# Cognitive Radio Architecture for Massive Internet of Things services with Dynamic Spectrum Access

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Pontificia Universidad JAVERIANA Bogotá

Doctoral Dissertation

# Cognitive Radio Architecture for Massive Internet of Things services with Dynamic Spectrum Access

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# Abstract

This research proposes a novel cognitive radio architecture for massive Internet of Things (IoT) services over TV White Spaces (TVWS). The proposal considers TVWS as suitable frequency bands for facing the limited-spectrum problem for massive IoT services. The architecture provides the available list of channels to IoT devices and its access mechanisms have Quality of Service (QoS) constrains. We define a novel access mechanism that is based on regulatory policies by interacting with TVWS Geolocation Database (GLDB) through the Protocol to Access White-Space (PAWS) for providing the available list of channels to IoT devices. Regarding QoS constraints, we explore different types of deployments and reference coverage areas considering a packet loss probability model. In addition, the research describes the optimization process to obtain the maximum service area while maintaining an outage probability below a given objective. Moreover, we applied a macro-diversity mechanism for improving the packet loss probability with respect to our proposal and one Master Device (MD) topology. We can evidence that the average packet loss probability is reduced in $26\%$ when the load is equal to $80\%$ in our proposal.

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# Contents


**1 Introduction** **1**

1.1 Motivation and Problem Statement . . . . . . . . . . . . . . . 1

1.2 Contribution and dissertation structure . . . . . . . . . . . . 4

**2 Overview** **9**

2.1 Radiolectric Spectrum . . . . . . . . . . . . . . . . . . . . . . 9

2.1.1 Radioelectric spectrum for IoT services . . . . . . . . 10

2.1.2 Dynamic Spectrum Access . . . . . . . . . . . . . . . 16

2.2 Massive IoT Services . . . . . . . . . . . . . . . . . . . . . . 19

2.2.1 Cognitive Radio in Internet of Things (IoT) . . . . . . 21

2.2.2 QoS of Massive IoT services over TVWS . . . . . . . . 23

2.3 Remarks . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 25

**3 Cognitive Radio Architecture** **27**

3.1 Overview . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 28

3.1.1 IoT Architectures over TVWS . . . . . . . . . . . . . 28

3.2 Cognitive Radio Architecture . . . . . . . . . . . . . . . . . . 31

3.3 Remarks . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 35

**4 Radio Access Mechanisms for Massive Internet of Things Services over White Spaces** **37**

4.1 Overview . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 37

4.1.1 PAWS . . . . . . . . . . . . . . . . . . . . . . . . . . 38

4.2 Radio Access Mechanisms for Massive Internet of Things Services over White Spaces . . . . . . . . . . . . . . . . . . . . 39

4.2.1 Radio Access Mechanism Evaluation . . . . . . . . . 41

4.2.2 Reference of comparison in the Radio Access mechanism . . . 43
4.2.3 IoT devices Positioning . . . 44
4.3 Remarks . . . 46

**5 Evaluation of the Radio Access Mechanisms for Massive Internet of Things Services over White Spaces 49**
5.1 Exploring different Master Device Deployments . . . 50
5.2 Propagation Model . . . 51
5.3 Packet loss probability on one link . . . 52
5.4 Service area . . . 54
5.5 Reference service area . . . 54
5.6 Outage with the proposed architecture . . . 56
5.7 Performance of a loaded network . . . 56
5.8 Results and Analysis . . . 58
5.8.1 Determination of the reference case . . . 58
5.8.2 Service area restricted to the deployment triangle . . . 59
5.8.3 Optimization of the Triangle Service Area . . . 61
5.8.4 Hexagon service area . . . 64
5.8.5 Service area rules . . . 65
5.8.6 IoT Devices Positioning Evaluation . . . 66
5.8.7 Performance analysis of a loaded system . . . 68
5.9 Remarks . . . 69

**6 Conclusion 71**
6.1 Contributions . . . 72
6.2 Future Work . . . 74

**A Okumura-Hata Model 87**

**B PAWS Protocol 91**

**C Heat map of TVWS available list of channels in Colombia 93**

**D Other service areas 95**

D.1 Hexagon service areas based on the optimization of the triangle service area . . . . . . . . . . . . . . . . . . . . . . . . 95
D.2 Enneagon service areas based on the optimization of the triangle service area . . . . . . . . . . . . . . . . . . . . . . . . 96

**E QoS constrains 99**

# List of Figures


1.1 Examples of IoT fields . . . . . . . . . . . . . . . . . . . . . . . 2

2.1 Global Mobile M2M Connections by 3G, 4G, 5G and LPWA . . 12
2.2 Spectrum hole concept . . . . . . . . . . . . . . . . . . . . . . . 17
2.3 A Taxonomy for Cognitive Radio and IoT . . . . . . . . . . . . 23

3.1 SNOW Architecture . . . . . . . . . . . . . . . . . . . . . . . . 30
3.2 Weightless Architecture . . . . . . . . . . . . . . . . . . . . . . 31
3.3 Radio Architecture . . . . . . . . . . . . . . . . . . . . . . . . 32
3.4 Cognitive Radio Architecture Attributes . . . . . . . . . . . . 35

4.1 PAWS Sequence . . . . . . . . . . . . . . . . . . . . . . . . . . 39
4.2 Sequences proposed of the radio access mechanism for only one Master Device of the three Master Devices . . . . . . . . . 40
4.3 New steps proposal when the IoT device is inside to the deployment . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 42
4.4 Radio Access Mechanism . . . . . . . . . . . . . . . . . . . . . 43
4.5 Macro-diversity Gain Access Mechanism . . . . . . . . . . . . 44
4.6 Beacon messages . . . . . . . . . . . . . . . . . . . . . . . . . . 45
4.7 Observed Time Difference of Arrival System . . . . . . . . . . 46

5.1 Master device deployments . . . . . . . . . . . . . . . . . . . . 51
5.2 Packet Loss Probability in one link in reference case with one MD. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 59
5.3 Packet Loss Probability in one link in deployment cases with 3 MDs characterized by $\delta \geq \pi/6$ with Shadowing . . . . . . . . 60
5.4 Deployment and service areas with $R_D$ and $R_S$ distance . . . . 62

5.5 Outage packet loss probability considering shadowing with different $R_S$ and $R_D$ distances in examples of Triangle service areas, red points show 1 $\%$ probability. . . . . . . . . . . . . . . 63
5.6 Outage packet loss probability considering shadowing and shadowing with fast fading with different $R_S$ and $R_D$ distances in examples of Triangle service areas, red points show 1 $\%$ probability . . . . . . . . . . . . . . . . . . . . . . . . . . . . 63
5.7 Hexagon service area . . . . . . . . . . . . . . . . . . . . . . . . 64
5.8 Outage packet loss probability considering shadowing with different $R_H$ and $R_D$ distances in examples of Hexagon service areas, red points show 1 $\%$ probability . . . . . . . . . . . . . 65
5.9 Outage packet loss probability considering Shadowing with Fast Fading with different $R_H$ and $R_D$ distances in examples of Hexagon service areas, red points show 1 $\%$ probability . . 65
5.10 Service areas gain considering shadowing . . . . . . . . . . . 66
5.11 Service areas gain considering Shadowing with Fast Fading . . 67
5.12 OTDOA in deployments of the radio access mechanism . . . . 67
5.13 CDF Error in IoT Devices positioning . . . . . . . . . . . . . . 68
5.14 Average Packet Loss Probability . . . . . . . . . . . . . . . . . 69
5.15 CDF of $p_s$ with load $\rho = 0.8$ . . . . . . . . . . . . . . . . . . . 70

C.1 TVWS Available Channels in the Colombian study case . . . . 93

D.1 Hexagon polygon . . . . . . . . . . . . . . . . . . . . . . . . . 96
D.2 Enneagon polygon . . . . . . . . . . . . . . . . . . . . . . . . 97

E.1 QoS constraints . . . . . . . . . . . . . . . . . . . . . . . . . . 99

# List of Tables


2.1 ISM Band frequencies . . . . . 11
2.2 Examples of IoT technologies and central frequencies . . . . . 13
2.3 Examples of IoT Networks applications . . . . . 14
2.4 IoT Network Examples . . . . . 15
2.5 Qos for IoT over TVWS . . . . . 24

3.1 Comparative analysis with other IoT networks . . . . . 29

5.1 Deployment cases . . . . . 52
5.2 Model parameters . . . . . 58
5.3 Outage probability when the service area is restricted to the deployment triangle . . . . . 61

A.1 Parameters Okumura-Hata Model . . . . . 88

B.1 Examples of PAWS length . . . . . 91
B.2 Access Mechanism JSON Length . . . . . 92

# Acronyms

**ADON** Adaptable Object Network

**ANE** National Spectrum Agency

**AP** Access Point

**ACB** Access Class Barring

**BAN** Body Area Network

**BWP** Bandwidth Part

**CDF** Cumulative Distribution Function

**CEPT** European Conference of Postal and Telecommunications Administrations

**CSMA** Carrier-Sense Multiple Access

**CU** Central Unit

**DARPA** Defense Advanced Research Projects Agency

**D-OFDM** Distributed Orthogonal Frequency Division Multiplexing

**DL** Downlink

**DSA** Dynamic Spectrum Access

**DTT** Digital Terrestrial Television

**ECC** Electronic Communications Committee

**EIRP** Effective Isotropic Radiated Power

**ELH** Extremely High Frequency

**eMBB** Enhanced Mobile Broad Band

**eNodeB** Evolved Node B

**FCC** Federal Communications Commission

**GLDB** Geolocation Database

**HAAT** Height Above the Average Terrain

**HTTP** Hypertext Transfer Protocol

**HTPPS** Hypertext Transfer Protocol Secure

**ICT** Information and Communications Technologies

**IoT** Internet of Things

**IEEE** Institute of Electrical and Electronics Engineers

**IMT** International Mobile Telecommunications

**IETF** Internet Engineering Task Force

**IP** Internet Protocol

**ISM** Industrial, Scientific and Medical

**ITU** International Telecommunication Union

**JSON** JavaScript Object Notation

**LPWA** Low Power Wide Area

**LPWAN** Low-Power Wide-Area Network

**LTE** Long Term Evolution

**MAC** Medium Access Control

**MAR** Mobile Autonomous Reporting

**mMTC** Massive MTC

**mIoT** Massive IoT

**M2M** Machine to Machine

**MD** Master Device

**MIT** Massachusetts Institute of Technology

**MHz** Megahertz

**MTC** Machine-Type Communication

**NB-IoT** Narrowband-IoT

**OTDOA** Observed Time Difference Of Arrival

**OFDM** Orthogonal Frequency Division Multiplexing

**ODFMA** Orthogonal Frequency Division Multiple Access

**OSA** Opportunistic Spectrum Access

**OSI** Open System Interconnection

**PAWS** Protocol to Access White-Space

**PHY** Physical

**PPP** Poisson Point Process

**PSD** Power Spectral Density

**PRS** Positioning Reference Signals

**PU** Primary User

**QoS** Quality of Service

**RA** Radio Access

**RAN** Radio Access Network

**RFC** Request for Comments

**RFID** Radio Frequency Identification

**RF** Radio Frequency

**RPC** Remote Procedure Call

**RU** Resource Unit

**RSTD** Reference Signal Time Difference Measurement

**SCMA** Sparce Code Multiple Access

**SD** Slave Device

**SNOW** Sensor Network Over White Spaces

**SNR** Signal Plus Noise Ratio

**SINR** Signal to Interference Plus Noise Ratio

**TOA** Time of Arrival

**TV** Television

**TVWS** Television White Spaces

**TDoA** Time Difference of Arrival

**UHF** Ultra High Frequency

**UK** United Kingdom

**UML** Unified Modeling Language

**USA** United States

**URI** Uniform Resource Identifier

**URLLC** Ultra-Reliable and Low Latency Communications

**UWB** Ultra Wide Band

**VHF** Very High Frequency

**VLF** Very Low Frequency

**WEF** World Economic Forum

**WLAN** Wireless Local Area Network

**WSD** White Space Device

**WSN** Wireless Sensor Network

**WSM** White Space Manager

**WSO** White Space Object

**WRC** World Radiocommunication Conferences

**3GPP** 3rd Generation Partnership Project

# 1 Introduction

## 1.1 Motivation and Problem Statement

In the last 20 years, the Internet has changed the way people communicate, work and do business. Nowadays, the communication paradigm has changed because not only people establish connection to Internet but the things too. The things are defined as virtual or physical objects, such as household appliances, wearable and means of transport, among others. This new communication paradigm has caused an impact on different sectors of the society, for instance, energy, transport, health, and manufacture of goods or services [1, 2, 3, 4, 5]. The impact of this technology can be measurable according to information about different processes over Internet that could report the behavior of physical or chemistry variables. These variables in a process could be effective early warnings that may improve the quality of the life of population. The applications are classified in fields, for instance, smart agriculture and smart environment as shown in Figure 1.1. These fields have applications such as water quality, air pollution reduction, forest fire, landslide, earthquake early detection, smart greenhouses, agricultural automation and robotics, and toxic gas levels, among others.

The concept of IoT was initially defined by the International Telecommunication Union (ITU) in 2005 in the world summit on information society [6]. According to [7], IoT is defined as a global infrastructure for the information society, enabling advanced services by interconnecting physical and virtual things through the interoperability of the Information and Communications Technologies (ICT). The ITU also states that IoT adds a third dimension to ICT about the communication with any object [7]. Moreover, Cisco [8] presents IoT as the next evolution of the Internet that represents

**(a)** Smart agriculture **(b)** Smart environment

**Fig. 1.1.:** Examples of IoT fields

a massive leap in the intrinsic capacity of the Internet to gather, analyze and distribute data that can become information and knowledge.

Moreover, IoT devices have wireless access networks for accessing Internet. Therefore, the radielectric spectrum is an important resource in this technological paradigm. The IoT could access to Industrial, Scientific and Medical (ISM) bands (i.e. unlicensed bands) or licensed bands. The main disadvantage of licensed bands is the access cost and of unlicensed bands is that these bands are overcrowded with IoT services and other services [9, 10, 11].

A wide area network in unlicensed bands has a band of frequencies with a central frequency of 915 MHz and bandwidth equal to 6 MHz in Americas, and 866,5 MHz with bandwidth of 3MHz in Europe [12]. Then, when the number of IoT devices increase, frequency bands congestion increases. For this reason, these band of frequencies have challenges, particularly for massive IoT services with special requirements such as low cost, low energy consumption, delay-tolerance, and Quality of Service (QoS) [13].

In this aspect, massive IoT networks have substantial challenges regarding scalability, restrictions on the headers size of the protocols messages and QoS. In addition, due to the exponential growth of IoT services [14], additional issues arise regarding spectrum access such as (i) congestion and unavailability of their services implemented in ISM bands, (ii) QoS, (iii) limited bandwidth, (iv) scalability, and costs of licensed bands. For the above reasons, it is necessary that massive IoT services have innovative solutions for increasing the radioelectric spectrum access in bands below 1 GHz.

TV bands are identified as frequency bands below 1 GHz with favorable technical conditions for massive IoT service deployment. Besides, these frequency bands have a regulation to avoid interference on TV primary users while allowing access to opportunistic secondary users (i.e. IoT devices). In massive IoT services with dynamic access to TV bands; IoT services must establish a coexistence mechanism with the TV primary users.

In this context, we propose a cognitive radio architecture that: (i) the available list of channels to IoT devices are provided considering the IoT requirements, (ii) the architecture has QoS constrains for defining the deployments and service areas, and (iii) the architecture is based on macro-diversity gain scheme. Therefore, we define a novel access mechanism that is based on regulatory policies by interacting with Television White Spaces (TVWS) Geolocation Database (GLDB) through the Protocol to Access White-Space (PAWS) for providing the available list of channels to IoT devices. Regarding QoS constraints, the cognitive radio architecture proposes deployments, services area and macro- diversity gain for facing the packet loss challenges.

## 1.2 Contribution and dissertation structure

In this dissertation, we propose a cognitive radio arquitecture for massive IoT services with Dynamic Spectrum Access (DSA). The contribution according to the chapters is presented below.

**Chapter 2**

In this chapter, we introduced concepts such as radioelectric spectrum and massive IoT services. Regarding radioelectric spectrum, we summarized the main characteristics about this scarce natural resource and we identified the challenges in order to use it rationally, efficiently and effectively. Then, we identified that IoT services need innovative solutions for increasing the radioelectric spectrum access in bands below 1 GHz. Finally, we selected the DSA over TV bands as suitable bands of frequencies for facing these challenges.

In terms of QoS, through a review of cognitive radio in IoT, we realized that the QoS for IoT has been developed with techniques such as spectrum-aware and cross layer, while regarding services the QoS is focused on critical services. However, the QoS over DSA is a concept that need to be explored for massive IoT services over DSA over TV bands. This chapter is based on the following publications.

- ESPINOSA, Monica; PEREZ, Manuel; REINALES, Doris. Espectro radioeléctrico para el desarrollo de internet de las cosas. El reino digital transformación y aplicaciones multidisciplinares. Edición 2019. pp: 105-131. ISBN: 978-958-782-242-7

- G. Roncancio, M. Espinosa, M. R. Pérez and L. C. Trujillo, "Spectral Sensing Method in the Radio Cognitive Context for IoT Applications," 2017 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData), 2017, pp. 756-761, doi: 10.1109/iThings-GreenCom-CPSCom-SmartData.2017.116.

**Chapter 3**

This chapter presents a novel cognitive radio architecture focused on policy-based cognitive radio where IoT devices have to obtain the available list of channels provided by the GLDB. In the overview of other architectures [15, 16, 17], which are centralized in one Master Device (MD), the key point of our proposal is to deploy several MDs that are synchronized, which can be 3 MDs or more. A higher the number of MDs produces a better the performance. We consider the minimum number, set as 3, which provides triangle deployments and service areas. This chapter is based on the following publications:

- ESPINOSA, Monica; ZONA, Tatiana; REINALES, Doris. Huecos Espectrales en televisión. El reino digital transformación y aplicaciones multidisciplinares. Edición 2019. pp: 57-79. ISBN: 978-958-782-242-7

**Chapter 4**

In this chapter, a radio access mechanism is presented for massive IoT overTVWS. An analytical model was developed to compute the packet loss probability on the service areas and deployments. The main contribution of this chapter is a novel radio access mechanism that allows the deployment of IoT massive services on TVWS frequencies. This radio access mechanism is based on the PAWS standardized by the Internet Engineering Task Force (IETF), and it requires no geolocation receiver for IoT end-devices when deployed inside the network.

This chapter is based on the following paper.

- ESPINOSA, Monica; PEREZ, Manuel; LAGRANGE,Xavier; ZONA Tatiana. Radio Access Mechanism for Massive Internet of Things Services over White Spaces. IEEE Access. IEEE Access. IEEE Access. DOI: 10.1109/ACCESS.2021.3105131

**Chapter 5**

In this chapter, we evaluated the radio mechanism for massive IoT services over TV White Spaces (i.e. TVWS). The main contributions of this chapter are presented below.

- A performance comparison of several possible deployments and service areas with outage probability equal to 1%.

- Guidelines for service areas on TVWS with respect to the MDs deployment.

