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DESIGNING AND MODELING OF A COEXISTENCE MECHANISM FOR VEHICULAR COMMUNICATIONS ON TV WHITE SPACES

TESIS PARA OPTAR AL GRADO DE
DOCTOR EN INGENIERÍA ELÉCTRICA

ADRIANA ARTEAGA ARCE

PROFESORA GUÍA:
DRA. SANDRA LORENA CÉSPEDES UMAÑA

PROFESOR CO-GUÍA:
DR. CÉSAR AUGUSTO AZURDIA MEZA

MIEMBROS DE LA COMISIÓN:
DR. CLAUDIO IGNACIO ESTÉVEZ MONTERO
DRA. NATHALIE MITTON
DR. DIEGO DUJOVNE HELMAN

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CO-ADVISOR: PROF. DR. CÉSAR AUGUSTO AZURDIA MEZA

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The expected growth in the number of connected vehicles and the data generated by applications and information systems will require alternative technologies to expand the spectrum for communications. The IEEE 802.22 is a standard for wireless regional area networks to operate in TV bands opportunistically; however, sharing the TV White Space (TVWS) spectrum creates a problem of coexistence among secondary networks because no mechanism is defined for coordinating channel usage. This thesis addresses the challenge of enabling the coexistence of fixed secondary and vehicular networks when no vacated TVWS channels are available for allocation, and both networks share the same TVWS channel. The proposed White Space Resource Sharing mechanism (WSRS) based on power control and channel access allocates resources to vehicles even when the density of fixed nodes and the transmission power of the fixed network cause high interference to the vehicular network. The WSRS mechanism implements a strategy to protect the fixed secondary network from interference caused by vehicular transmissions while promoting that both networks simultaneously use the channel. The offered channel capacity to the vehicular network increases up to 40% using the WSRS mechanism compared to channel capacity when TVWS channel sharing is not allowed.

RESUMEN DE LA TESIS PARA OPTAR
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DISEÑO E IMPLEMENTACIÓN DE UN MECANISMO DE COEXISTENCIA PARA COMUNICACIONES VEHICULARES EN ESPACIOS EN BLANCO DE TELEVISIÓN

El crecimiento esperado en el número de vehículos conectados y los datos generados por las aplicaciones y los sistemas de información requerirán tecnologías alternativas para expandir el espectro de comunicaciones. El estándar IEEE 802.22 especifica la operación oportunista de redes inalámbricas de área regional (WRAN) en las bandas de televisión; sin embargo, compartir el espectro de espacios en blanco de televisión (TVWS por sus siglas en inglés) crea el problema de coexistencia entre redes secundarias porque el mecanismo para coordinar el uso del canal TVWS no está definido. Esta tesis aborda el desafío de habilitar la coexistencia entre redes fijas y redes vehiculares secundarias cuando no hay canales de TVWS disponibles para asignar, y ambas redes deben compartir el canal TVWS. Se propone el mecanismo *White Space Resource Sharing mechanism (WSRS)* basado en control de potencia y acceso al canal, que asigna recursos a los vehículos aún cuando la densidad de los nodos fijos y su potencia de transmisión ocasionan alta interferencia a la red vehicular. El mecanismo WSRS implementa una estrategia para proteger a la red fija secundaria de la interferencia causada por la red vehicular, mientras promueve que ambas redes continúen utilizando el canal TVWS. La capacidad ofrecida a la red vehicular incrementa en hasta un 40% usando el mecanismo WSRS comparada con la capacidad de canal cuando el uso compartido no está habilitado.

Dedicada a la Luz Suprema del Amor Supremo.
A mis amados papá, mamá, hermana y hermano.
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Con Amor y Gratitud,
Adriana Arteaga Arce.

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List of Abbreviations

3GPP	Third Generation Partnership Project
5G	Fifth Generation
A-BS	Advanced Base Station
A-CPE	Advanced Consumer Premise Equipment
A-WRAN	Advanced Wireless Regional Access Network
ADPS	Adaptive Data Pipe Selection
AP	Access Point
AWGN	Additive White Gaussian Noise
BS	Base Station
BPSK	Binary Phase Shift Keying
C-V2X	Cellular Vehicle-to-Everything
CAFOVA	Channel Availability for Opportunistic Vehicular Access
CAP	Channel Allocation Process
CCH	Control Channel
CMRS	Commercial Mobile Radio Service
CEPT	Conférence Européenne des Administrations des Postes et des Télécommunications
CPE	Consumer Premise Equipment
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSN	Cognitive Secondary Network
CVN	Cognitive Vehicular Network
D2D	Device-to-Device
DAMA	Demand Assigned Multiple AccesS
DSA	Dynamic Spectrum Access
DSRC	Dedicated short-range communications
FCC	Federal Communications Commission
FSN	Fixed Secondary Network
GL	Geolocation Function
GDBS	Geolocation Database Server

HetVNETs	Heterogeneous Vehicular Ad Hoc Networks
IEEE	Institute of Electrical and Electronics Engineers
IIoT	industrial Internet of Things
ITS	Intelligent Transport Systems
LIDAR	Laser Imaging Detection and Ranging
LiFi	Light-Fidelity
LLC	Logical Link Control
LOS	Line-of-sight
LTE	Long Term Evolution
MAC	Medium Access Control
mmwave	Millimeter Waves
MNO	Mobile Network Operator
MV	Manager Vehicle
NLOS	Non-line-of-sight
OBU	On-board Unit
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PCP	Power Control Process
PLCP	Physical Layer Convergence Procedure
PLMS	Private Land Mobile Service
PMD	Physical medium dependence
PHY	Physical Layer
PHY-OM1	Physical Layer Operation Mode 1
PHY-OM2	Physical Layer Operation Mode 2
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
QoS	Quality of Service
RAF	Resource Allocation Function
R-CPE	Relay Consumer Premise Equipment
RLSS	Registered Location Secure Server
RSU	Road Site Unit
SM	Spectrum Manager
SCH	Service Channel
SDN	Software-Defined Network
SDR	Software-Defined Radio
SINR	Signal-to-Interference Plus Noise Ratio
SIUF	Scheduling Information Updating Function
SNR	Signal-to-Noise Ratio
SSF	Spectrum Sensing Function

SULF	Spectrum Usage Learning Function
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TVWS	TV White Spaces
TVWS CH	TV White Space Channel
UE	User Equipment
UHF	Ultra High Frequency
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VANETs	Vehicular Ad Hoc Networks
VCN	Vehicular Communications Network
VDSA	Vehicular Dynamic Spectrum Access
VHF	Very High Frequency
VN	Vehicular Network
WLAN	Wireless Local Area Network
White-Fi	Wifi over TV White spaces
WHO	World Health Organization
WRAN	Wireless Regional Access Network
WSRS	White Space Resource Sharing

Chapter 1

Introduction

Vehicular communications are considered one of the foundations to support the deployment of Intelligent Transportation Systems (ITS). Transportation systems are crucial for economic productivity and sustainable urban and rural development since these systems move food, raw materials, supplies, and assets as well as people in public and private transportation. Innovative applications for vehicular environments promise to help increase safety and comfort for passenger and drivers, to the point that government offices, such as the U.S. National Highway Traffic Safety Administration, are recommending the mandatory use of vehicular communications shortly [1]. Vehicular communications allow the exchange of information in transportation systems, improving safety and mobility on the route through coordination among vehicles and providing information and entertainment services for drivers and passengers.

According to the market research report from Markets and Markets released in 2020, the global connected car market size is expected to be USD 99 billion in 2022 and is projected to reach USD 166.0 billion by 2025 [2]. BI Intelligence in March 2020 reports that over 77 million connected cars will be on the road by 2025 [3]. The vehicles are connected through a built-in antenna and chipset or using hardware to allow drivers to connect to their cars via a smartphone. Also, connected vehicles have several systems and sensors that generate a large amount of data such as the pedal travel sensor, the vision system, the proximity sensors, among others. In the case of autonomous vehicles, each vehicle will be generating approximately 4,000 GB of data a day due to the cameras, radar, sonar, GPS, and laser imaging detection and ranging (LIDAR) components [4]. All these data is used to keep the vehicle's performance and safety, and vehicles share the data with other vehicles and with the road infrastructure to support vehicular applications, providing better infotainment services and enhancing road safety and efficiency. All efforts will improve road safety for drivers, pedestrian, cyclists, and motorcycles, promoting the coexistence between vehicles and people.

There are several challenges for achieving the ITS deployment. One of them is to enable the communication between vehicles, the signalizing infrastructure, and the other information systems on the road. Vehicular communication networks (VCN) correspond to networks formed by vehicles where communications are vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) [5]. Several technologies have been explored to allow VCN through cellular or WiFi networks, meanwhile standardization bodies have developed the dedicated short-range communication (DSRC) technology for V2V and V2I communications [6] and cellular vehicle-to-everything (C-V2X) [7]. In 2020, the Federal Communications Commission (FCC) decreased the spectrum allocation for vehicular communications in the 5.9 GHz band from 75 MHz to 30 MHz (5,890-5,925 GHz) for enhanced automobile safety using C-V2X technology instead of DSRC [8]. Modification addresses the automotive market to adopt C-V2X for vehicular communications, leaving aside DSRC. However, there are still 70 MHz allocated to DSRC technology in Europe [9] and 80 MHz in Japan [10] in the 5.8 GHz frequency band. Nevertheless, the expected growth in the number of connected vehicles and the data generated by applications and information systems have led to exploring alternative technologies to expand the spectrum for communications. The scarcity of radio spectrum is a problem for several services based on wireless technologies [11], including vehicular communications, making the secondary use of spectrum on television bands, known as TV White Spaces (TVWS), a key alternative to extend the available bandwidth [12]. Secondary spectrum access uses available licensed frequencies when the spectrum is underutilized or when the licensed users are inactive in the area [13].

1.1 Motivation

The benefits of exploiting connectivity in TV bands have brought attention to TVWS technologies and the deployment of cognitive secondary networks over the TVWS spectrum [14]. Recent studies have proposed the deployment of secondary networks to improve broadband access in rural areas [15, 16], to provide connectivity for educational initiatives [17, 18, 19] and emergency response plans [20], and to support agricultural projects [21]. Furthermore, commercial initiatives and manufacturers such as a5Systems, 6HARMONICS, Airband, and First Broadband provide technological services for rural broadband connectivity, the Industrial Internet of Things (IIoT), communications for critical infrastructure and environmental monitoring, among other applications, all operating over TVWS. However, the increasing deployment of such secondary networks creates a problem of coexistence among groups of secondary networks: the opportunistic use of spectrum does not necessarily require prior agreement among the secondary networks intending to use the same TV frequency channel.

Although the IEEE 802.19.1 standard [22] defines methods and algorithms for co-existence between secondary cognitive networks, these have been deemed impractical due to the complexity of the architecture and the nature of fixed network management, for which adjustment of interference-reducing operational parameters is not obligatory. The IEEE 802.22 standard [23] indicates only that when no vacated TVWS channels are available for allocation, or when different groups share the TVWS channel for spectrum efficiency purposes, then "the A-BS may use a mechanism for proper resource sharing between the overlapping groups or the A-BS and some groups after channel switching" [23]. However, such a resource sharing mechanism is not detailed or defined by the standard.

1.2 Problem definition

Even though there are different methods and algorithms for coexistence between secondary cognitive networks, the complexity of the architecture and the non-obligatory adjustment of the operating parameters to achieve coexistence avoiding mutual interference have made it a challenge to enable the TVWS channel sharing. The lack of a mechanism for sharing the TVWS spectrum can lead to denial of service to networks due to no vacant TVWS channels available, especially considering the expected growth in the deployment of fixed and mobile secondary networks. Besides that, not enabling the TVWS channel sharing also causes inefficient spectrum use, a limited resource that provides high-impact services. Failure to promote the efficient use of secondary spectrum could lead to the same spectrum scarcity drawbacks as the exclusive-usage spectrum.

In the preliminary analysis to model the coexistence scenario without the use of a TVWS channel sharing mechanism, the results showed that the normalized channel capacity offered to a vehicular network decreases as the presence of fixed secondary networks on the TVWS channels increases. The normalized channel capacity offered to the vehicular network decreases from 0.6 to zero when the presence of the fixed secondary networks varies from 25% to 100%.

Besides that, not enabling TVWS sharing would force the vehicles to execute spectrum detection techniques until they find an available TVWS channel. When the vehicles find the available TVWS channel, the vehicles move their data transmissions to the new TVWS channel. If the selected TVWS channel becomes busy by a secondary network farther along the route, the vehicles shall rerun the process to find a new TVWS channel. Considering the increment in the deployment of secondary networks, the process of finding a TVWS channel for exclusive vehicular access may take around 0.2 s when the presence of fixed secondary networks is approximately 70%, and the TVWS channel sharing is not enabled.

1.3 Hypotheses

1. There are opportunities for vehicular access even when a fixed secondary network occupies the TVWS channel. The number of the channel access opportunities for vehicular communications could be estimated using parameters such as the probability of channel occupation made by the fixed secondary network, and the speed of the vehicles.
2. Vehicles may use these opportunities for transmission, instead of spending time looking for a new available TVWS channel. Sharing the TVWS channel with a fixed secondary network reduces the average channel access delay for vehicular communications in at least 10%.
3. Enabling the TVWS sharing among fixed secondary and vehicular networks increases the offered channel capacity at least 10%, in scenarios where active fixed secondary networks are along the route. The increment in the channel capacity is compared with the offered by the system when sharing the TVWS channel is not allowed, and the vehicular network must stop transmitting.

1.4 Objectives

1.4.1 General Objective

To design and model a resource sharing mechanism to enable the coexistence among fixed secondary networks and vehicular networks when no vacant TVWS channels are available for allocation, allowing resource sharing between the overlapping groups according to the IEEE standard 802.22. The effectiveness and level of service provided by the proposed mechanism will be evaluated using standard metrics and comparing with the IEEE 802.22 standard scenarios with no coexistence enabled among secondary networks.

1.4.2 Specific Objectives

1. To design a system model and a quantitative metric for establishing the feasibility of opportunistic channel access for vehicular communications over TVWS considering the primary TV users as well as other opportunistic secondary networks.
2. To design and model a resource allocation mechanism for vehicular communications on TVWS spectrum in scenarios considering the presence of fixed secondary networks and no vacated TVWS channels available for allocation.
3. To evaluate the performance of the resource sharing mechanism via numerical evaluations and simulations, considering metrics such as channel capacity, Jain's Index, spectral efficiency, and comparing with the IEEE standard 802.22 mechanism.

1.5 Contributions

The contributions of this thesis are:

- A feasibility study of the opportunistic access for vehicular networking considering the TV primary users and secondary users on the TVWS spectrum. This study presents a system model that integrates the technical requirements of primary users, and the conditions that must be met to allow secondary users on TV bands. The study analyzes the impact of vehicle speed and channel verification distance on the perception of channel occupancy and the identification of transmission opportunities over the TV band.
- The proposal of a new metric, the Channel Availability for Opportunistic Vehicular Access (CAFOVA) that relates the channel occupation policy over the White-Fi network, the vehicle's speed, and the channel verification distance.
- The proposal of a White Space Resource Sharing (WSRS) mechanism for vehicular networks based on power control and channel allocation. This mechanism is used when the fixed and vehicular networks are overlapped, no vacated TVWS channels are available for allocation, and both networks have to share the same TVWS channel.
- A thorough analysis of the impact of TVWS channel sharing between a vehicular network and secondary fixed networks in terms of the channel capacity offered to the vehicular network and attention to fairness and spectral efficiency of resource allocation.

1.6 Publications

Journals

J1. **A. Arteaga**, S. Céspedes, and C. Azurdia-Meza, “Vehicular Communications over TV White Spaces in the Presence of Secondary Users,” IEEE Access, vol. 7, pp. 53496–53508, 2019.

J2. **A. Arteaga**, S. Céspedes, and C. Azurdia-Meza, “Towards the Coexistence of Cognitive Networks for Vehicular Communications on TVWS for IEEE Std. 802.22", *submitted to IEEE Transactions on Cognitive Communications and Networking, Sep 2021.*

International and national conferences

C1. **A. Arteaga**, P. Palacios, S. Céspedes and C. Azurdia-Meza, "Evaluation of Opportunistic Access Strategies for Vehicular Networking Over TVWS," 2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall), 2020, pp. 1-5.

C2. **A. Arteaga**, S. Céspedes, and C. Azurdia-Meza, "Next Generation Vehicular Communications via Interworking of DSRC and TV White Space," in *Proc. 2018 18th International Symposium on Antenna Technology and Applied Electromagnetics*, Waterloo, Canada, August 2018.

C3. T. Lara, **A. Arteaga**, and S. Céspedes, "Comparison of Path Loss Models for Vehicular Communications in TV White Spaces," in *Proc. of the IV Spring School on Networks*, Valdivia, Chile, October 2018, 2178: 6-8.

C4. **A. Arteaga**, S. Céspedes, and C. Azurdia-Meza, "Next Generation Vehicular Communications via Interworking of DSRC and TV White Space," Poster in *VII Encuentro de Mujeres en Ingeniería - Chile WiC*, Valparaíso, Chile, October 2018, 2178: 6-8.

C5. **A. Arteaga**, S. Céspedes, and C. Azurdia-Meza, "Spectrum Sensing for Vehicular Dynamic Spectrum Access," in *Proc. of the II Spring School on Networks*, Santiago, Chile, November 2016, vol. 1727, pp: 8-13.

1.7 Outline of the thesis

The rest of the thesis is structured as follows:

- **Chapter 2** presents the state of the art of the main topics related to cognitive vehicular networking, dynamic spectrum access for vehicular networking on the TVWS spectrum, the IEEE standard 802.22, and secondary opportunistic networks and coexistence on TVWS spectrum.
- **Chapter 3** presents the general coexistence scenario for vehicular communications on the TVWS Spectrum, which includes the TV bands primary users, secondary networks, and vehicular networks. Then, the coexistence problem is focused on the resource sharing between IEEE 802.22 secondary networks. Finally, the White Space Resource Sharing mechanism is detailed.

- **Chapter 4** presents the evaluation of the scenarios to study the coexistence for vehicular communications in the TVWS spectrum. The evaluation includes a feasibility study of TVWS spectrum sharing in the general scenario; a comparative evaluation of two strategies for opportunistic vehicular access over the TVWS spectrum in the presence of other opportunistic networks; and the performance evaluation of the White Space Resource Sharing mechanism for the coexistence according to the IEEE standard 802.22.
- **Chapter 5** describes the main conclusions of this thesis and presents an outlook on future research regarding these topics.

Chapter 2

Literature review

This section presents the main topics and concepts of this thesis related to:

- Vehicular networking, applications, and communications technologies
- Cognitive vehicular networks
- Dynamic spectrum access for vehicular networking over TVWS
- IEEE standard 802.22
- Secondary opportunistic networks over TVWS and coexistence

2.1 Vehicular Networks

Traffic congestion, environmental pollution, and traffic accidents have driven research and development in the automotive industry, not only in the manufacture of cars but also in the use of technologies to improve safety on the road. According to the 2015 global status report on road safety provided by the World Health Organization (WHO) [24], the total number of victims by road traffic accidents has plateaued at 1.25 million per year; almost half of all road traffic deaths are among pedestrians, cyclists, and motorcyclists. Traffic congestion decreases the transport systems efficiency especially in urban areas, which harms the quality of life of the people. Exchanging information between the transport systems has been explored as an alternative to improve traffic efficiency [25] and road safety [26], which is known as Intelligent Transport Systems (ITS).

Vehicular networking provides the information exchange for vehicular ad hoc networks (VANETs) via vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) communications which are fundamental features for the ITS deployment [27]. These communication modes allow offering different types of vehicular applications using different technologies. Some technologies are of general purpose such as the cellular network and WiFi, while others are designed specifically for vehicular communications. The following presents a more detailed description of the vehicular applications and the principal technologies used in vehicular networking.

2.1.1 Applications and services

Vehicular applications and services are into several categories depending on the purpose of the applications which are active road safety, efficient traffic coordination, and information and entertainment (infotainment) [5], or on a broader categorization of safety and non-safety applications [28]. The applications and services have minimum quality of service (QoS) requirements depending on the maximum latency, the minimum transmission frequency of the messages, the communication mode (broadcasting, cooperative, V2X, Internet access, among others.), and the required reliability. Table 2.1 shows the main vehicular applications and services for ITS, and the QoS requirements.

Safety applications: These applications seek to reduce the risk of traffic accidents through sharing safety-related information. Shared information could be related to vehicle's traveling state information (e.g., current position, real-time speed, and direction), or event-driven safety information (e. g., emergency vehicle warning, traffic condition warning, emergency electronic brake lights, among others.). Safety applications are used to avoid collisions between vehicles, to assist the driver in lane changes detection dangerous situations, and to maintain a safe distance and a constant speed for platoon-based driving. In general, these applications require a maximum delay of 100 ms and a message transmission frequency of 10 Hz.

Non-safety applications: These applications are focused on providing traffic management and infotainment support to enhance the comfort of the drivers and passengers. Traffic management applications seek to improve traffic flow, helping drivers reroute in traffic jam situations or improving the efficiency of the traffic lights schedule. Infotainment applications support location information services, entertainment, Internet access, among others. These applications can be considered delay-tolerant applications up to 500 ms, and they could demand a high data rate to download the information.

Table 2.1: Quality of service requirements of vehicular applications and services. Adapted from [26]

Use case	Category	Safety/Non-safety application	Security/ Reliability	Communication mode	Maximum frequency	Minimum delay
Emergency electronic break lights	Active road safety	Safety	High/High	Time limited periodic broadcast on event	10 Hz	100 ms
Slow vehicle warning	Active road safety	Safety	High/High	Periodic triggered by the vehicle	2 Hz	100 ms
Vulnerable road user warning	Active road safety	Safety	High/High	V2X cooperative awareness	1 Hz	100 ms
Stationary vehicle warning	Active road safety	Safety	High/High	Time limited periodic broadcasting on event	10 Hz	100 ms
Traffic condition warning	Active road safety	Safety	High/High	Time limited periodic safety broadcasting or authoritative message triggered	1 MHz	100 ms
Lane change assistance	Active road safety	Safety	High/High	V2X cooperative awareness	10 Hz	100 ms
Overtaking vehicle warning	Active road safety	Safety	High/High	V2X cooperative awareness	10 Hz	100 ms
Pre-crash sensing warning	Active road safety	Safety	High/High	Broadcast of pre-crash state	2 Hz	100 ms
Regulatory/ contextual speed limits	Traffic management	Non-safety	High/High	Authoritative message triggered by traffic management entity	1 Hz	N/A
Intersection management	Traffic management	Non-safety	High/High	Periodic, permanent message broadcasting	2 Hz	100 ms
Traffic light optimal speed advisory	Traffic management	Non-safety	High/High	Periodic, permanent message broadcasting	2 Hz	100 ms
Cooperative flexible lane change	Traffic management	Non-safety	High/High	Periodic, permanent message broadcasting	1 Hz	500 ms
Electronic troll collect	Traffic management	Non-safety	High/High	I2V broadcasting and unicast full duplex session	1 Hz	500 ms
Point of interest notification	Infotainment	Non-safety	Medium/ Medium	Periodic, permanent message broadcasting	1 Hz	500 ms
Local electronic commerce	Infotainment	Non-safety	High/High	Duplex communication between the RSU and vehicles	1 Hz	500 ms
Media download	Infotainment	Non-safety	Medium/ Medium	User access to Internet for download	1 Hz	500 ms
Map download and update	Infotainment	Non-safety	Medium/ Medium	Access to Internet for download and update	1 Hz	500 ms

2.1.2 Communication technologies

V2V, V2I, V2X communications may be supported by several wireless technologies including general purpose technologies such as the cellular network and WiFi, through technologies designed specifically for vehicular communications such as the dedicated short-range communications (DSRC), or using novel technologies such as millimeter waves. Each technology has different characteristics regarding the coverage range, the data rate, the channel access mechanism, among others; these characteristics may benefit or harm the applications' performance considering the minimum QoS requirements compliance. The following presents a more detailed description of the traditional and novel communication technologies used in vehicular networking.

DSRC

DSRC is a technology designed to support a variety of applications in V2V and V2I scenarios in the 5.9 GHz band, mainly to enable road safety applications [6]. Each DSRC-equipped vehicle has an on-board unit (OBU) to broadcast its safety messages with information such as speed, location, and acceleration, and to receive the safety messages from the neighbors. In safety applications, the vehicle uses the received safety messages to calculate the trajectory of other vehicles and to avoid possible collisions with other vehicles. Vehicles may also communicate with DSRC roadside units (RSUs) which are infrastructure equipment installed on the route. The RSU may communicate higher level information obtained by the processing the messages sent by several vehicles. The coverage of the OBU is up to 300 m, and the RSU is up to 1 km.

Due to the requirements of road safety applications, several countries have assigned exclusive spectrum to DSRC. The DSRC spectrum in Europe is 70 MHz (5.855-5.925 GHz), and 80 MHz (5.770-5.850 GHz) in Japan. There is a 5 MHz band guard at the beginning of the DSRC band, and each channel is 10 MHz but pairs of channels can be combined into a 20 MHz channel; the CCH is in the middle of the six SCH as shown in Figure 2.1.

