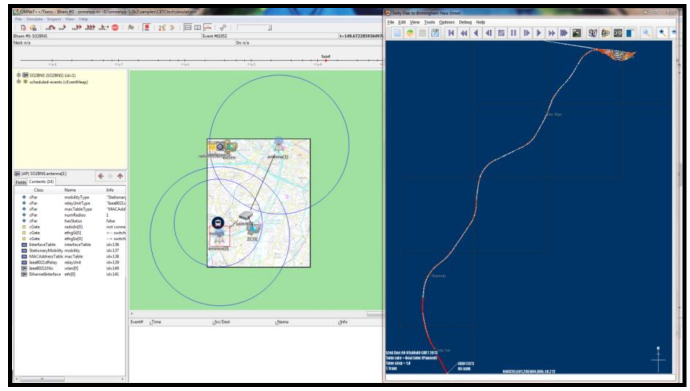

Figure 8: OMNET++ and BRaVE simulating a moving train from Selly-Oak Station and University Station using TVWS network

The network frequency and transmission power remained the same for the simulation period. The table below summarizes the main initial results obtained from the OMNET++/Brave Simulation. The throughput obtained from the simulation with the usage of only one communication channel of 6 MHz width satisfies the requirements of RCM mentioned in the last part. Channel availability is dependent upon the regulator's database, which has not yet been introduced to the proposed simulator. From the perspective of reliability, most of the packets were communicated successfully for both uplink and downlink.

Network Performance Factors	Parameters	Value
Base Station	Throughput	5.724 Mbps (Mean Value)
	Sent Packets	149
	Sent Packets Without Retry	149
	Number of Received Packets	151
	Packet Error Rate	0.003311
	Min SNIR	45
	Packet Error Rate	0.003311
Train	Throughput	1.470 Mbps (Mean Value)
	Number of Received Packets	149
	Sent Packets	151
	Sent Packets without Retry	150
	Packet Error Rate	0.0
	Min SNIR	59.59

Table 2: Simulation Results obtained from OMNET++ and BRaVE Simulation

However, the results do not indicate a realistic performance of TVWS, as TV broadcasting as the primary user was not introduced due to simulator limitations. The existence of the primary user will limit both the allowed transmission power and the number of channels used for the communication link. This will affect the system performance in terms of both reliability and throughput factors. OMNET++ does not have the capability of simulating two interfering networks as they transmit and operate at the same time. On the other hand, SEAMCAT (Spectrum Engineering Advanced Monte-Carlo), developed by the European Communication Office (ECO), permits statistical modelling of different radio interference scenarios for performing sharing and compatibility studies between radio-communications systems in the same or adjacent frequency bands.

Besides its capability of interference simulation, SEAMCAT enables the definition of a more detailed physical layer for the transmitter and receiver. For each transmitter, it is possible to define: Antenna Peak Gain, Antenna Height and Pointing, Antenna Transmission Pattern, Transmission Power and Emission Mask. It is also possible to define the same antenna configurations for the receiver in addition to Blocking Mask, Reception Sensitivity and Bandwidth. The user can also define the path between the transmitter and receiver that includes a detailed propagation model and Tx/Rx outdoor and indoor probability.

The expected output from SEMACAT is the primary system Desired Received Signal Strength (dRss), Interfering Received Signal Strength (iRss), interference probability for each scenario and allowed transmission power for secondary spectrum users (e.g. rail communication network). In this simulation, the DVB-T system has been defined as the primary system and the railway communication network as a secondary system in accordance with the technical parameters stated in the previous table.

The SEAMCAT simulation mainly aims to find the best network configurations that could give a preferable performance in terms of reliability and throughput. The first term that was considered during this simulation is the propagation environment where the transmission should take place; either it is rural, suburban or urban. The following table summarizes the results assuming DVB-T as the primary system for the case of a DVB-T receiver being located between the moving train and TVWS base station for different propagation environments.