- An analytical model to evaluate the performance of the loaded network considering the service areas and a comparative analysis of the proposed architecture topology with only one Master Device, showing the advantages of the macro-diversity gain.

This chapter is based on the following paper.

- ESPINOSA, Monica; PEREZ, Manuel; LAGRANGE,Xavier; ZONA Tatiana. Radio Access Mechanism for Massive Internet of Things Services over White Spaces. IEEE Access. IEEE Access. DOI: 10.1109/ACCESS.2021.3105131

**Chapter 6**

We conclude this dissertation by providing a summary of our contributions and discussing some prospects and opportunities for the future regarding the construction of Cognitive Radio Architecture for massive IoT services with DSA.

# Overview 2

In this chapter, we present the overview of this thesis. The overview is focused on the main concept of the thesis such as radioelectric spectrum and massive IoT services. In terms of radioelectric spectrum for IoT services, we identify the bands of frequencies for IoT networks and the challenges for the lack of radioelectric spectrum. Moreover, we describes the regulatory process for DSA over TV bands. Finally, we establish the relation between DSA, IoT and QoS.

## 2.1 Radiolectric Spectrum

The radioelectric spectrum is a scarce natural resource that allows the transmission of services that propagate in free space. These services are called unguided and well-known examples of them are mobile phones, television and sound broadcasters, among others. The radioelectric spectrum is divided into frequencies from 3 kHz to 3000 GHz in different frequency bands ranging from Very Low Frequency (VLF) to Extremely High Frequency (ELH) [18]. By allowing wireless communications for different telecommunications services through the radiolectric sprectrum, countries recognize that it is a resource of great importance for the economic and social development [18].

Due to the importance of the radioelectric spectrum, its regulation is necessary in order to use it rationally, efficiently and effectively. The ITU is one of the entities that generates recommendations for such regulation. Within its basic regulation principles of commercialization, the ITU includes price, technical control and spectrum management found in the radio regulations. It is adopted by the World Radio communication Conference

(WRC) [19]. However, each country manages the use of the radioelectric spectrum by allocating frequencies to the different radio services and establishes the technical conditions, so that maximizing the use of each frequency bands for the benefit of the general society [20].

In the licensed spectrum, operators pay to have the exclusive use of a part of the spectrum. There are some constraints about the transmitted signal by base stations or terminals, but there is no constraint regarding the channel access mechanisms, which means that any device can a priori transmit at any time. Examples of systems that work in a licensed spectrum are 2G, 4G and 5G cellular networks.

In the unlicensed spectrum, a frequency can be used by any device without administrative authorization process and payment. However, the devices have to follow rules about duty cycle and power transmission, among the others. The rules depend on each country regulation. Only a part of the spectrum is unlicensed and different spectrum parts are grouped in the ISM band. The definition of range of frequencies for ISM bands is not the same in all countries. Table 2.1 presents the international table of frequency allocation by the ITU[21].

### 2.1.1 Radioelectric spectrum for IoT services

Since the radioelectric spectrum is a scarce resource, some challenges arise about IoT access. Regarding the exponential growth of IoT services, according to Cisco [8], Internet-based Business Solutions Group, one way to see the fast emergence of IoT is by localizing the specific moment in time when more things or objects than people get connected. In 2003 there were approximately 6.3 billion people on the planet, and 500 million devices connected to the Internet, thus indicating the existence of less than one device per person (0.08). In 2010, since the exponential growth of smart-phones and tablet PCs, the number of devices connected to the Internet

| Frequency Band | Central Frequency |
|---|---|
| 6.765-–6.795 MHz | 6.780 MHz |
| 13.553-–13.567 MHz | 13.560 MHz |
| 26.957-–27.283 MHz | 27.120 MHz |
| 40.66-–40.70 MHz | 40.68 MHz |
| 433.05-–434.79 MHz | 433.92 MHz |
| 902-–928 MHz | 915 MHz |
| 2400-–2500 MHz | 2450 MHz |
| 5725-–5875 MHz | 5800 MHz |
| 24-–24.25 GHz | 24.125 GHz |
| 61-–61.5 GHz | 61.25 GHz |
| 122-–123 GHz | 122.5 GHz |
| 244-–246 GHz | 245 GHz |

**Tab. 2.1.:** ISM Band frequencies[21]

rose to 12.5 billion, while the world population increased to 6.86 billion, so the relationship of devices connected by person increased to 1.84 for the first time in history [8]. Furthermore, the advent of IoT can be traced back to the period between 2008 and 2009, taking into account the rapidly increasing numbers of things connected to Internet. In this lapse of time, the number of things or devices connected to Internet surpassed the number of population in the world. These numbers allow to make projections about the expected growth for the number of connections, estimated in 50 billion by 2020 [8], which in turn it positions IoT technologies with great potential in the current market.

Regarding connections, Figure 2.1 shows the global mobile Machine to Machine (M2M) connection from 2018 to 2023 [14]. This statistic analyzes the billion of devices or connections 3G, 4G, 5G and Low Power Wide Area (LPWA) technologies. On the one hand, in this period of time, the 3G technology has decreased its number of devices connected, whereas the 4G and LPWA have increased the number of connections. Moreover, by 2023 5G and LPWA connections will have been increasing to 10.6% and

14.4%, respectively. In conclusion, IoT services with LPWA networks will have increased with respect to the other networks in 2023.

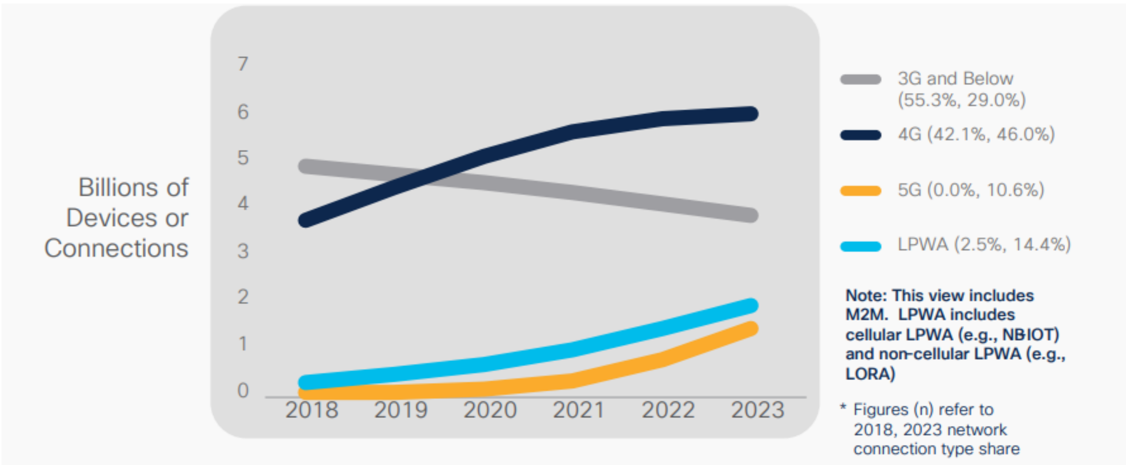


**Fig. 2.1.:** Global Mobile M2M Connections by 3G, 4G, 5G and LPWA [14]

.

According to [22], there is not a unique description about IoT radioelectric spectrum constraints and requirements, since they depend on the particular nature of IoT services. For instance, from a technical point of view, the lower frequencies have wider coverage and they manage better the obstacles. From a regulation point of view, the licensed spectrum guarantees the reliable data delivery. Regarding the energetic consumption, the radioelectric spectrum access will have to use highly qualified technologies for guaranteeing that the device battery lasts more than 10 years.

The IoT services have a wireless access network that establishes a centralized and distributed communication for data transmission to the Internet. On the one hand, a large percentage of IoT applications use ISM or unlicensed bands that operate in different technologies, such as WiFi [23, 24], ZigBee [23], Bluetooth [25, 26, 24], and Low-Power Wide-Area Network (LPWAN) [27, 28]. On the other hand, licensed bands operate with technologies such as Long Term Evolution (LTE), 5G, Narrowband-IoT (NB-IoT), and LTE Machine [29, 30], among others. Finally, Table 2.1.1 presents technologies with examples of spectrum frequencies bands based on the range of coverage. According to [22] and [1], we can conclude that IoT is an heterogeneous service with multiple applications and operations, which involves demanding requirements such as bit rates, reliability, coverage and power transmission. Moreover, the number of IoT devices or connections has increased exponentially, for this reason, IoT demands innovations for access mechanism to the radioelectric spectrum bellow in the sub-1GHz frequency band.

| Example of technologies | Example central frequencies | Range |
|---|---|---|
| NFC<br>EMV | 2.4 GHz<br>5 GHz | <10cm |
| Zigbee<br>WiressHART<br>802.11 a/b/g/n/ac<br>802.11 ah (1Km)<br>Zigbee (6LowPAN) | 915 MHz<br>866,5 MHz<br>2.4 GHz<br>5GHz | <5km |
| SIGFOX<br>Lora<br>Ingenu RPMA<br>Telensa | 433,92 MHz<br>915 MHz (Americas)<br>866,5 MHz (Europe) | <100km |
| NB-IoT<br>3GPP LTE-MTC<br>eMTC/CAT M | 800 MHz<br>900 MHz<br>1.8 GHz<br>2.6 GHz<br>2.3 GHz<br>2.1 GHz<br>3.2 GHz | <100km |

**Tab. 2.2.:** Examples of IoT technologies and central frequencies

Regarding IoT Wide Area Network (i.e. LPWAN), there are different applications according to different fields, such as smart environment, smart water, smart metering, smart grid and energy, and smart agriculture and farming, as shown in Table 2.3. The radioelectric spectrum for these networks in technologies such as Sigfox, Lora and NB-Fi comprises the bands of frequencies sub-1 GHz with bandwidth of 3MHz in Europe and 26 MHz in Americas [12]. Table 2.4 presents examples of LPWAN, considering channel bandwidth for an IoT device, range and transmission power according to [31].

| Field | Major Applications |
|---|---|
| Smart Environment | Water quality, air pollution reduction, climate temperature rise reduction, forest fire, landslide, animal tracking, snow level monitoring, and earthquake early detection |
| Smart Water | Water quality, water leakage, river flood monitoring, swimming pool management, and chemical leakage |
| Smart Metering | Smart electricity meters, gas meters, water flow meters, gas pipeline monitoring, and warehouse monitoring |
| Smart Grid and Energy | Network control, load balancing, remote monitoring and measurement, transformer health monitoring, and windmills/solar power installation monitoring |
| Smart Agriculture and Farming | Temperature, humidity, and alkalinity measurement, wine quality enhancement, smart greenhouses, agricultural automation and robotics, meteorological station network, compost, hydroponics, offspring care, livestock monitoring and tracking, and toxic gas levels |

**Tab. 2.3.:** Examples of IoT Networks applications[32]

In [32], the authors reviewed LPWAN challenges regarding bandwidth, priority structures, mobility and adherence to standards. The authors defined a design guideline for LPWAN networks with characteristics such as traffic, capacity and densification, energy efficient, coverage, location identification, security and privacy, among others. We highlight that the authors define interference management, Time Difference of Arrival (TDoA) and reliable and energy efficiency communication as desired design considerations. By improving the performance, energy efficiency, and scalability

| IoT Networks | Operation frequencies | Channel bandwidth | Range | Tx Power (dBm) |
|---|---|---|---|---|
| Sigfox | Sub-1 GHz EU 865-868 MHz Americas 902 -928 MHz | 100 Hz | 10km (urban) 50km (rural) | 14 (UL), 27 (DL) |
| NB-Fi | Sub- 1 GHz EU 868 | 100 Hz | 0-16km (urban) >50km (rural) | 14 (UL), 27 (DL) |
| LoRaWAN | Sub-1 GHz EU 865-868 MHz Americas 902 -928 MHz | 125/250kHz(UL) & 125 kHz (DL) in EU, 125/500KHZ (UL) and 500KHz (DL) Americas. | 5km (urban) 15km (rural) | 14 (UL), 27 (DL) |

**Tab. 2.4.:** IoT Network Examples [31]

in IoT applications, the authors recommended the use of 5G cellular technology.

In [31], challenges and open problems in LPWAN are presented. The research identified issues such as coexistence, massive access scheme, energy efficiency, and interference management, among others. Regarding the massive access scheme, the authors discussed the lack of radioelectric spectrum for massive access. They considered that the interference management for massive IoT access is open issue.

According to [33], the main challenges are scaling networks to a massive number of devices, interference control and mitigation and location, among others. Moreover, the authors discuss research directions about scalability for LPWAN as channel diversity, opportunistic spectrum access, and adaptive transmission strategies with cross-layer systems. Regarding interference control and mitigation, the authors highlighted the future problem of the exponential increase of IoT services. Finally, the localization is considered an open issue for LPWAN that requires techniques for improving the accuracy.

### 2.1.2 Dynamic Spectrum Access

The DSA over primary users is focused on improving the unused spectrum in some bands of frequencies as shown in researches [34, 35, 36, 37, 38, 39, 40, 41, 42]. For avoiding interferences with primary users, there are different types of radios for accessing to holes. The holes in Figure 2.2 are presented, which are in frequency, time or power in a geographical zone. Therefore, the opportunist secondary users are designed to access to the frequency holes without interfering with primary users through smart techniques such as detection algorithms or spectrum aware schemes and policies by the body spectrum regulators. The DSA mechanism over licensed bands is presented in literature as a new alternative for improving the radioelectric spectrum use efficiency [43, 44]. In this dissertation, we specifically focus on DSA over TV frequency bands for massive IoT devices operating as secondary users.

The transition to digital television generated an unoccupied spectrum over TV primary users. The regulator bodies follow challenges about spectrum use, they developed a regulation for DSA over TV bands. DSA gives a temporary license to opportunist secondary users over TV primary users. On the one hand, the license depends on possible changes in the frequency plan used by broadcasters. On the other hand, an available list of channels have changes according to the location of opportunist secondary users. The spectrum holes over TV bands are considered holes in frequencies in a geographical zone.

DSA over TV bands policies are interested in providing unused band of frequencies for opportunistic secondary users. The aim of these regula-

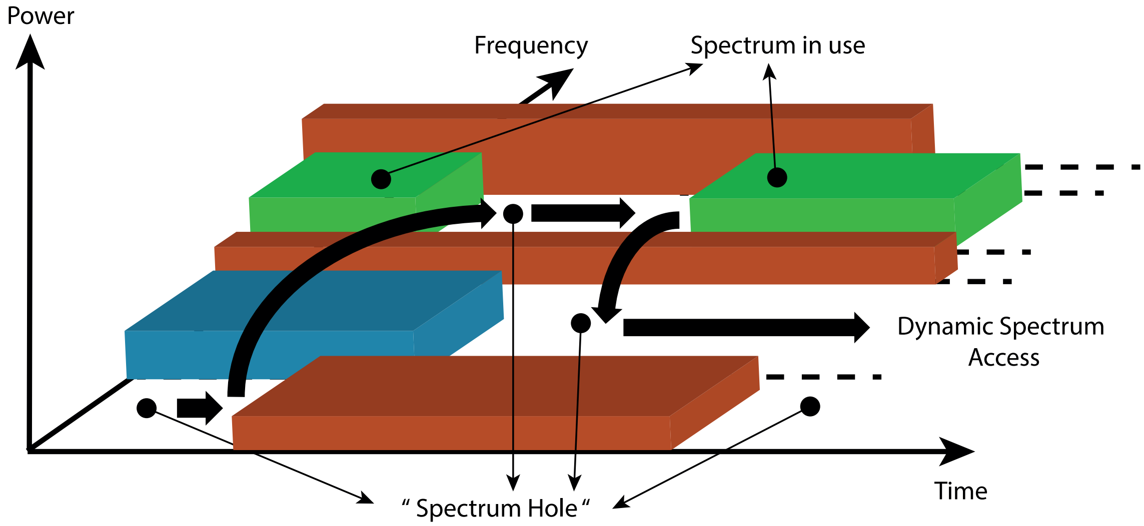


Fig. 2.2.: Spectrum hole concept [45]

tions is shared on the radioelectric spectrum, only when the opportunistic secondary users make no interferences to TV primary users.

Since TVWS devices have to avoid interference with primary Television (TV) users, it is important that devices follow the radioelectric spectrum regulatory policies. According to these policies, TVWS networks must have a minimum of three components, namely GLDB, Master Device (MD) and Slave Device (SD). A set of rules for spectrum access are in the GLDB, which in turns provides the available list of channels, taking into account the device location, the allocated frequency for TV primary users and co-canal and adjacent interferences analysis. A MD requests the available list of channels to the GLDB and, at the same time, interacts with the GLDB on behalf of the SD.

Regarding policies, the Federal Communications Commission (FCC) in the FCC 04-113, FCC 08-260, FCC 10-174 and FCC 14-144 defined an unlicensed operation in the TV Broadcast Bands [46]. The TV stations operate on 6 MHz channels designated from channels 2 to 51 in four bands of frequencies in the Very High Frequency (VHF) and Ultra High

Frequency (UHF) regions of the radioelectric spectrum (54-72 MHz, 76-88 MHz, 174-216 MHz and 470-698 MHz). The fixed devices may operate on any available channel within that range, while personal/portable devices may operate only on channels 21 to 51, excluding channel 37 in the following frequencies: 512-608 MHz (TV channels 21 to 36) and 614-698 MHz (TV channels 38 to 51)[46]. The fixed White Space Device (WSD) can utilize an external antenna up to 30 meters above the ground and is allowed to transmit with a higher power up to 4W of Effective Isotropic Radiated Power (EIRP) with a 6 dBi antenna gain. These devices cannot be located at a site where the ground Height Above the Average Terrain (HAAT) exceeds 250 meters [47]. Personal/portable devices are limited to a maximum EIRP of 100mW or 40mW if the device is operating on an adjacent channel to an occupied TV channel [47].

According to [48], Ofcom defined TVWS in a band of frequencies from 470 to 550 MHz and from 614 to 790 MHz. Besides, Ofcom verified the commercial implementation of the WSD by involving the regulatory bodies, industry stakeholders, and users to verify the process. Ofcom has the technical objective of the correct functioning of WSD, the operation of the GLDB, calculations and operation of the database, the programming of special events in Digital Terrestrial Television (DTT), interference management, and coexistence[49].

Regarding the European regulation in [50], the report number 159 by the Electronic Communications Committee (ECC) within European Conference of Postal and Telecommunications Administrations (CEPT) assumes the GLDB operation in the 470-790 MHz frequency band. In the report, three cognitive techniques are proposed: sensing, GLDB and beacon. In addition, the report number 236 defines the main functions of the framework for TV WSD into the GLDB and TVWS applications [51].

In the Colombian case [52], devices can use 470-698 MHz frequency band for two types of communications: point to point and broadcast with bandwidth equal to 6MHz per channel. Similarly in the communication system, the SD has to use the same transmission channel of the device associated with the MD. Before they have their own available list of channels, the network uses a belonging channel (e.g. ISM bands). Furthermore, the MD can not start neither continue its operation when the list of available channels delivered by the GLDB is empty, thus sending an error signal to cease the operation. Moreover, the SD will not be able to start neither to continue its operation when there is no communication with the MD or when its list of available channels have no common entries with the MD.