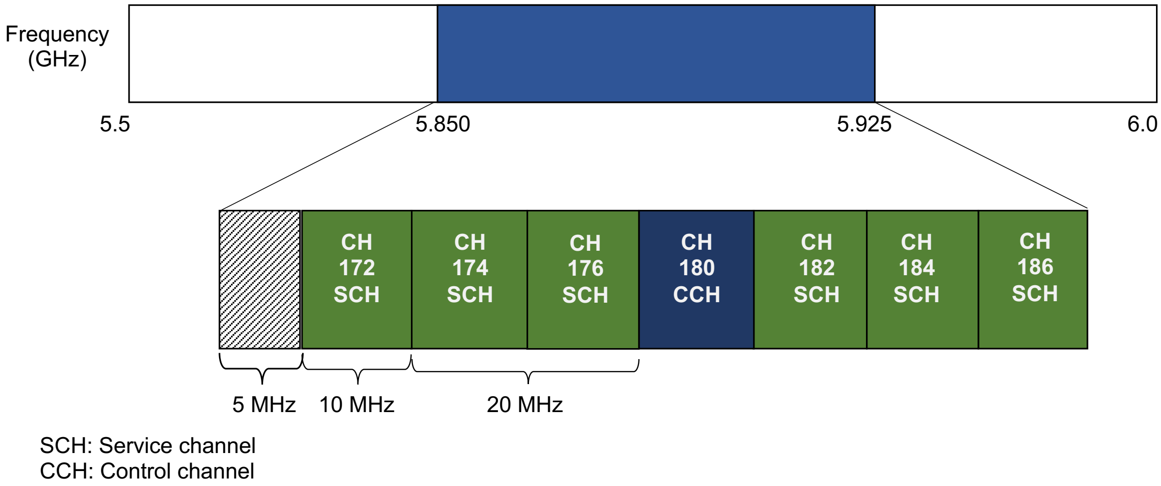


Figure 2.1: DSRC frequency band allocation. Source: Own elaboration based on [6].

The IEEE 802.11-2012 standard defines the DSRC physical layer [29]. The layer is divided into two sub-layers: the physical medium dependent (PMD) sub-layer and the physical layer convergence procedure (PLCP) sub-layer. The PMD is connected to the wireless medium using orthogonal frequency division multiplexing (OFDM), while the PLCP defines the mapping between the MAC frame and the OFDM symbol. Because the DSRC channels are 10 MHz, the PHY layer uses the 10 MHz OFDM channel parameters shown in Table 2.2. Table 2.3 shows the data rate options in DSRC 10 MHz OFDM channel depending on the modulation technique, the code bit rate, and the coding rate. Selecting a specific modulation scheme and the coding rate affects the achieved data rate, and the minimum sensitivity required to decode a received frame [29].

Table 2.2: 10 MHz OFDM channel parameters for IEEE 802.11p [6]

Parameter	Value
Number of data subcarriers	48
Number of pilot subcarriers	4
Subcarrier frequency spacing	156.25 kHz
Guard interval	1.6 μsec
Symbol interval (including guard interval)	8 μsec

Table 2.3: Data rate options in a DSRC 10 MHz OFDM channel [6]

Modulation technique	Coded bit rate (Mb/s)	Coding rate	Data rate (Mb/s)	Minimum sensitivity (dBm)
BPSK	6	1/2	3	-85
BPSK	6	3/4	4.5	-84
QPSK	12	1/2	6	-82
QPSK	12	3/4	9	-80
16–QAM	24	1/2	12	-77
16–QAM	24	3/4	18	-73
64–QAM	36	2/3	24	-69
64–QAM	36	3/4	27	-68

The DSRC data link layer is also divided into two sub-layers: the medium access control (MAC) sub-layer responsible for sharing the wireless medium, and the logical link control (LLC) that defines the data transfer over the channel. Medium access in 802.11p is carrier sense multiple access/collision avoidance (CSMA/CA) where the sender can send its message if the channel is idle. If the medium is busy, the sender must wait a number of idle time slots according to a random backoff process. Using CSMA/CA for access channel increases the number of collisions in high vehicular density scenarios, especially for vehicular applications based on broadcasting.

One aspect to consider when using DSRC for vehicular networking is the unbalance between the links due to the difference in the OBU and the RSU coverage range. The reliable communication range from the RSU to the OBU is up to 1,000 m, while the communication range from the OBU to the RSU is up to 300 m. In this case, the OBU is capable of receiving the RSU message when the vehicle is into the RSU coverage, but the RSU only receives the OBU messages when the OBU is close enough to cover the RSU. This situation should be considered in the application design and implementation because the QoS requirements compliance could be affected, especially the maximum delay. When the application requires a shorter response time or a lower delay, technologies such as LTE with a higher coverage range can be used.

LTE-V

LTE-based V2X services have been specified by the Third Generation Partnership Project (3GPP) to take advantages of widely deployed LTE networks and the low cost of the user equipment (UE) [30]; the standard is commonly referred to as LTE-V, LTE-V2X, or cellular V2X. Release 14 LTE supports one-to-many communications that are useful for broadcasting, and the device-to-device communications through the PC5 interface to enable V2V links without routing via the base station (the evolved NodeB or eNodeB) [31]. For V2I communications, LTE Release 15 enables the access network (Uu) interface to establish communication between the vehicle and the eNodeB. Release 15 that will support fifth-generation (5G) V2X communications in under discussion. New use cases will be considered in Release 15, including autonomous driving, platooning, sensor and map sharing, information sharing for partial/conditional and high/full automated driving, and remote driving, among others [32]. A comprehensive study of LTE-V V2V communications that shows its potential as an alternative to DSRC is shown in [33].

WiFi

This technology is a popular option to provide wireless connectivity because there are WiFi hotspots deployed in urban areas, the WiFi access is low-cost, there is a very high number of devices with WiFi interfaces, and the WiFi technology can provide data rates up to 54 Mb/s. However, the limited coverage range of the WiFi access point and the high mobility of vehicles causes unstable connections. For this reason, WiFi has been considered as an offloading technology more than the main technology for vehicular networking [34]. Each vehicle can get a short duration to connect to a WiFi hotspot depending on the vehicle mobility to send short messages, or to download a relatively small data volume of the Internet [35].

Novel technologies

Considering that the amount of spectrum for vehicular communications is limited and that it is mainly intended for security applications, other emerging technologies have been explored to extend the available spectrum for vehicular networking. Among the technologies explored are the millimeter waves, light fidelity (LiFi), and TV White Spaces (TVWS).

Millimeter waves (mm-wave): this spectrum corresponds to the 60 GHz frequency band, the operation of anti-collision radars and other short-range ITS applications in V2V scenarios is allowed [36, 37, 38], following the IEEE 802.11ad standard [39]. This technology offers a bandwidth channel up to 2.5 GHz in the 59-66 GHz band and a coverage range of a few meters, increasing the available bandwidth for short-range vehicular applications.

Light-Fidelity (LiFi): It is a high speed bi-directional wireless technology that uses the visible light to transmit data, exploiting the visible light unlicensed spectrum [40]. This technology could be used in short-range applications by sending messages through light-emitting diode (LED) bulbs and a photo-diode. Prototypes have been presented to send a warning message from the front vehicle to the rear vehicle when the front vehicle slows down the speed [41]. Enhanced prototypes with LED transmitter and a camera receiver for experiments under real driving conditions is presented in [42], and visible light communications (VLC) systems using LED-based traffic lights has been explored for ITS deployment [43].

TV white spaces (TVWS): These are the available channels in TV frequency bands (470 MHz-806 MHz). Among the reasons why TVWS may exist in a specific area are: *a)* there are no TV transmitters using the channel in the area of interest; or *b)* there is a TV transmitter using the channel in the area of interest, but the TV emission is OFF during specific hours (e.g., at night). Spectrum regulators in several countries allow fixed and portable/mobile secondary users in the TV bands with the condition of protecting the TV primary user against harmful interference. There are several studies about using TVWS in vehicular networking because the TV band propagation characteristics allow a greater transmission range than that achieved with DSRC [44, 45, 46, 47, 48, 20, 49, 50]. The TVWS network has been proposed as the offloading technology when there is degradation in the DSRC channels, as the backup network for sending control messages in V2V and V2I scenarios, and as the principal network for Internet access for infotainment services. The availability estimation and the use of the TVWS for vehicular networking will be addressed in detail in Section 2.3 related to dynamic spectrum access for vehicular networking.

2.2 Cognitive Vehicular Networks

Several technologies were explored to allow VANETs communication through cellular or WiFi networks, while the automotive industry developed the DSRC technology for V2V and V2I communication [6]. As previously mentioned, the Federal Communications Commission (FCC) in the U.S. allocated 75 MHz of licensed spectrum in the 5.9 GHz band for DSRC communication [51] divided in 7 channels of 10 MHz each, and 5 MHz guard band at the beginning of the DSRC band. However, DSRC channels could become congested in scenarios of high traffic density, which impairs the performance of the applications in situations of high vulnerability for drivers and passengers. Considering there are ITS applications with different bandwidth and maximum tolerated delay requirements, resource allocation within DSRC channels and the radio spectrum scarcity must be considered in the VANETs approach. Taking into account the different technologies that can be used for the deployment of vehicular communications (see Section 2.1.2), cognitive radio in vehicular networking has been explored to extend the available spectrum for vehicular applications combining the access to several technologies such as DSRC, WiFi, LTE, and TVWS [52, 53]. Software-defined radio allows to implement OBUs and RSUs based on Cognitive Radio [54], which is a paradigm to use software routines to adjust the operational parameters of the devices (e. g., the active wireless technology, the modulation scheme, the transmission power, etc.) according to the current network environment.

Vehicular networks based on cognitive radio allow integrating multiple technologies to implement a heterogeneous network with extended capabilities, and to provide a flexible network to react to different communication requirements according to changes in the vehicular traffic. Network features such as beaconing, routing, and message dissemination may be adapted according to the channel congestion, the vehicular density, or the application requirements. This paradigm is used to design the architecture for the interworking between technologies because it facilitates the data collection, the decision making, and the configuration of the network elements. Flexibility could increase implementing the network through software-defined networking (SDN), a paradigm based on the separation of the control plane and the data plane [55]. SDN has been explored to improve the vehicular network capabilities through scalability, flexible resource allocation, and advanced network management using SDN controllers that sent configuration settings to SDN switches in the OBU and the RSU [56, 57, 58, 59]. This approach allows study alternatives to solve some challenges related to messages dissemination [60], service QoS guaranty in mobile environment [61], the integration with cloud and fog computing [62] and the optimization of resource allocation in heterogeneous VANETs (HetVNETs) [63, 64].

2.3 Dynamic Spectrum Access for Vehicular Networking

Channel availability is a fundamental requirement for the successful operation of vehicular applications, but the lack of available spectrum for wireless technologies is a threat for current and future applications designed for ITS. Theoretical analysis and simulations have shown that the DSRC spectrum is insufficient for the reliable transmission of the messages in safety applications, especially in high vehicular density scenarios when the packet delivery ratio decreases [65, 66, 67]. Since the DSRC spectrum is used mainly by the safety applications, it is necessary to define what spectrum will be available for the applications such as video streaming or file downloads, which demand a high data rate and bandwidth. There is a spectrum scarcity problem for the effective ITS deployment, considering the limited available spectrum for the vehicular application and the increment in the number of vehicles on the roads.

As an alternative to face the radio spectrum scarcity problem, not only for vehicular networking but also in other networks, dynamic spectrum access (DSA) has been explored. This approach allows unlicensed users to use available licensed frequencies with the condition of avoiding harmful interference to licensed (primary) users [13]. Several primary services have been reviewed by spectrum regulators to determine which services better support the presence of secondary users, according to the spectrum occupancy rate, the tolerance to interference, the band regulation, and the international coordination agreements for the service operation. Reports on the use of radio spectrum show there is low occupancy in the frequencies allocated to the television service (470 MHz-806 MHz) [68]. Moreover, some frequencies will become vacant due to the transition from analog to digital TV [69]; the available channels in TV frequency bands are known as TV White Spaces (TVWS) (see Section 2.1.2). Spectrum regulators such as the FCC in the U.S[70], and the CEPT [71] in Europe defined the technical requirements to allow secondary devices over the TV bands, in order to guarantee the protection of the primary user against harmful interference.

The FCC defines three types of secondary devices over TVWS [70]:

- Fixed: The power transmission is up to 4 W. It is used to bring wireless internet access in rural areas through TV bands. A fixed device must consult the geolocation database to determine the list of available channels and the position of the device. Also, a spectrum sensing technique can be used to detect wireless microphones or other allowed signals in TV bands. Fixed devices must communicate between them using the following frequencies: 54-60 MHz, 76-88 MHz, 174-216 MHz, and 470-512 MHz.
- Portable: The power transmission is up to 100 mW, and it is implemented as a wireless interface or an access point. There are two types of portable devices:

  - Mode-I: a portable device that gets the spectrum occupancy information via a fixed device or a portable mode-II device.
  - Mode-II: a portable device that can connect directly with the geolocation database to get the spectrum occupancy information, or using a spectrum detection technique. It must check the spectrum occupation every time it moves 100 meters.

The CEPT defines three types of secondary devices which are [71]:

- Personal or portable: a small device that can be transported by people as a mobile device, or it can be embedded in computers. It can be used inside the house, on the street or in transportation systems. It must have an Internet connection, allowing communication with other secondary devices.
- Home and office device: Devices such as television, video console, among others. It could be used in homes and offices but cannot be transported by people. It is useful to offer services that require a greater bandwidth or greater processing capacity than personal devices.
- Private and public access points: A device that provides WiFi service but with greater coverage, taking advantage of the propagation characteristics of the television band.

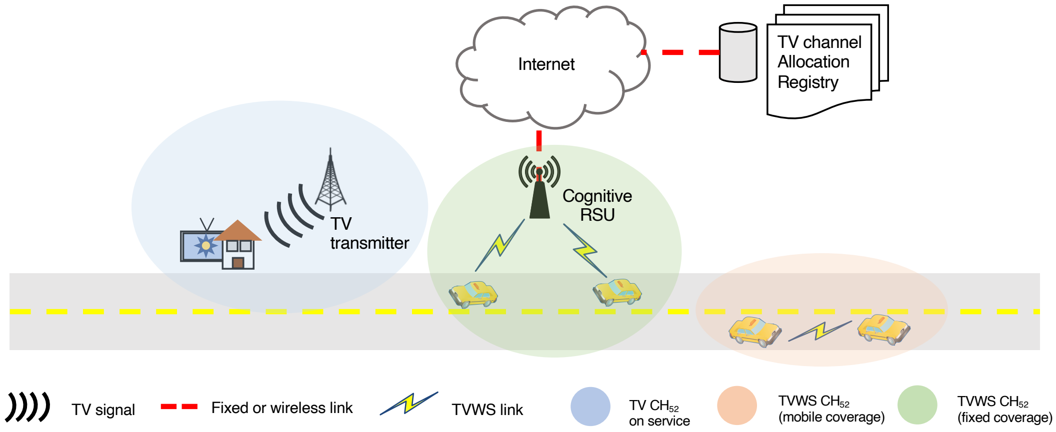


Figure 2.2: General architecture for vehicular dynamic spectrum access. Source: Own elaboration.

According to the classification of the secondary devices defined by the FCC and the CEPT, the cognitive RSU must follow the specifications of the fixed device (private/public access point according to the CEPT), while the cognitive OBU must be a portable mode-II device (a portable device according to CEPT). In the literature, dynamic spectrum access for vehicular networking is also known as vehicular dynamic spectrum access (VDSA) [72]. Figure 2.2 shows the general architecture for VDSA. The information about TV channel allocation is stored on a geolocation database accessible by the Internet. Cognitive OBUs can check the spectrum occupation locally using spectrum detection technique, or via the cognitive RSU.

2.3.1 Available spectrum estimation mechanisms

Secondary devices interested in the use of TVWS must ensure the channel is available before to transmit and must be ready to release the channel when a primary user requires it. There are two methods to determine the channel availability: *a)* using a geolocation database with information of the channel allocation or *b)* using a spectrum detection technique to recognize the presence of an active signal on the channel. The following presents the details of both methods.

Geolocation database

This database contains information of the incumbent services on TV bands, which are TV broadcasting, private land mobile service (PLMS), commercial mobile radio service (CMRS) on channels 14-20, offshore radiotelephone service, and low power auxiliary service (wireless microphones) [73]; the database also has information about the protected TV receive sites that are outside the protected contour of the TV stations. The FCC in the U.S. and Ofcom in U.K. offer access to the white space database through database administrators such as Google, LStelcom, and Spectrum Bridge, to obtain the lists of available channels. A fixed or portable mode-II device must consult the database periodically using its geolocation capacities and an Internet connection, while a portable mode-I device must use a fixed or a portable mode-II device. The secondary device must use a non-TV channel technology to connect to the geolocation database (e.g., a cellular connection, a WiFi connection or a fixed connection), because this connection must always be available to consult the database.

The use of geolocation databases has been broadly proposed for VDSA [44, 45, 46, 74] because it is easily implementable and because the allocation of the TV channels remains stable. If a channel is assigned to a TV transmitter, the channel will be busy while the TV transmitter is operating. However, the database dependency for enabling V2V communications over TWVS could be unsuitable due to the additional latency required for accessing the database, not to mention that it is not clear where the geolocation database should be stored to guarantee that vehicles always have access to it, especially if there is no connection to the infrastructure.

Spectrum detection techniques

The spectrum detection techniques allow obtaining the real-time status of the channel occupation because they detect if the channel is idle, or if there are incumbent or a secondary users on the channel. There are several spectrum sensing techniques for the available spectrum estimation, but the complexity of a detection technique depends on *a)* the knowledge of the transmitted signals according to features such as the modulation scheme, the packet format, the pulse shape, among others, *b)* the signal processing required over the reception, and *c)* the number of receivers required to process the potential primary signal. The more known information about the potential primary signals, the more reliable is the spectrum detection process.

In DSA for vehicular networking, spectrum detection techniques have been proposed as a way to check channel status locally, in particular when the access to a geolocation database is restricted by the nature of the ad hoc network, especially in V2V scenarios. In the following, we revisit three of the most frequently used spectrum detection techniques employed in opportunistic spectrum detection [75], and discuss how to apply the techniques to VDSA.

Energy detection: This is a simple spectrum detection technique because of its low computational cost and low implementation complexity [76]. A signal is detected by comparing the energy in the channel with a threshold λ_E [dB], which in its simplest definition depends on the noise floor. If the energy in the channel exceeds λ_E, it means that a user is occupying the channel; otherwise, the channel is available to a secondary user. If $y(n)$ is the received signal, its energy is defined as:

$$E = \frac{1}{N}\sum_{n=0}^{N} |y(n)|^2, \tag{2.1}$$

where N is the number of samples of the signal. The threshold definition is an essential aspect for achieving an effective detection if there are low Signal-to-Noise ratio (SNR) conditions in the channel. The receiver does not need a priori knowledge of the primary user signal, but the accuracy of detection is affected if SNR is low. Improved versions of this technique are proposed for VDSA, where cooperative sensing is one alternative to increase the detection reliability in highly mobile scenarios, where several detection measures are combined to avoid missing a detection or producing a false alarm that prevents the use of available channels [77, 78, 79].

In [80], the authors present a TV spectrum measurement campaign to analyze the availability of vacant channels from a vehicular perspective. Also, several experimental V2V studies have been conducted to analyze the feasibility of the use of TVWS for vehicular communications [81, 82, 45].

Cyclostationary analysis: This technique is based on the cyclostationary characteristics of the received signal, which are modelled by its periodic behavior with period T_0, the mean value $M_x(t)$, and the auto correlation function $R_x(t, \tau)$, calculated in (2.2) and (2.3), respectively, as follows [83]:

$$M_x(t) = M_x(t + T_0), \tag{2.2}$$

$$R_x(t, \tau) = R_x(t + T_0, \tau + T_0). \tag{2.3}$$

With this technique, it is possible to differentiate a primary signal from noise, since the noise is a random process and its autocorrelation function is not periodic. The detector calculates the autocorrelation function of the received signal and compares it with a known value λ_C, which can be the cyclic frequency of the signal [84]. The technique is considered of medium complexity because is robust to noise uncertainty, but a priori knowledge of the primary signals is required. Performance of this technique does vary depending on channel noise. If the channel noise is stationary, the performance of this technique is low; nevertheless, this technique performs well when the SNR is low because λ_C does not depend on the signal level, but on the periodic behavior of the signal. However, a long sensing time is required for accurate detection results, which is inconvenient when vehicles move at high speeds since sensing data may become outdated very fast. Studies in [85, 86] show the performance of the cyclostationary analysis in fading channels, with similar conditions to the ones expected for vehicular communications.

Waveform Based Detection: This technique is applicable when some of the signal patterns are known (e.g., preamble, spread spectrum sequence, pilot signal, etc.). Identifying a primary user requires that the receiver calculates the correlation between one of the known patterns of the received signal and a bank of known patterns of the possible primary signals. If $y(t)$ is the received signal, $s(t)$ is a known signal, and $w(t)$ is the white Gaussian noise, the correlation between both signals is calculated as follows [75]:

$$M = R_{\mathrm{e}} \left[\sum_{n=0}^{N} y(n) s^{*}(n) \right] , \tag{2.4}$$

where * is the conjugate. Correlation when the primary user is present or absent can be expressed according to (2.5) and (2.6), respectively:

$$M = \sum_{n=0}^{N} |s(n)|^{2} + R_{\mathrm{e}} \left[\sum_{n=0}^{N} w(n) s^{*}(n) \right] , \tag{2.5}$$

$$M = R_{\mathrm{e}} \left[\sum_{n=0}^{N} w(n) s^{*}(n) \right] . \tag{2.6}$$

M is compared with a λ_W value to determine if the correlation is high, indicating there is a primary user in the channel; if the correlation is low, it means there is only noise in the channel. The complexity of waveform-based detection is high because in some cases it needs to demodulate the signal to obtain the preamble, so the cognitive device must support the processing of all possible primary signals.

Waveform-based detection can rely on the mechanisms used by the primary communications systems to correct possible errors and use corrected information for detection when the SNR is low. This technique is similar to a matched filter with a perfect knowledge of the primary user; before sensing, features such as channel bandwidth, modulation scheme, or packet format are required. The sensing time is low because the features are known in advance, but the reliability of the technique depends on the level of knowledge of both users and signal patterns. The technique has been evaluated for fading channels, showing that time variations introduce degradation in the detection performance [87].

Due to the low latency in the execution of the energy detection technique, this could be useful in vehicular scenarios to allow each vehicle to check channel status across the route, reducing the latency of continuous access to the geolocation database due to the rapid changes of location of the moving vehicles. Cooperative sensing is one alternative to increase the detection reliability in highly mobile scenarios, where several detection techniques are combined to avoid missing a detection or producing a false alarm that prevents the use of available channels [77, 78, 79].

2.3.2 Spectrum estimation based on the infrastructure

One approach for the available spectrum estimation is using an infrastructure-based architecture, where the spectrum occupation information is stored in the elements of the network as proprietary servers, or via Internet. The proposed architecture presented by Matinmikko *et al.* [88] will be used as an example to define the elements that can be used for an estimation of the available spectrum based on infrastructure.

The proposed architecture to manage the spectrum occupancy information in [88] uses four components: the database, the cooperative spectrum sensing system, the pilot channel, and the decision component. The database can be like the geolocation database presented in Section 2.3.1, which has information about the primary services on the TV band. The cooperative spectrum sensing system is a set of cognitive radio nodes executing a spectrum detection technique such as energy detection, correlation-based detection, or waveform based detection (see Section 2.3.1), collecting the information about the real-time channel status. The results of all the nodes are combined and stored on a database as sensing results. The pilot channel is a dedicated TV channel to announce the status of each channel on the band.

The decision component has three stages: the first stage is selecting the spectrum estimation tool according to the scenario: if the channel occupation made by the primary users change frequently, a spectrum detection technique such as energy detection is the best option; using the database could cause to make the decision using outdated occupancy information. The second and third stages are applied if a spectrum detection technique is selected. In the second stage, the measurement procedure and the parameters of the technique are defined such as the sensing duration, the channels to be sensed, the thresholds, among others. In the third stage, the cooperative sensing scheme combines the sensing results of the cognitive radio nodes to make the channel occupation decision. The spectrum availability information is announced to the user device via the pilot channel.

The architecture for dynamic spectrum access based on infrastructure is commonly used for V2I scenarios, where the infrastructure is responsible for obtaining the spectrum occupancy information and to attend the spectrum request of the vehicles via the RSU. In [44] and [46], the geolocation database is used as the only spectrum availability estimation tool because the studied problem assumes that the information of the TV channels does not change frequently. In [44], the vehicle keeps communication with the RSU to obtain the list of the available channels in the vehicle location, and the control of the spectrum allocation is centralized to exploit the spectrum more efficiently. The proposed infrastructure has a geolocation database server, the RSUs installed on the road, and an application server for the infotainment content. In [46], the authors propose an Internet-based TVWS infrastructure for media streaming services, as known as White-Fi Infostation [74]. The infrastructure includes the Geolocation Database Server (GDBS), the Registered Location Secure Server (RLSS), and the fixed White-Fi Infostations. The GDBS make the query of the available TVWS to the geolocation database via Internet, and the RLSS coordinates the optimal spectrum utilization for the White-Fi Infostations. When a TVWS is allocated for a vehicle, the multimedia content is transmitted using the TVWS. Other studies that use the available spectrum estimation based on infrastructure are the database approach are [44, 45, 46, 74, 80, 89].