Propagation Environments	Results
Rural	**Interference** = 82% **dRss** = - 56.63875 dBm **iRss**= - 67.1425 dBm
Suburban	**Interference** = 27% **dRss** = -57.703 dBm **iRss**= - 83.082 dBm
Urban	**Interference** = 11% **dRss** = -59.053 dBm **iRss**= -91.229 dBm

Table 3: DVB-T Receiver dRss and iRss for different propagation environments

The rural environment indicated the highest interference probability as the signal is less susceptible to distraction. However, the intensity of TV receivers is less in rural areas, as mentioned in [15]. It is more common to have large coverage areas without TV receivers being in between (e.g. macro cells). With a higher number of TV receivers in suburban and urban areas, the cell size will tend to be smaller (e.g. micro cells), which increases the network cost. In addition, in rural areas more continuous channels will be available to provide high network throughput for the railway network.

The previous simulation showed that 100% interference probabilities would occur if the train base station transmission power is around 43 dBm. Reducing the transmission power can contribute to a decrease in the interference probability, however, that contradicts the research objective which aims to enhance and ensure a certain QoS level for the railway network. The next table considers various coverage radii of the TVWS rail network in rural areas, given that the DVB-T receiver is not located between a rail transmitter and receiver, with a distance of 5 Km between the rail base station and the TV receiver.

Distance	Results
12 Km	**dRss** = - 48.88 dBm **iRss** = - 86.96 dBm **Interference Probability** = 2% 100% interference at 76 dBm
8 Km	**dRss** = - 48.67 dBm **iRss** = - 87.82dBm **Interference Probability** = 1.3% 100% interference at 82.3 dBm
5 Km	**dRss** = - 49.11 dBm **iRss** = - 94.32 dBm **Interference Probability** = 0.33% 100% interference at 79 dBm

Table 4: Effect of the secondary system Coverage Radius on performance of primary system

Smaller cells for the secondary system can cause less interference probability and originally have higher allowed transmission power, such as in the case of 8 and 5 Km. The sensed interfering signal from the rail network is getting smaller, from -86.96 dBm to - 94.32, which means enough protection is provided for TV primary users in smaller cells. From an economic point of view, it is better to cover a certain area using fewer base stations. The first case of 12 Km will be considered for further detailed simulation to find the balance between cost and protection of the primary user.

Usage of standard directional antenna used in GSM 870-960 MHz for the same 12 Km coverage radius in rural areas can enhance the results as follows: dRss = - 51.4 dBm, iRss = -112.07 dBm, Interference Probability= 0%, and the ability to transmit using 45 dBm without causing any interference, however, 100% interference occurs at 97 dBm. This can increase the secondary system performance noticeably with enough protection for the primary user. The use of directional antenna sounds an appealing solution that can provide enough protection for primary users and enhance the QoS of the secondary system at the same time. However, the mobility of trains represents a challenge for building perfectly aligned directional antennas between the base station and the moving train. Simulation of a dual antenna system where an omnidirectional antenna is responsible for communicating the train speed and direction to ensure perfect alignment for the directional antenna is required.

V. CONCLUSION AND FUTURE WORK

The switch-over from analogue to digital terrestrial TV has freed up highly valuable radio frequencies known as TV White spaces (TVWS) which have desirable characteristics for the railway environment. Through this paper, a development roadmap has been drawn to implement a TVWS based system, recommending certain configurations that can enhance the QoS of the network while ensuring enough protection for the primary users.

The flexible nature of Remote Condition Monitoring in terms of reliability, data rate and discrete coverage, along with its strategic value to the rail industry, makes it a great candidate that suits the current development stage of TVWS. The simulation undertaken proved that a TVWS system can provide a throughput of 1.47 Mbps for each train. The network provided reliable connection, as all the packets were delivered successfully. Simulation from SEAMCAT proved that rural areas with a smaller radius can ensure a lower interference probability for the primary users.

However, the use of directional antenna can enable a large coverage radius with higher allowed transmission power and more protection for the primary users. Future work will include integration between OMNET++ and SEMACAT aiming to build a comprehensive simulator that takes into account more detailed rail variables including high speed train network architecture. Different spectrum access methodologies, along with physical layer solutions will be introduced and evaluated as an essential step towards demonstration of a real life system.

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