The available list of channels, in Colombian study case, is calculated taking into account data UIT-R p.1546-6, minimum electric field of the TV networks deployments, margin of protection TV channel in co-channel and adjacent channels, assigned TV channel in each municipality. The GLDB is designed according to some regulatory policies and constraints such as HAAT limitation, prohibited zones and primary user protection. When the GLDB system returns the available list of channels to TVWS devices, if the link between the SD and MD has channels in common, both devices can establish communication over TVWS. The number of available list of channels is shown in Annex C. The results was obtained with consults in whole positions (latitudes and longitudes) from Colombia with a resolution equal to 200 mts. Hence, we can conclude that 87.37% Colombian territory has more than 4 available list of channels and it is important because the lack of radioelectric spectrum massive IoT services and these TVWS can face this challenge.

## 2.2 Massive IoT Services

In terms of types of IoT services, there are different definitions according to the number of sensor in the network, criticality, and latency. In the International Mobile Telecommunications (IMT) for 2020 by ITU, some use cases are defined, such as Enhanced Mobile Broad Band (eMBB), Massive MTC (mMTC) and Ultra-Reliable and Low Latency Communications (URLLC) [53]. Regarding mMTC or Massive IoT (mIoT), in this use case there is a huge number of connected sensors with a performance and operational requirements that consider low-cost and low-complexity device types, as well as wide extension of coverage. Moreover, in a project of the Mobile and Wireless Communications Enablers for Twenty-twenty (2020) Information Society-II (METIS) [54], [55], IoT services are identified as critical Machine-Type Communication (MTC) and mMTC.

The critical MTC types (also called uMTC for Ultra-Reliable) are represented by industrial applications, such as smart grid, traffic safety and control and "Tactile Internet". The communication networks should be ultra reliable, have very low latency ($< 1$ms) and offer very high availability. In this context, reliability is defined as the capability of guaranteeing successful message transmissions within a defined delay budget. In [56], a value of 0.9999 (factor of availability [99.99%]) is given for critical MTC and the availability factor is defined as the proportion of the time that a device has in order to use the service. In [56], an availability factor of 0.999 is considered, but other works [57] considered a more precise factor with 9 digits of precision. Robust transmission, active channel assignment, and multi-level diversity are required to guarantee the expected level of availability and reliability for critical MTC applications.

The mMTC types are represented by the number of applications based on sensors and actuators. The mMTC service provides wireless connectivity for tens of billions of network-enabled devices [54]. The constraints are different from critical MTC: low cost, low energy ($> 10$ years on AA battery [55]), generally no strict time constraint and small data volume (20 to 125 bytes according to TC11 [56]), but with a massive number of terminals (tens of billions of network-enabled devices, typically in the order of 100.000 per access point according to [54]). Therefore, all protocols in the connectivity chain for IoT services must have low overhead and be scalable. In summary, the mIoT or mMTC services are characterized by a large number of sensors and actuators, low-complexity and energy-constraints. Besides, the mIoT periodically sends short packets with relaxed delay requirements [58].

Regarding massive IoT challenges, in [13] the authors classified them for massive IoT cellular networks according to devices-level challenges and network-level challenges. On the one hand, in device-level challenges, the dynamic traffic and random access time in massive IoT must have mixed traffic models with event-driven and periodic traffics. Besides, the contention-based radio access schemes have to coordinate the massive number of devices with a density of about $10^6$ devices per km2 in an urban environment and with latency of about 10 seconds or less on the uplink. In terms of hardware requirements, ultra-low device complexity and low battery lifetime are important features for mIoT taking into account that the devices have to be inexpensive and the battery last more than 10 years. As far as the signaling is concerned, the mIoT networks have to avoid long payloads, and manage efficient channel coding and higher resource granularity. On the other hand, at the network-level, there are diverse QoS requirements, networks congestion, highly scalable network and wide coverage, which are challenges in the design of networks for massive IoT.

### 2.2.1 Cognitive Radio in IoT

Considering the challenges about IoT networks, the cognitive radio has gained momentum because this technology could improve the radielectric spectrum access. The cognitive radio aim is found spectrum spectral holes, in Figure 2.2 is shown the spectrum hole concept, they could be in time, frequency and power.

The cognitive radio is a technology that allows the access to unused band of frequencies as spectrum holes. There are different type of radios and they depend on the radioelectric spectrum access. On the one hand, there are radios whose use spectrum sensing algorithms to find spectrum holes. Moreover, the radios must avoid interference with primary user with sensing techniques. In addition, the holes can be in time, frequency and power in this type of radios. On the other hand, the policy-based radios obtains the holes considering spectrum policies by body regulators.

According to [11], there are three types of cognitive radios such as policy, procedural, and ontological cognitive radios. First, policy cognitive radio is based on spectrum regulators policies and their constraints are focused on avoiding interferences with the primary user Policy radio usually have no reasoning engine. Then, procedural radios are based on sensing algorithms for accessing the radioelectric spectrum. Finally, ontological cognitive radios are based on a reasoning engine and a learning engine.

In terms of cognitive radio in IoT networks, in [9] the authors described reasons why IoT networks needs to integrate cognitive radio taking into account interference, coexistence and scalability issues, due to a lack of bandwidth in ISM bands for IoT applications.

In [10] a dynamic spectrum access is proposed for Internet of Things services. The authors devised a spectrum channel contention for improving the capacity of unlicensed users over licensed users without interferences through the spectrum sensing, taking into account procedural radios.

In [11], the authors present a review about M2M applications and they devise a taxonomy for IoT and cognitive radio approaches which classified into two categories such as flexible and efficient networking and tackling heterogeneity the applications of cognitive radio for IoT. In Figure 2.3 the taxonomy is shown and considering the flexible and efficient networking category, spectrum efficiency as an issue that cognitive radio could solve and it is the aim in our proposal.

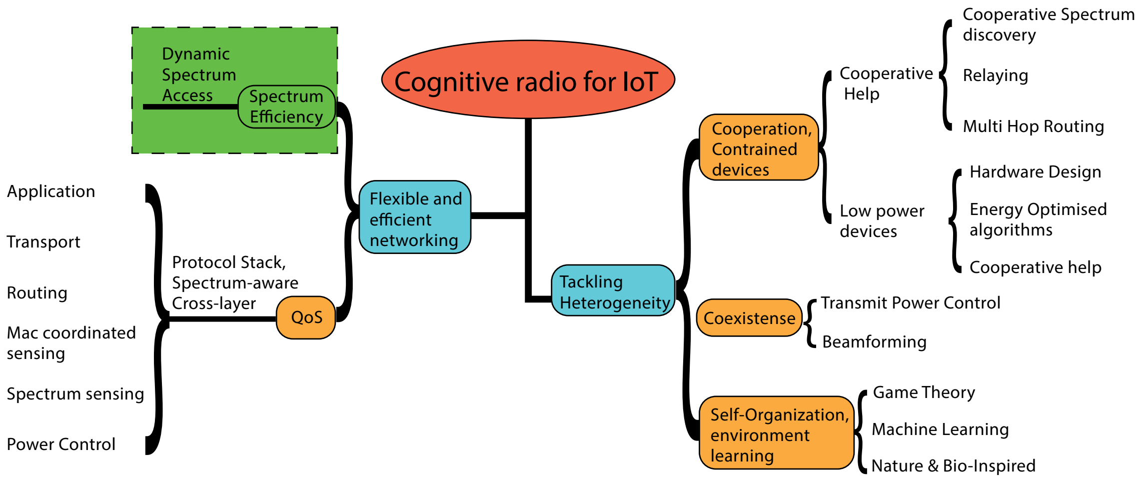


**Fig. 2.3.:** A Taxonomy for Cognitive Radio and IoT [11]

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We highlight the spectrum effiency issue because it is focused on DSA. We realize that QoS has been developed with protocol stack, spectrum-aware and cross layer systems. However, the QoS over DSA is a concept that needs to be explored. Since our proposal consider the lack of radioelectric sprectrum for IoT with band of frequencies less than 1GHz, the DSA is the suitable scheme. Moreover, the QoS is an important challenge in massive IoT services. A review about QoS of massive IoT services over TVWS is presented below.

### 2.2.2 QoS of Massive IoT services over TVWS

Regarding frequency bands in IoT services, the choice of band type of the radioelectric spectrum influences the level of QoS. Licensed bands can guarantee QoS thanks to the protection of interferences. Unlicensed bands guarantee no level of QoS since the devices have no exclusive use of a part of the spectrum. In the dynamic access spectrum, the devices must have authorization for the use of a frequency band througth GLDB in TV Bands. Moreover, in DSA devices have no exclusive use of a part of the spectrum as ISM bands. However, there are some researches about QoS in IoT over

TVWS that improve the level of different features and these researches are focused on only in critical services. In Table 2.5 the description and QoS features for IoT over TVWS are presented.

| References | Description | QoS features |
|---|---|---|
| Sadip [59] | The authors proposed a system allocation for Vehicle-to-Vehicle (V2V) communication | Throughput optimization with mobility critical schemes in adhoc manner. |
| Ngoc [60] | The research presents a QoS metrics modeling for Smart Grid services | QoS metrics for mission-critical schemes |
| Naveed [61] | In this work an architecture is proposed in unlicensed bands by operator for using free spectrum in Smart Grid application | High priority channels for critical services |
| UlHassan [62] | In this research a framework is proposed. The framework is focused on Spectrum leasing over TVWS in Smart Grid application | High priority TVWS channels for critical services |
| Angela [63] | In the research an analytical framework is proposed. The framework is focused on switching between TVWS and ISM bands in Smart Grid application | Outage rate optimization for critical services in urban scenarios |

**Tab. 2.5.:** Qos for IoT over TVWS

Due to massive IoT services features, such as delay-tolerance and low priority, the TVWS are suitable. Moreover, massive IoT services have challenges in scalability, interferences and QoS. However, in DSA can not be guaranteed QoS as licensed bands. However, it is important to develop networks and access mechanism with QoS constraints for driving the packet loss considering interference and scalability issues.

In the literature, to the best of our knowledge, there are no proposals about spectrum efficiency considering policy-based cognitive radio for massive IoT services, and QoS constrains. For these reasons, we propose a cognitive radio architecture for massive IoT services with DSA.

## 2.3 Remarks

In summary, the aim of this chapter is to provide an overview about the main concepts in our proposal, such as radioelectric spectrum, massive IoT services, DSA over TV band, cognitive radio for IoT and QoS for IoT over TVWS.

We conclude that IoT services need innovative solutions for increasing the radioelectric spectrum access in bands below 1 GHz. The DSA over TV bands is suitable for massive IoT devices because these bands are below 1 GHz. The cognitive radio faces IoT challenges, such as interference, coexistence and scalability issues, due to the lack of bandwidth in ISM bands for IoT applications and the high cost of licensed bands. Finally , the QoS for massive IoT over TVWS is still an open issue that needs to be addressed.

# 3

# Cognitive Radio Architecture

The cognitive radio architecture is a proposal focuses on facing challenges of massive IoT devices regarding radioelectric spectrum access. Due to exponential growth of massive IoT services, these services have to find other bands of frequencies below 1GHz which supports the access to IoT devices over radioelectric spectrum. Moreover, the access over band of frequencies below 1GHz faces new challenges for IoT accessing with requirements such as long range communication, low cost, low energy consumption, delay-tolerance and low priority.

In our proposal we considered TVWS as suitable band of frequencies for supporting the access challenges for IoT devices. Because, these band of frequencies are below 1GHz, they could have more bandwidth than ISM bands and they have no cost to access. In ISM band of frequencies below 1GHz the bandwidth 26 MHz and 3MHz in Americas and Europe respectively. In TVWS the bandwidth could be from 6MHz to 132MHz considering Annex C. However, TVWS is a DSA over TV bands and the opportunist secondary users (e.g. IoT devices) must avoid interferences with TV primary users and they have no exclusive use of a part of the spectrum.

For avoiding interference with a primary in policy-based cognitive radio, the IoT devices have to obtain the available list of channels providing by GLDB throughout a MD. In this cases, the access mechanism are in charge of MD which is an advantage for IoT constraints because the the MD could have techniques for improving the IoT access. Due to all the above, we proposed policy-based cognitive radio.

Since the radio architecture is focused on policy-based cognitive radio, it avoids interference with the TV primary taking into account the body spectrum regulators policies. Particularly, when a IoT device wants to access to a TVWS has to communicate to MD through PAWS and the MD provides available list of channels from GLDB. The number of channels can vary considering the geographical zone, policies and TV primary user allocation frequencies, among others. Moreover, the IoT devices have to renew the available list of channels at least every 24 hours according to policies.

## 3.1 Overview

Our proposal has features such as long coverage, low energy consumption and short payload, which can be easily related to a LPWAN for IoT deployments. However, in the previous literature review, a complete quantitative comparison of the existing LPWAN technologies with our proposal is not possible since the main proposal is a cognitive radio analytical framework for massive IoT deployments over TVWS, which can be in general adapted to several network technologies. To better explain our approach, not a quantitative but qualitative comparison was made with the main LPWAN technologies, as shown in Table 3.1.

### 3.1.1 IoT Architectures over TVWS

Few works in the literature have addressed the deployment of IoT networks over TVWS. The work in [15] proposes an architecture called Sensor Network Over White Spaces (SNOW). The architecture, which is single hop, is based on the Distributed Orthogonal Frequency Division Multiplexing (D-OFDM) and Carrier-Sense Multiple Access (CSMA) mechanisms, where D-OFDM is used for managing the TVWS bandwidth and CSMA as the coexistence method. The SNOW architecture is based on

**Tab. 3.1.:** Comparative analysis with other IoT networks

| Networks | Type of frequency | Type of coverage | Frequency Band | Comments |
|---|---|---|---|---|
| SigFox Lora | Unlicensed | Continuous coverage nation-wide | Sub-GHz 865-868 MHz 902-924 MHz | Low cost but overcrowded frequencies |
| NB-IoT | Licensed | Continuous coverage nation-wide | 700-900MHz | High cost to use the frequencies |
| Our Proposal | Dynamic Spectrum Access over TV Bands | Local system | Sub-GHz 470-698 MHz | Obtain the list available channels from a GLDB Device positioning is mandatory |

one MD (i.e. base station) for archiving scalable and robust bidirectional communication between base station numerous nodes. The authors assumed that the network base station knows all the end device locations either through manual configuration, which only applies for static sensor nodes, or using some existing Wireless Sensor Network (WSN) localization based on ultrasonic techniques, which do not necessarily guarantee low energy consumption for IoT devices. Furthermore, the architecture proposal considers no use of QoS variables for defining the network service and deployments areas. In Figure 3.1 is shown SNOW radio architecture.

The awareness that we observed in this architecture are: (i) the architecture uses only one base station (i.e. centralized process), in this cases each sensor have to request for available list of channels independently which has challenges in scalability and long payloads for massive IoT services, (ii) trilateration is not considered in this architecture, (iii) the CSMA mechanism for massive IoT services has challenges in energy consumption, and (iv) QoS constraints are not considered in this architecture.

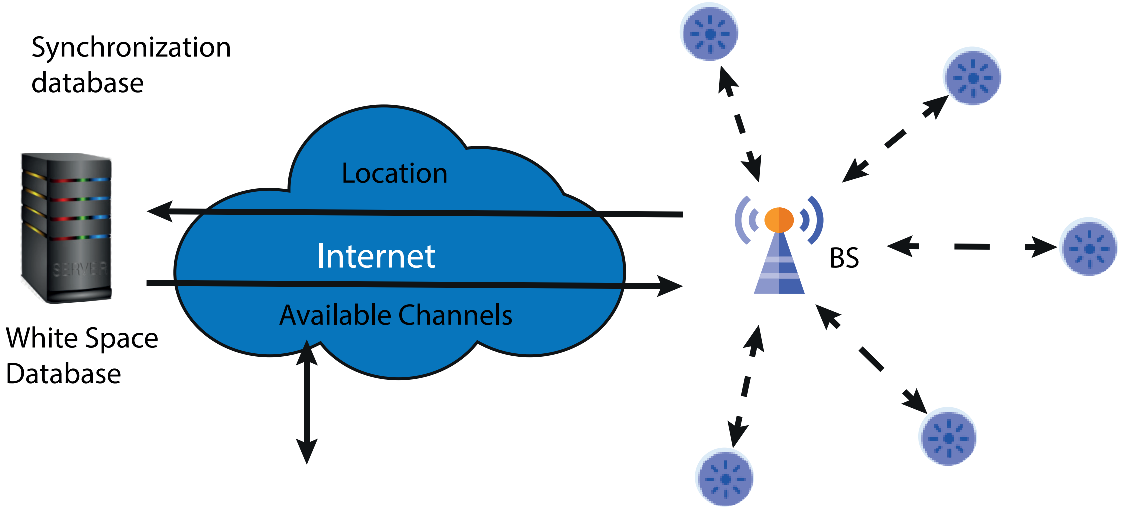



Fig. 3.1.: SNOW Architecture

Weightless is a radio architecture that supports IoT devices over TVWS [17]. The architecture is focused in a services with charged per requirement. Moreover, Weightless supports a large number of terminals. In Figure 3.2 is shown Weightless radio architecture. The awareness in this architecture are: (i) the architecture is based on one base station, (ii) the messages for obtaining the available list of channels are not considered, and (iii) an access mechanism with QoS constraints are not defined.

In [16], a framework with dynamic spectrum management for M2M in LTE-A is defined. This work proposed a system considering the radio spectrum policy and spectrum sensing techniques for M2M over LTE-A. This study considers no IoT constraints such as low cost, low energy consumption and scalability.

The awareness in this architecture are: (i) the architecture is based on one base station, (ii) the spectrum sensing is a technique that might use for DSA, however, the GLDB has the available list of channels considering interference with primary users, (iii) the messages for obtains the available list of channels are not considered, and (iv) an access mechanism with QoS constraints are not defined.