2.3.3 Spectrum estimation based on the vehicles

The estimation of the available spectrum based on vehicles has been studied for V2V scenario where there is no intervention of infrastructure elements such as the RSU. In this approach, the OBU is a portable mode-II secondary device that implements a spectrum detection technique to check the channels occupation locally. Other approaches because it can access to geolocation database directly using its location capabilities, and it can implement a spectrum detection technique.

In [48], the performance of energy detection over a Rayleigh fading channel is analyzed, using the average probability of missing detection which is the probability that a primary user is not detected because of a high threshold in the detection technique. Energy detection on fading channels is also analyzed in [90, 91]. Experiments of energy detection for V2V communications are presented in [80, 92, 81]. In [80], spectrum measurements are collected using a conventional spectrum analyzer when a vehicle travels between Boston, MA and West Stockbridge, MA at an average velocity of 96 km/h. Results show that energy values increase near to a TV transmitter and the energy levels decrease in rural areas far away from an active TV transmitter. In [92], a prototype of a cognitive radio device for energy detection on board of a vehicle is presented. The prototype implements the control channel and the data channel on TV band using spectrum sensing and distributed coordination functions on an SDR device. In [81], another secondary device prototype is used to transmit a video from a vehicle to another using the data channel over a TVWS. When an emulated primary user is detected, the secondary device must change to a new data channel according to the coordination function decisions.

Spectrum detection made by an OBU is useful for V2V communications because a local spectrum estimation can be done. One advantage is that mobility effects can be considered when available channels are searched. For the geolocation database, the FCC recommends that a mobile device must consult the channel availability when the device moves 100 meters, (e.g. every 3 seconds if the vehicle travels up to limit speed of highway in the USA which is 120 km/h.) A drawback of spectrum detection based on vehicles is there is not possible to have centralized control of spectrum allocation, then there is no guaranty of efficient spectrum usage. Also, it is not possible to get priority treatment for the transmission when its connection is lost. Another aspect to consider is the device must stop its current transmission to make spectrum detection in case of having only one transmitter/receiver, which reduce the effective data throughput. Also, there must be a mechanism to coordinate the channel tuning between the vehicles to establish communication between them. This coordination has been explored through the rendezvous protocol that defines sequences of channel jumps to get a transmitter and receiver to tune the same channel as many times [93, 94]. This approach requires increasing the number of successful meetings and decreasing the percentage of failed meetings, ensuring the establishment of communication between vehicles.

2.3.4 Resource allocation mechanisms

When the available opportunistic spectrum has been identified, the next step is to decide how to assign it when there are several interested users. In DSA, the channels that will be assigned correspond to those that are not being used by TV transmitters which varies from one area to another. It must be considered in VDSA because the vehicles will use an available TVWS at one location, but the same TVWS may be busy a few kilometers later along the route. The busy TVWS may be being used by an active TV transmitter, or by other secondary users such as IEEE 802.11af or IEEE 802.22 networks. Spectrum must be assigned according to some criteria defined by the network, considering aspects such as *a)* the efficiency of spectrum utilization, *b)* the interference reduction, *c)* the traffic's QoS requirements, among others. The evaluation of the criteria and the resource allocation decision can be done using centralized, distributed, or cluster-based approaches:

Centralized: A central node collects the information about spectrum occupation and users requirements to make decisions about channel allocation. In VDSA, the information about spectrum occupation may come from the geolocation database, or the cognitive RSUs that detect the spectrum occupation using spectrum detection techniques, or both (see Section 2.3.2). Centralized resource allocation has several advantages including the efficient spectrum usage because there is a controlled allocation of the resource to avoid the interference, and to know in a broad way the network status and the users' requirements. However, the centralized approach requires to mitigate the possible failures in the central node, to avoid that the resource allocation process stops working if the central node fails.

Distributed: Each node makes decisions based on its information or by cooperation with neighboring users. In cooperative approaches for VDSA, each vehicle detects one or more TVWS and share the information with near vehicles to decide if the TVWS is busy or available. Each vehicle selects an available TVWS, or a cooperative mechanism could be used to assure that several vehicles choose the same TVWS (see Section 2.3.3). This approach has advantages such as lower signaling overhead, and faster decision time, among others. As to drawbacks, there is no efficient spectrum use because each vehicle chooses an available TVWS without considering the global spectrum occupation, and there is no guarantee that interference will not occur between users and other secondary users.

Cluster-based: This is a hybrid between centralized and distributed approaches in which the nearby nodes are grouped into clusters, and the cluster head is responsible for collecting and combining the sensing information from all the nodes in the cluster [95]. The cluster head provides the spectrum allocation vector for the cluster; in case the cluster head fails, another node must assume the cluster head role. The spectrum allocation scheme for each cluster may be shared with a centralized node to get the global spectrum occupation on the vehicular network.

For modeling the resource allocation problem for VDSA considering other secondary users, the author in [49] proposed a cognitive vehicular network where the road is divided into segments with an RSU in each segment that uses the geolocation database and spectrum sensing techniques to estimate the TVWS occupancy. The vehicles must register with the RSU of the current segment to send their channel allocation request and to obtain channel allocation results. This proposal divides the time into equals scheduling cycles, and RSU allocates channels to vehicles at the beginning of every scheduling cycle. This approach assumes that the primary user tolerates a maximum collision probability, and defines the transmission time of the vehicle on a TVWS depending on the data rate, the number of packets vehicle tends to transmit in the current schedule, and the maximum allowed scheduling time on the channel. To maximize the throughput for all the vehicles, these are classified in priority classes to schedule a channel for higher priority vehicles earlier than lower priority vehicles. This scheduling for vehicular communications make flexible three constraints related to meet the FCC's requirements on the total transmission power on a TVWS channel; other to provide fairness among the vehicles, and other to avoid mutual interference among the vehicles. This resource allocation mechanism is proposed for the coexistence between 802.22 networks and a cognitive vehicular network: the vehicular network knows the 802.22 upstream scheduling information and sends burst traffic during the idle slots on the 802.22 upstream.

Another approach to the resource allocation task in VDSA is to achieve optimal TVWS network capacity considering to reduce or avoid the co-channel and adjacent channel interference in a White-Fi network (i.e., IEEE 802.22/802.11af network) form by White-Fi access points and vehicles. Authors in [96] propose a define the configuration profiles for each TVWS and a set of transmission power configuration profiles. Obtaining the joint channel-power selection profile is possible to obtain the optimal channel/power selection profile for all the White-Fi access points in order to maximize the network throughput.

There are other approaches to resource allocation for general cognitive radio network based on the economic perspective of the secondary use of licensed spectrum [97], but this approach will not be considered in this thesis proposal.

2.4 IEEE standard 802.22

The IEEE standard 802.22 uses TV band frequencies (54-862 MHz) with 6, 7, or 8 MHz channel bandwidth. The standard defines two PHY operation modes (i.e., PHY-OM1 and PHY-OM2) to support the basic and advanced 802.22 systems. The PHY layer mechanism is Orthogonal Frequency Division Multiple Access (OFDMA) with up to 2,048 subcarriers divided into data sub-carriers, pilot sub-carriers, guard, and null sub-carriers. Binary phase-shift keying (BPSK) up to 64-bit Quadrature Amplitude Modulation (64-QAM) schemes are supported; Table 2.4 lists additional 802.22 PHY features.

The Medium Access Control (MAC) protocols provide functions for the protection of TV band incumbent services and self-coexistence between WRANs. The MAC supports unicast, multicast, and broadcast services, implementing a combination of access schemes that control contention between users, including polling, to simplify the access operation.

The A-WRANs provide all the functionalities of PHY, MAC, and cognitive radio technologies defined in the previous version of the standard, with the latest version including an additional PHY Operational mode PHY-OM2 to provide multi-hop relay operations using a Relay CPE (R-CPE), multiple channel operations, advanced security for regional monitoring applications, and enhanced broadband services. Multi-channel operation and multi-hop relay are optional features to increase network capacity. Therefore, although originally defined as a fixed communication system, in its most recent version, the IEEE 802.22 standard

Table 2.4: IEEE 802.22 PHY and MAC Parameters [23]

Parameter	**Specifications PHY-OM1**	**Specifications PHY-OM2**
Frequency range	54-862 MHz	54-862 MHz
Channel bandwidth	6, 7, or 8 MHz	6, 7, or 8 MHz
Data rate (6 MHz case)	4.54 to 22.69 Mb/s	3.61 to 18.05 up to 25.27 Mb/s for SISO and single channel operation. 57.77 to 288.85 up to 404.39 Mb/s for 4 stream MIMO and 4 channel operation.
Payload Modulation	QPSK, 16-QAM, 64-QAM	QPSK, 16-QAM, 64-QAM, 256-QAM
Transmit EIRP	4 W maximum for fixed CPEs and BSs. 100 mW maximum for mobile/portable CPE (USA regulatory domain)	4 W maximum for fixed CPEs and BSs. 100 mW maximum for mobile/portable CPE (USA regulatory domain)
Multiple access	OFDMA	OFDMA
FFT Size	2048	1024
Cyclic prefix modes	1/4, 1/8, 1/16, 1/32	1/4, 1/8, 1/16, 1/32

also has the potential to provide connectivity to Intelligent Transportation Systems with cost-effective, extended coverage [98].

Figure 2.3 illustrates an advanced base station (A-BS) providing broadband services for an advanced customer premise or portable equipment (A-CPE) through direct connectivity to the A-BS or through a relay CPE (R-CPE). A large number of A-CPEs may be connected to the A-BS, and several A-CPEs form a group managed by an R-CPE. An A-WRAN supports fixed and mobile (or portable) groups, depending on the mobility of the R-CPE. The R-CPE of a fixed group may be installed on top of a building, a house, or a tower, among others. The R-CPE of a mobile (or portable) group may operate in a vehicle, with other mobile users including cyclists and pedestrians, or even in animals for tracking purposes.

The cognitive radio capabilities in the 802.22 standard provide the mechanisms for protection of incumbents and the efficient operation of A-WRANs. The cognitive plane provides the spectrum sensing function (SSF), the geolocation (GL) function, the spectrum manager/spectrum sensing automaton (SM/SSA), and a dedicated security sub-layer 2. The SSF implements spectrum sensing algorithms, and the GL module provides the information to determine the location of the IEEE 802.22 device (A-BS or A-CPE).

Spectrum Manager (SM)

The SM plays a critical role in the network architecture. The SM maintains spectrum availability information, manages channel lists and quiet-period scheduling, and implements coexistence mechanisms. The SM also takes requests from the MAC/PHY and functions as the central point in the A-BS cognitive plane because it gathers all the spectrum availability information resulting from the spectrum sensing function and the database service. Using this information, the SM provides information to the MAC to remotely configure all the registered A-CPEs.

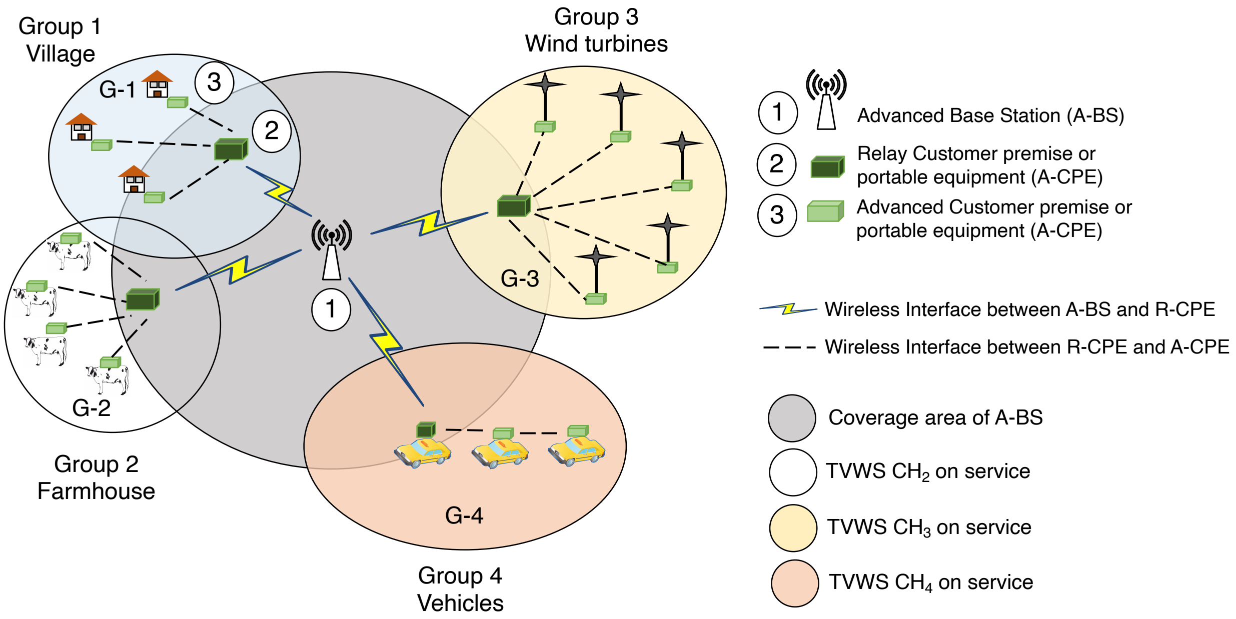


Figure 2.3: Advanced Wireless Rural Area Network (A-WRAN). Source: Own elaboration based on [23]

Spectrum Sensing Automation (SSA)

This entity is present in the A-BS and the A-CPEs. It independently implements specific procedures for sensing the RF environment at the initialization of the A-BS and before registering an A-CPE with the A-BS. The CPEs power up by first searching all of the channels in the area to see if an A-BS is present. Once an A-CPE locates an A-BS, authentication and connection setup are done. In addition, the standard requires incumbent-user sensing measurement and detection. The SSA at the A-CPE includes features to allow the A-CPE operation when it is not under the A-BS control. When the A-CPE is idle, the SSA conducts out-of-band sensing and reports to the BS to update the status of the channel list.

Geolocation Function and TV Bands Database

The A-BS SM communicates with the TV bands' database service to get a set of available channels in its location. The SM generates the available channel list using only those channels indicated for every device on the network. Each A-BS has a list of backup and candidate channels. A backup channel is one that has been verified as available; therefore, its use does not affect an incumbent service. A candidate channel is a channel that, once cleared from potentially harmful interference to incumbents, may become a backup channel.

2.5 Secondary opportunistic networks over TVWS and coexistence

Opportunistic usage of the available spectrum in TV bands have been explored as an option to deal with the spectrum scarcity caused by the growth in the devices connected to the Internet via wireless technologies, and by the high bandwidth requirement of the applications. IEEE has published two related standards for wireless communications via TVWS as a technology that extends the wireless coverage due to propagation characteristic in the VHF and UHF bands. The IEEE 802.11af standard is the specification of physical and medium access control layers for wireless local area networks employing TV bands [99], whereas the IEEE 802.22 standard specifies physical and medium access control layers for cognitive radio networks over TV bands [100]. IEEE 802.11af and IEEE 802.22 networks have been proposed to improve broadband access in rural areas [15, 16], to provide connectivity in education initiatives [17, 18, 19], to support agricultural projects [21], and to provide connectivity in emergency response plans [20]. Furthermore, commercial initiatives and manufacturers such as a5Systems, 6HARMONICS, Airband, and First Broadband provide technological services for rural broadband connectivity, the industrial Internet of Things (IIoT), communications for critical infrastructure and environmental monitoring, among other applications, all operating over TVWS.Table 2.5 shows the main parameters of the secondary networks implemented according to the 802.22 and 802.11af technologies. It is expected for a secondary network to be used for similar purposes as a typical WiFi network, being Internet access the most prominent application.

Table 2.5: Comparison parameters of 802.11af and 802.22 standards

	802.11af	802.22
Coverage	Indoor: up to 100 m Outdoor: up to few km	17 - 33 km
Max delay spread	Indoor: less than 1 μsec Outdoor: 1 - 10 μsec	11 - 60 μsec
Total bandwidth	5, 10, 20, 40 MHz	6, 7, 8 MHz
Maximum data rate	12 Mb/s	22,69 Mb/s
Payload modulation	BPSK, QPSK 16-QAM, 64-QAM	QPSK 16-QAM, 64-QAM

Coexistence

Coexistence between cognitive radio networks both fixed and mobile is an active topic under study. Along that line, the IEEE 802.19.1 [22] standard defines a coexistence framework for cognitive networks over TVWS, but it is not yet clear where to implement the proposed entities, such as the coexistence manager (CM), the coexistence discovery and information server (CDIS), and the coexistence enablers (CE), to guarantee that any secondary network will be discovered and managed [101]. Although the coexistence framework may provide the operating parameters (e.g., the frequency, the transmission power, the modulation, among others) that avoid interference among networks, changing the operating parameters in each network is optional to date, which means that, in terms of the aforementioned standard, the coexistence between the networks has no warranties. Furthermore, the mobility in the cognitive vehicular networks is a condition that should be included to propose efficient coexistence methods, considering that the residence time within the secondary network coverage area is variable, and the coexistence process must be low latency to guarantee the delay requirements of applications [12].

Coexistence between cognitive vehicular networks and 802.22 networks has been explored by Han *et al.* [49], considering that 802.22 networks use time division multiple access (TDMA) to share the channel. The authors propose a coexistence 802.22-CVN framework where the upstream scheduling information of 802.22 Consumer Premise Equipment (CPE) devices is included in the downstream messages that are periodically broadcast by the 802.22 base station (BS). The CPE and the vehicles obtain the 802.22 upstream scheduling information by listening to the downstream messages from the BS, and the vehicle can access the TVWS channel according to the upstream scheduling information. They propose that the low-power CVN and 802.22 networks could reuse the same TVWS using adaptive resource allocation, thus avoiding mutual interference and reducing the need to search for another TVWS for the CVN when there are secondary networks in the area. Their resource allocation mechanism seeks to maximize the transmission rate in the vehicular network, penalizing the violation of restrictions such as the maximum transmission power allowed for secondary users and the interference caused to the secondary network.

2.6 Discussion

Most of the reviewed articles that study the feasibility of using TVWS for vehicular communications only consider the presence of the primary TV users. On the one hand, previous works propose a geolocation database that stores the information about the TV channel allocation, which is mainly used for V2I scenarios because the vehicles must request the available TVWS before transmission. On the other hand, for V2V scenarios, the reviewed articles propose to use a spectrum sensing technique to determine if a TV transmitter occupies a TV channel; the decision can be made using cooperative sensing among vehicles to improve the reliability. Once a TVWS is detected, the reviewed articles assume that the TVWS remains available along the road, focusing the attention to other aspects of the interworking. However, the presence of active IEEE 802.22 and IEEE 802.11af networks may affect the use of TVWS, and the coexistence between secondary networks and vehicular communications has been little studied.

Furthermore, coexistence among secondary networks has been studied considering that the opportunistic spectrum is used for different scenarios. Coexistence methods among secondary networks over TVWS are defined in the IEEE 802.19.1 standard [22], where a coexistence framework based on entities such as managers, enablers, and information servers interacts to collect operational settings and adjust the high-level operating parameters such as the operating channel and the power transmission of the secondary networks to avoid mutual interference. Also, each network has to agree on allowing automatic setting reconfiguration to operate under specific conditions to avoid the mutual interference between networks.

Although the IEEE standard 802.19.1 proposes different methods and algorithms for coexistence between secondary cognitive networks, the complexity of the architecture and the non-obligatory adjustment of the operating parameters to achieve coexistence avoiding mutual interference have made implementing the standard impractical. On the other hand, [49] proposes a mechanism for adjusting operational parameters only in the vehicular network to maximize throughput, penalizing non-compliance with the maximum power constraint and the interference caused to the fixed network. However, this mechanism does not guarantee the technical protection of the fixed secondary network operation beyond reducing throughput in the vehicular network as the incentive to choose the operating parameters in the vehicular network.

Chapter 3

Coexistence of Cognitive Networks for Vehicular Communications on TV White Spaces

This chapter presents the coexistence scenario for vehicular communications on TVWS Spectrum. First, the general scenario of study for vehicular networking on TVWS spectrum, also known as vehicular dynamic spectrum access (VDSA), is presented. The scenario includes the TV bands primary users, secondary networks, and vehicular networks. Then, a coexistence scenario among fixed secondary and vehicular networks based on the IEEE standard 802.22 is presented. Finally, the White Space Resource Sharing mechanism is detailed.

3.1 Introduction

Channel availability is a fundamental requirement for the successful operation of vehicular applications, but the lack of available spectrum for wireless technologies is a threat for current and future applications designed for ITS. For example, in the presence of traffic congestion, the sending of a critical warning message may fail when concurrent transmissions overflow the control channel assigned to vehicular communications. Therefore, the dynamic and opportunistic use of available spectrum, coupled with cognitive radio technology, has been proposed to ensure more available channels and successful transmissions in both fixed and mobile environments.

Dynamic Spectrum Access is the opportunistic detection and usage of the available radio spectrum. DSA for vehicular communication (VDSA) has been explored as an alternative or complementary option to dedicated short-range wireless communications (DSRC) [72], the technology for vehicular communications in the 5.9 GHz band. VDSA considers the use of available channels in TV frequency bands (470 MHz-806 MHz), known as TV White Spaces (TVWS), to exploit the propagation features of frequencies below 1 GHz, achieving higher transmission distances in vehicle-to-everything (V2X) scenarios. Among other reasons, TVWS may exist in a specific area when there are no TV transmitters using the channel in the area of interest or when a TV transmitter uses the channel in the area, but the TV transmission is OFF during specific hours (e.g., at night).

Spectrum regulators have defined the technical requirements for allowing DSA in TV bands to guarantee the protection of the primary user against harmful interference [70, 71, 102]. Secondary users interested in the TVWS have to make sure the channel is available before transmission and be ready to release the channel when a primary user requires it. Accordingly, IEEE has published two related standards for wireless communications for TVWS. The IEEE 802.11af standard is the specification of physical and medium access control layers for wireless local area networks employing TV bands [99], whereas the IEEE 802.22 standard specifies physical and medium access control layers for cognitive radio networks over TV bands [23] (see Section 2.4 for more details of the standard).

The traditional approach to VDSA has been to exploit TVWS as an offloading channel when traffic congestion causes the degradation of the DSRC control and data channels [46], and to provide an exclusive channel for Internet access [103]. Results have shown that the use of TVWS may increase the dissemination distance for safety messages in vehicular ad-hoc networks (VANETs), reducing collisions and latency caused by multi-hop dissemination [104, 93]. The work that has been done to date on VDSA on the TVWS spectrum reflects the fact that the TV channel is only occupied by a TV transmitter, and opportunistic access is available outside of the transmitter's coverage area [46, 44, 45, 47, 79, 86]. In these scenarios, vehicles travel across a route where the availability of TV channels depends on the distance between the TV transmitter and the vehicles. Channel availability is checked accessing a geolocation database with information of the spectrum occupation [46, 44, 45] or using a spectrum detection technique such as energy detection, cyclostationary analysis, or matched filter detection [47, 79, 86, 87].

A more realistic VDSA scenario should take into consideration the presence of other secondary opportunistic networks when they operate on the TVWS spectrum, potentially affecting the vehicular communications when the vehicles meet with these secondary networks on the route. Since the TVWS spectrum provides resources for secondary spectrum usage, all the secondary devices have the same right to use the TVWS channel. However, the impact of other opportunistic networks on the dynamic spectrum access for vehicular networking over TVWS is still under exploration.

3.2 Modeling primary and secondary TV bands users for vehicular networking on TVWS

Figure 3.1 illustrates the general scenario of study, where there is an active TV transmitter providing TV services using, for example, channel 52. Outside the coverage area of the TV transmitter, there is a V2V link established over the same channel because it has become a white space in that area. However, there is an IEEE 802.11af fixed secondary network (also known as a White-Fi network) farther along on the route, which is also using channel 52. The following presents a more detailed model of the TV primary users, the White-Fi network, and the vehicular network intending to access the TV channel.

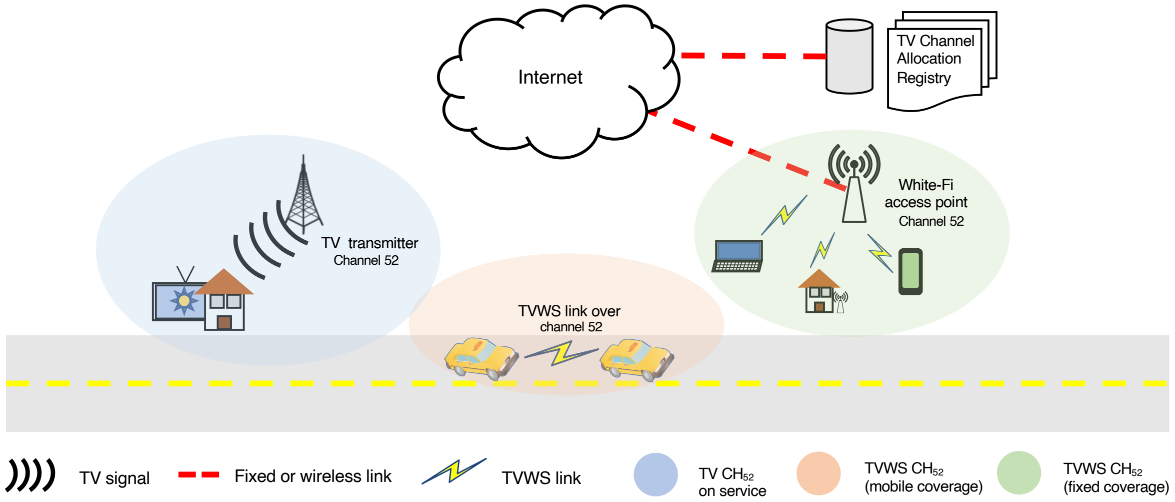


Figure 3.1: Scenario of study: opportunistic access for vehicular networking considering the presence of primary TV users and secondary White-Fi networks over the TV band. Source: Own elaboration.