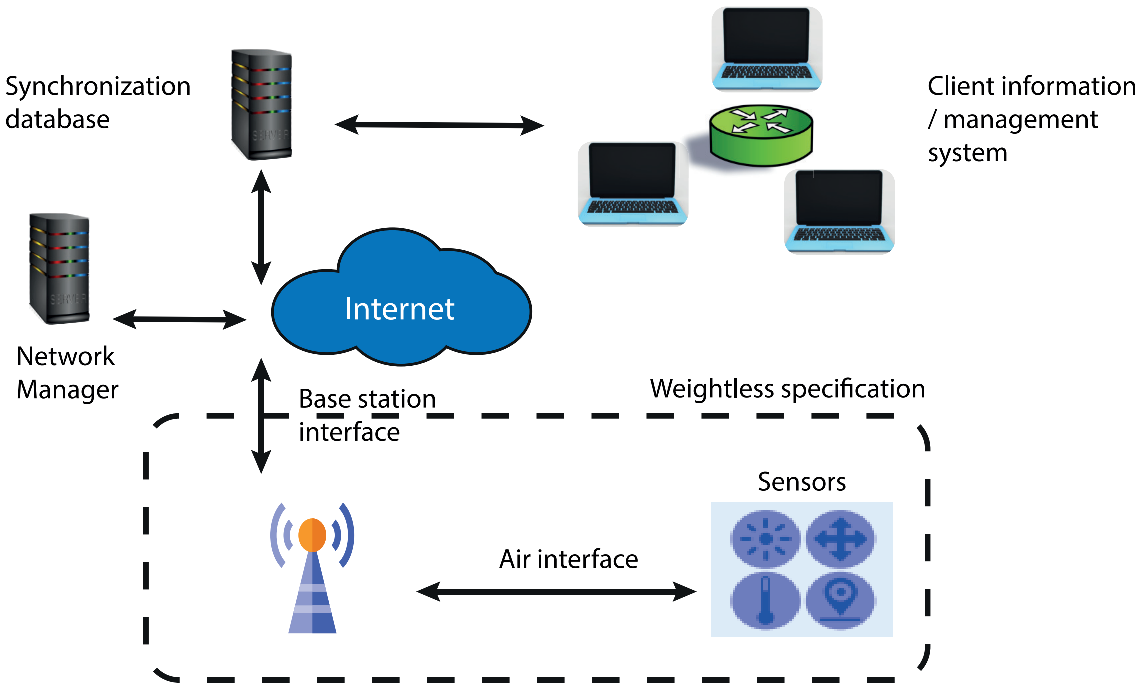



Fig. 3.2.: Weightless Architecture [17]

## 3.2 Cognitive Radio Architecture

Due to the lack of spectrum for massive IoT services, we propose a cognitive radio that is based on government policies. The DSA in this case depends on GLDB for obtaining the available list of channels. The available list of channels is provided considering the geographical positions (latitude and longitude) from GLDB.

Our proposal is focused on local system in open areas, because according to government policies, TVWS are mainly considered for improving connectivity in rural areas. Since the architecture uses TVWS, we propose massive IoT services over TVWS because the massive IoT services periodically sends short packets with relaxed delay requirements. As a result, the massive IoT services adjust their requirements to TVWS because the opportunist secondary users have no exclusive use of a part of the spectrum.

The cognitive radio architecture is shown in Figure 3.3. The architecture considers only GLDB to access to TVWS. Moreover in our network, there are four main components: GLDB, Central Unit (CU), MD and SD. The GLDB is the spectrum data base and it is compliant with PAWS protocol. The CU is in charge of removing duplicated packets. The MD is a tower-mounted transceiver equipped with a geolocation and synchronization receiver. There are at least 3 MDs in a geographical area. The SD includes a simple transceiver that is able to work in the TVWS spectrum but does not need to manage other bands of frequencies (e.g. ISM bands). Although our proposal can work with more than 3 MDs, we consider in the following only the 3-MDs case for the sake of simplicity. Note that the 3-MDs configuration is also the one that minimizes the deployment cost. We call the triangle formed by the three MDs the *deployment* triangle.

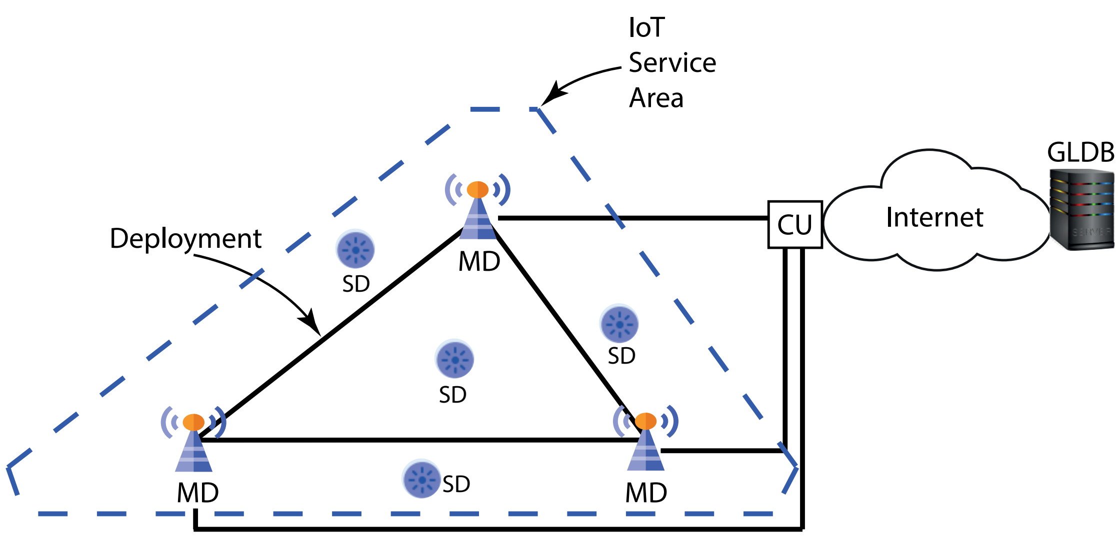



**Fig. 3.3.:** Radio Architecture

A *service area* is defined as a polygon-based area in which an SD can transmit data packets with a given maximum packet loss probability. As shown in Figure 3.3, the service area is generally a polygon larger than the deployment area. In our proposal, an SD is able to check whether it is in the service area and which frequency is able to use. Regarding the IoT devices positioning, the architecture guarantee the location inside of the *deployment*. When the devices are outside to *deployment* and inside to *service area*, they have to use Global Navigation Satellite System.

Due to the architecture definition, Mitola [64] defined an architecture as set of design rules by which a specific set of components achieves a specific set of functions in products and services that evolve through multiple design points over time. Our proposal the architecture has two main functions: (i) Coexistence between the massive IoT services and TV primary user, and (ii) To allow QoS for IoT massive services over TVWS.

Coexistence between the massive IoT services and TV primary user. The aim in this function is to provide the available list of channels to massive IoT services. The cognitive radio that is based on government policies and it depends on GLDB for obtaining the available list of channels. Thus, the available list of channels is provided considering the geographical positions (latitude and longitude) from GLDB. The challenges in this functions are focused on massive IoT services, since these services have a special requirements such as ultra-low device complexity and low battery consumption. Therefore, the function has a radio access mechanism with short payloads and polygons for broadcast transmission of the available list of channels.

To allow QoS for IoT massive services over TVWS. The architecture is based on polygons such as *deployment* and *service area*. In the *deployment* are located the MDs. However, the architecture has macro-diversity gain the deployment can be increased as *service area*. The *service area* are considered spectrum holes or TVWS in DSA. In our proposal, we defined two stages for allowing the QoS over massive IoT services. First, a packet loss model considering Signal Plus Noise Ratio (SNR) for defined the area (i.e. spectrum hole) of the *service area*. Second, a packet loss model considering Signal to Interference Plus Noise Ratio (SINR) and macro-diversity gain.

In Figure 3.4 the cognitive radio architecture attributes are presented. First coverage, our proposal is focused on this coverage because the TVWS are developed for connecting rural areas or urban areas as show in Annex C. Moreover, In rural and urban areas are suitable IoT fields such as smart agriculture and smart environment. These fields have applications such as water quality, air pollution reduction, forest fire, landslide, earthquake early detection, smart greenhouses,agricultural automation and robotics, and toxic gas levels, among others.

Capacity, the proposal is scalable because the available list of channels is transmitted through a broadcast message inside of the *service area*. The architecture has beacon messages from MD to SD. In PAWS the SD start the communication with messages with long payloads, for this reason, we proposed a novel mechanism based on beacons.

Low Power, PAWS is based on JavaScript Object Notation (JSON) messages and they have long payloads Annex B. In our proposal with beacon messages, the MD send the initial communication and that avoid long payloads in the SD. Moreover, we propose new messages to face the challenges of the payloads.

Enhanced characteristics in our proposal are focused on QoS constraints. We design the *Service Areas* considering packet loss model in the areas and Macro-Diversity Gain for driving the packet loss probability with a load network.

Moreover, the architecture is based on a radio access mechanism. The mechanism has the next features: (i) the available list of channels is provided to SDs (i.e. IoT devices) in the *service area* considering IoT constrains, (ii) the mechanism is based on PAWS for providing the available list of channels from GLDB, (iii) *deployment* and *service area* polygons are defined considering QoS constraints, and (iv) the macro-diversity gain is applied in the mechanism.

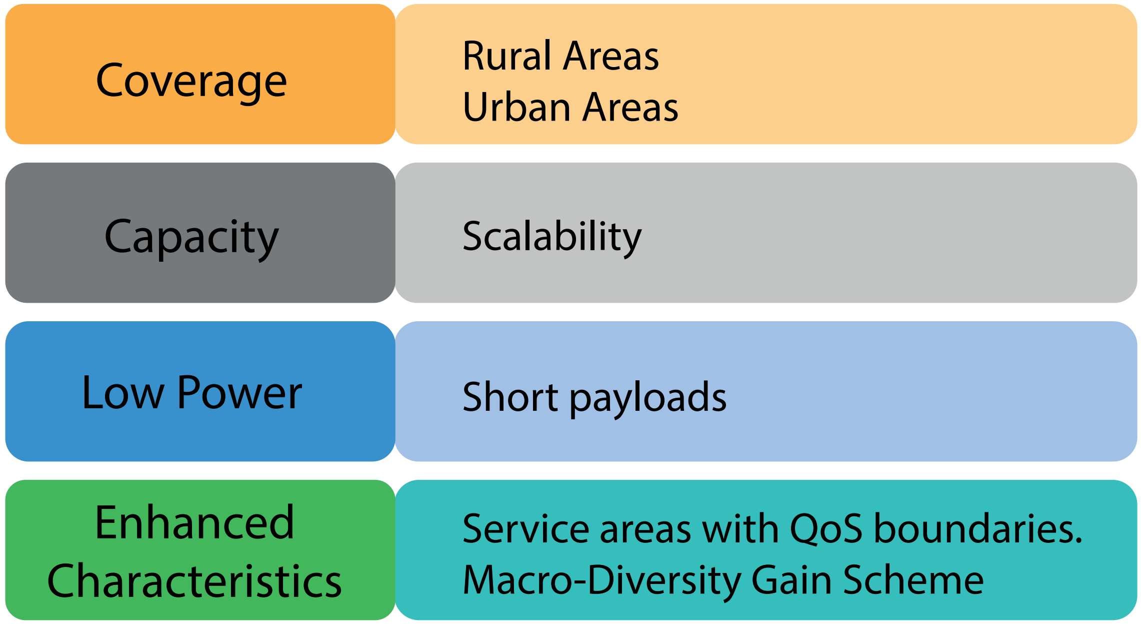



**Fig. 3.4.:** Cognitive Radio Architecture Attributes

## 3.3 Remarks

In this chapter, we presented a review about IoT over TVWS architectures. We concluded that IoT architectures over TVWS are based on a centralized scheme and these proposals have no QoS constraints.

Consequently, a novel cognitive radio architecture for massive IoT with DSA is proposed. The key point of our proposal was to deploy several MDs (3 or more) that are synchronized. A higher number of MDs produce a better the performance. We considered the minimum number, which is 3 and thus gives *deployments* and *service areas*. Moreover, our proposal had a radio access mechanism that: (i) provides the available list of channels considering IoT constraints, (ii) considers QoS constrains for defining the *deploymemts* and *service areas*, and (iii) is based macro-diversity gain access.

# 4

# Radio Access Mechanisms for Massive Internet of Things Services over White Spaces

## 4.1 Overview

TVWS networks are based on DSA techniques. These techniques find access to available frequencies over licensed bands, such as TV bands. The access mechanism avoid interferences with users in licensed bands, namely, primary users. In the case of TV bands, there are policies defined for establishing DSA over these bands of frequencies. These policies are developed considering body spectrum regulators through GLDB for coexisting with TV primary users. Moreover, the TVWS users, namely, opportunistic secondary users (i.e. IoT devices), must have the available list of frequencies channels to access TV bands. In our research, we are focused on how the massive IoT services obtain the available list of frequencies for coexisting with the primary user. Finally, the access mechanism considers QoS constrains for defining the *deploymemts* and *service areas*, and is based macro-diversity gain access.

### 4.1.1 PAWS

PAWS is a recommendation, it is defined by IETF [65]. The aim of this protocol is to allow any kind of device to exchange information with a GLDB in order to accomplish the spectrum policy. The network entities in this protocol are master and slave devices where the MD has access directly with GLDB and it sends a request on behalf of the SD. The protocol is based on JSON messages [66], also in PAWS, there is a special protocol JSON Remote Procedure Call (RPC) [67].

PAWS has functionalities, namely, initialization, device registration, available spectrum query, device validation and spectrum use. In Figure 4.1, we show the PAWS sequence. In addition, there are messages such as INIT, REGISTRATION and AVAIL SPECTRUM that can not use TVWS frequencies because the MD and SD do not have available list of channels yet. For this reason, the network has to use other band of frequencies as ISM bands. Moreover, the PAWS geolocation information may be a single point or a region described by a polygon [65]. When the MD or SD received the available list of channels, the devices can use the channels taking into account a timestamp defined by PAWS. For instance, in Request for Comments (RFC) 7545 [65], the timestamp is 24 hours. Furthermore, when the timestamp is over the devices have to renew their available list of channels.

In terms of disadvantages of of PAWS for massive IoT services, we can highlight the next challenges: (i) long payloads, (ii) the devices have to report their locations and they need bands of frequencies as ISM for first access to GLDB before to know the available list of channels, and (iii) scalability, because each SDs must request independent their available list of channels.

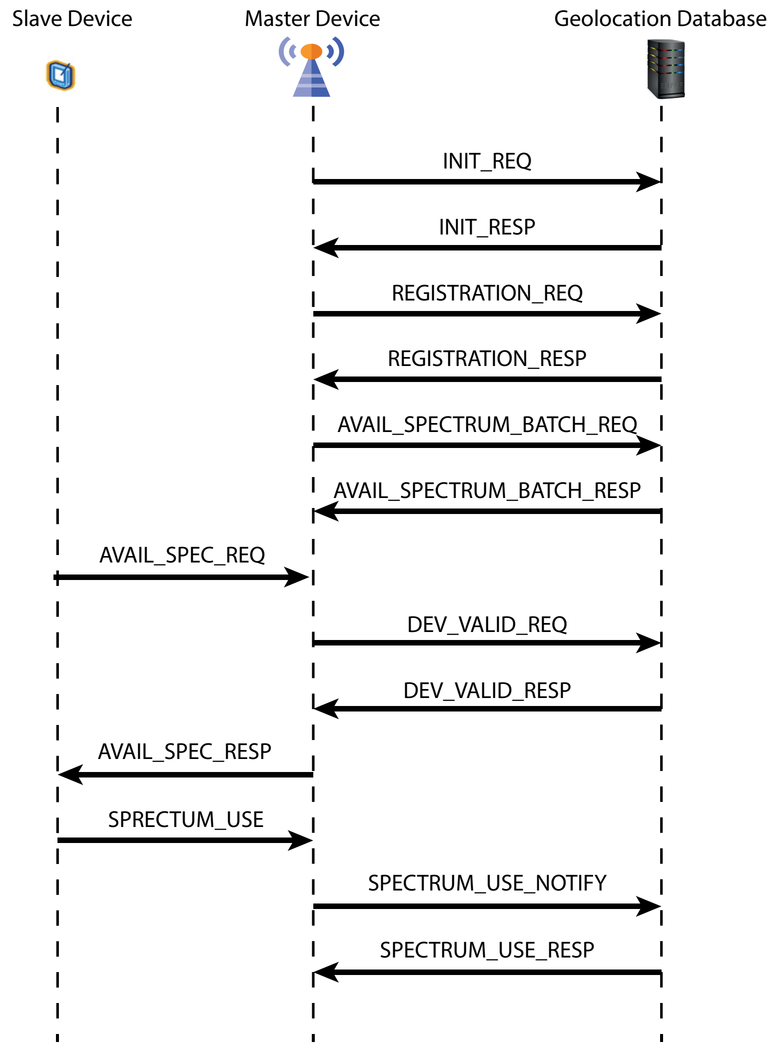



Fig. 4.1.: PAWS Sequence

## 4.2 Radio Access Mechanisms for Massive Internet of Things Services over White Spaces

In this section is presented the radio access mechanism for massive IoT services over TVWS. The novel steps propose for accessing to TVWS are shown in Figure 4.2. The MDs obtain the list of available channels from the GLDB by specifying the service area (i.e. the location of all points that define the polygon). Then, the MDs can start the transmission as they are sure that channels are available for SD devices (i.e. IoT devices).