3.2.1 TV primary users

Primary users of TV bands are the analog and digital TV transmitters, which are located in valleys or low to medium-sized mountains, providing directional coverage toward densely populated areas. When there is an active TV transmitter in the area, the channel assigned to the transmitter remains busy within the TV transmitter's coverage area, which means the channel cannot be used for secondary users inside that coverage area. However, spectrum regulators define that a TVWS may be used if the received power of the TV signal is lower than a specific threshold; in the case of the FCC, the detection threshold is -114 dBm [70].

In the presence of an active TV transmitter, opportunities for VDSA must be located outside the TV transmitter's coverage area. One way to estimate the TV transmitter's coverage area is by calculating the maximum distance between the transmitter and the potential receivers, in which the received power is higher or equal to the detection threshold. The received power is calculated using a long scale path loss model since the frequencies of TV service (470-806 MHz) have a high obstacle penetration. In [105], several path loss models to predict TV service coverage for secondary use are compared with path loss measurements in urban, suburban, and rural environments. Among the evaluated models, Hata [106] and Hata-Davidson [107] models showed similar results regarding path loss. The Hata model is used for frequency ranges of 100 MHz to 1,500 MHz, distances of 1 km to 20 km, base station antenna heights between 30 m and 200 m, and reception antenna heights between 1 m and 10 m.

Nevertheless, the TV transmitter's coverage is expected to be larger than 20 km in some rural areas. Therefore, the Hata-Davidson model is adopted in the system, which incorporates a correction factor to increase the distance between the transmitter and the receiver up to 300 km. The received power P_{Rx} corresponds to:

$$P_{Rx}(\mathrm{d}B) = P_{Tx} - PL_{HD}, \tag{3.1}$$

where P_{Tx} is the transmitted power and PL_{HD} is the Hata-Davidson path loss, which is describe as follows.

Hata-Davidson Pathloss Model

The Hata-Davidson path loss model includes correction factors to the well-known Okumura-Hata path loss model in order to expand the model's parameters [107]. The Hata-Davidson pathloss PL_{HD} is calculated as follows.

$$PL_{HD}(\mathrm{d}B) = PL_{Hata} + K_{Davidson}, \tag{3.2}$$

where PL_{Hata} is the Hata path loss and $K_{Davidson}$ is the Davidson correction factor. $K_{Davidson}$ includes several terms to adjust the loss due to the expanded parameters: $A(h_{bs}, \mathrm{d})$ and $S_1(\mathrm{d})$ are distance correction factors; $S_2(h_{bs}, \mathrm{d})$ is the base station antenna height correction factor; $S_3(f)$ and $S_3(f, \mathrm{d})$ are the frequency correction factors. Table 3.1 depicts the main variables used for the $K_{Davidson}$ derivation.

Table 3.1: Summary of variables in Hata path loss model and $K_{Davidson}$ derivation.

Variable	Definition
PL_{HD}	Hata-Davidson path loss (dB)
PL_{Hata}	Hata path loss (dB)
$K_{Davidson}$	Davidson correction factor (dB)
PL_U	Hata path loss in urban area (dB)
PL_S	Hata path loss in suburban area (dB)
PL_R	Hata path loss in rural area (dB)
d	Distance between transmitter and receiver (km)
f	Transmitter frequency, $150 \leq f \leq 1000(MHz)$
h_{bs}	Transmitter antenna height (m)
h_m	Receiver antenna height (m)
$A(h_{bs}, \mathrm{d})$	Distance correction factor
$S_1(\mathrm{d})$	Distance correction factor
$S_2(h_{bs}, \mathrm{d})$	Base station antenna height correction factor
$S_3(f)$	Frequency correction factor
$S_4(f, \mathrm{d})$	Frequency correction factor

The equations to calculate the correction factors are given below.

$$K_{Davidson} = A(h_{bs}, \mathrm{d}) - S_1(\mathrm{d}) - S_2(h_{bs}, \mathrm{d}) - S_3(f) - S_4(f, \mathrm{d}) \tag{3.3}$$

$$A(h_{bs}, \mathrm{d}) = \begin{cases} 0, \mathrm{d} < 20km \\ 0.62317(\mathrm{d} - 20)[0.5 + 0.15\frac{h_{bs}}{121.95}], 20km \leq \mathrm{d} < 300km \end{cases} \tag{3.4}$$

$$S_1(\mathrm{d}) = \begin{cases} 0, \mathrm{d} < 64.38km \\ 0.174(\mathrm{d} - 64.38), 64.38km \leq \mathrm{d} < 300km \end{cases} \tag{3.5}$$

$$S_2(h_{bs}, \mathrm{d}) = 0.00784 \left| log_{10}(\tfrac{9.98}{\mathrm{d}}) \right| (h_{bs} - 300), h_{bs} < 300m \tag{3.6}$$

$$S_3(f) = \frac{f}{250 log_{10}(\frac{1500}{f})} \tag{3.7}$$

$$S_4(f, \mathrm{d}) = \left[0.112 log_{10}(\tfrac{1500}{f}) \right] (\mathrm{d} - 64.38), \mathrm{d} > 64.38km \tag{3.8}$$

According to the path loss calculated in Eq. (3.2) and the detection threshold established by the FCC, the coverage areas of a typical TV transmitter in urban, suburban, and rural areas are estimated. Figure 3.2 shows the received power for distances up to 100 km between the TV transmitter and receiver. Table 4.6 lists the parameters for transmission and reception of the primary users. Results show that a channel assigned to an active TV transmitter remains busy for reception distances up to 75 km, 125 km, and 220 km in urban, suburban, and rural environments, respectively. For greater distances, the channel can be considered as TVWS and could be used opportunistically. However, the vehicle should use the energy detection VDSA technique to sense the channel occupation. As mentioned in Section 2.3, energy detection is the predominant spectrum detection technique in V2V scenarios because of its low latency execution. Since the FCC determines that a portable secondary device must verify the TV occupation every 100 m to protect TV primary users against harmful interference, a spectrum detection technique with low-latency is more convenient for vehicular secondary users that travel at 30-120 km/h. Note that Figure 3.2 shows a jump of the received power between kilometers 19 and 20; this is because the distance correction factor, $A(h_{bs}, \mathrm{d})$, employed in the Hata-Davidson model is a piece-wise function defined for the intervals [1, 20) km and [20, 300) km.

3.2.2 White-Fi network description and traffic modeling

Considering the deployment of TVWS secondary networks (i.e., 802.11af or IEEE 802.22 networks), the main interest is to analyze if there are possible opportunities for vehicular communications even in the presence of such secondary users. In this case, it is necessary to estimate the coverage area of the White-Fi access point (AP) to define a bounded area where the TVWS could be busy. The scenario of study considers an AP antenna height of 30 m, which is the height of a 10-floor building in an urban area, or an antenna on a water tank or a small hill in a rural area. All of the receivers of the secondary users (i.e., White-Fi users or vehicular users) are assumed to have an antenna height of 1.5 m.

Fixed secondary users must limit the transmission power up to 36 dBm [70] according to the FCC. To estimate the AP coverage, the received power depending on the distance between the AP and the potential receivers according to the Hata-Davidson model is calculated. Since the White-Fi AP is also a secondary user, there is no specific detection threshold from the

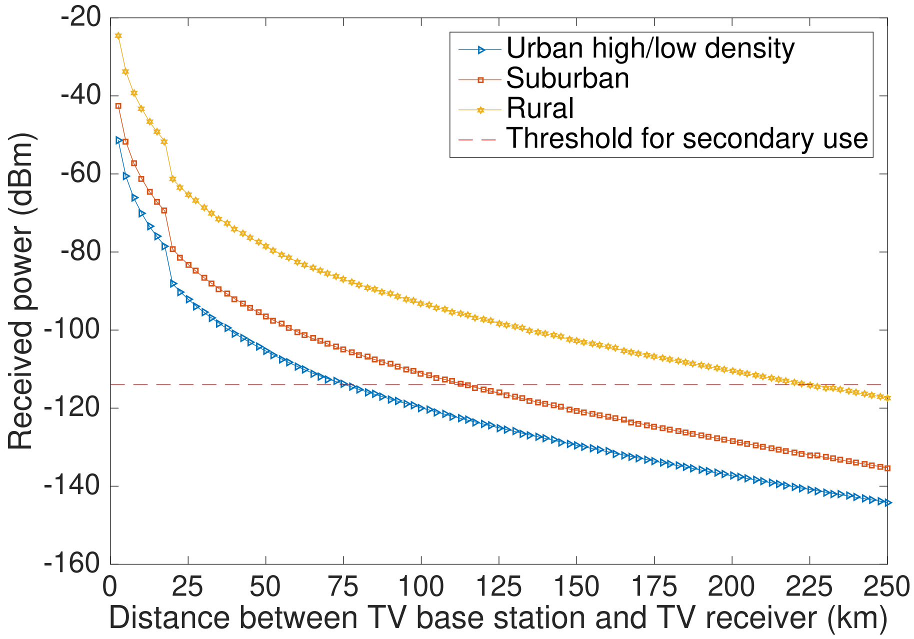


Figure 3.2: Received power depending on the distance between a TV transmitter and a potential TV receiver.

transmissions of the secondary users to determine that a TVWS is available. Hence, the receiver sensitivity is employed to determine the area of coverage of the White-Fi network. According to the IEEE 802.22 standard, the receiver sensitivity for a successful reception is -90 dBm. Table 4.6 shows the parameters employed for transmission and reception of the White-Fi network system.

Figure 3.3 illustrates the received power when the distance between the AP and the potential receiver increases. According to the Hata-Davison model, the White-Fi network has a radio range of approximately 2 km in urban areas, 3.2 km in suburban areas, and 11 km in rural areas. Vehicular communications intending to use the TVWS inside such coverage areas should consider the channel occupation derived from the White-Fi network users' traffic.

White-Fi network traffic

A White-Fi network is expected to be used for similar purposes as a typical WiFi network with Internet access as the most prominent application. White-Fi could be also used to extend the coverage area of a monitoring network. The medium access channel in a White-Fi network is carrier sense multiple access (CSMA), and for this scenario of study the White-Fi network traffic is modeled in two ways. First, with sources of traffic that occupy the channel following a uniform distribution probability. Four channel occupation policies with 10%, 30%, 50%, and 70% probabilities of busy channel (P_{bc}) were defined. The probability density function of the uniform distribution $f(x)$ is:

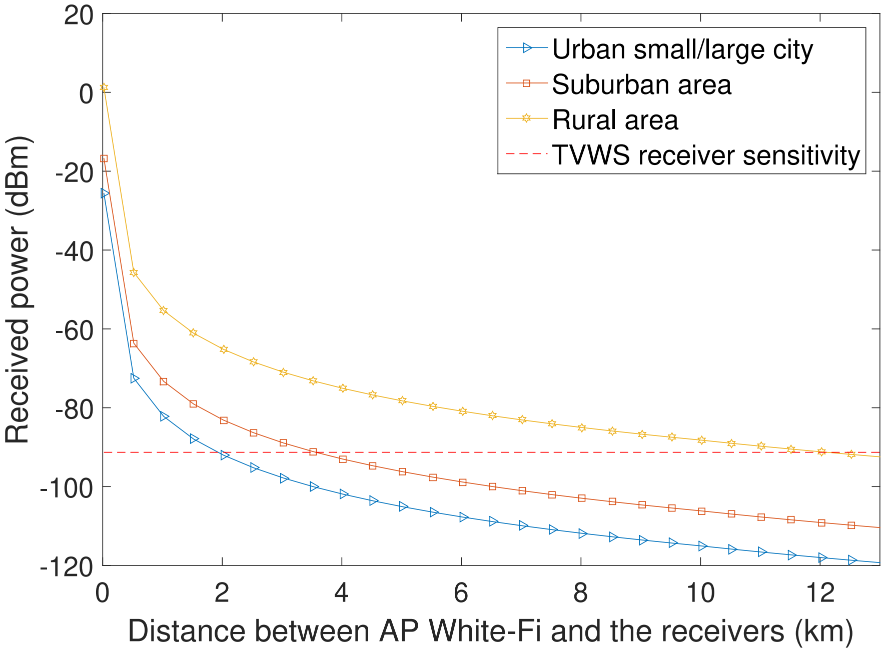


Figure 3.3: Received power depending on the distance between the White-Fi access point and a potential TVWS receiver.

$$f(x) = \begin{cases} 0, x < a \\ \frac{1}{b-a}, a \leq x \leq b, \\ 0, x > b \end{cases} \tag{3.9}$$

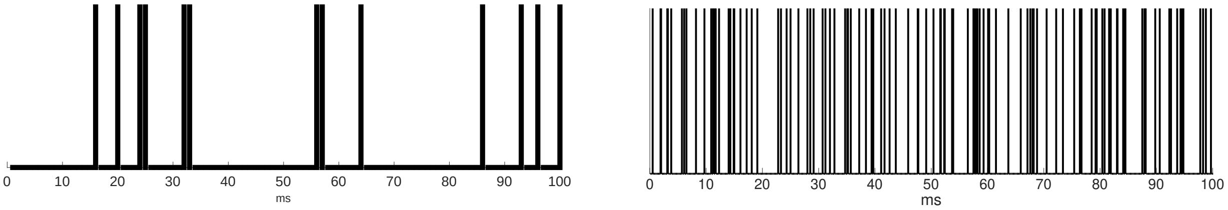
where a and b are two boundaries that depend on the observation time, for example, from 0 to 100 ms. Figures 3.4a and 3.4b show examples of the 10% and 50% occupation policies. Second, with sources of bursty traffic that represent the Internet traffic. This traffic follows a Pareto ON/OFF distribution, where packets are sent during ON periods according to the mean burst time (b_t), and no packets are sent during the OFF periods defined by the mean inter-arrival time (i_t). Figure 3.4c shows an example of the Pareto occupation policy.

To establish the ON/OFF periods in the Pareto distribution, the packet duration p_{dur} and burst length b_l (in packets) are calculated according to:

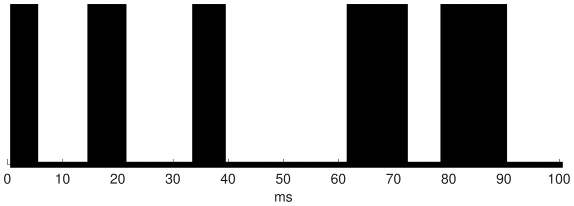
$$p_{\mathrm{dur}} = \frac{p_s}{R}, \tag{3.10}$$

$$b_l = \frac{b_t}{p_{\mathrm{dur}}}, \tag{3.11}$$

where p_s is the packet size in bits, R is the data rate in bits per second during the burst, and b_t is the mean burst time. The burst length b_l and the idle time i_t correspond to the expected value $E(X) = b_l$ and $E(Y) = \mathrm{i}_t$ of the Pareto distribution for each variable:



(a) Uniform distribution with $P_{bc} = 10\%$. (b) Uniform distribution with $P_{bc} = 50\%$.



(c) Pareto distribution with $b_t = 10$ ms and $\mathrm{i}_t = 20$ ms.

Figure 3.4: Examples of channel occupation policies: (a, b) uniformly distributed probability of busy channel and (c) burst traffic. Source: Own elaboration.

$$E(X) = b_l = b_1 * \frac{a}{(a-1)}, \tag{3.12}$$

$$E(Y) = \mathrm{i}_t = b_2 * \frac{a}{(a-1)}, \tag{3.13}$$

where $a > 1$ is the Pareto shape parameter. The Pareto scalar parameters b_1 and b_2 are extracted from $E(X)$ and $E(Y)$ as follows:

$$b_1 = b_l * \frac{(a-1)}{a}, \tag{3.14}$$

$$b_2 = \mathrm{i}_t * \frac{(a-1)}{a}. \tag{3.15}$$

Three configurations of the Pareto distribution were defined to model the bursty traffic according to values previously reported in the literature [108], [109]: $b_t = 10$ ms and $\mathrm{i}_t = 20$ ms; $b_t = 20$ ms and $\mathrm{i}_t = 10$ ms; and $b_t = 20$ ms and $\mathrm{i}_t = 20$ ms.

3.2.3 Vehicular network modeling

In the scenario of interest, the intend is to analyze the impact of the vehicles' speed on the perceived spectrum availability for vehicular dynamic spectrum access. The FCC determines that portable/mobile secondary devices in TV bands must verify the channel occupation every 100 m, to detect the possible presence of a primary user. In this study, the verification distance is also used to establish the presence of other users within the White-Fi network. Considering that the time it takes for a vehicle to travel 100 m depends on its speed, two

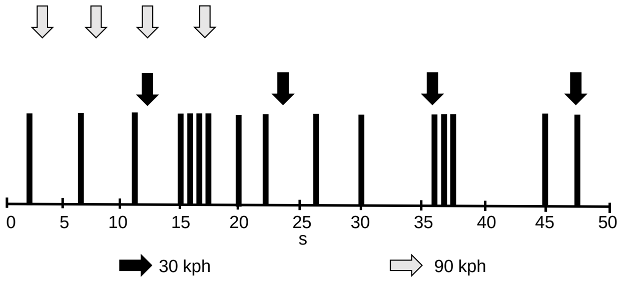


Figure 3.5: Differences in channel verification times for two vehicles traveling at 30 km/h and 90 km/h to cover a distance of 400 m. The channel occupation policy follows a Pareto Distribution. Source: Own elaboration.

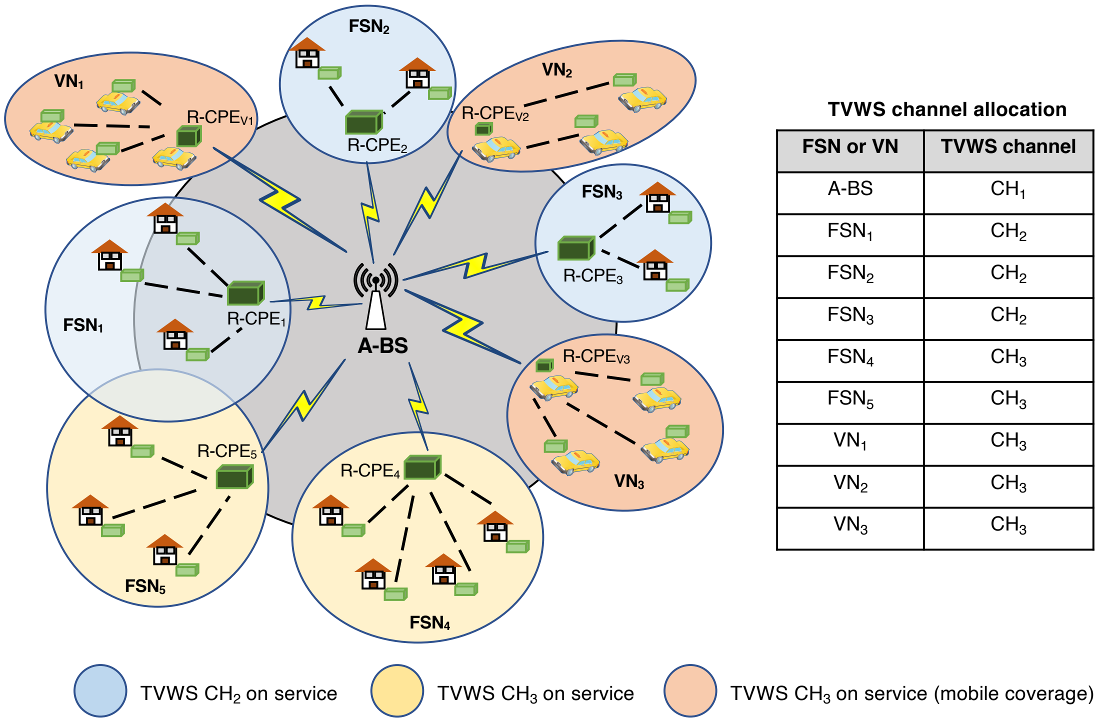
vehicles with different velocities will meet the verification time (i.e., will cover the 100 m) at different moments. This situation causes the vehicles to have different perceptions of channel occupation, which is illustrated in Figure 3.5. For example, two vehicles moving at 30 km/h and 90 km/h, respectively, and both traveling 400 m, detect different channel occupations as follows: the vehicle moving at 30 km/h travels 100 m in 12 seconds, whereas the vehicle moving at 90 km/h travels 100 m in four seconds. If the channel occupation along a route is represented on a timeline, the opportunities for VDSA could be different for each vehicle as shown in Figure 3.5.

The scenario of study described above presents the most relevant elements to enable vehicular communications in the TVWS spectrum. The secondary network was modeled according to the IEEE standard 802.11af where the medium access channel is CSMA, then the channel usage is random access following one of the channel occupation policies. This scenario is used to analyze the impact of vehicle speed and channel verification distance on the perception of channel occupancy and the identification of transmission opportunities on the TV band. Evaluation and simulation results are described in Section 4.1.

The other IEEE standard for secondary spectrum access on the TV bands is the IEEE 802.22 [23], which also has the potential to provide connectivity to Intelligent Transportation Systems with cost-effective, extended coverage [98]. The following section describes the scenario of study focused on the coexistence between fixed secondary and vehicular networks, analyzing the TVWS channel sharing between the overlapping fixed secondary and vehicular networks, and presenting the proposed resource sharing mechanism. For the coexistence scenario, it is assumed that secondary fixed and vehicular networks only operate on vacated TV channels, with no primary users. The georeferenced database provides the list of vacated TV channels, then both the secondary fixed and the vehicular network only operate in vacated TV channels. Therefore, the TV band primary users are omitted in the coexistence scenario to focus on the coexistence between the vehicular and secondary networks.

3.3 Coexistence between fixed and mobile (vehicular) secondary groups on the IEEE standard 802.22

Fig. 3.6 illustrates an example of coexistence between fixed and mobile secondary groups in an A-WRAN as defined in the IEEE 802.22 standard [23]. Fixed or mobile groups operate as networks; therefore, the term *network* is used to refer to a group. In the scenario, there are five fixed secondary networks (FSN) (FSN_1, ..., FSN_5) managed by the A-BS using three TVWS channels (CH_1, CH_2, CH_3). FSNs provide different services such as broadband Internet access for rural communities, connectivity for IoT deployments, and emergency network deployments. According to [23], several FSNs could use the same TVWS channel when networks are in non-overlapping areas, for example, FSN_4 and FSN_5 are non-overlapped so both networks use TVWS CH_3.



FSN or VN	TVWS channel
A-BS	CH_1
FSN_1	CH_2
FSN_2	CH_2
FSN_3	CH_2
FSN_4	CH_3
FSN_5	CH_3
VN_1	CH_3
VN_2	CH_3
VN_3	CH_3

Figure 3.6: Example of advanced fixed and vehicular secondary networks managed by a single A-BS. Source: Own elaboration.

Each FSN has one R-CPE as the central node and may have one or several A-CPEs connected. In this example, the A-BS and all the R-CPEs are connected through CH_1 to receive configuration parameters and send uplink traffic generated by A-CPEs. The R-CPE manages the A-CPEs' access to the allocated channel in each FSN, following a frame structure with upstream and downstream sub-frames. The frame structure of the 802.22 system is dynamically partitioned according to Time Division Duplex (TDD). The downstream medium access is time division multiplexed (TDM) for transmissions from the A-BS to A-CPEs/R-CPEs. The upstream medium access is managed using Demand Assigned Multiple Access (DAMA)/OFDMA at the A-CPEs/R-CPEs for coordinating the channel access. The downstream sub-frame includes the information for the upstream sub-frame assignment (i.e., burst start time, burst length, and sub-channel usage) to be processed by all the A-CPEs/R-CPEs within the A-BS coverage area.

In the example of Fig. 3.6, there are several vehicular networks (VN_1, VN_2, and VN_3) arriving to the coverage area of the A-BS. The standard defines the group resource allocation on PHY-OM2 to manage the spectrum sharing between fixed and mobile secondary groups within the A-BS coverage area. The A-BS creates a new group, identifies the devices that belong to the group, and allocates the resources on a group basis. The allocated TVWS channel (named backup channel in [23]) and candidate-for-use TVWS channels are selected according to the mobility and location of the R-CPEs.

The group resource allocation of the standard specifies that several fixed groups may use the same channel unless the R-CPEs' coverage ranges overlap (e.g., in Fig. 2.3, Group 1 and Group 2 are overlapped). For fixed groups overlapping, the A-BS allocates a different channel to each group to avoid interference among groups. The same applies for overlapping fixed and mobile groups, as well as for overlapping mobile groups, if there are remaining TVWS channels available. The case of a fixed and a vehicular (mobile) groups overlapping is illustrated in Fig. 3.7. If there are no TVWS channels available, or when groups share the TVWS channel for spectrum efficiency purposes, the standard states that "the A-BS may use a mechanism for proper resource sharing between the overlapping groups or the A-BS and some groups after channel switching. [23]". However, such a resource sharing mechanism is not defined in the standard.

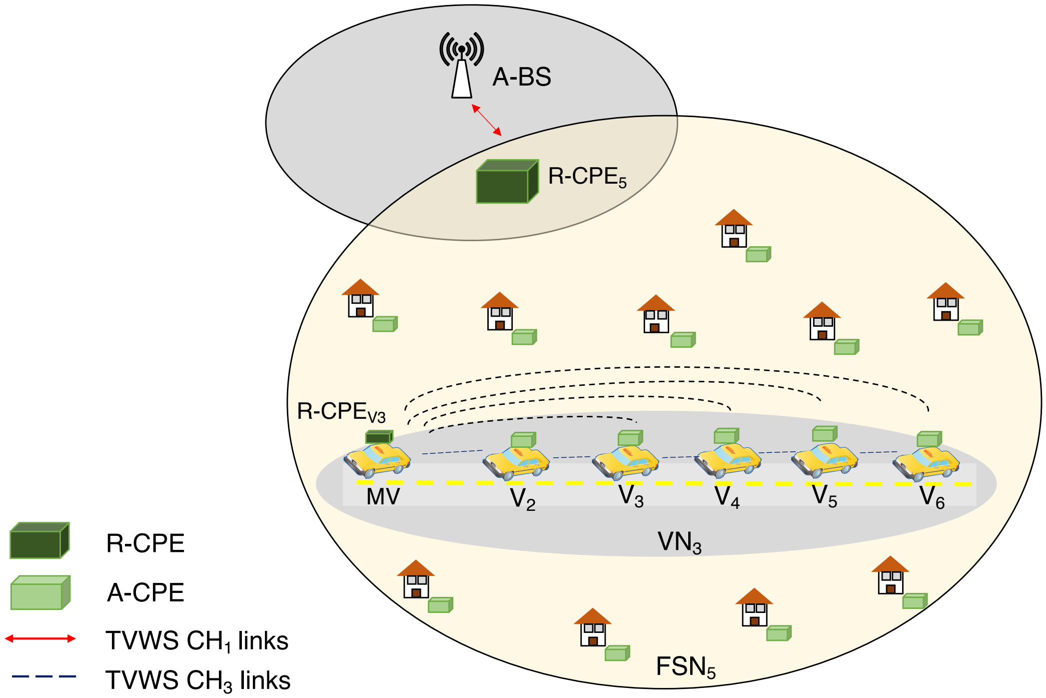


Figure 3.7: Scenario of study. Source: Own elaboration.

In the following section, the proposed WSRS mechanism is introduced, which allows the coexistence of fixed and vehicular secondary networks that share the TVWS channel when operating in overlapping areas. Our proposal is to use a resource-sharing approach based on joint power control and channel allocation to make it feasible for both networks to share the same TVWS channel. Below, the study scenario is described.

3.4 White Space Resource Sharing (WSRS) Mechanism

Each vehicle network (VN) acts as a cluster of N vehicles where one vehicle is an R-CPE, which will be known as the Manager Vehicle (MV) in charge of resource allocation (detailed later in Section 3.4.2). The remaining N-1 vehicles are A-CPE. The MV communicates to the vehicular network with the A-BS to send the uplink traffic of the vehicular network.

The White Space Resource Sharing (WSRS) mechanism for the coexistence between FSNs and VN involves scheduling vehicular transmissions depending on the FSN upstream scheduling information. Vehicles and fixed nodes may transmit at the same time using an adjusted transmission power, reducing mutual interference. The WSRS mechanism consists of three main functionalities shown in Fig. 3.8:

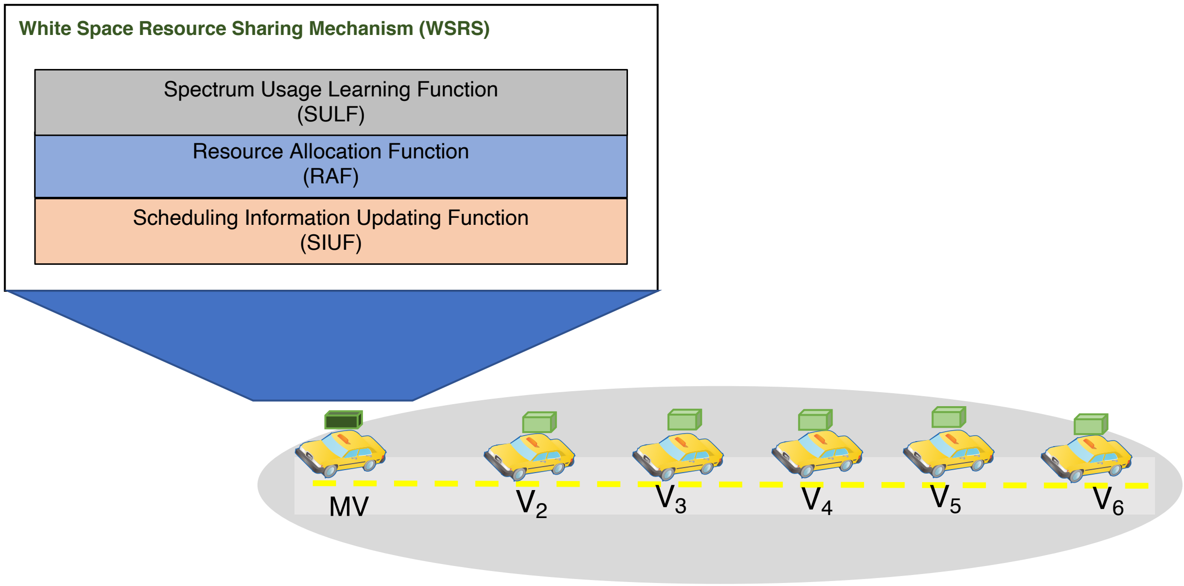


Figure 3.8: White Space Resource Sharing (WSRS) Mechanism. Source: Own elaboration.

- *Spectrum Usage Learning Function (SULF):* Learn the TVWS channel occupation due to the FSN traffic by listening to the FSN downstream.
- *Resource Allocation Function (RAF):* Execute the power control and channel access processes to generate the scheduling information for the vehicular network.
- *Scheduling Information Updating Function (SIUF):* Update the scheduling information (i.e., the transmit power and the slot-time) to the vehicles via broadcasting.

3.4.1 System's operation

The coexistence among FSNs and VSNs is based on the channel access shown in Fig. 3.9. A TVWS channel is divided in sub-channels, and each sub-channel is divided in upstream and downstream. Upstream and downstream access in 802.22 systems is TDM-based. The frame structure is partitioned into upstream and downstream sub-frames using TDD. Bursts conform the upstream sub-frame; each burst is a two-dimensional segment of OFDM sub-carriers (frequency-domain) and symbols (time-domain). Upstream bursts are allocated by contention or polling, depending on the network's configuration; then, the A-BS (or the R-CPE acting as the relay node between the A-CPEs and the A-BS in the network) includes the upstream scheduling information in the downstream sub-frame and broadcasts it.

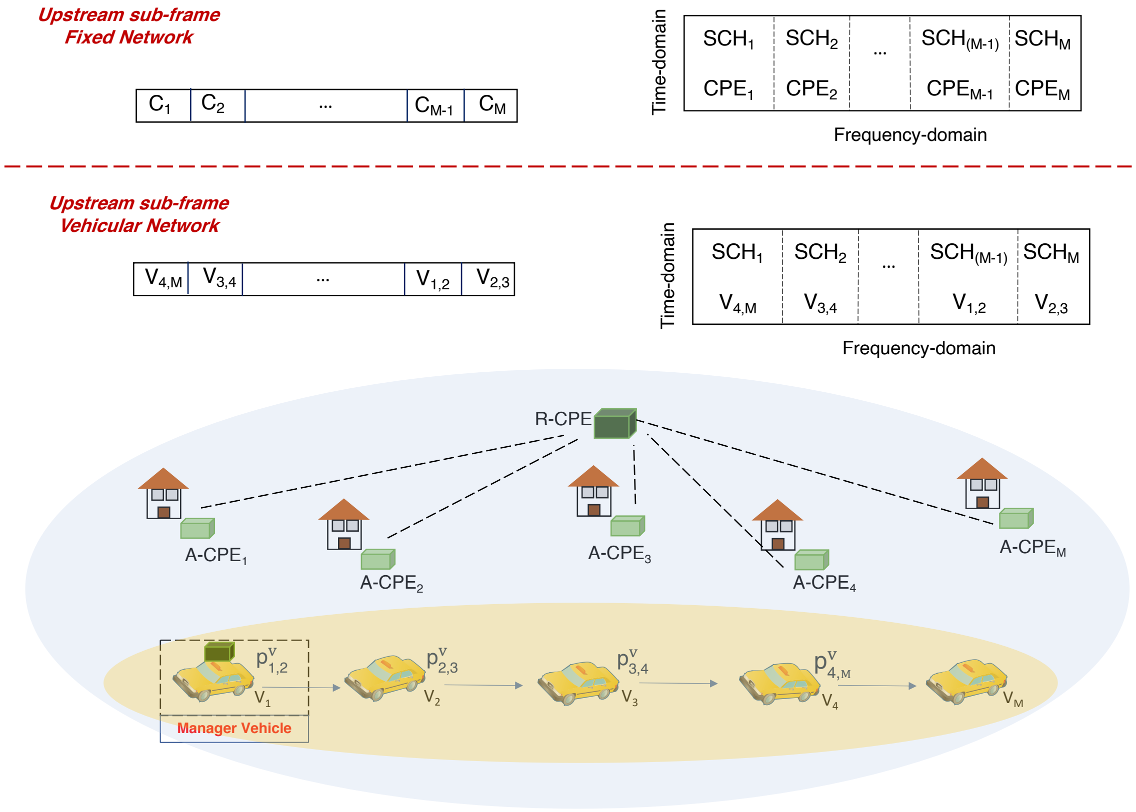


Figure 3.9: Upstream sub-frame scheduling for vehicular and fixed network. Source: Own elaboration.

It is assumed that the TVWS channel allocated to each FSN is divided into sub-channels equal to the number of fixed users. Each fixed A-CPE uses an exclusive frequency range within the TVWS channel. The number of sub-channels and the bandwidth may be adjusted up to 105 sub-channels according to the IEEE 802.22 standard. When the number of fixed A-CPEs increases, the channel access in the time domain may also be adjusted to extend the network capacity, making it possible for several fixed A-CPEs to share the same sub-channel at different times.

3.4.2 Resource allocation in WSRS

Using the example scenario depicted in Fig. 3.7 as a reference, in this case, the R-CPE$_5$ manages the channel access for the fixed network FSN$_5$. When the vehicular network VN$_3$ enters into the coverage area of R-CPE$_5$, the MV$_3$ receives the upstream scheduling information of R-CPE$_5$, from which it learns the TVWS channel utilization and the location of fixed A-CPEs. With this knowledge, the MV_3 executes the resource allocation based on power control and channel allocation to generate the vehicular transmission scheduling for each time frame (see Fig. 3.9). When the vehicles are informed of the WSRS scheduling, concurrent transmissions are placed from A-CPEs and VNs over the same TVWS channel.

Allocation based on the power control process and the channel control process is detailed below. Table 3.2 summarizes the most important symbols and variables.

Table 3.2: WSRS mechanism symbols and variables

Symbol	**Variable**
N	Number of vehicles
M	Number of fixed nodes
V_p	Vehicles' position
C_p	A-CPEs' location
P_{A-CPE}	A-CPEs' transmit power
f	Operational frequency (MHZ)
c_j	A-CPE ID j
v_i	Vehicle ID i
j	A-CPE transmitting during burst j
v_i^T	Transmitter vehicle in i-link
v_i^R	Receiver vehicle in i-link
d_v	Inter-vehicular distance (m)
p_i^j	Vehicle's i transmit power on burst j
p_c^j	A-CPE's transmit power on burst j
L_{v_i}	Pathloss in i-th vehicular link
L_j^i	Pathloss in link between c_j y v_i^T
W_j	Bandwidth of burst j
I_i^j	Interference over v_i^R caused by j-th S-CPE
I_j^i	Interference over j-th A-CPE caused by v_i^T
N_i	Noise over v_i^R
X_i	Channel capacity for vehicular link i (Mb/s)
$J(X)$	Jain's Index
S_R	Service Rate
E	Spectral Efficiency
$SINR_V$	Signal-to-interference plus noise ratio of vehicular network

Power Control Process (PCP)

The power control process (PCP) calculates the required transmission power for each link between two vehicles (e.g., vehicle v_i and $v_{\mathrm{i}+1}$), depending on the path loss of the vehicular link and the received interference caused by the fixed network. In the study scenario, the N vehicles are connected through *N-1* one-to-one links between the transmit vehicle v_i^T and the receiver vehicle v_i^R.

For path loss in the vehicular links $L_{v_{\mathrm{i}}}$, a path loss model suitable for vehicular networks operating at TV band frequencies [110] is used. This path loss model is based on several channel measurements for different environments (i.e., urban, suburban, rural, and highway), road traffic densities, line-of-sight (LOS) and non-line-of-sight (NLOS) paths, and vehicle speeds. The propagation model parameters are derived from the channel measurements and used in the classical log-distance power law to calculate the path loss. The required parameter for this path loss model is the vehicular positions V_p to obtain the inter-vehicular distance d_v.

Interference made by the fixed nodes is the other aspect that affects the required transmit power to maintain the vehicular links within the FSN coverage area. This interference I_{i}^{j} received by the vehicle v_{i}^{R} from the A-CPE j signal is calculated as

$$I_{\mathrm{i}}^{j} = p_c^j - L_j^{\mathrm{i}}, \tag{3.16}$$

where p_c^j is the transmit power of the A-CPE j and L_j^{i} is the path loss between the A-CPE j and the vehicle v_{i}^{R}, as shown in Fig. 3.10.

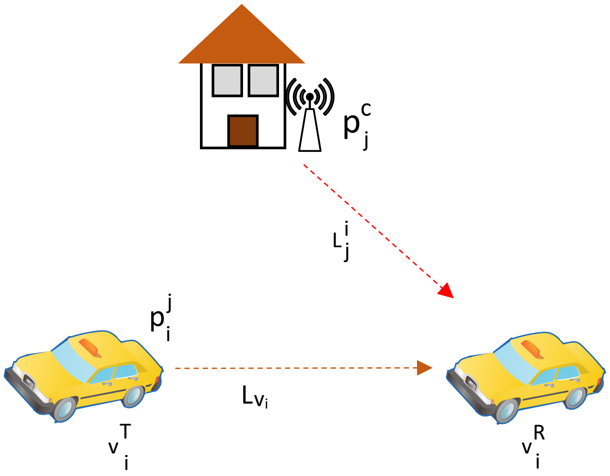


Figure 3.10: Power control function variables. Source: Own elaboration.

The PCP defines a signal-to-noise plus interference ratio to maintain the vehicular links ($SINR_V$) within the FSN coverage area, considering the path loss of the vehicular link and the interference caused by the fixed nodes. SINR in terms of transmit power and path loss is calculated as follows:

$$SINR_V = \frac{\frac{p_{\mathrm{i}}^j}{L_{v_{\mathrm{i}}}}}{\frac{p_c^j}{L_j^{\mathrm{i}}} + W_j N_0} \tag{3.17}$$

The required transmit power for each vehicular link i to transmit at the same time as the

A-CPE j is

$$p_{\mathrm{i}}^{j} = SINR_V + L_{v_{\mathrm{i}}} + p_c^j - L_j^{\mathrm{i}} + W_j N_0, \tag{3.18}$$

The output of PCP is an *N-1* x *M* matrix *P*, which contains the required transmit power for all combinations of vehicular link (v_{i}- $v_{\mathrm{i}+1}$) transmitting at the same time as each A-CPE. If p_{i}^{j} is more than the 20 dBm maximum transmit power allowed for secondary mobile users according to the IEEE Std. 802.22, the required power is not feasible. To simplify the notation in what follows, the vehicular link (v_{i}- $v_{\mathrm{i}+1}$) will be identified as i.

Channel Allocation Process (CAP)

The channel allocation process (CAP) generates a set of triads $K = < \mathrm{i}, c_j, p_{\mathrm{i}}^{j} >$ where the vehicular link i uses the transmit power p_{i}^{j} to transmit in the same burst to the A-CPE c_j. If there is no feasible power for the vehicular link i, its triad will be $< \mathrm{i}, 0, 0 >$. The inputs of CAP are the matrix P as well as the matrix D that contains the distance between all the A-CPEs and the vehicles. CAP seeks to match the vehicular link i with the farthest A-CPE j as a strategy to protect the A-CPEs' transmission from the vehicular link interference.

To maximize the distance between vehicular links and A-CPEs, CAP applies the Hungarian algorithm [111] to matrix D. The combinations i, c_j selected by the Hungarian algorithm correspond to the vehicular link i and A-CPE j pair that may transmit at the same time. The corresponding p_{i}^{j} value is chosen from matrix P using the i, j index to form the triad $< \mathrm{i}, c_j, p_{\mathrm{i}}^{j} >$.

Algorithm 1 White Space Resource Sharing (WSRS) Mechanism

```
Input: $N, M, SINR_V, V_p, C_p, P_{A-CPE}$ and $W_j, \forall j$
Output: $K = < \mathrm{i}, j, p_{\mathrm{i}}^{j} >$
for Time frame do
    Calculate $L_{v_{\mathrm{i}}}, \forall v_{\mathrm{i}}^T$
    Calculate $L_j^{\mathrm{i}}, \forall v_{\mathrm{i}}^T, c_j$
    Calculate $I_{\mathrm{i}}^{j}, \forall v_{\mathrm{i}}^R, c_j$ using Equation (3.16)
    Calculate matrix $P = \{p_{\mathrm{i}}^{j}, \forall \mathrm{i}, j\}$ using Equation (3.18)
    Calculate matrix $D =$distance$(v_{\mathrm{i}}^T, c_j)$, $\forall \mathrm{i}, j$
    Solve Hungarian Algorithm for matrix D
    return $< \mathrm{i}, c_j, p_{\mathrm{i}}^{j} > \forall v_{\mathrm{i}}^T, c_j$
end for
```

The proposed WSRS mechanism is an approach to improve network coexistence within the framework of the IEEE standard 802.22 by adjusting the operating parameters of the vehicular networks rather than those of the fixed networks. Section 4.3 presents the evaluation of the WSRS mechanism exploring the use case when vehicular networks (i.e., mobile secondary groups) move within an area where there are several fixed secondary networks (i.e., fixed groups), and there are not enough vacated TVWS channels to allocate, so overlapped fixed and vehicular networks must share the TVWS channel.

Chapter 4

Evaluation and Results

This chapter presents the evaluation of the scenarios to study the coexistence for vehicular communications in the TVWS spectrum:

- The feasibility study of TVWS spectrum sharing for vehicular communications in the general scenario considering primary TV band users and secondary networks. A new metric is introduced, the Channel Availability for Opportunistic Vehicular Access (CAFOVA), which relates the channel occupancy of the White-Fi network, the speed of the vehicle, and the channel verification distance. This study analyzes the impact of vehicle speed and channel verification distance on the perception of channel occupancy and the identification of transmission opportunities over the TV band.
- A comparative evaluation of two strategies for opportunistic vehicular access over the TVWS spectrum in the presence of other opportunistic networks is presented. One strategy is searching for a new TVWS channel for vehicular access when the current TVWS channel is occupied with other opportunistic secondary network. In the other strategy the vehicular networks share the TVWS channel with a fixed secondary. The comparative evaluation analyzes the channel access delay and the packet loss rate for both strategies.
- The performance evaluation of the White Space Resource Sharing mechanism for the coexistence among fixed secondary and vehicular networks according to the IEEE standard 802.22. This is an analysis of the impact of TVWS channel sharing between a vehicular network and secondary fixed networks in terms of the channel capacity offered to the vehicular network and attention to fairness and spectral efficiency of resource allocation.

4.1 Feasibility study of TVWS spectrum sharing for vehicular communications on TVWS spectrum

4.1.1 Evaluation scenario

The evaluation scenario for this study is presented in Figure 4.1, where there is a TV transmitter offering the TV service, a White-Fi network outside the TV transmitter coverage

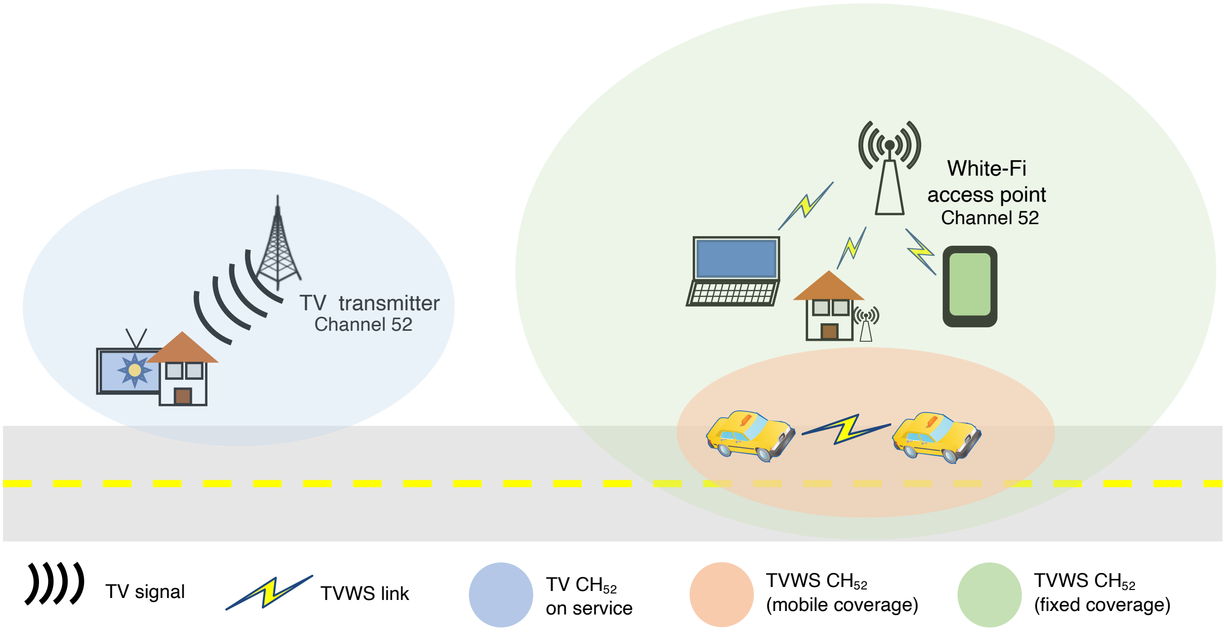


Figure 4.1: Evaluation scenario. Source: Own elaboration.

area, and a V2V link over the same TVWS coverage area as the White-Fi network. Table 4.1 presents the parameters employed in the scenario to model the primary TV service, the White-Fi network and traffic, and the vehicular network. The parameters follow the FCC requirements for TVWS [70], the IEEE 802.22 standard [100], and typical speed values employed in vehicular urban, suburban, and highway scenarios.

According to the White-Fi access point (AP) coverage range calculated in Section 3.2.2, the maximum White-Fi AP coverage is around twice the coverage radio (i.e., 4 km, 8 km, and 24 km, in urban, suburban, and rural areas, respectively). The channel occupation of the White-Fi network traffic is represented by a timeline where each millisecond is set to busy or idle according to the channel occupation policies described in Section 3.2.2. The vehicle moves along a straight route within the White-Fi coverage area. The evaluation considers several speed values to analyze the effect of the speed in the channel occupation perception. A vehicle senses the channel status every time it meets the channel verification distance; this is to ensure there is no TV primary user around, and also to determine if the TVWS is available or busy according to the channel occupation policy of the White-Fi network. The scenario is evaluated with several verification distances, including the 100 m specified by the FCC. The number of channel sensing verifications (C_{sv}) depends on the length of the route (R_l), and the channel verification distance (l), as follows:

$$C_{sv} = \frac{R_l}{l}. \tag{4.1}$$

To calculate the channel access opportunities, a new metric is introduced, known as *channel availability for opportunistic vehicular access (CAFOVA)* along the route, which represents the percentage derived from the number of times the TVWS is available (C_{sv}^{A}) with

Table 4.1: Evaluation Parameters.

Parameter	**Value**
Primary users	
TV transmission power	70 dBm [112]
TV transmitter antenna height	70 m
Receiver antenna height	3 m
Channel frequency	590 MHz
Route length	100 km
Detection threshold	-114 dBm [70]
White-Fi network	
AP power transmission	36 dBm [70]
Channel frequency	590 MHz
Height of the base station	30 m
Height of the receiver	1.5 m
Receiver sensitivity	-90 dBm [100]
Busy channel probability	10%, 30%, 50%, and 70%
Mean burst duration (Pareto distribution)	10 ms, 20 ms [109]
Mean burst inter-arrival time (Pareto distribution)	10 ms, 20 ms [109]
Pareto shape parameter	1.5 [109]
Vehicular network	
Vehicle speed	10 to 120 km/h
Height of the receiver	1.5 m
Receiver sensitivity	-90 dBm [100]
Channel frequency	590 MHz
Channel verification distance	25, 50, 100, and 200 m

respect to the number of channel sensing verifications ($C_{sv} = R_l/l$) as follows:

$$CAFOVA = \frac{C_{sv}^A}{C_{sv}} \times 100\%. \tag{4.2}$$

CAFOVA considers the channel occupation policy of the White-Fi network, the speed of the vehicle, and the channel verification distance.

The evaluation scenario was built in Matlab and ran simulations to estimate the opportunities for VDSA across a route on urban, suburban, and rural areas. A Monte Carlo simulation was used to simulate the scenario 100 times for each combination of parameters, for a total of 28,000 simulations.