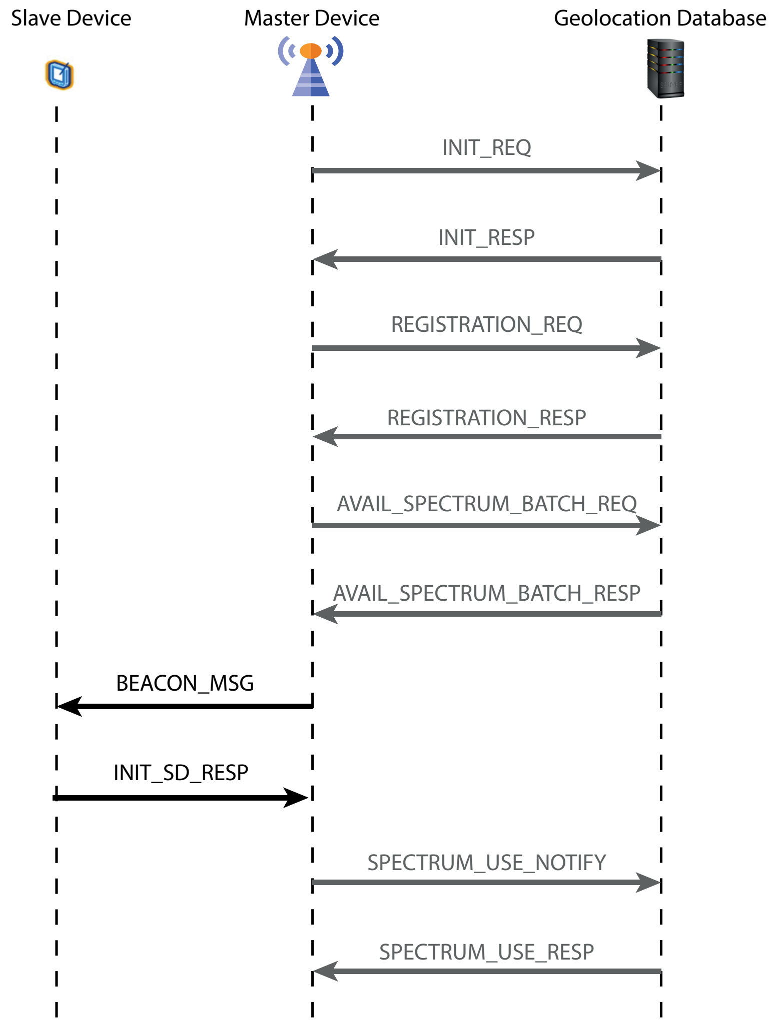



**Fig. 4.2.:** Sequences proposed of the radio access mechanism for only one Master Device of the three Master Devices

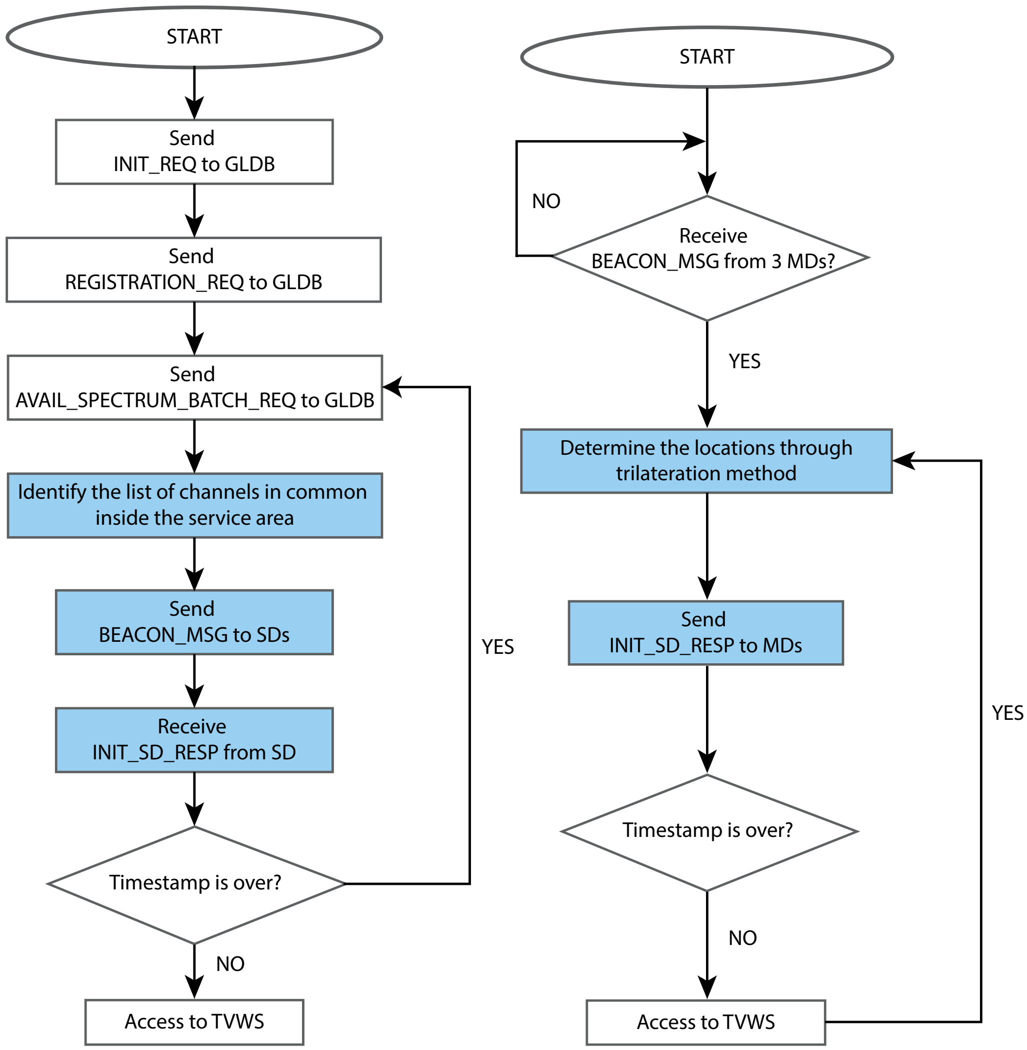
In these new sequences two messages between the SD and MDs are created, namely, BEACON-MSG and INIT-SD-RESP. The BEACON-MSG includes the available list of channels inside the service area, the MD locations and timestamp for access to TVWS. The INIT-SD-RESP has the SD location and available channel that the SD has selected. In Figure 4.3 we illustrate the steps when the IoT devices are inside to *deployment*. Moreover, in Annex B, we presented examples of the payload in PAWS and our proposal. When the IoT devices are outside to *deployment*, they have to use Global Navigation Satellite System. In this case, the SD can receive the messages for obtaining the available list of channels and then it sends INIT-SD-RESP.

The proposal has the next features: (i) the network is fixed, (ii) the three MDs work on the same frequency, (iii) a packet transmitted by a SD can be received by any of the three MDs.

### 4.2.1 Radio Access Mechanism Evaluation

In Figure 4.4 is shown the evaluation variables of the mechanisms proposed. The aim of the radio architecture is defined QoS constraints for IoT devices (*i.e.,* secondary opportunist users). The access mechanism has been devising considering the next features: (i) packet loss constraints in *deployments*, *service areas*, and (ii) packet loss in macro-diversity gain scheme. Therefore, the radio access mechanism for massive IoT services over TVWS define $p_o$ as outage packet loss probability equal to 1% for defining QoS constraints considering *deployments* and *service areas*. Second, the macro-diversity gain access mechanism for massive IoT services over TVWS taking into account *deployments* and *service areas* which establish $p_s$ as packet loss probability considering macro-diversity gain in a load network.

The radio access mechanism has three stages. The first stage is a proposal to send the available list of channels in a *service area* considering beacon messages. The second stage considers the *service area* as boundary for defining the outage packet loss probability ($p_o$) equal to 1%. The third stage provided macro-diversity gain with three MDs for improving average packet loss with respect to a topology with a MD and our proposal with three MDs.




**(a)** Master Device. **(b)** Slave Device.

**Fig. 4.3.:** New steps proposal when the IoT device is inside to the deployment

The mechanism is based on our *deployments* and *service areas* proposed considering $p_o$ restriction as as shown in Figure 4.5. Moreover, we consider the distribution of nodes in a random process taking into account Poisson Point Process (PPP) and the boundary of the *service areas*. In addition, the link level transmission success probability is based on SINR. Regarding, packet loss characterization for radio access mechanism is focused on evaluating interferences into a slot of time. Considering the distribution of the number of packets sent in the same slot is a Poisson distribution.

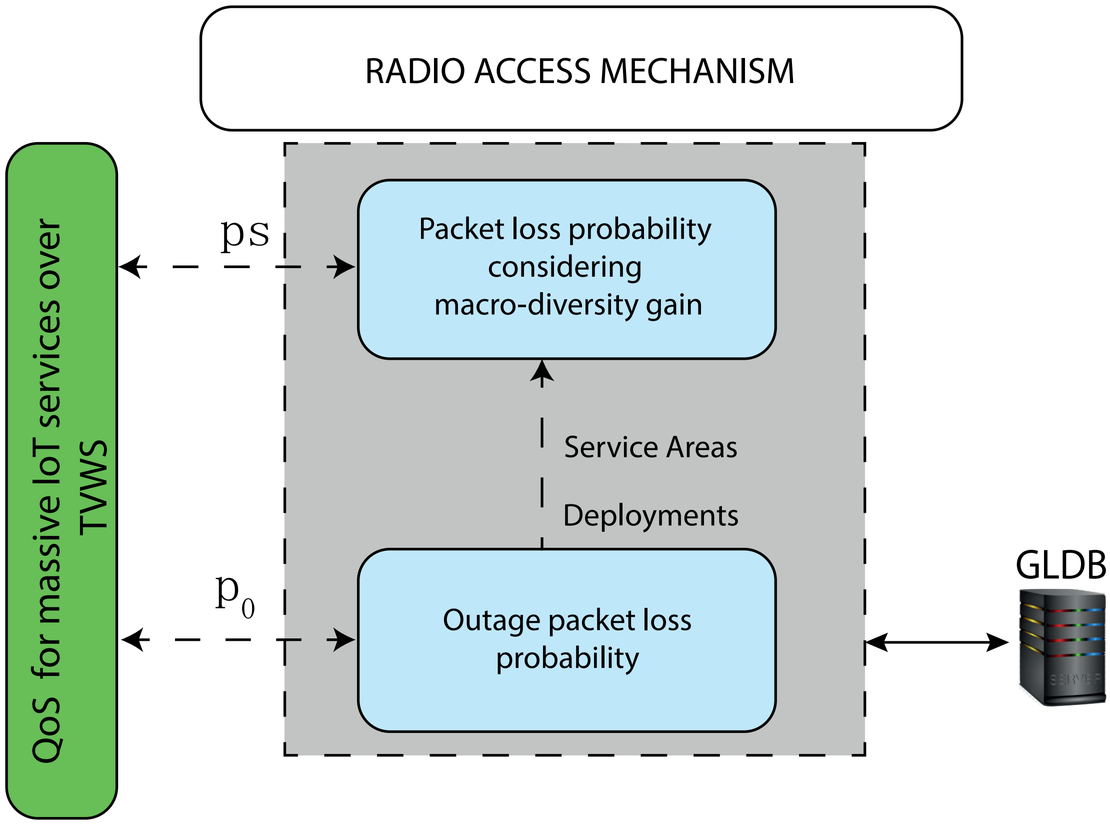



**Fig. 4.4.:** Radio Access Mechanism

Finally, the SD (i.e. IoT device) transmits the packets with macro-diversity gain to MDs.

### 4.2.2 Reference of comparison in the Radio Access mechanism

According to the review, we detect that the proposal PAWS and IoT over TVWS are focused on centralized MD process. In our proposal, we define to compare the topology with one MD and three MDs. In both stages of evaluations access mechanism, we define the areas of reference case considering a disk with only one MD. Moreover, the areas in the reference cases and in our proposal are equal for fair comparisons.

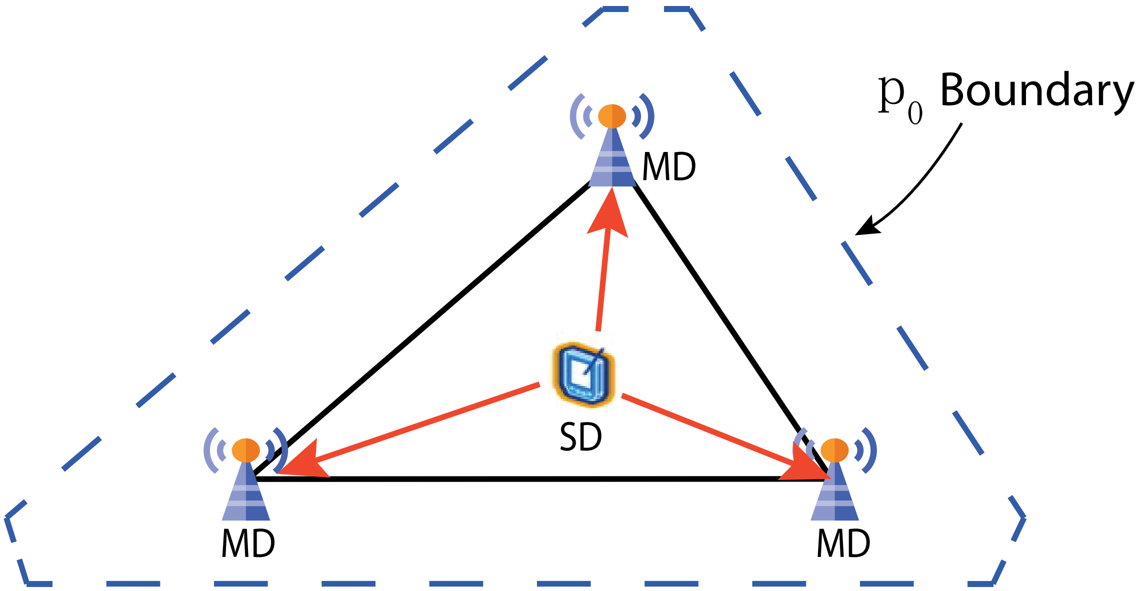



Fig. 4.5.: Macro-diversity Gain Access Mechanism

### 4.2.3 IoT devices Positioning

In our proposal, we applied Observed Time Difference Of Arrival (OTDOA) method for IoT devices positioning. As a result our proposal is based on beacon messages and we develop the devices positioning inside of *deployments*. Moreover, outside of the *deployments* the device must use Global Navigation Satellite System. In OTDOA method the SD measures the Time of Arrival (TOA) signal beacon received from multiple MDs. as shown in Figure 4.6.

The OTDOA method is based on the intersection between hyperbolas considering TOA. The intersection between hyperbolas is the desired SD (i.e. IoT device) location [68]. In this process is calculated the TOA for each MD as $t_1 = \tau_2 - \tau_1$, $t_2 = \tau_3 - \tau_1$, and $t_3 = \tau_3 - \tau_2$, let $\tau_1$, $\tau_2$, and $\tau_3$ be the TOA for each MD respectively. For instance, in Figure 4.7 the OTDOA method with two hyperboles is presented. The blue zone represents the method accuracy.

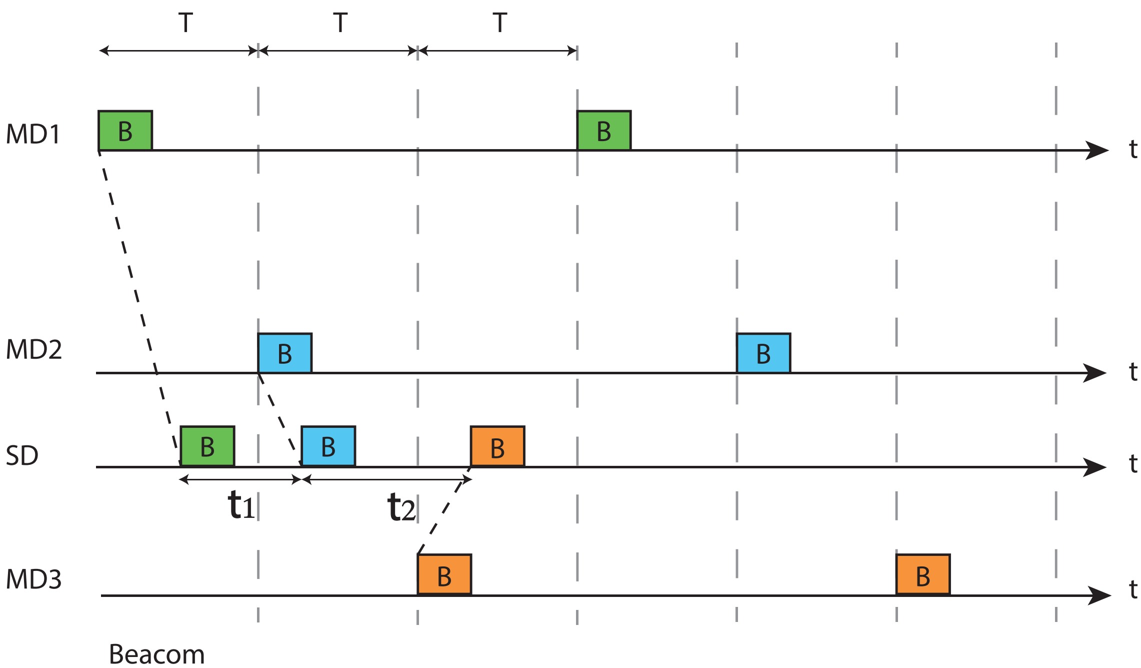



**Fig. 4.6.:** Beacon messages

Each MD transmits a beacon message in a synchronized round robin fashion. By using OTDOA, an SD can deduce its position without any dedicated geolocation receiver with a certain precision when it is inside the so called *deployment triangle*. OTDOA system degrades its precision when the SD it is located outside so a different geolocation system should be used.

Regarding IoT implementations, OTDOA is used by Laboratories as Ericson [69]. The authors presented simulation with OTDOA, they concluded that the technique is suitable for IoT, due to network scalability with beacons. Regarding the simulation results in outdoor IoT case, the error in position is less than 100 meters in the 70 *th* percentile.

In [70], the authors made a hardware implementation and a laboratory test-bed for IoT positioning with OTDOA. In indoor case, the authors obtained a error equal to 65.5 m with -116 dBm Rx Power.

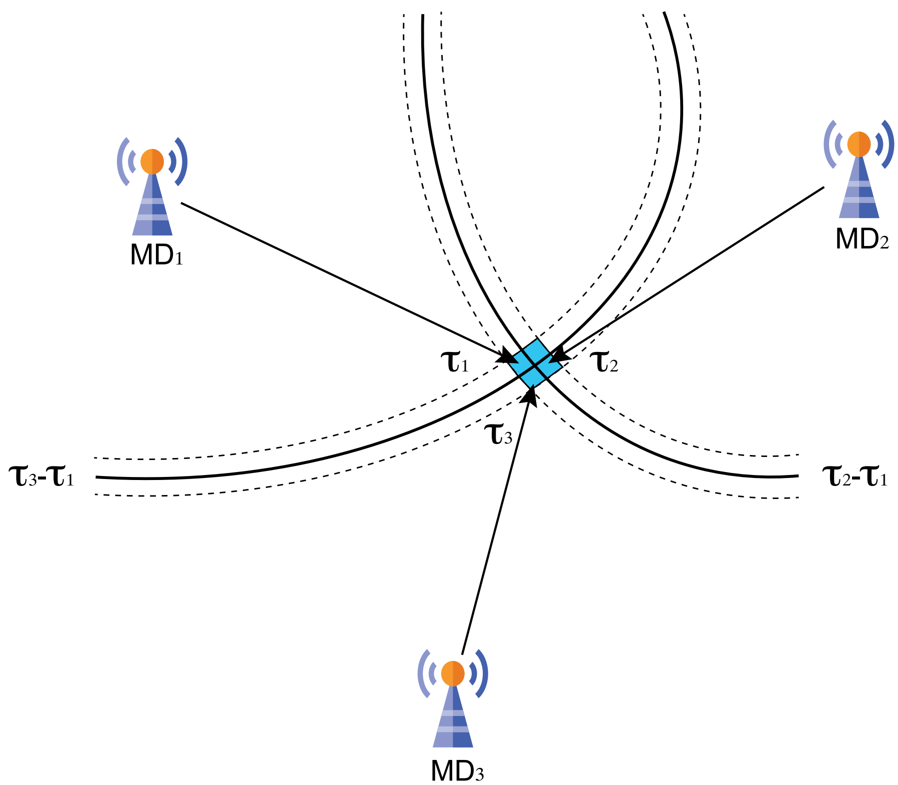



**Fig. 4.7.:** Observed Time Difference of Arrival System [68]

## 4.3 Remarks

This chapter presents a radio access mechanism for massive IoT Services over TVWS. Regarding the overview, PAWS has challenges such as long payloads, needs to use other bands of frequencies before knowing the available list of channels, and network scalability. Therefore, we proposed a novel access mechanism for facing these challenges.

The main contributions of this chapter are: (i) a novel radio access mechanism that is proposed based on PAWS standardized by the IETF, (ii) the mechanism that requires no geolocation receiver in the IoT devices inside the *deployments*, (iii) the proposal is based on beacon messages with short payload, (iv) mechanism is scalable, and (v) only uses TVWS bands for accessing to the available list of channels.

# 5

# Evaluation of the Radio Access Mechanisms for Massive Internet of Things Services over White Spaces

In this chapter, we evaluated the radio mechanism for massive IoT services over TVWS. First, we explore different MD deployments. Intuitively, deploying the MDs in an equilateral triangle maximizes the service area for a given target outage probability. However, operational constraints can make this operation difficult. Therefore, we consider any type of *deployment* triangles, compute the outage probability in the general case and then deduce *deployment* guidelines. Second, average packet reception models are explored. Moreover, we define the reference case considering shadowing and shadowing with fast fading, and establish a fair comparison with our *deployments* and *service areas*. Third, we define the *deployment* rules taking into account triangle inner angles. Next, we optimize the *services areas* and obtain the corresponding *service areas* rules. Then, we evaluate the IoT positioning inside our *deployments*. Finally, an analysis of a loaded system is presented considering macro-diversity gain.