4.1.2 Simulation Results

In the following, the discussion about the behavior of the CAFOVA metric under different channel occupation policies is presented. Also, the impact on the CAFOVA of the following variables is shown: the type of area of deployment, vehicle speed, and channel verification distances.

Impact of the type of deployment area

Results in Figure 4.2 show the CAFOVA metric within the White-Fi network coverage in *a)* urban small/large city, *b)* suburban area, and *c)* rural area. The channel occupation policy follows a uniform distribution whereas the verification distance l is set to 100 m, according to the FCC specifications. The CAFOVA obtained is around the complement of P_{bc} in all environments. Note also that the percentage of opportunities for vehicular access increases as the speed of the vehicle increases in the three areas under evaluation.

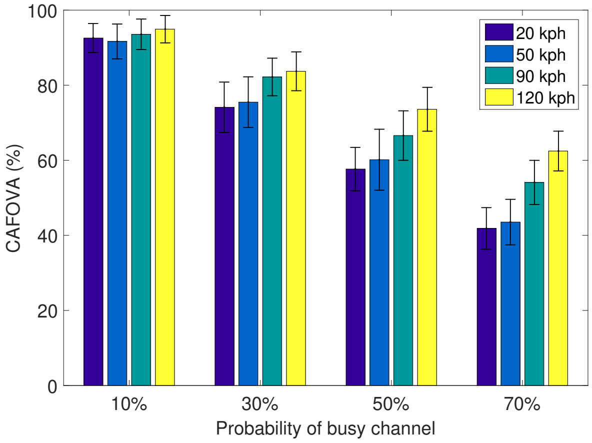
A statistical analysis was performed to understand the relationship between the CAFOVA, P_{bc} (10%, 30%, 50%, and 90%), the speed of the vehicle v (20, 50, 90, and 120 km/h), and the number of channel sensing verifications C_{sv} when $l = 100$ m (i.e., 41 verifications in urban scenarios, 84 verifications in suburban scenarios, and 241 verifications in rural scenarios). Table 4.2 shows the correlation analysis among the variables. The Pearson correlation value (P_c) indicates the extent to which two variables are linearly related. The p-value (P_v) determines if the correlation between the variables is statistically significant.

The analysis shows that the linear relationship between the CAFOVA and P_{bc} is -0.913, which means that the CAFOVA decreases when P_{bc} increases. Since the p-value is 0.00 and it is lower than the significant value 0.05, the correlation between these variables is statistically significant. Since the P_c between CAFOVA, v, and C_{sc} is 0.00, there is no linear relationship between these variables when they are analyzed together. The blank cells in Table 4.2 indicate the correlation and p-value are not calculated when it corresponds to the crossing of the same variable.

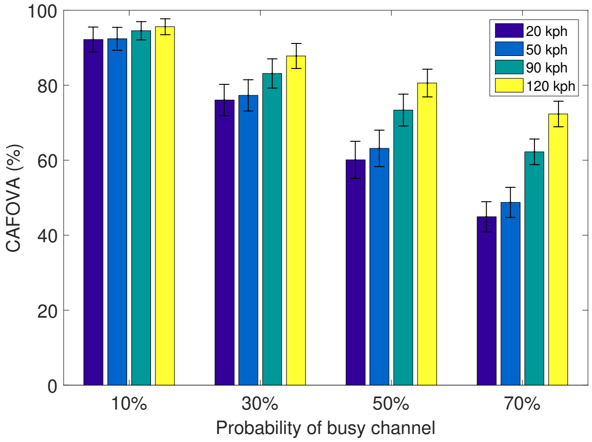
Table 4.2: Correlation between the CAFOVA, P_{bc}, v, and C_{sv}.

	CAFOVA		P_{bc}		v	
	P_c	P_v	P_c	P_v	P_c	P_v
P_{bc}	-0.91	0.00			0.00	1.00
v	0.19	0.00	0.00	1.00		
C_{sv}	-0.17	0.00	0.00	1.00	0.00	1.00

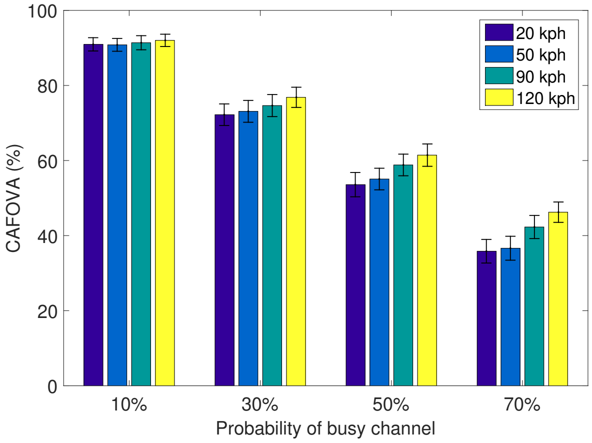
In the analysis for bursty traffic, there are three different occupation policies: A ($b_t = 20$ ms, $\mathrm{i}_t = 10$ ms), B ($b_t = 20$ ms, $\mathrm{i}_t = 20$ ms), and C ($b_t = 10$ ms, $\mathrm{i}_t = 20$ ms). A separate evaluation for urban, suburban, and rural areas is also provided. In this scenario, the vehicle is traveling at 50 km/h and the channel verification distance is 100 m. Results in Figure 4.3 show that the CAFOVA increases substantially when i_t is higher than b_t, regardless of the type of area. This is because the channel remains available more time between two data transmissions that are short. When b_t and i_t are the same, the CAVOFA is around 50% in all areas. The Pearson correlation and the p-value between CAFOVA, b_t, i_t, and v are shown in Table 4.3. The correlation shows the positive linear relationship between CAFOVA and the inter-arrival time, and the negative linear relationship between the CAFOVA and the burst time.



(a) Urban small/large city



(b) Suburban area



(c) Rural area

Figure 4.2: CAFOVA in uniformly distributed channel occupations P_{bc}, when v is set to 20 km/h, 50 km/h, 90 km/h, and 120 km/h. $l = 100$ m.

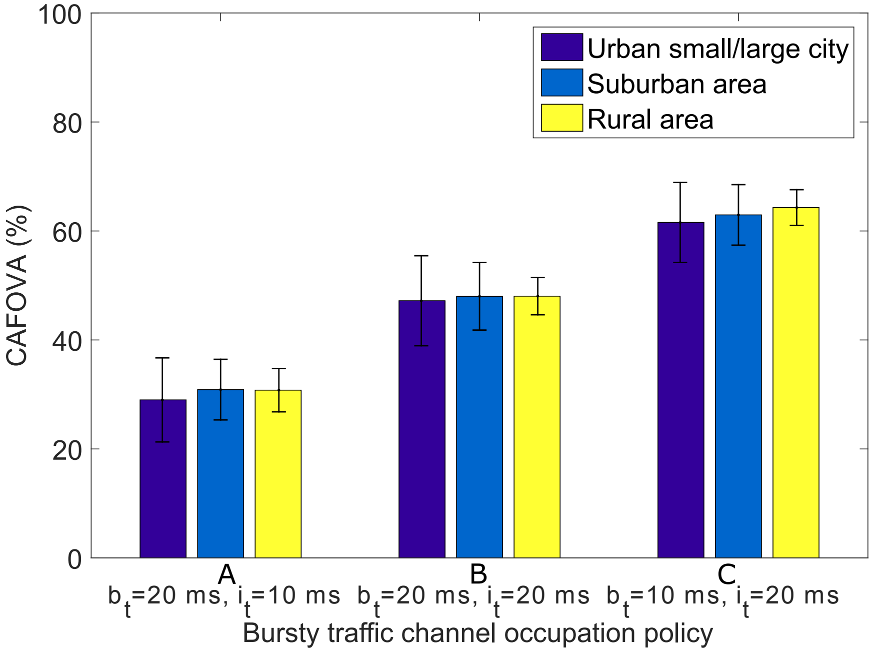


Figure 4.3: CAFOVA in Pareto distributed channel occupations A, B, and C, when the area type is urban, suburban, and rural. v= 50 km/h, l = 100 m.

Table 4.3: Correlation between the CAFOVA, b_t, i_t, and v.

	CAFOVA		b_t		i_t	
	P_c	P_v	P_c	P_v	P_c	P_v
b_t	-0.85	0.00			-0.50	0.00
i_t	0.88	0.00	-0.50	0.00		
v	0.00	0.98	0.00	1.00	0.00	1.00

Impact of the vehicles speed

Table 4.4 presents the statistical analysis based on Pearson correlation P_c and the p-value P_v when CAFOVA and v are analyzed for each P_{bc}, and for v between 10 to 120 km/h in the urban scenario. Since the correlation for both variables is 0.78 and the p-value is 0.00, there is a positive linear relationship between both variables. This means that the CAFOVA increases when the speed of the vehicle increases in scenarios where the White-Fi network traffic follows a uniformly distributed channel occupation P_{bc}.

Furthermore, Table 4.5 shows the Pearson correlation and the p-value between the CAFOVA and speeds ranging from 10 km/h to 120 km/h for the A, B, and C bursty traffic policies. Since the correlation is near to 0 and the p-value is higher than 0.05, there is no linear relationship between the CAFOVA and the speed of the vehicle when the White-Fi network traffic is bursty.

Table 4.4: Correlation between the CAFOVA and v for four different uniformly distributed traffic policies 10%, 30%, 50%, 70%. Urban scenario

	CAFOVA							
	P_{bc}=10%		P_{bc}=30%		P_{bc}=50%		P_{bc}=70%	
	P_c	P_v	P_c	P_v	P_c	P_v	P_c	P_v
v	0.78	0.00	0.78	0.00	0.78	0.00	0.78	0.00

Table 4.5: Correlation between the CAFOVA and v for three different bursty traffic policies A, B, and C.

	CAFOVA					
	A		B		C	
	P_c	P_v	P_c	P_v	P_c	P_v
v	-0.001	0.99	-0.002	0.99	-0.007	0.97

Impact of the channel verification distance

To understand the effects of the channel verification distance, the CAFOVA is evaluated when the channel verification distance, l, differs from the one recommended by the FCC. Additional values of 25 m, 50 m, and 200 m are included in the evaluation. The number of channel verifications obviously depends on l and the route length. In the urban area where the route length is 4 km, the number of channel verifications is 161, 81, 41, and 21 times when l is 25, 50, 100, and 200 m, respectively. The vehicle is moving at an average speed of 50 km/h.

On the one hand, if the traffic of the White-Fi network follows a uniformly distributed P_{bc}, the CAFOVA is calculated to be around the complement of P_{bc}, as mentioned previously. Also, when the spacing distance between the number of verifications is longer, the CAFOVA is higher. Such results are illustrated in Figure 4.4. On the other hand, if the traffic of the White-Fi network follows a Pareto distribution, the behavior of the CAFOVA seems not to be sensitive to the channel verification distance l. Nevertheless, the CAFOVA clearly varies depending on the values of b_t and i_t. Such results are illustrated in Figure 4.5.

4.1.3 Discussion

According to the results, it has been confirmed that, as expected, the nature of traffic in the White-Fi network impacts the channel availability for opportunistic vehicular access. This study analyzed seven channel occupation policies to model the traffic in the White-Fi network and considered several types of applications running on the network. On the one hand, given a channel occupied by bursty traffic, when the idle time is longer than the burst time, CAFOVA improves, i.e., there are more opportunities for the vehicular access because the channel remains idle more time. On the other hand, when the probability of busy channel follows a uniform distribution, the CAFOVA metric is around the complement of the probability of a busy channel.

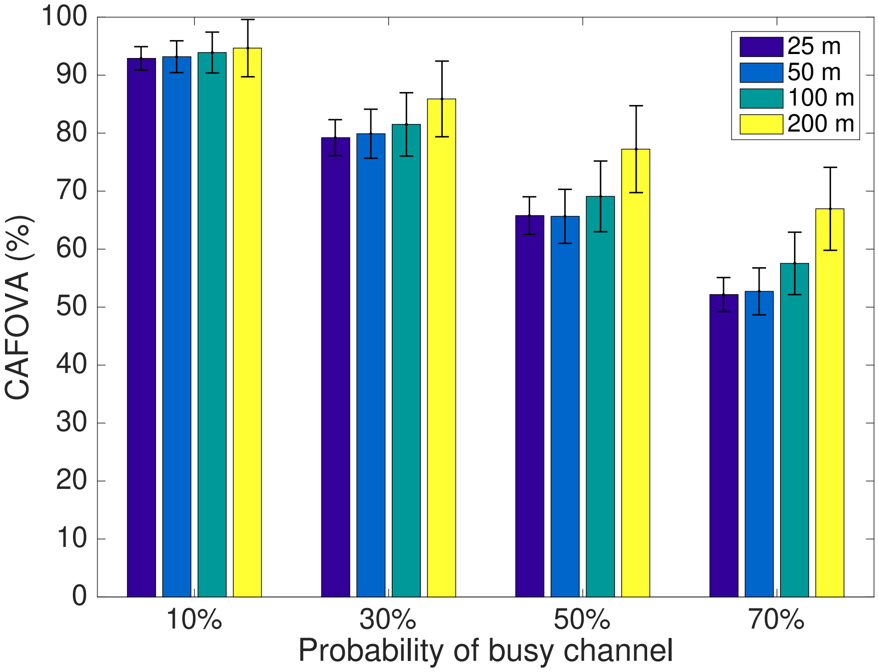


Figure 4.4: CAFOVA in uniformly distributed channel occupations P_{bc}, when l is set to 25 m, 50 m, 100m, and 200 m. $v = 50$ km/h.

Speed has an impact on the CAFOVA when the channel occupation policy follows a uniformly distributed probability of a busy channel: the CAFOVA increases when the speed of the vehicle increases and the probability of a busy channel decreases. The reason is that the speed determines how long the vehicle will remain inside the White-Fi's coverage area. For example, a vehicle moving at 90 km/h observes a shorter timeline compared to a vehicle moving at 120 km/h. Although the probability of a busy channel is uniformly distributed, the number of busy milliseconds in a shorter timeline is proportional to the probability in the entire timeline. As a result, the percentage of opportunities for vehicular access is approximately the complement of the occupied channel probability, and increases linearly as the speed of the vehicle increases.

For bursty traffic, vehicle speed has little effect on the CAFOVA. Although vehicle speed determines when the channel occupation is sensed along the timeline, when the vehicle moves from 10 km/h to 120 km/h, there are no changes in the CAFOVA due to vehicles moving faster or slower inside the White-Fi's coverage area.

The channel verification distance is also analyzed, considering distances different from the 100 m recommended by the FCC. For the same trip, changing the verification distance affects the number and frequency of channel verifications. On the one hand, the results have confirmed that the CAFOVA increases when the channel verification distance increases, when the channel occupation policy follows a uniformly distributed probability of a busy channel. On the other hand, the CAFOVA is insensitive to changes in the number of verifications when the traffic follows a Pareto distribution.

According to the results, it is possible to enable opportunistic vehicular communications

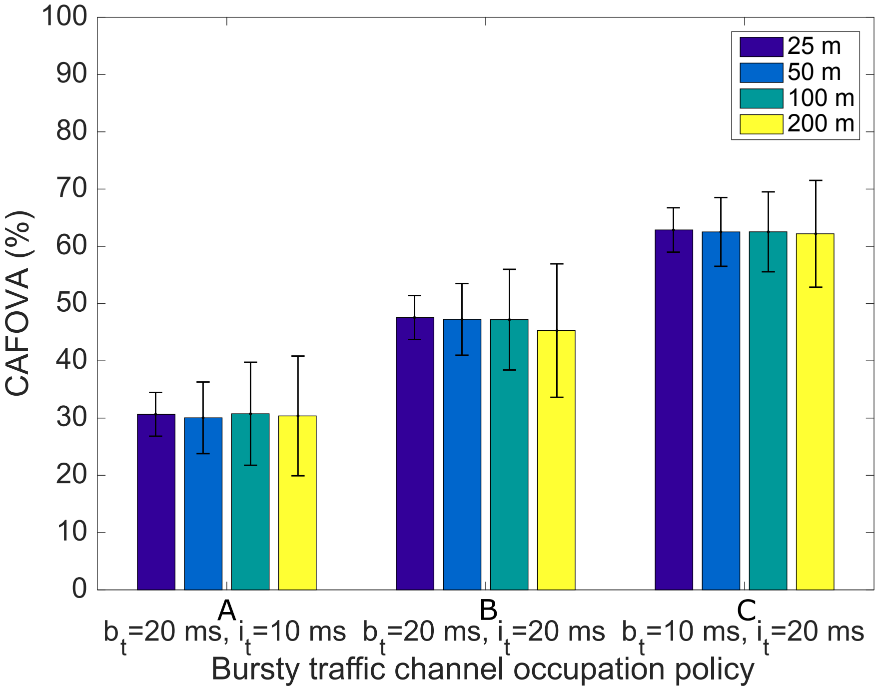


Figure 4.5: CAFOVA in Pareto distributed channel occupations A, B, and C, when l is set to 25 m, 50 m, 100m, and 200 m. $v = 50$ km/h.

in the presence of White-Fi networks sharing the same TVWS. Although this study is not focused on determining how long the channel is available along the route, one feasible type of use, considering the channel opportunities observed, would be to use the TVWS as a backup technology for sending duplicate messages when the primary technology (e.g., DSRC channels) is highly congested. Sharing the same TVWS with a White-Fi network is feasible when the vehicles spend short times within the White-Fi coverage area, to avoid delays in searching for a new TVWS and to ensure vehicles tune to the same TVWS to maintain communications.

4.2 Evaluation of Opportunistic Access Strategies for Vehicular Networking Over TVWS spectrum

The feasibility study showed that both networks could coexist in the same TVWS channel, based on the CAFOVA metric that relates the channel occupation policy over the fixed cognitive network, the vehicle's speed, and the channel verification distance [14]. However, the coexistence between these networks would require a mechanism for channel access control to coordinate the TVWS channel usage. The other alternative is for the vehicular network to avoid using the occupied TVWS channel and starting the search for an available TVWS channel. However, the time spent looking for a new TVWS channel may degrade the application's performance if the vehicles need to verify a considerable number of TVWS channels before finding an available one. The following evaluation compares both alternatives to establish the channel access delay and the packet loss rate.

4.2.1 Scenario of Study

Fig. 4.6 illustrates an example of the scenario of study, where there is an opportunistic vehicular network running an application based on clustering such as a routing protocol [113] over the TV channel 34, and there are several fixed secondary networks farther along on the route. The fixed secondary networks are operating on available TVWS channels via secondary base stations (BS); one or more of the secondary BS may use the TV channel 34 as long as their coverage areas do not overlap. Since the opportunistic access over TVWS spectrum provides the same right to access the spectrum for secondary users, both the vehicular network and the fixed secondary network have the same right to use the TVWS channel 34. This study assumes no coordination mechanism is employed between the opportunistic networks. When the vehicular cluster meets the fixed secondary network in channel 34, it should apply one of the strategies for opportunistic spectrum access. The opportunistic vehicular network crosses the coverage area of several secondary BS along the route. The details of such strategies are described as follows.

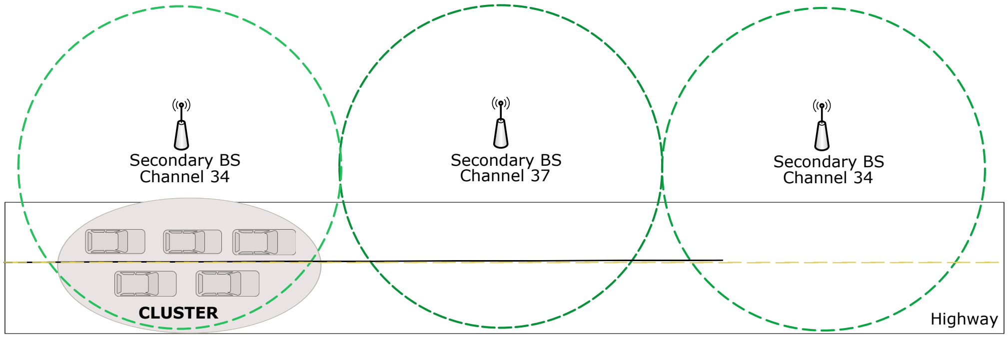


Figure 4.6: Scenario of study. Source: Own elaboration.

Searching for a new TVWS channel for exclusive opportunistic vehicular access (strategy A)

This strategy requires the following steps before completion: first, the vehicles use a cooperative spectrum detection technique to decide if the current TVWS channel is available or busy [114]. If the TVWS channel is busy, the second step is the search for an available TVWS channel where the vehicles change the frequency to the next consecutive TVWS channel and execute the spectrum detection and decision step again. When the vehicles find an available TVWS channel, the third step is that vehicles move their data transmissions to the new TVWS channel. In case the selected TVWS channel becomes busy by a secondary network farther along the route, the vehicles shall rerun the process to find a new TVWS channel.

The channel access delay for this strategy is measured from the moment when the spectrum detection and decision process starts to the moment when the process finds an available TVWS channel. The channel access delay for strategy A (D_A) is calculated as follows:

$$D_A = N \times T_{SD}, \tag{4.3}$$

where N is the number of TVWS channels that the vehicles have to change before they find an available TVWS channel, and T_{SD} is the time taken by the CR modules to perform the spectrum detection and decision process. Since there are several vehicles participating in the cluster-based application, there could be a basic mechanism for coordinating the search, which may consist of all the vehicles performing the cooperative sensing technique for searching the channel in order, i.e., jumping to the next consecutive TVWS channel and sensing if the channel is available or occupied. Other mechanisms are based on rendezvous protocols that help the vehicles find a common channel to establish communications [115]. In this work, the use of the basic mechanism is assumed.

Sharing the same TVWS channel with a fixed secondary network (strategy B)

In this strategy, when the opportunistic vehicular network meets a fixed secondary network in the same TVWS channel, the vehicles decide to stay and find an opportunity of transmission when the TVWS channel remains idle, similar to the carrier sense multiple access with collision avoidance (CSMA/CA) process. When the vehicles detect the channel is idle, they start a timer which is a delay time that vehicles must wait to ensure the channel is still idle; when the timer ends, the vehicles can use the TVWS channel to transmit the data. If the TVWS channel becomes busy before the timer ends, the vehicles must start to listen to the channel until it becomes idle again. The channel access delay for strategy B (D_B) is calculated as follows:

$$D_B = T_L + T_D \tag{4.4}$$

where T_L is the time spent by the vehicles listening to the channel for the first time until it is detected that the TVWS channel is idle, and T_D is the timer that the vehicles must remain listening to ensure the channel is still idle.

The comparative evaluation is carried out using the NS-3 simulator, including the CR modules for spectrum detection and decision process. Both processes work jointly based on the Singular Value Decomposition (SVD) detection method, which is a cooperative energy detection process [116]. The vehicles execute the spectrum detection technique and report a detection bit to decide if the channel is busy or available. To obtain the results, the delay and packet loss rate is measured using the simulator developed by Palacios [117].

The evaluation scenario consists of a cluster of vehicles traveling across an area similar to the one depicted in Fig. 3.1, where there are 10 TVWS channels, and each TVWS channel has a fixed secondary network. Two probabilities of busy channel (P_B) for the fixed secondary networks (i.e., 50% and 70%) as defined to study the average case and a near-to-worst case of channel occupancy. P_B means that the traffic in the TVWS channel follows a uniformly distributed probability of busy channel, then the TVWS channel will be occupied by the fixed secondary network, for example, 50% of the time during the spectrum detection and decision process. In strategy A, the cooperative spectrum detection and decision process takes $T_{SD} = 0.5$ ms [100].

In strategy B, i.e., sharing the same TVWS channel with a fixed secondary network, the vehicles continuously listen to the channel, executing the spectrum detection and decision process as a background process. When vehicles detect a fixed secondary network, they stay in the same TVWS channel and start listening until the TVWS channel becomes idle. Then the decision process starts the T_D timer (i.e., $T_D = 2\times$Slot Time in 802.11a [118]) to ensure the channel remains idle during that period, as a way to avoid a collision with the users of the fixed secondary network. When the T_D stops the vehicles can use the TVWS channel.

The packet loss rate P_{LR} is measured between two consecutive executions of the strategy using the received packet P_R, the lost packets P_L as follows:

$$P_{LR} = \frac{P_L}{P_L + P_R} \tag{4.5}$$

Using a Monte Carlo simulation, each strategy is simulated 10 times for each probability of busy channel for a total of 80 simulations. Table 4.6 shows the simulation parameters used in NS-3 simulator to set up the scenario. The propagation models provided by NS-3 to implement the vehicular communications, the TV transmitter and the secondary BS consider the effects of path loss, multipath, and shadowing [116]; the vehicular network moves with a constant velocity model.

Table 4.6: Simulation Parameters

Parameter	**Value**
Number of TVWS channels	10
Secondary BS for each TVWS channel	1
Secondary BS coverage area	3.2 km in urban areas[14]
Secondary BS Tx Power	10 kW [112]
TV Channel frequency	470 - 806 MHz [112]
TV Channel bandwidth	6 MHz [112]
Number of vehicles in cluster	5
Vehicle Tx Power	0.037 W [119]
Vehicle Rx Power	0.06 mW [119]
Speed of the vehicles	60 km/h
Mobility model	Constant Velocity Model
Probability of busy channel (P_B)	50% and 70%
Sensing and detection time (T_{SD})	0.5 ms [100]
Timer for strategy B (T_D)	32 us [118]

4.2.2 Simulation results

Results in Fig. 4.7 show the channel access delay for the strategies depending on the probability of busy channel. When P_B=50%, the 75% of the attempts to use the TVWS channel when the vehicular network shares the TVWS channel with the fixed secondary network (i.e., strategy B) were reached in maximum 100 ms; in strategy A, when the vehicles search for a new TVWS channel, the 75% of the attempts took up to 120 ms. Hence, strategy B reduces the average channel access delay by 15% when P_B = 50% and a 16% when P_B=70%, regarding strategy A.

The minimum channel access delay is near to 20 ms for both strategies regardless P_B, and it is achieved when the current TVWS channel remains available, and the vehicles can continue to use it. The maximum channel access delay is different for each strategy and each P_B. In strategy A, the maximum delay should be expected when the vehicles have to sense all the TVWS channels before finding one available. In strategy B, the maximum delay is expected when the vehicles must remain listening to the channel while the fixed secondary network uses the TVWS channel in a sustained transmission equals to P_B. Reducing the access channel delay is a critical condition to meet the requirements of safety applications, and a desirable condition for more flexible applications.

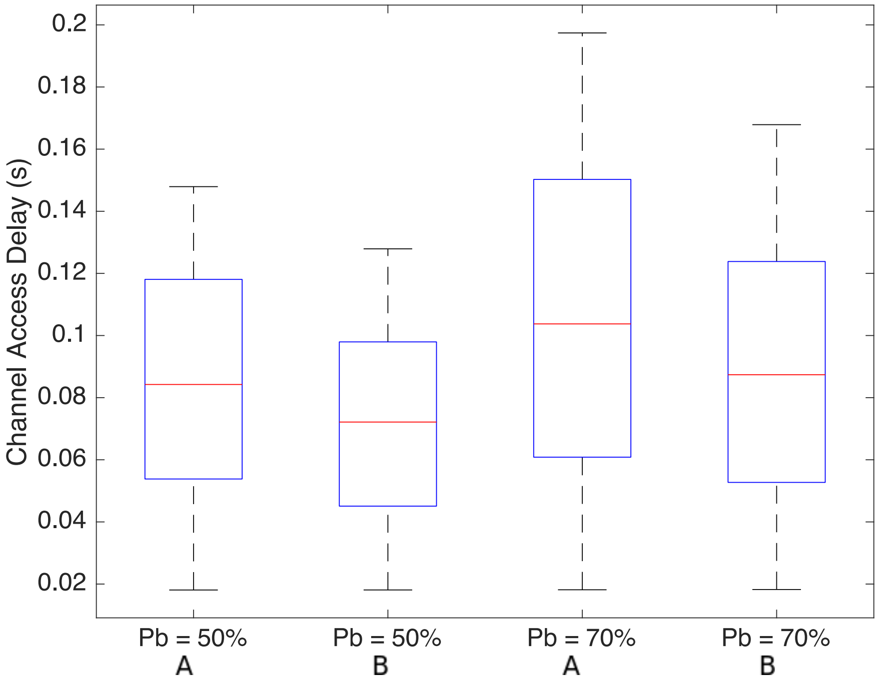


Figure 4.7: Channel access delay for strategy A and strategy B depending on the probability of busy channel (P_B)

The number of attempts before successful access to the TVWS channel using the two strategies affects the channel access delay. In strategy A, the number of attempts increases when P_B is higher because the vehicles have to move to another TVWS channel every time the vehicular network detects the fixed secondary network; in each attempt the vehicles must run the sensing mechanism which increase the channel access delay. In strategy B, an attempt is every time the vehicles remain listening to the TVWS channel until it becomes idle. Since strategy B does not execute a cooperative spectrum detection technique, there is no delay time caused by the spectrum detection and decision process.

Results in Fig. 4.8 show the packet loss rate. When $P_B = 50\%$, the maximum packet loss rate is 6% in strategy A and 5% in strategy B. When $P_B = 70\%$, the maximum packet loss rate is 9% in strategy A and 8% in strategy B. Hence, strategy B reduces the maximum packet loss rate by 17% in P_B=50% and an 11% in $P_B = 70\%$, with respect to strategy A.

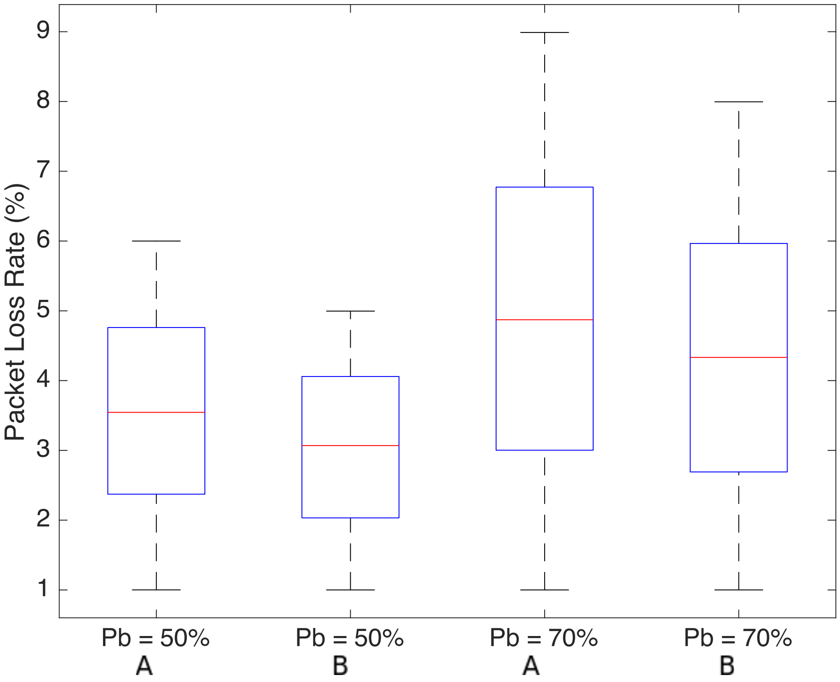


Figure 4.8: Packet loss rate for strategy A and strategy B depending on the probability of busy channel (P_b)

4.2.3 Discussion

According to the results, the vehicular network may share the TVWS channel with the fixed secondary network instead of searching for a new TVWS channel, as a strategy to reduce the channel access delay in opportunistic spectrum access. The reduction in the channel access delay impacts in the packet loss rate. For the average case of study, when the probability of busy channel is 50%, the strategy B reduces the maximum channel access delay by 15% and the maximum packet loss rate by 17%, regarding strategy A. For the near-to-worst case scenario, when the probability of busy channel is 70%, the strategy B reduces the maximum channel access delay by 25% and the maximum packet loss rate by 11%, regarding strategy A. Reducing the channel access delay and the packet loss rate are critical requirements for many applications such as safety applications that tolerate a maximum delay (usually 100 ms), and beaconing application for which the perceived location precision is affected by the packet loss.

4.3 Performance Evaluation of the White Space Resource Sharing mechanism

4.3.1 Evaluation scenario

The scenario employed to evaluate the proposed resource allocation mechanism's performance is shown in Fig. 4.9. A vehicular network travels across a route of 9 km where there are four non-overlapping FSNs deployed. The presence of FSNs (R) is defined as the percentage of active FSNs on the route using the same TVWS channel (e.g., $R = 50\%$ means that two FSNs are active on the route). The vehicular network has the same TVWS channel assigned as the FSNs to analyze the mechanism's performance depending on the active FSNs. In a situation in which vehicles travel across an area without an active FSN, the vehicular network uses the maximum transmit power, but in this scenario as vehicles enter the coverage area of an active FSN, the vehicular network applies the WSRS mechanism to share the TVWS channel.

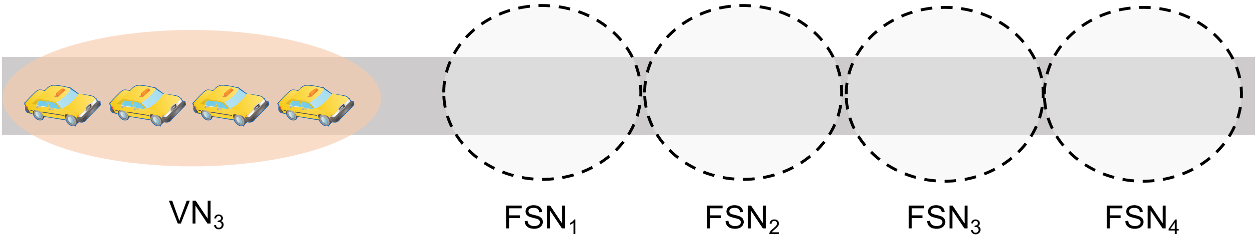
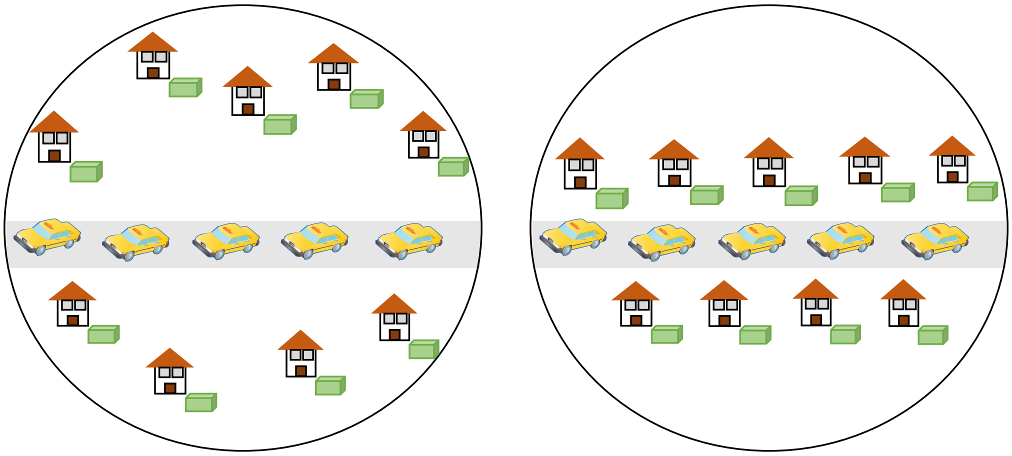


Figure 4.9: Simulated scenario. Source: Own elaboration.

The evaluation considered two cases, shown in Fig. 4.10, for the distribution of the fixed nodes within the network coverage area: Case A is when the fixed nodes are far from the road uniformly distributed throughout the coverage area, whereas Case B is when the fixed nodes are near the road. Using the Montecarlo method, the effect of the fixed nodes' transmit power in the power control function and the feasibility of allowing fixed and mobile nodes to share the TVWS channel due to mutual interference is also analyzed. For this analysis, 21 simulations were done in Matlab per each fixed node distribution and fixed node transmit power. The simulation parameters are detailed in Table 4.7.

Table 4.7: Parameters for simulated scenario

Parameter	**Value**
N	10
M	10
f	710 MHz
p_c^j	20 dBm - 36 dBm
$SINR_V$	5 dB
d	25 m
PL_0	29.83 [110]
γ	2.04 [110]
σ_S	2.48 [110]
W_j	600 kHz
t_r	5 beacons per seconds
P_{max}	20 dBm



Case A
A-CPEs are far from the road

Case B
A-CPEs are near the road

Figure 4.10: Fixed node distribution within the network coverage area. Source: Own elaboration.

The proposed WSRS mechanism is compared with the scenario in which the vehicular network stops transmitting when the vehicles travel across an active FNS that uses the same TVWS channel as the vehicular network. Both scenarios are evaluated using the following metrics:

Cumulative Channel Capacity

This metric is the channel capacity achieved by the set of vehicles for each time frame, which is calculated as

$$X = \sum_{\mathrm{i}=1}^{N-1} W log_2 \left(1 + \frac{P}{I+N} \right), \tag{4.6}$$

where the variables depend on whether the WSRS mechanism is used or not. Using the WSRS mechanism, a vehicle i requests the allocation of a time slot and the allowed transmit power for a time frame. Assuming that the allocated time slot is the same as the A-CPE j, the bandwidth W of the slot is W_j, the allowed transmit power P is p_{i}^{j} according to the power control function detailed in Section 3.4.2, the interference I caused by A-CPE j over the vehicle i is I_j^{i}, and the channel noise is N_{i}. In the scenario in which the WSRS mechanism is not used, vehicles only transmit in areas where there are no FSNs; then, the transmit power is the maximum (20 dBm), and there is no interference caused by an FSN.

Service Rate

A vehicle requests resource allocation in each time frame. The service rate is the ratio between the number of successful resource allocation requests (S_Q) and the total number of requests (T_Q). It is calculated as

$$S_R = \frac{S_Q}{T_Q} \tag{4.7}$$

When the WSRS mechanism is not used and the vehicle travels within an active FSN coverage area, the service rate is zero; otherwise, the service rate is 1.

Jain's Index

Jain's Index is a fairness measure based on the offered channel capacity to the vehicles according to the allocated transmit power and channel access.

$$J(X) = \frac{\left(\sum_{\mathrm{i}=1}^{N-1} X_{\mathrm{i}}\right)^2}{(N-1)\sum_{\mathrm{i}=1}^{N-1} X_{\mathrm{i}}^2}, \tag{4.8}$$

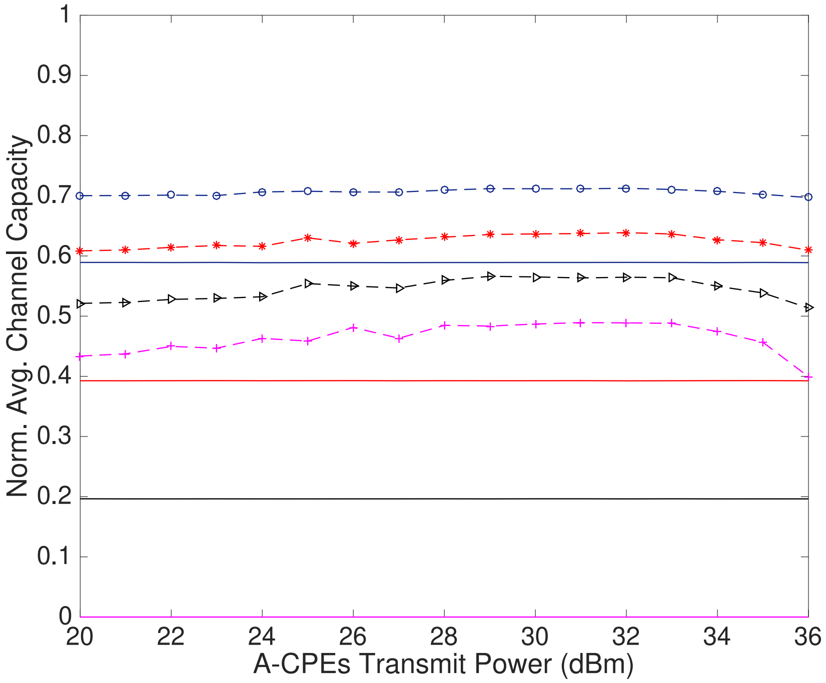
Spectral Efficiency

The spectral efficiency determines the spectrum utilization made by the entire system, which includes the vehicular network and the fixed secondary network. Spectral efficiency is the number of bits per second per hertz sent by all the channel users. For the vehicular network's TVWS channel utilization (X_V), the channel capacity achieved due to the vehicular transmit power and the interference caused by the active FNSs when the WSRS mechanism is used; if the WSRS is not used, the vehicles use the maximum transmit power without additional interference. For the FNS's TVWS channel utilization (X_F), the channel capacity depends on the A-CPEs transmit power and the interference caused by the vehicular network on the A-CPEs. The TVWS channel's bandwidth (W_{TVWS}) is 6 MHz. Spectral efficiency is calculated as

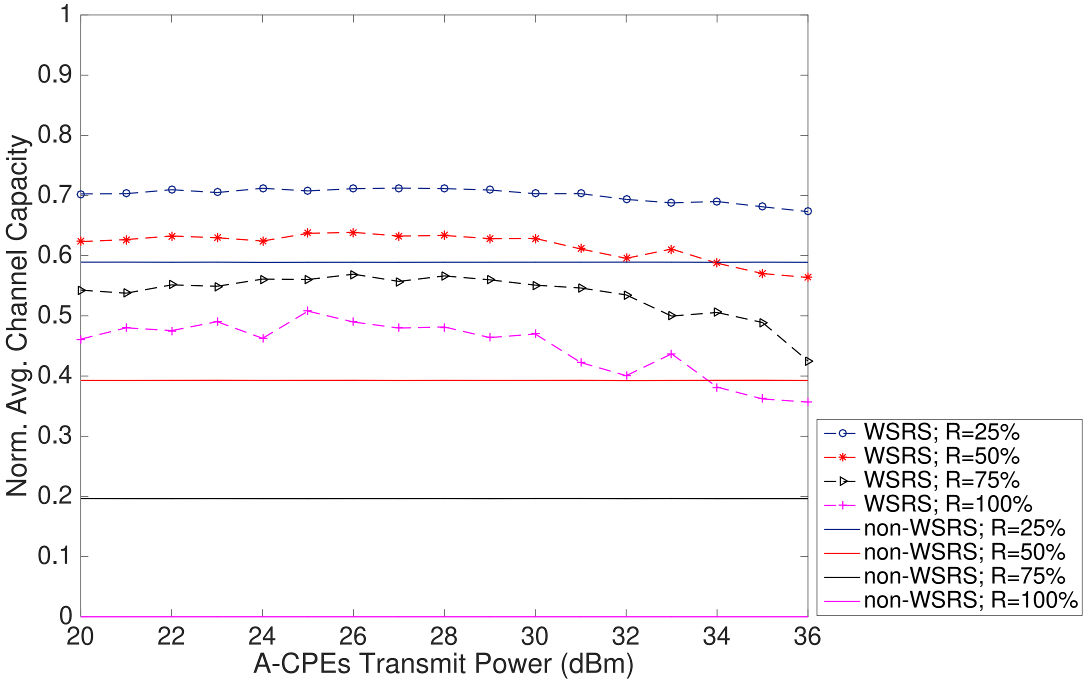
$$E = \frac{X_V + X_F}{W_{TVWS}} \tag{4.9}$$

4.3.2 Simulation Results

This section presents the evaluation performance of the White Space Resource Sharing (WSRS) mechanism in the simulated scenario (see Fig. 4.9) in Matlab, comparing the system using the WSRS mechanism and without the WSRS mechanism (non-WSRS). The non-WSRS scenario corresponds to the vehicular network conditions when the coexistence mechanism between the secondary fixed network and the vehicular network on the same TVWS channel is not enabled.



(a) Case A



(b) Case B

Figure 4.11: Normalized Average Channel Capacity per time frame for the set of vehicles

Normalized Cumulative Channel Capacity

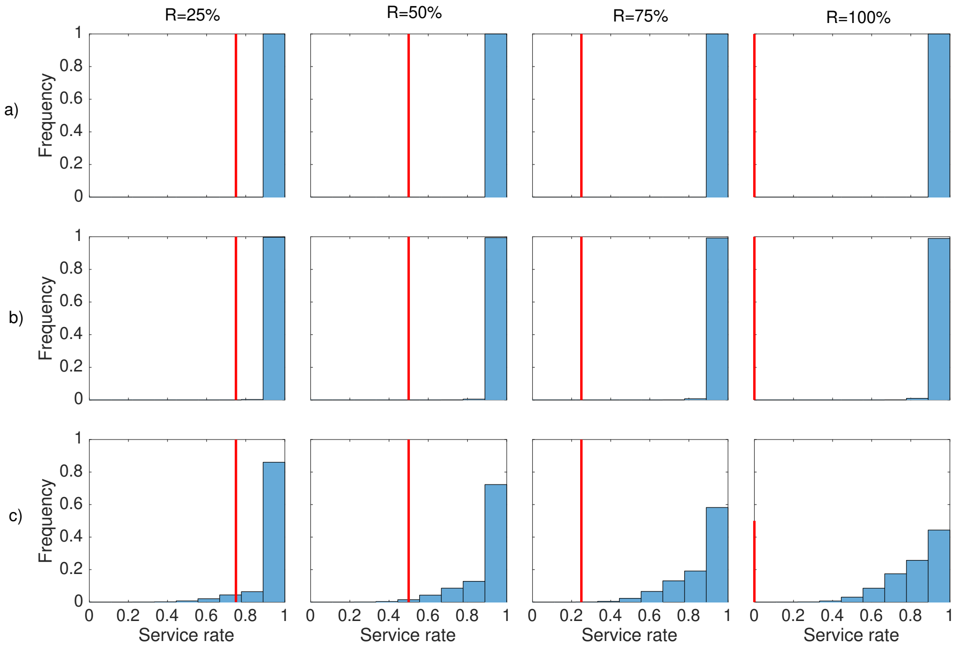
The normalized cumulative instantaneous channel capacity for the set of 10 vehicles is shown in Fig 4.11a (Case A) and Fig 4.11b (Case B). The normalized cumulative instantaneous channel capacity is higher as the presence of secondary fixed networks (R) in the path decreases, regardless of the use of the WSRS mechanism or non-WSRS and the A-CPES distribution with respect to the road. When the WSRS mechanism is used, the vehicles transmit with maximum power (20 dBm) in areas with no fixed networks, then the cumulative channel capacity increases. In areas with fixed networks, the vehicles adjust their transmit power to reduce the interference caused to the fixed network. The cumulative channel capacity decreases due to the reduction in the vehicular transmit power and the interference received from the fixed secondary network.

The cumulative channel capacity decreases when the A-CPE transmit power is around 33 dBm for Case A (see Fig. 4.11a) and around 29 dBm for Case B (see Fig. 4.11b). In Case B, the A-CPEs are closer to the road, then the interference caused by the fixed network also increases, and more vehicular transmit power is required. If the vehicular transmit power is greater than the maximum power (20 dBm), the vehicle does not receive resource allocation, which affects the cumulated capacity for the set of vehicles. In the non-WSRS scenarios, the normalized average channel capacity is the same depending on the presence of the fixed secondary network. The A-CPE transmit power does not affect the channel capacity because the vehicles do not transmit in the areas where there is a fixed secondary network.

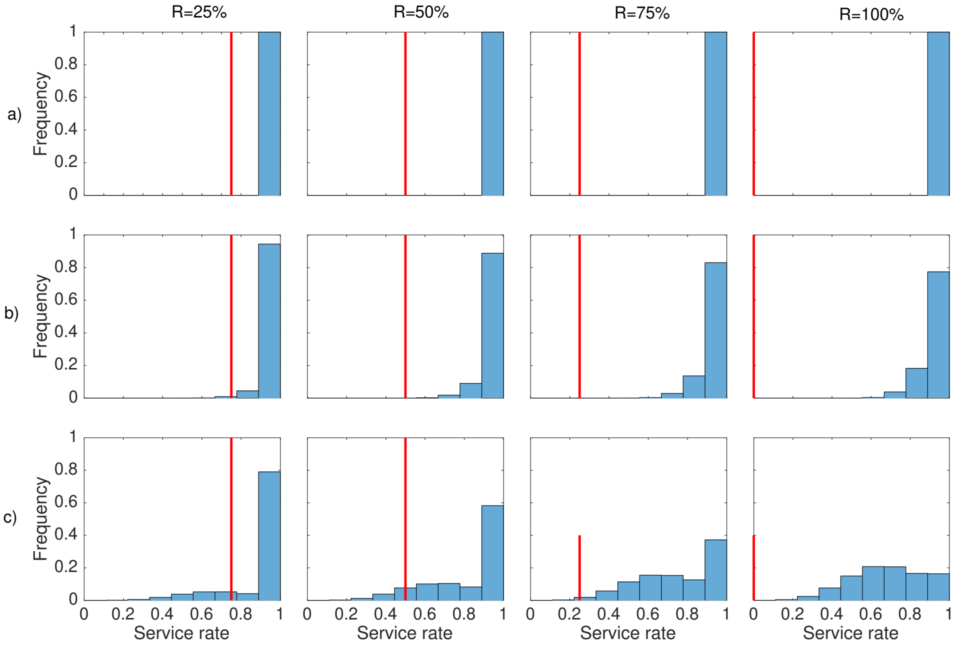
Service Rate

The service rate measures whether resources were allocated to a target vehicle or not during the time frame evaluated (see Fig. 4.12). The red line represents the service rate of the non-WSRS scenario depending on the presence of fixed secondary networks. As the presence of fixed secondary networks increases, the non-WSRS scenario's service rate decreases because the vehicles do not transmit in areas where there are fixed secondary networks. When the A-CPE transmit power increases, the distribution of the service rate varies. When the presence of the secondary fixed networks is 100% (R = 100%) and the A-CPE transmit power is 20 dBm, the service rate for the set of vehicles is 1.0, which means that all requests for resources from vehicles are serviced in both Case A (Fig. 4.12a) and Case B (Fig. 4.12b).

For Case A, when the A-CPE transmit power increases to 36 dBm (Fig. 4.12a-c), the service rate varies between 0.4 and 1.0, which indicates that not all requests for resource allocation from the vehicular network are met. For Case B, the service rate varies between 0.3 and 1.0 when the A-CPE transmit power is 36 dBm (Fig. 4.12b-c). Increasing the A-CPE transmit power also increases the interference caused by the fixed secondary network on the vehicular network. If the required vehicular transmit power is greater than the maximum power to face the interference of the fixed secondary network, the resource allocation for the vehicle cannot be met; therefore, the service rate decreases. Results show that the service rate is higher with the use of the WSRS mechanism, offering better conditions for the operation of the vehicular network, even in situations of coexistence and interference of the fixed secondary network compared to the scenario without shared use.