## 5.1 Exploring different Master Device Deployments

We consider different deployments for the triangle formed by the three MDs. Let $(O, N, Q)$ be the triangle vertices and $\alpha$, $\beta$ and $\delta$ be the angles of the triangle. Let $D$ be the distance between $O$ and $Q$ as shown in figure 5.1.

Without loss of generality, we assume the relation between each angle is as follows:

$$0 < \delta \leq \beta \leq \alpha. \tag{5.1}$$

After a few elementary computation steps, it is easy to show that:

$$\begin{aligned} \text{if } \alpha \in \left[\frac{\pi}{3}, \frac{\pi}{2}\right) &\begin{cases} \beta \in \left[\frac{\pi-\alpha}{2}, \alpha\right] \\ \delta \in \left[\pi - 2\alpha, \frac{\pi-\alpha}{2}\right] \end{cases} \\ \text{if } \alpha \in \left[\frac{\pi}{2}, \pi\right) &\begin{cases} \beta \in \left(\frac{\pi-\alpha}{2}, \pi - \alpha\right] \\ \delta \in \left(0, \frac{\pi-\alpha}{2}\right] \end{cases} \end{aligned} \tag{5.2}$$

There is of course an infinite number of triangles. In order to have a set of representative cases, we consider only angles that are multiples of $\pi/12$. Thus $\alpha = \frac{\pi}{3} + \frac{k\pi}{12}$ with $k \in [0, 7]$. Considering possible values of $\beta$ and $\delta$ given by (5.2), we identified eleven different triangles that are listed in table 5.1.

The size of the deployment triangle is fixed by choosing $D$. The area $A_d$ is given by:

$$A_d = \frac{1}{2} D^2 \sin(\delta) \left[\cos(\delta) + \frac{\sin(\delta)}{\tan(\beta)}\right], \tag{5.3}$$

We propose in this section an approach for determining the deployments area taking into account the distance $D$ and the triangle angles. Figure 5.1 shows the approach.

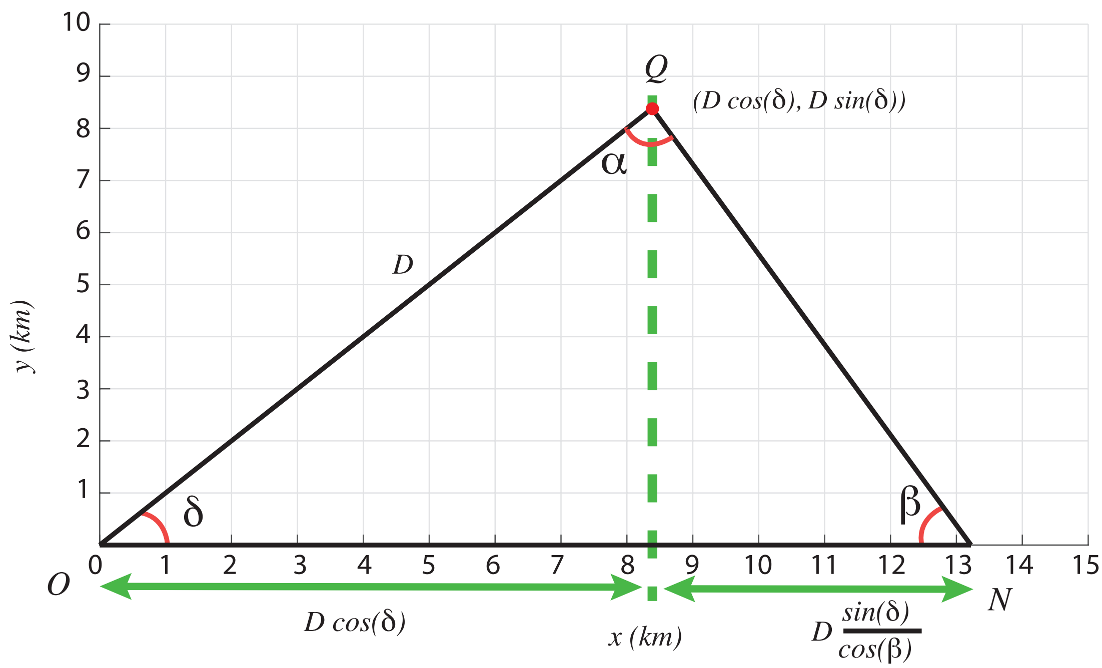



**Fig. 5.1.:** Area of the master device deployments

## 5.2 Propagation Model

The propagation channel follows the Okumara-Hata propagation model as shown in Annex A. Let $P_r$ and $P_t$ be the received and transmitted power, respectively.

$$P_r = P_t \left( \frac{d_0}{d} \right)^{\gamma} 10^{\frac{\sigma \xi}{10}} \chi \tag{5.4}$$

where $d_0$ is a reference distance related to the environment, $\gamma$ is the propagation exponent, $\xi$ is a standard normal random variable ($\xi = N(0,1)$), $\sigma$ is the shadow standard deviation in dB, $\chi$ is an exponential random

Tab. 5.1.: Deployment cases

| Triangle Index | $\alpha$ | $\beta$ | $\delta$ |
|---|---|---|---|
| 1 | $\pi/3$ | $\pi/3$ | $\pi/3$ |
| 2 | $5\pi/12$ | $\pi/3$ | $\pi/4$ |
| 3 | $\pi/2$ | $\pi/4$ | $\pi/4$ |
| 4 | $\pi/2$ | $\pi/3$ | $\pi/6$ |
| 5 | $\pi/2$ | $5\pi/12$ | $\pi/12$ |
| 6 | $7\pi/12$ | $\pi/4$ | $\pi/6$ |
| 7 | $7\pi/12$ | $\pi/3$ | $\pi/12$ |
| 8 | $2\pi/3$ | $\pi/6$ | $\pi/6$ |
| 9 | $2\pi/3$ | $\pi/4$ | $\pi/12$ |
| 10 | $3\pi/4$ | $\pi/6$ | $\pi/12$ |
| 11 | $5\pi/6$ | $\pi/12$ | $\pi/12$ |

variable. Note that the shadowing effect is taking into account by $\xi$ and fading by $\chi$.

Fading is due to multipath propagation and only occurs for narrow-band system. When the signal spectrum is larger than the coherence bandwidth, the multi-path effect is addressed by equalisation and factor $\chi$ can be removed from (5.4). We consider both cases (i.e. with shadowing and fading, with shadowing only) because our architecture does not have any restrictive assumption in the type of transmission technique.

## 5.3 Packet loss probability on one link

We assume low load conditions. Hence, there is no interference and only background noise. The SNR is given by:

$$\theta = \frac{P_r}{N}, \tag{5.5}$$

where $N$ is the background noise power.

Since we consider a simple reception model a packet is correctly decoded if the SNR is above a given threshold $\theta_T$. In this section, we consider only one receiver. Hence, the packet loss probability $p_{L,i}$ between a slave device and master device $i$ is given by:

$$p_{L,i} = \mathbb{P}\left(\theta_i < \theta_T\right). \tag{5.6}$$

where $\theta_i$ is the SNR on link $i$.

Combining (5.4) and (5.5) we get

$$\theta_i = \frac{P_t}{N}\left(\frac{d_0}{r_i}\right)^{\gamma} 10^{\frac{\sigma\xi}{10}}\chi \tag{5.7}$$

where $r_i$ is the distance between the slave device and master device $i$.

Rewritten (5.7) into (5.6) for a given value of the fading we have

$$\mathbb{P}\left(\theta_i < \theta_T \mid \chi = u\right) = \mathbb{P}\left(\xi \leq \frac{10}{\sigma}\log_{10}\left[\frac{\theta_t N}{P_t u}\left(\frac{r_i}{d_0}\right)^{\gamma}\right]\right), \tag{5.8}$$

thus,

$$\begin{gathered}\mathbb{P}\left(\theta_i < \theta_T \mid \chi = u\right) = \\ \frac{1}{2}\left(1 + \text{erf}\left(\frac{10}{\sqrt{2}\sigma}\log_{10}\left[\frac{\theta_T N}{P_t u}\left(\frac{r_i}{d_0}\right)^{\gamma}\right]\right)\right)\end{gathered} \tag{5.9}$$

which can be re-written as

$$\begin{gathered}\mathbb{P}\left(\theta_i < \theta_T \mid \chi = u\right) = \\ \frac{1}{2}\left[1 + \text{erf}\left(a_1\left(b_2 - \ln\left(u\right)\right) + \gamma \ln r_i\right)\right].\end{gathered} \tag{5.10}$$

with $a_1 = \frac{10}{\ln(10)\sigma\sqrt{2}}$ and $b_2 = \ln \frac{\theta_T N}{P_T d_0^\gamma}$.

The loss probability is the average for all fading values. Thus,

$$p_{L,i} = \int_0^{+\infty} \mathbb{P}\left(\theta_i < \theta_T \mid \chi = u\right) \exp(-u) du \tag{5.11}$$

When there is no fading, the loss probability is just given by (5.9) with $u = 1$.

## 5.4 Service area

For each location, the loss probability can be computed either by (5.9) or by (5.11). The outage probability $p_o$ is defined as the packet loss probability over a given area. The service area $S$ should fulfill QoS objective, which is defined as the largest area for which the outage probability is smaller than a given threshold $P_T$.

The service area $S$ is such that

$$p_o = \frac{\iint_S p_{L,i}\, ds}{S} \leq P_T. \tag{5.12}$$

## 5.5 Reference service area

The reference case with which we compare our proposal is made of one MD covering an area. As we assume omni-directional antennas, the service area is a disk and $R$ be the radius of this disk.

Equation (5.12) becomes

$$p_o = \frac{2}{R^2} \int_0^R p_L(r) r dr \tag{5.13}$$

where $p_{L,i}$ is rewritten $p_L(r)$ to make the dependency with distance $r$ clear and to avoid unnecessary indices.

Combining (5.10), (5.11) and (5.13), we get:

$$p_o = \frac{1}{R^2} \int_0^R \int_0^\infty [1 + \text{erf}\,(a_1\,(b_2 - \ln u) \\ + \gamma \text{ln} r)] \exp\,(-u) r\, du dr. \tag{5.14}$$

Switching the two integrals and using $x = r/R$, we get

$$p_o = \int_0^\infty \exp\,(-u) \int_0^1 [1 + \text{erf}\,(A(u) + B \text{ln} x)]\, x\, dx du. \tag{5.15}$$

with $A(u) = a_1\,(b_2 + \gamma \ln R - \ln\,(u))$ and $B = a_1 \gamma$.

As shown in [71], the inside integral can be easily computed. We thus have:

$$p_o = \frac{1}{2} \int_0^\infty \exp\,(-u) \Big[1 + \text{erf}\,(A(u)) \\ - \exp\left(\frac{1 - 2A(u)B}{B^2}\right)\left(1 + \text{erf}\left(A(u) - \frac{1}{B}\right)\right)\Big]\, du. \tag{5.16}$$

There is no known closed formula for (5.17) but the outage formula can be easily computed by any numerical method. When there is shadowing but no fading, the outage probability is just given by

$$p_o = \frac{1}{2}\Big[1 + \text{erf}\,(A(1)) \\ - \exp\left(\frac{1 - 2A(1)B}{B^2}\right)\left(1 + \text{erf}\left(A(1) - \frac{1}{B}\right)\right)\Big]. \tag{5.17}$$

## 5.6 Outage with the proposed architecture

When several MDs are used, the packet is received as soon as the SNR is above the threshold for at least one MD. Thus

$$p_L = p_{L,1}\, p_{L,2}\, p_{L,3} \tag{5.18}$$

Hence, the outage probability is given by

$$p_o = \frac{\iint_S p_{L,1} p_{L,2} p_{L,3}\, ds}{S}. \tag{5.19}$$

The outage formula depends on the deployment and on the considered service area. It is computed by a numerical method.

## 5.7 Performance of a loaded network

The main performance indicator is the packet loss probability. As in the previous sections, we use a simple model to compute the transmission success probability $p_s$

$$p_s = \mathbb{P}\left\{ \text{SINR} = \frac{P_r}{I+N} \geq \theta_I \right\} \tag{5.20}$$

where $I$ and $N$ be the cumulative interference at the master device during packet transmission and the background noise power, respectively. The interference is computed with propagation equation (5.4).

For our proposal with 3 MDs that can receive a packet. The success probability is given by

$$p_s = 1 - \prod_{i=1}^{3} (1 - p_{s,i}) \tag{5.21}$$

where $p_{s,i}$ is computed with (5.20) by considering the power and the interference received at MD $i$. Moreover, the packet loss probability is:

$$p_l = 1 - p_s \tag{5.22}$$

Terminals are assumed to be located according to a PPP with spatial density $\lambda_m$ in the service areas.

The radio interface is slotted and each device gets synchronisation by listening the beacon information. The slot duration is denoted by $T$.

Our study is focused on massive IoT services with periodic reports. Each type of device has its own report period and from an application point of view devices are not synchronised. Thus, the global transmission process created by all devices can be approximated by a Poisson Process with parameter $\lambda_s$. Note that $\lambda_s$ is the number of packets generated per second in the service area (which can either be a triangle as in section 5.8.3 or an hexagon as in section 5.8.4).

Let $\lambda_u$ be the average number of packets per time sent by a device. We have

$$\lambda_s = \lambda_m S \lambda_u \tag{5.23}$$

where $S$ is the surface of the service area.

The average load is thus

$$\rho = \lambda_s T = \lambda_m S \lambda_u T. \tag{5.24}$$

Tab. 5.2.: Model parameters

| Parameter | Value | Comment |
|---|---|---|
| $W$ | $125$ kHz | Bandwidth |
| $T$ | $10$ ms | Slot duration |
| $P_t$ | $20$ dBm | Transmission power |
| $f_{NF}$ | 3 dB | Noise factor |
| $\theta_T = \theta_I$ | 3 dB | SNR and SINR threshold |
| $d_0$ | $0.00057$ km | ref distance for propagation |
| $\gamma$ | $3.377$ | propagation exponent |
| $\sigma$ | $4$ dB | st. dev. of shadowing |
| $P_T$ | 1% | outage objective |
| $\lambda_u$ | $1$ packet/hour | traffic per device |

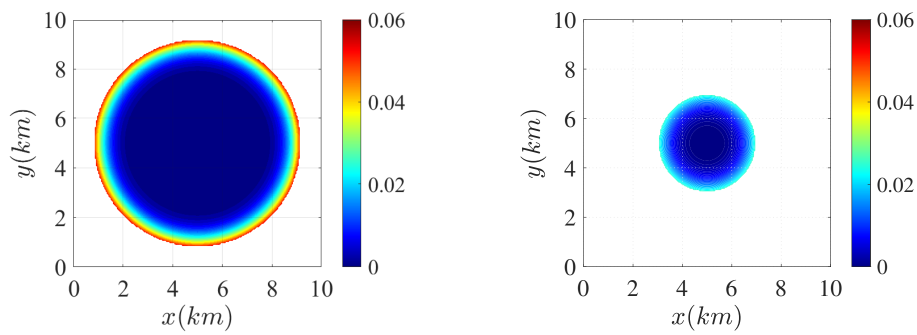
## 5.8 Results and Analysis

In this section, we consider to determine the parameters of our reference taking into account Section 5.5. Then, we analyze the basic configuration for which the service area is equal to the triangle deployment area. This helps us to identify deployment rules. We then optimize our system by jointly determining the best deployment and service areas.

The analysis is made for the $500$-MHz bandwidth, which is used for TV transmission. More precisely, the Okumura-Hata Model [72] is applied for a frequency equal to 584 $\mathrm{MHz}$ and the suburban area case. The transmission power of devices is $100$ mW, which is equivalent to $20$ dBm. Other parameters are shown in Annex A.

### 5.8.1 Determination of the reference case

The reference case consists of a single MD and a disk service area. By a simple iteration method, we determine the radius for which (5.17) gives a $1\%$ outage. For shadowing only, the obtained values are $R = 4.2$ km and




**(a)** Shadowing

**(b)** Shadowing with Fast Fading

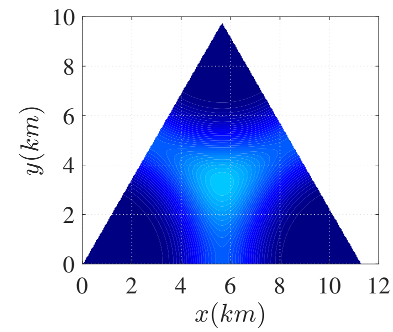
**Fig. 5.2.:** Packet Loss Probability in one link in reference case with one MD.

$S = 55.4$ km$^2$ and for shadowing effect with fast fading, the values are $R = 1.98$ km and $S = 12.3$ km$^2$ as shown in Figure 5.2 .

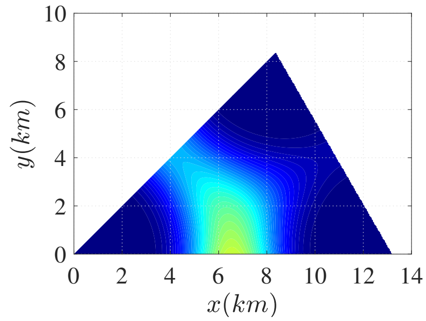
## 5.8.2 Service area restricted to the deployment triangle

We consider hereafter the simplest configuration: the service area is the triangle defined by the 3 MDs. The objective is to characterize the deployment that can provide an acceptable QoS. In order to make a fair comparison, we consider triangles that have the same area as our reference case (e.g. $55.4$ km$^2$ with shadowing only, and $12.3$ km$^2$ in shadowing with fast fading). We computed the outage probability according to (5.19) for each typical *deployment* with shadowing only and shadowing with fast fading. The results are shown in Table 5.3.

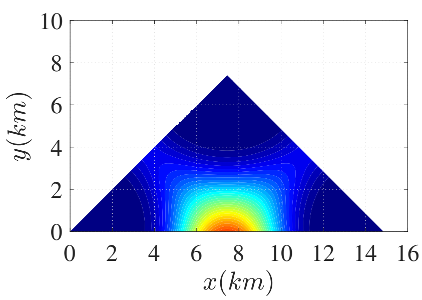
In the shadowing-only case, the outage with 3 MDs is larger than $1\%$ in all cases. In the fading-case, the outage is reduced if compared with the reference case (i.e. it is lower than $1\%$) for triangle $1-4$, $6$ and $8$. By analyzing Table 5.1, we deduce that such triangles are characterized by $\delta \geq \pi/6$. These configurations also give the lowest outage probability in the shadowing-only case. In the following, we will consider only *deployments* for which the smallest angle of the triangle is larger than $\pi/6$. In Figure 5.3, we show the packet loss probability in one link in the cases of $\delta \geq \pi/6$.



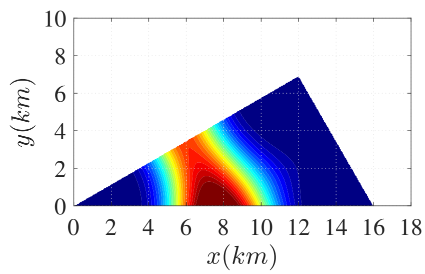

**(a)** Deployment 1



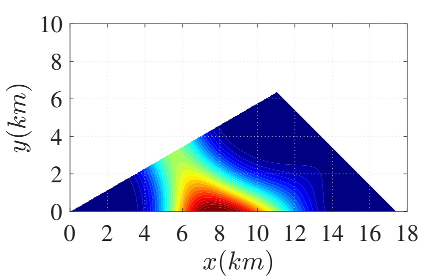

**(b)** Deployment 2



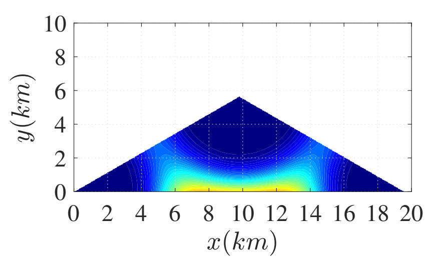

**(c)** Deployment 3




**(d)** Deployment 4




**(e)** Deployment 3




**(f)** Deployment 4

**Fig. 5.3.:** Packet Loss Probability in one link in deployment cases with 3 MDs characterized by $\delta \geq \pi/6$ with Shadowing

Tab. 5.3.: Outage probability when the service area is restricted to the deployment triangle

| Triangle Index | Outage with shadowing only | Outage with shadowing and fast fading |
|---|---|---|
| 1 | 0.0430 | 0.00089 |
| 2 | 0.0549 | 0.0011 |
| 3 | 0.0571 | 0.0013 |
| 4 | 0.1088 | 0.0025 |
| 5 | 0.3112 | 0.0187 |
| 6 | 0.0846 | 0.0024 |
| 7 | 0.2946 | 0.0181 |
| 8 | 0.0651 | 0.0027 |
| 9 | 0.2580 | 0.0167 |
| 10 | 0.1925 | 0.0136 |
| 11 | 0.1583 | 0.0117 |

### 5.8.3 Optimization of the Triangle Service Area

In this section, our objective is to optimize the system. The transmission power and the noise level are kept constant. However, the size of the deployment triangle and of the service area is maximized while a maximum $1\%$ outage probability is considered as a constraint.

In this part, the service area is still a triangle but larger than the deployment triangle. This new triangle can be defined by three points $A$, $B$ and $C$ as illustrated in Figure 5.4. Let $R_D$ and $R_S$ be the distances between the center of mass of the deployment triangle with the deployment top vertex (point $Q$) and the service-area top vertex (point $C$), respectively. $D_A$ and $S_A$ represent the Deployment Area and the Triangle Services Area, respectively. In addition, we define $p_o$ as the outage probability in the service area according to (5.19). In the case of the triangle service area $S$ is equal to $S_A$.

The optimization can be written as

$$\max_{R_S, R_D} S_A \text{ s.t. } p_o \leq 10^{-2} \tag{5.25}$$

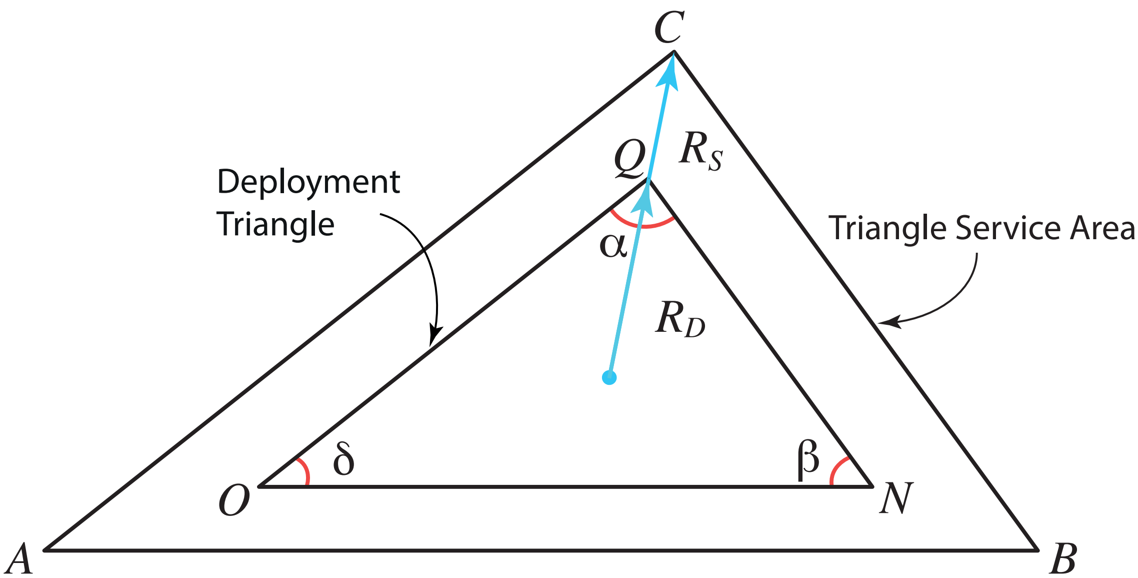
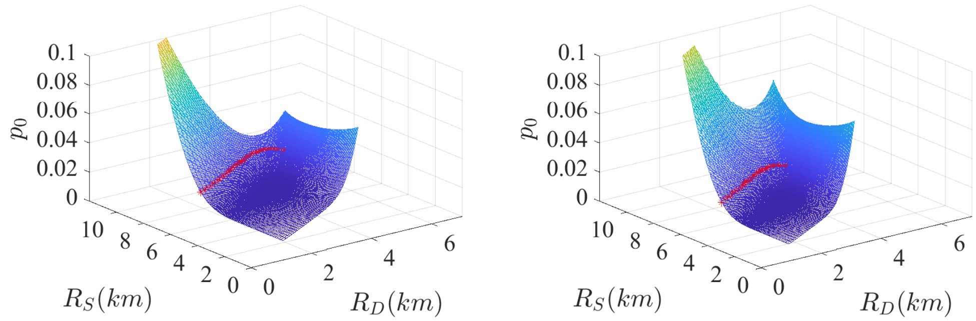



**Fig. 5.4.:** Deployment and service areas with $R_D$ and $R_S$ distance

There are only 2 variables in the optimization process. Thus, an exhaustive research of the optimal solution is possible. Figure 5.5 and Figure 5.6 shows the variation of $p_0$ for different values of $R_S$ and $R_D$. The red points on Figure 5.5 and Figure 5.6 represent the cases when $p_o$ is equal to $0.01$. The largest area is reached when $R_S = 11.22$ km and $R_D = 5.22$ km in triangle 1 with shadowing.

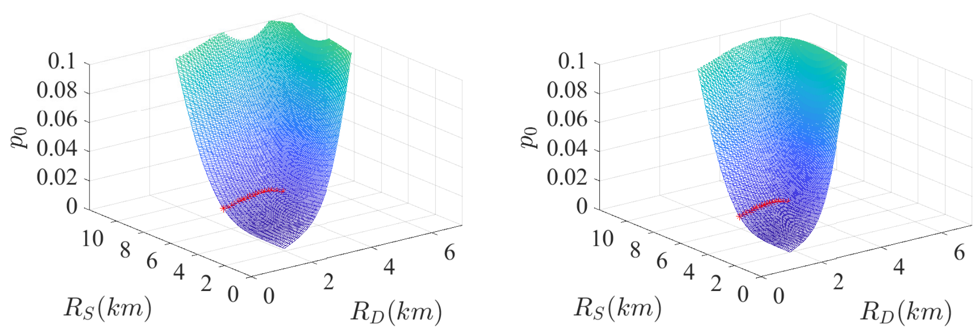
For the sake of brevity, all deployments are not shown. We observed that for triangles $1 - 4$, $6$ and $8$, there exist $R_D$ and $R_S$ values that reach the maximum outage constraint in (5.25).

In the proposed architecture, since there are 3 MDs instead of one in the reference case, the capital expenditure and the operational cost is higher. Covering the same area with a slightly lower outage probability is not




**(a)** Triangle Service Area 1 **(b)** Triangle Service Area 2

**Fig. 5.5.:** Outage packet loss probability considering shadowing with different $R_S$ and $R_D$ distances in examples of Triangle service areas, red points show 1 % probability.




**(a)** Triangle Service Area 1 **(b)** Triangle Service Area 2

**Fig. 5.6.:** Outage packet loss probability considering shadowing and shadowing with fast fading with different $R_S$ and $R_D$ distances in examples of Triangle service areas, red points show 1 % probability

enough to justify the additional investments required by the proposal. Consequently, we studied other shape of service area to improve the performance of our system. Moreover, in Annex D, we developed services areas based on triangle optimization. However, these service areas were not suitable. Thus, we proposed other optimization in the next section.

### 5.8.4 Hexagon service area

We considered an hexagonal service area defined by points $A$ to $F$. According to the deployment vertices ($O$,$N$,$Q$), we defined hexagon vertices. First, let $L0$, $L1$ and $L2$ be the lines that join triangle vertices and $R_H$ as the distance between the triangle deployment and hexagon service area ($S_{Ah}$) in Figure 5.7. In Hexagon service area case $S$ is equal to $S_{Ah}$.

The optimization goal can be written as

$$\max_{R_H, R_D} S_{Ah} \text{ s.t. } p_o \leq 10^{-2} \tag{5.26}$$

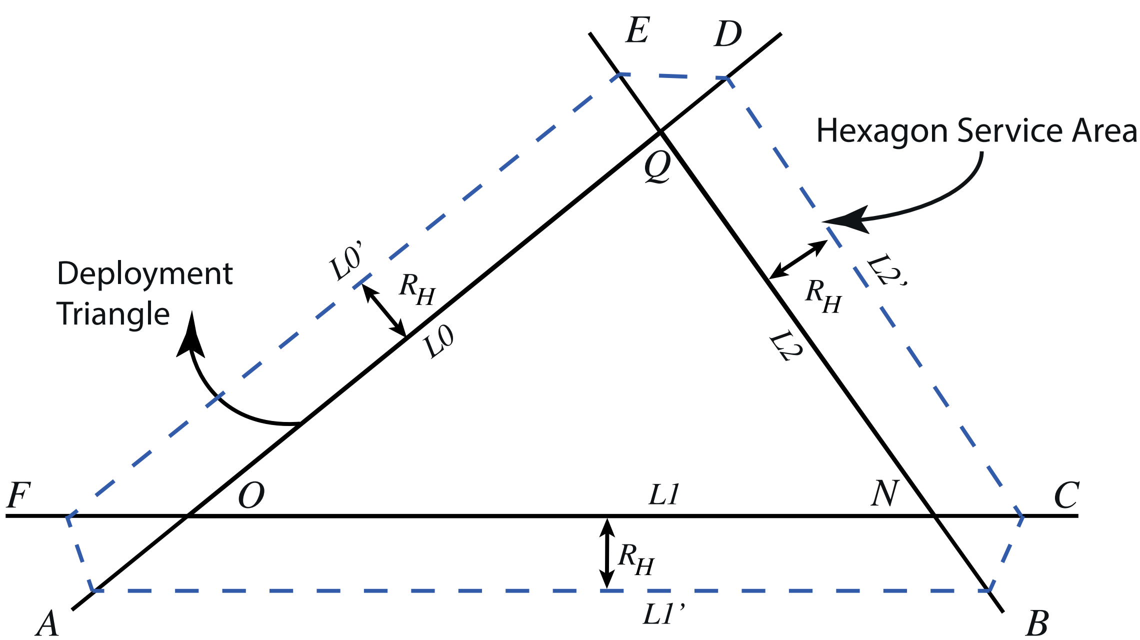
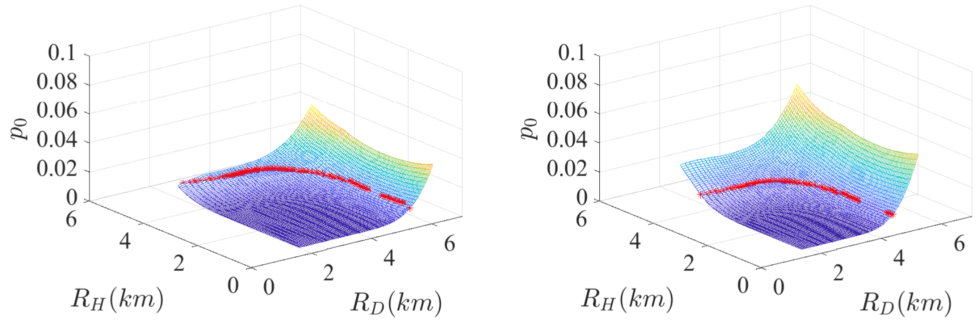


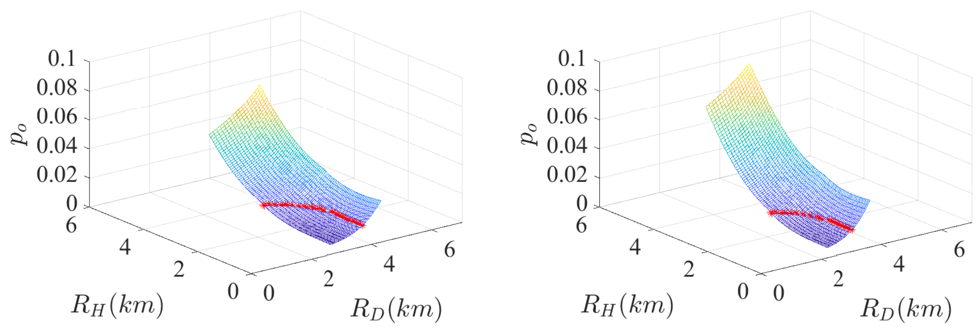

**Fig. 5.7.:** Hexagon service area

By following the same optimization process in as the triangle case, Figure 5.8 and Figure 5.9 show the optimization results for the Hexagon service area considering $R_H$ and $R_D$ as the optimization variables. We evidence that there are $S_{Ah}$ values with the goal described in (5.26).




**(a)** Hexagon Service Area 1 **(b)** Hexagon Service Area 2

**Fig. 5.8.:** Outage packet loss probability considering shadowing with different $R_H$ and $R_D$ distances in examples of Hexagon service areas, red points show 1 % probability




**(a)** Hexagon Service Area 1 **(b)** Hexagon Service Area 2

**Fig. 5.9.:** Outage packet loss probability considering Shadowing with Fast Fading with different $R_H$ and $R_D$ distances in examples of Hexagon service areas, red points show 1 % probability

### 5.8.5 Service area rules

The rules of the service area are defined considering the gain in the service area between the largest service area and the reference area ($55.41\ \mathrm{km}^2$ or $12.14\ \mathrm{km}^2$, as mentioned in section 5.8.1).

As shown in Figure 5.10, hexagons $1-3$ in the shadowing case had a gain of more than 3 times. In the case of shadowing with fast fading case the gain is larger than 3 in all hexagons and triangles evidenced in in Figure 5.11 . It is even larger than or equal to 6 for 3 deployment cases when the service area is an hexagon. Our objective is to provide the network access with our architecture to at least the same surface area per MD as an ideal system where each MD covers a disk area. To reach this objective, we can establish the following deployment rules: for a wide-band system (i.e. no fading), the service area should be a hexagon and the smallest angle of the deployment triangle should be larger than $\pi/4$ ; for a narrow-band system (i.e. with fading), the service area can be either a hexagon or a triangle and the smallest angle of the deployment triangle should be larger than $\pi/6$. In the latter case, if the angle is larger than $\pi/4$ and the service area is a hexagon, the surface area per MD can be doubled. In other words, with our proposal the same service area could be provided but with half of MDs.

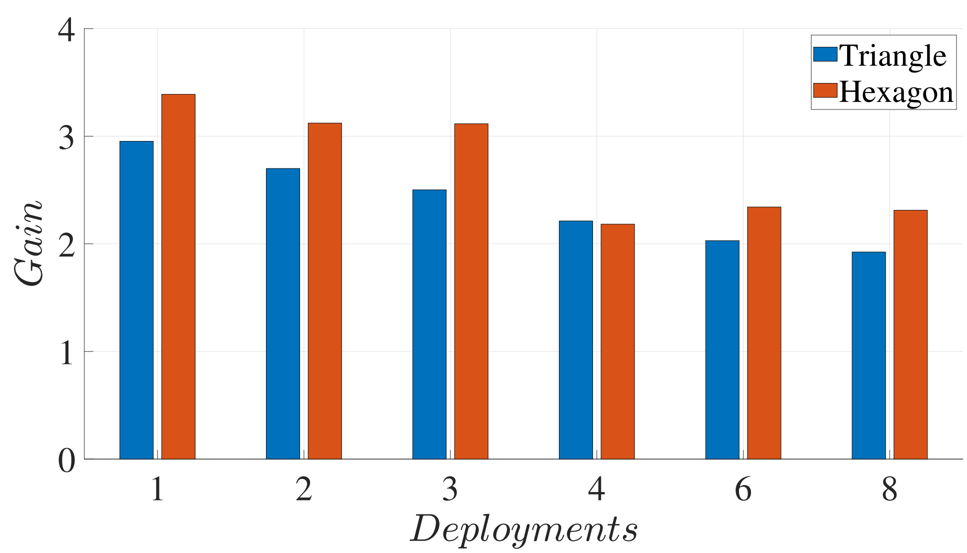



**Fig. 5.10.:** Service areas gain considering shadowing

## 5.8.6 IoT Devices Positioning Evaluation

We simulate OTDOA method considering the largest deployment in Section 5.8.5 and TOA correlation-based [70] with Zadoff-Chu sequences [73].

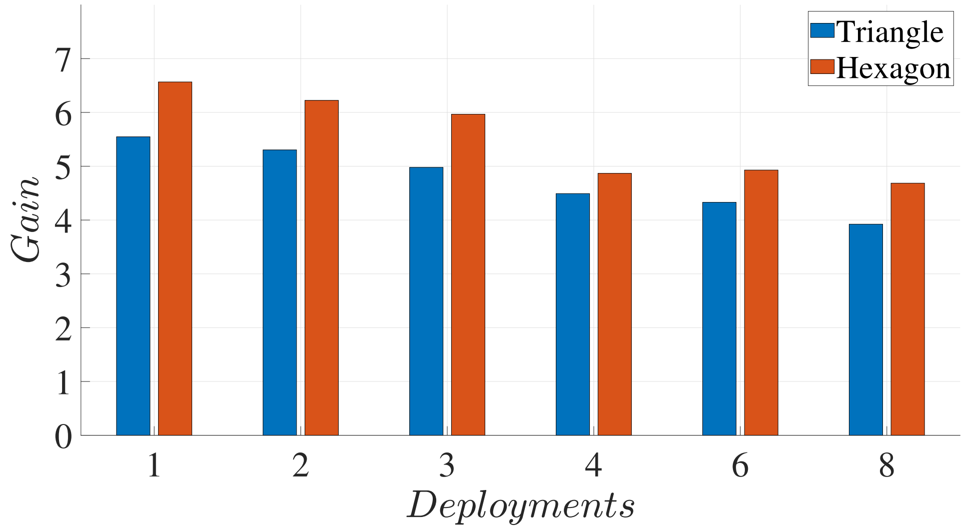



**Fig. 5.11.:** Service areas gain considering Shadowing with Fast Fading

The location error was calculated considering the distance between the IoT location and hyperbolas intersection as shown in Figure 5.12.