(a) Case A



(b) Case B

Figure 4.12: Service rate for the set of vehicles

Jain's Index

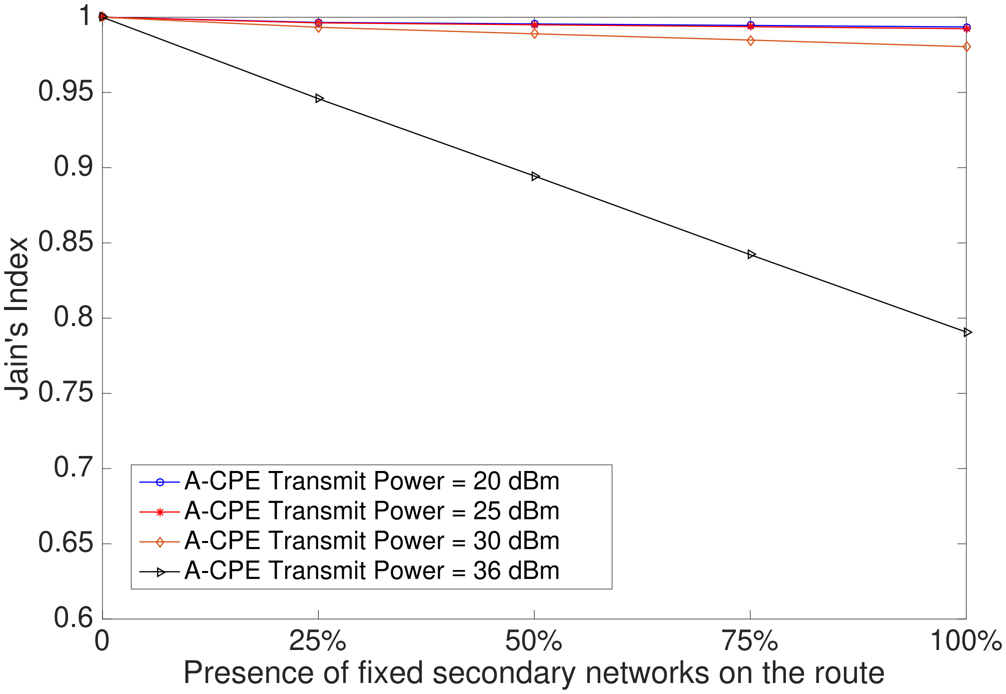
The A-CPE transmit power affects the Jain's Index of the system in both Case A and Case B, as shown in Fig. 4.13a and Fig. 4.13a respectively. As the transmit power increases, the interference caused by the fixed secondary network also increases, causing the vehicles to require a higher transmit power. If the required vehicular transmit power is higher than the maximum power, the vehicle will not receive the resource allocation. Therefore, the channel capacity offered to the vehicle is zero affecting the Jain's Index of the set of vehicles. For Case A, the A-CPEs are far from the road and the Jain's Index for the vehicular network is above 0.8. For Case B, where the A-CPEs are nearer to the road, the Jain's Index goes down to 0.6 because the interference of the fixed secondary network is higher than in Case A.

Spectral Efficiency

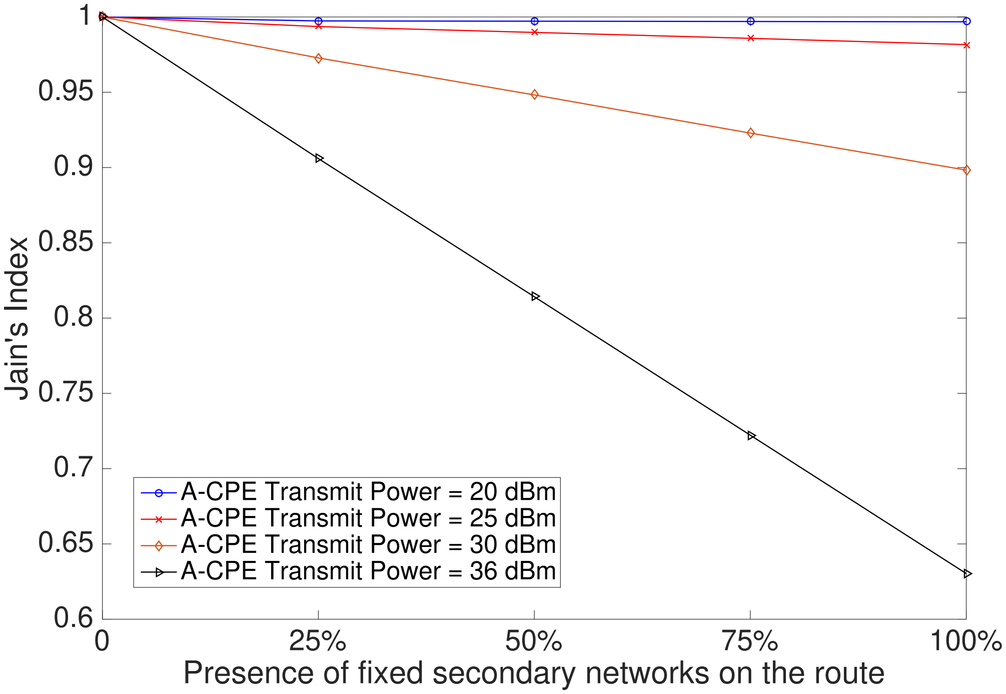
The spectral efficiency determines the spectrum utilization made by the entire system that includes the fixed secondary network and the vehicular network. The fixed network contributes the highest spectral efficiency in the system as the A-CPE transmit power increases. For both Case A (Fig. 4.14a) and Case B (Fig. 4.14b), the spectral efficiency of the system is higher as the presence of fixed secondary networks on the road increases. When the presence of secondary fixed networks is 100%, the spectral efficiency in the non-WSRS corresponds to the spectral efficiency achieved when the fixed secondary network is the only one using the TVWS channel.

The system's spectral efficiency increases when the sharing of the TVWS channel is allowed because the transmissions made by the vehicular network are added to the transmissions of the fixed secondary network. When the A-CPE transmit power is 20 dBm, the system's spectral efficiency is 17 bits/s/Hz. By increasing the A-CPE transmit power to 36 dBm, the system's spectral efficiency is 21 bits/s/Hz. Using the WSRS mechanism to share the TVWS channel, when R=100%, the spectral efficiency increases up to 32% (8 bits/s/Hz) with the transmissions of the vehicular network. The increment in the A-CPE transmit power also increases the spectral efficiency because this metric is related to the channel capacity (see Section 4.3.2 for more details of this metric). The effect of the interference caused by the vehicular network is taken into consideration in the spectral efficiency metric. Although the spectral efficiency achieved by the fixed secondary network decreases due to the interference caused by the vehicular network, the spectral efficiency provided by the vehicular network increases the spectral efficiency of the whole system.

Comparing Case A (A-CPEs furthest from the road) with Case B (A-CPEs closest to the road), the spectral efficiency curves follow the same trend. However, the spectral efficiency flattens out slightly at the end of the A-CPE transmit power range in Case B. Furthermore, in Case B, the channel capacity of the vehicular network decreases as the A-CPE transmit power increases (see Section 4.3.2 for more details of this metric), which decreases the contribution of the vehicular network to the spectral efficiency of the system.

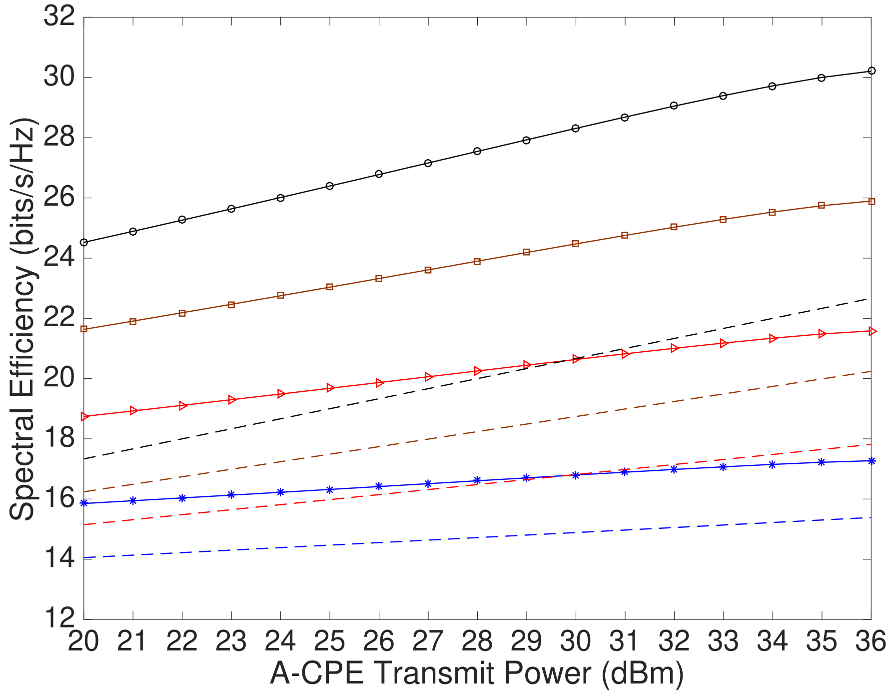


(a) Case A

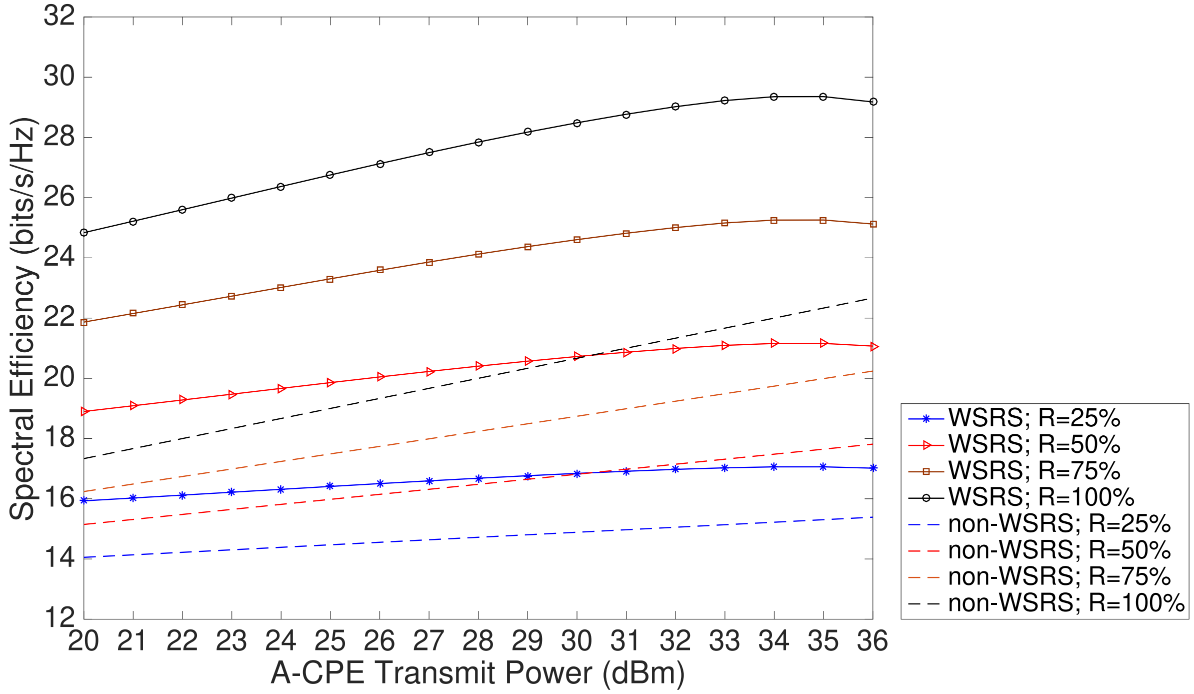


(b) Case B

Figure 4.13: Average Jain's Index per time frame for the set of vehicles



(a) Case A



(b) Case B

Figure 4.14: Spectral efficiency for the FNS and VN system

4.3.3 Discussion

The WSRS mechanism was evaluated when vehicular networks move within an area where there are several fixed secondary networks, and there are not enough vacated TVWS channels to allocate, so overlapped fixed and vehicular networks must share the TVWS channel.

The offered channel capacity for the vehicular network is higher as the presence of active secondary fixed networks in the path decreases for both Case A and Case B, regardless of the use of the WSRS mechanism or non-WSRS. The channel capacity increases up to 40% using the WSRS mechanism when the presence of active fixed secondary networks along the road is 100%. The interference caused by the fixed secondary network affects the offered channel capacity for the vehicular network. Results showed the offered channel capacity begins to decrease when the A-CPE transmit power is around 33 dBm for Case A and around 29 dBm for Case B. If the vehicular transmit power required to face the fixed secondary network is greater than the maximum power (20 dBm), the vehicle does not receive resource allocation, which affects the channel capacity for the set of vehicles.

The service rate measures whether resources were allocated to a target vehicle or not during the time frame evaluated. As the presence of active fixed secondary networks increases, the non-WSRS scenario's service rate decreases because the vehicles do not transmit in areas where there are active fixed secondary networks. For Case A, when the A-CPE transmit power increases to 36 dBm, the service rate varies between 0.4 and 1.0, which indicates that not all requests for resource allocation from the vehicular network are met. For Case B, the service rate varies between 0.3 and 1.0 when the A-CPE transmit power is 36 dBm. Increasing the A-CPE transmit power also increases the interference caused by the fixed secondary network on the vehicular network. If the required vehicular transmit power is greater than the maximum power to face the interference of the fixed secondary network, the resource allocation for the vehicle cannot be met; therefore, the service rate decreases. The Jain's Index metric is also affected if vehicles do not receive the resource allocation when the required transmission power is higher than the maximum power. For Case A, the A-CPEs are far from the road and the Jain's Index for the vehicular network is above 0.8. For Case B, where the A-CPEs are nearer to the road, the Jain's Index goes down to 0.6 because the interference of the fixed secondary network is higher than in Case A.

The spectral efficiency determines the entire system's spectrum utilization, including the fixed secondary network and the vehicular network. The fixed secondary network contributes the highest spectral efficiency in the system as the A-CPE transmit power increases, because the channel capacity of the fixed secondary network increases, and active fixed secondary networks also increase. The system's spectral efficiency increases when the sharing of the TVWS channel is allowed because the transmissions made by the vehicular network are added to the transmissions of the fixed secondary network. When the A-CPE transmit power is 20 dBm, the system's spectral efficiency is 17 bits/s/Hz. By increasing the A-CPE transmit power to 36 dBm, the system's spectral efficiency is 21 bits/s/Hz. Using the WSRS mechanism to share the TVWS channel, when the 100% of the fixed secondary networks are active, the spectral efficiency increases up to 32% (8 bits/s/Hz) due to the transmissions of the vehicular network. Comparing Case A (A-CPEs furthest from the road) with Case B (A-CPEs closest to the road), the spectral efficiency curves follow the same trend. However, the spectral efficiency flattens out slightly at the end of the A-CPE transmit power range in

Case B. Furthermore, in Case B, the channel capacity of the vehicular network decreases as the A-CPE transmit power increases, as was explained before, which decreases the vehicular network's contribution to the system's spectral efficiency.

Results show that sharing the TVWS channel between fixed and mobile networks using the WSRS mechanism is feasible and increases the radio spectrum's efficiency. The WSRS mechanism is proper for scenarios where there are not enough vacated TVWS channels to allocate, so overlapped fixed and vehicular networks must share the TVWS channel. The WSRS mechanism's strengths are:

- The WSRS mechanism implements a Power Control Process to adjust the vehicles' transmission power and maintain vehicular communication, facing the interference caused by the fixed secondary network. The power control process respects the maximum power allowed for mobile devices in TVWS systems according to the spectrum regulation. This is a consideration also protects the primary TV systems in the event that vehicles move within the coverage area of TV systems.
- The WSRS mechanism considers the interference caused by the secondary fixed network, depending on the proximity of the A-CPEs to the vehicles. The Channel Allocation Process seeks to match each vehicular link with the farthest A-CPE as a strategy to reduce the mutual interference. The lower the interference caused by the secondary fixed network over the vehicular link, the lower the vehicle's transmission power. The decrease in the transmission power of the vehicles is a mechanism that protects the fixed secondary network from mutual interference.
- The WSRS mechanism is helpful for coexistence scenarios in other frequency bands in addition to the TVWS bands. The Power Control Process can be adjusted to include more detailed aspects of the channel model for both the mobile and fixed secondary network, but keeping the algorithm. The adjustments in the Power Control Process consist of changing the path loss models to calculate the variables $L_{v\mathrm{i}}$ (the path loss in the vehicular link i) and L_j^{i} (the path loss in the link between A-CPE j and vehicle i). The rest of the WSRS algorithm remains the same.
- The Channel Allocation Process is also flexible to implement different cost functions beyond maximizing the distance between the vehicle and A-CPE using the same sub-channel to reduce the mutual interference. Another cost function to maximize could be the channel capacity in the vehicular network.

The WSRS mechanism's weaknesses are:

- The allocation of resources could constantly vary if the vehicular channel has a high path loss measure. In that case, the mechanism could not allocate resources if the required vehicular transmit power is higher than the maximum power, causing degradation in vehicular communication.
- Nor does the mechanism seek to guarantee the stable assignment of the same sub-channel for vehicles. The WSRS mechanism does not consider the impact of the frequency shifting process on the TVWS radio interface.
- The WSRS mechanism was designed for scenarios where the number of vehicles and A-CPEs is the same. The mechanism does not require adjustments when the number of A-CPEs is greater than the number of vehicles, and the number of sub-channels is

equal to the number of A-CPEs. However, the WSRS mechanism has to be adjusted to support scenarios where the number of vehicles is greater than the number of sub-channels. The adjustment could consist of dividing the sub-channel in the time-domain allowing more vehicles to use the same sub-channel as the A-CPE. The adjustment would require considering A-CPE interference on multiple vehicles in the Power Control Process. Also, it may require to adjust the cost function of the Channel Assignment Process to match multiple vehicles to one A-CPE.

Chapter 5

Conclusions

This chapter concludes the main research results and discuss the further work. The objectives were fulfilled with the design of the White Space Resource Sharing mechanism (WSRS). The WSRS mechanism allocates spectrum resources when not enough vacant TVWS channels are available and fixed secondary and vehicular networks must share a TVWS channel. Regarding to the specific objectives, a new metric was introduced, the Channel Availability for Opportunistic Vehicular Access (CAFOVA), which relates the channel occupancy of the fixed secondary network with random access channel, the speed of the vehicle, and the channel verification distance. This metric estimates the transmission opportunities for vehicular access when the vehicles move within the fixed secondary network's coverage area. The WSRS mechanism was evaluated using standard metrics such as offered channel capacity, service rate, Jain's Index, and spectral efficiency. Furthermore, the proposed mechanism was compared with the IEEE standard 802.22 mechanism.

The fulfillment of the hypotheses and the objectives are detailed below.

5.1 Major Research Results

The objective of this research is to investigate the coexistence among secondary networks for vehicular networking on the TVWS spectrum. The deployment of cognitive secondary networks over the TVWS spectrum creates a problem of coexistence because prior agreements for coordinating the sharing of channel usage are not required. Even though there are different methods and algorithms for coexistence between secondary cognitive networks, the complexity of the architecture and the non-obligatory adjustment of the operating parameters to achieve coexistence avoiding mutual interference have made it a challenge to enable the TVWS channel sharing. In what follows, a summary of the main research results are provided.

The first approach to explore the coexistence problem was to analyze the opportunistic use of the TVWS spectrum for vehicular communications when primary and IEEE 802.11af secondary fixed users are active. Primary and secondary TV band users were modeled, and several traffic profiles based on probability of busy channel were used to represent the TVWS channel occupation made by the fixed users.

A new metric called CAFOVA was introduce. The CAFOVA corresponds to the percentage of channel availability for opportunistic vehicular access when there are other opportunistic networks over the same TVWS channel. The CAFOVA relates the channel occupancy of the fixed secondary network with random access channel, the speed of the vehicle, and the channel verification distance. Results demonstrated that the CAFOVA depends on the TVWS channel occupation policy used by the IEEE 802.11af fixed secondary network (the White-Fi network). When the traffic in the White-Fi network follows a uniformly distributed probability of busy channel, the percentage of opportunities is around the complement of the probability of occupation. On the other hand, the CAFOVA was shown to be insensitive to bursty traffic occupation policies. This first approach demonstrated that vehicular networks may use the TVWS even if there are other opportunistic networks.

The vehicular network may share the TVWS channel with the fixed secondary network instead of searching for a new TVWS channel, as a strategy to reduce the channel access delay in opportunistic spectrum access. The reduction in the channel access delay impacts in the packet loss rate. For the average case of study, when the probability of busy channel is 50%, sharing the TVWS channel reduces the maximum channel access delay by 15% and the maximum packet loss rate by 17%, regarding searching for a new TVWS channel. For the near-to-worst case scenario, when the probability of busy channel is 70%, sharing the TVWS channel reduces the maximum channel access delay by 25% and the maximum packet loss rate by 11%, regarding searching for a new TVWS channel. The reduction in the channel access delay and the packet loss rate are highlights to continue exploring the TVWS channel sharing as the strategy for vehicular communication on TVWS.

The second scenario of study was focused on the coexistence among overlapping IEEE 802.22 fixed and mobile secondary networks, when not enough vacant TVWS channels are available for allocation. Based on this scenario, the proposed White Space Resource Sharing mechanism (WSRS) was designed and modeled. The WSRS mechanism coordinates the channel access in the vehicular network according to the scheduling information of the fixed secondary network. The WSRS mechanism uses the flexibility of the cognitive vehicular network to improve network coexistence without requiring any changes in fixed network operating parameters.The WSRS mechanism implements a strategy to protect the fixed secondary network from interference caused by vehicular transmissions while promoting that both networks simultaneously use the channel.

The WSRS mechanism was evaluated when vehicular networks move within an area where there are several fixed secondary networks, and there are not enough vacated TVWS channels to allocate, so overlapped fixed and vehicular networks must share the TVWS channel. Simulation results show the offered channel capacity to the vehicular network increases up to 40% using the WSRS mechanism compared to offered channel capacity when TVWS channel sharing is not allowed, and no other TVWS channel is available. The WSRS mechanism allocates resources to vehicles even when the density of fixed nodes and the transmission power of the fixed network cause high interference to the vehicular network. Using the WSRS mechanism, the service rate varies between 0.3 and 1.0. When the TVWS channel sharing is not enabled, the service rate varies between zero and 0.8 because the vehicular network must stop transmitting when a fixed secondary network uses the TVWS channel. The system's spectral efficiency increases up to 32% when the vehicular network and the fixed secondary network overlap along the route, and both share the same TVWS channel.

5.2 Future Work

This research has investigated the coexistence among secondary networks for vehicular networking on the TVWS spectrum. Nevertheless, the are still several research directions in which this research can be extended.

- **Estimation of the time that the TVWS channel is available at each channel access opportunity:** The estimation of how much time the TVWS channel is available as a way to complement the CAFOVA metric. This estimate would be helpful to determine the channel capacity offered to the vehicular network at each channel access opportunity and to establish which additional services could use the TVWS channel.

- **Coexistence among TV primary networks and vehicular secondary networks:** The spectrum regulation defines that secondary networks cannot use the TV channels occupied by primary TV users to avoid harmful interference against the incumbent users. However, the proposed WSRS mechanism could be adapted to analyze the technical viability of facilitating TV channel sharing among primary and vehicular networks (or mobile groups in general). One alternative is to use the WSRS mechanism in areas where the vehicular network and the television network overlap, but the service level of the television network is below the sensitivity levels of the TV receivers. The WSRS mechanism could be adjusted to consider planning aspects of the TV network, such as the service contours of the transmitters.

- **Supporting high-density fixed networks and variable transmit power:** commercial initiatives and manufacturers are providing technological services for rural broadband connectivity, the industrial Internet of Things (IIoT), communications for critical infrastructure and environmental monitoring, among other applications, all operating on TVWS spectrum. These deployments have different characteristics, such as the number of nodes, density, mobility, and quality of service parameters. Because of the mobility of the vehicular network, the probability that the vehicular network and another secondary network overlap will increase. An alternative is to extend the strategies for resource allocation to support different secondary network profiles.

- **Evaluation of the acceleration of the vehicles in the Power Control Process:** In the proposed WSRS mechanism, the path loss model for the vehicular link could be changed to explicitly consider the acceleration parameter or other aspects of mobile channel propagation in the TVWS frequency band. This changes the calculation of the path loss in the vehicular link (L_{vi}), but the power control process in the Resource Allocation Function (RAF) remains the same.

- **Present the proposed WSRS mechanism as a contribution to the IEEE standard 802.22 Working Group:** The IEEE 802.22 standard indicates only that when no vacated TWVS channels are available for allocation, or when different groups share the TVWS channel for spectrum efficiency purposes, then "the A-BS may use a mechanism for proper resource sharing between the overlapping groups or the A-BS and some groups after channel switching" [23]. However, such a resource sharing mechanism is neither detailed nor defined by the standard. The proposed WSRS mechanism may be a baseline to evaluate different use cases and adjust the power control or the channel access strategy according to the expected standard evolution.

Chapter 6

Appendix

Main code repository: WSRS mechanism's code

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