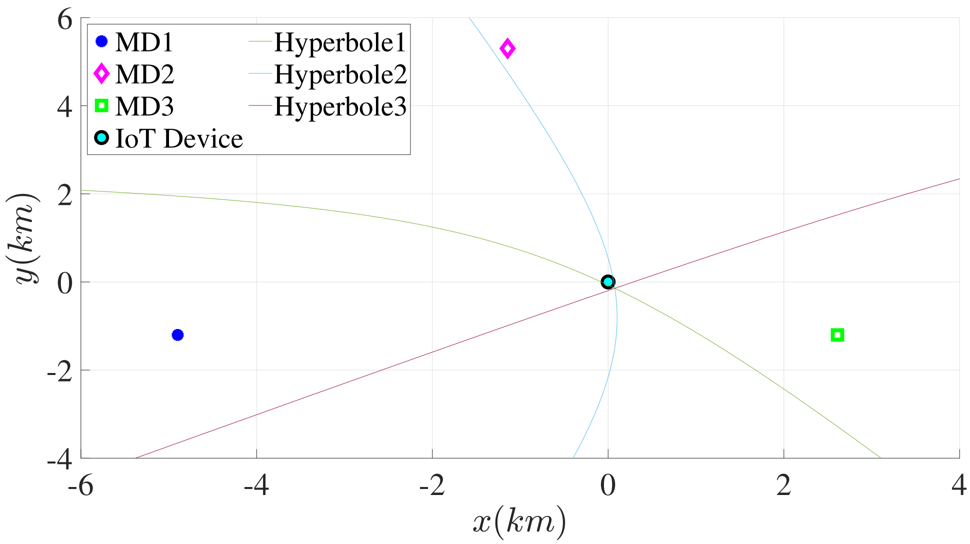



**Fig. 5.12.:** OTDOA in deployments of the radio access mechanism

In Figure 5.13 the Cumulative Distribution Function (CDF) of location errors inside the deployment is presented. Results shows that in 90% of the cases, the obtained OTDA error is less than 200 meters and the 70% of the cases reach less than 100 meters. Since in our access mechanism is particularly important to verify if the IoT end-device is inside the service area, by simulation results we verified that in 100% of the cases the end-devices were correctly located inside the service area.

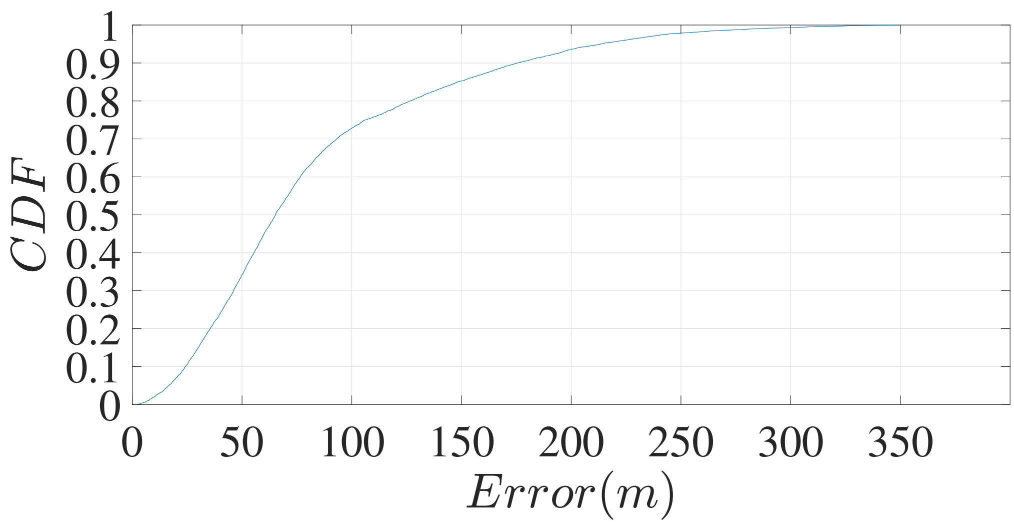



**Fig. 5.13.:** CDF Error in IoT Devices positioning

### 5.8.7 Performance analysis of a loaded system

We analyzed the performance of the system for moderate to high load for the maximum hexagon service areas and services with periodic reports [74]. According to appendix E of 3GPP TR 45.820 [74], the split of inter-arrival time periodicity for Mobile Autonomous Reporting (MAR) periodic is: 1 day (40%), 2 hours (40%), 1 hour (15%), and 30 minutes (5%). This gives a 10-hour average period. To check that our system can support a higher load, we consider 1 packet/hour.

The average packet loss probability is shown in Figure 5.14 considering our reference case with one MD and our proposal with three MDs. The load in this process is from 0.2 to 0.8. On the one hand, in the reference case the average packet loss probability is more than $10\%$ in all load cases. In our proposal with three MDs, average packet loss probability is equal to $10\%$ when $\rho = 0.6$. On the other hand, when $\rho = 0.8$, in our reference case the average packet loss is equal to $39.16\%$ and in our proposal the average packet loss is equal to $13.57\%$.

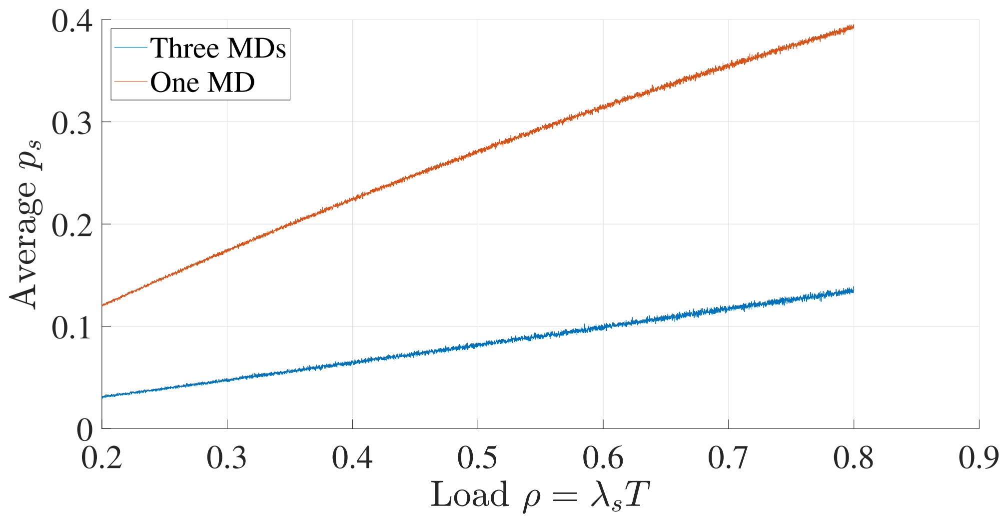



**Fig. 5.14.:** Average Packet Loss Probability (for the whole *service area*)

The CDF of the packet loss probability is given in Figure E.1 for our reference case (one MD) and our proposal (3 MDs) for the same load $\rho = 0.8$ in both cases. In the reference system, only $6\%$ of the devices have a loss probability lower than or equal to 10%. In our system, this proportion is increased up to $65\%$ and almost all devices have a loss probability less than $10\%$. We evidenced that in our proposal we can guarantee some level of QoS considering packet loss probability for massive IoT services

## 5.9 Remarks

In this chapter, we evaluated the radio mechanism for massive IoT services over TVWS. The performance comparison of several possible deployments and service areas was compared with the outage probability equal to

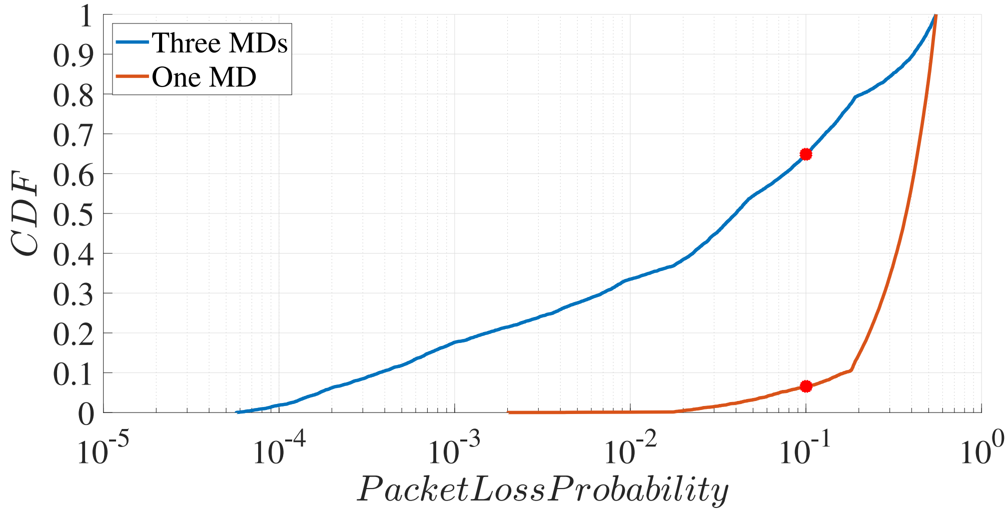



**Fig. 5.15.:** CDF $p_s$ with load $\rho = 0.8$

1%. Guidelines for service areas of TVWS were proposed with respect to the MD deployment. An analytical model was employed to evaluate the performance of a load network considering service areas and a comparison of the topology with one Master Device and our proposal.

# 6 Conclusion

We proposed a novel cognitive radio architecture that has the main features considering coexistence with TV primary user through GLDB and QoS constraints for defining *deployments* and *service areas*. With regard to *deployments* and *service areas*, first, we defined the reference case with respect to one MD topology. Then, we proposed service areas rules and macro-diversity gain model.

The results were divided into four processes according to the outage probability of the following areas: triangle deployments, triangle service areas, triangle service areas improvement, and hexagon service areas. In respect to the triangle deployments and triangle service areas, we evidenced that these processes did not have the outage probability equal to 0.01 in their areas. However, we evidenced that carrying out the optimization triangle service areas process was possible to find service areas with an appropriate levels of outage probability in deployments with $\delta \geq \frac{\pi}{6}$. In terms of hexagon service area, we implemented other optimization, it had optimal hexagons and it improved the triangle service areas. Finally, we defined hexagon service area rules according to the deployment triangle angles, we concluded that with our proposal we could provide the same service area but with half of MDs considering shadowing effect with fast fading and the reference case.

The performance of a loaded network in our proposal has the best values considering the average of packet loss probability and packet loss CDF with respect to the reference case with one MD. We can evidence that the average packet loss probability is reduced in $26\%$ when the load is equal to $80\%$ in our proposal. Therefore, we can guarantee some level of QoS for massive IoT services over TVWS.

## 6.1 Contributions

The contribution according to the chapters is presented below.

**Chapter 2**

We introduced in this chapter concept such as radielectric spectrum and massive IoT services. Regarding radioelectric spectrum, we summarized the main characteristic about this scarce natural resource and we identify the challenges in to order to use it rationally, efficiently and effectively. Then, we identified that IoT services need innovative solutions for increasing the radioelectric spectrum access in bands below 1 GHz. Finally, we selected the DSA over TV bands as suitable bands of frequencies for facing this challenges.

In terms of QoS, we realized through cognitive radio in IoT review that the QoS for IoT has been developed with techniques such as spectrum-aware and cross layer and with regard to services the QoS is focused on critical services. However, the QoS over DSA is a concept that need to be explored for massive IoT services over DSA over TV bands. The following publications have resulted from this contribution.

- ESPINOSA, Monica; PEREZ, Manuel; REINALES,Doris. Espectro radioeléctrico para el desarrollo de internet de las cosas. El reino digital transformación y aplicaciones multidisciplinares. Edición 2019. pp: 105-131. ISBN: 978-958-782-242-7

- G. Roncancio, M. Espinosa, M. R. Pérez and L. C. Trujillo, "Spectral Sensing Method in the Radio Cognitive Context for IoT Applications," 2017 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE

Smart Data (SmartData), 2017, pp. 756-761, doi: 10.1109/iThings-GreenCom-CPSCom-SmartData.2017.116.

**Chapter 3**

In this chapter, a novel cognitive radio architecture focused on policy-based cognitive radio where IoT devices have to obtain the available list of channels providing by GLDB is presented. Since in the overview the other architectures [15, 16, 17] are focused on centralized in one MD, the key point of our proposal is to deploy several MD that are synchronised. There can be 3 MD or more. The higher the number of MDs, the better the performance. We consider the minimum number, which is 3 and thus which gives us deployments and service areas. The following publication have resulted from this contribution.

- ESPINOSA, Monica; ZONA, Tatiana; REINALES,Doris. Huecos Espectrales en televisión. El reino digital transformación y aplicaciones multidisciplinares. Edición 2019. pp: 57-79. ISBN: 978-958-782-242-7

**Chapter 4**

In this chapter, a radio access mechanism for Massive Internet of Things Services over White Spaces is presented. An analytical model to compute the packet loss probability on the service areas and deployments. The main contribution in this chapter is a novel radio access mechanism that allows the deployment of IoT massive services on TVWS frequencies. This radio access mechanism is based on the Protocol to Access White-Space (PAWS) standardized by the Internet Engineering Task Force (IETF) and it requires no any geolocation receiver in the IoT devices in the deployments. The following publication have resulted from this contribution.

- ESPINOSA, Monica; PEREZ, Manuel; LAGRANGE, Xavier; ZONA Tatiana. Radio Access Mechanism for Massive Internet of Things Services over White Spaces. IEEE Access. DOI: 10.1109/ACCESS.2021.3105131

**Chapter 5**

In this chapter, we evaluate the radio mechanism for massive internet of things services over TV White Spaces (i.e. TVWS), below the main contribution in this chapter is presented.

- A performance comparison of several possible deployments and service areas with outage probability equal to 1%.
- Guidelines for service areas of TVWS with regard to the MD deployment.
- An analytical model to evaluate the performance of a load network considering service areas and a comparison with the topology with one MD and our proposal with three MDs.

The following publications have resulted from this contribution.

- ESPINOSA, Monica; PEREZ, Manuel; LAGRANGE, Xavier; ZONA Tatiana. Radio Access Mechanism for Massive Internet of Things Services over White Spaces. IEEE Access. DOI:10.1109/ACCESS.2021.3105131

## 6.2 Future Work

We consider that the contributions of this dissertation represent an essential step towards the construction of a cognitive radio architecture for massive IoT services with DSA. For the future work, we evidenced that the architecture could have the next improvements:

- We proposed to deploy several MDs that are synchronized, which can be 3 MD or more. We considered the minimum number, set as 3, which provides triangle deployments and service areas. A higher number of MDs produces a better the performance. Therefore, in the future we could consider more than 3 MDs and the Delaunay theorem.

- We only consider massive IoT services over TVWS framework. Consequently, the cognitive architecture could be integrated with other technologies such as, a 5G case study for massive IoT services or a wireless regional area network from IEEE 802.22.

- Regarding coexistence in TVWS, we estimated to applied processes of coexistence methods for geo-location capable devices operating under general authorization from IEEE 802.19.

- Deployments, service areas and macro-diversity gain in our proposal could be deployed in other bands of frequencies such as licensed and unlicensed bands considering other propagation models.

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# Appendices

# Okumura-Hata Model

# A

The Okumura-Hata Model [72] established empirical mathematical relationships to describe the graphical information given by Okumura. The model has limit in the input values and is applicable only over quasi-smooth terrain. The mathematical expression and their range of applicability with the logarithm in base 10, $h_r$ and $h_t$ are height of the antenna in transmission and reception and $a(h_r)$ such as a correction factor:

*Urban Area*

$$L = 69.55 + 26.16\log(f_c) - 13.82\log(h_t) - a(h_r) + (44.9 - 6.55\log h_t)\log d \quad \text{dB} \tag{A.1}$$

where

$(150 \leq f_c \leq 1500)$ ($f_c$ in MHz)

$(30 \leq h_t \leq 200)$ ($h_t$ in m)

$(1 \leq d \leq 20)$ ($d$ in km)

$a(h_r)$ is the correction factor for mobile antenna height and is computed as follows.

For a small or medium-sized city,

$$a(h_r) = (1.1\log f_c - 0.7)h_r - (1.56\log f_c - 0.8) \tag{A.2}$$

**Tab. A.1.:** Parameters Okumura-Hata Model

| Parameter | Value |
|---|---|
| $f_c$ | 584 MHz |
| $h_t$ | 50 m |
| $h_t$ | 1.5 m |
| $\gamma$ | 3.37 |

where $1 \leq h_r \leq 10m$.

For a large city,

$$a(h_r) = \begin{cases} 8.29(\log 1.54h_r)^2 - 1.1 & \text{if } f \leq 200\text{MHz} \\ 3.2(\log 11.75h_r)^2 - 4.97 & \text{if } f \geq 400\text{MHz} \end{cases} \tag{A.3}$$

*Suburban areas:*

$$L = L(\text{urban}) - 2\left[\log \frac{f_c}{28}\right]^2 - 5.4 \quad \text{dB} \tag{A.4}$$

*Open areas:*

$$L = L(\text{urban}) - 4.78(\log f_c)^2 - 18.33 \log f_c - 40.94 \quad \text{dB} \tag{A.5}$$

When all parameters are fixed except $d$, the Okumura-Hata model can be written as:

$$L = L_0 + 44.9 - 6.55 \log h_t \log d \tag{A.6}$$

where $L_0$ is computed according to A.1 and A.5 equations.

Thus, from (5.4) $10 \log P_R = 10 \log P_t + 10\gamma \log d_0 - 10\gamma \log d$.

Therefore, $L = 10 \log P_t - 10 \log P_R = -10\gamma \log d_0 + 10\gamma \log d$,

as a result, $\gamma = \frac{44.9 - 6.55 \log_{10}(h_t)}{10}$ and $d_0 = 10^{\frac{-L_0}{10\gamma}}$.

# B PAWS Protocol

In RFC 7545 [65] the payload length in bytes between MD and SD could be the values in Table B.1. Also, the payloads depend on too the rules set from body regulators. In IoT devices according to [74] the total payloads could be from 29 to 65 bytes without and with IP header compression respectively or from 20 to 125 bytes according to [56]. Second, for avoiding interference with TV primary users, the devices have to report their geolocation for a single point or a region described by a polygon. Thus, in TVWS the network needs this type of system and it is a differential factor in comparison with ISM bands. Moreover, the IoT devices before know the available list of channels must use other band of frequencies for avoiding interferences with TV primary users. Finally, the scalability in IoT services with PAWS protocol is no sustainable. Since, massive IoT are highly scalable for accessing to TVWS is important to device novel accesses mechanism for massive IoT devices. In our proposal, we device a radio architecture to face these challenges.

Regarding messages, the radio access mechanism is based on beacon messages and JSON recommendation. In this messages is sent the available

**Tab. B.1.:** Examples of PAWS length

| Message | Bytes |
|---|---|
| INIT_REQ | 329 |
| INIT_RESP | 174 |
| REGISTRATION_REQ | 535 |
| REGISTRATION_RESP | 182 |
| AVAIL_SPECTRUM_REQ_SLAVE | 565 |
| AVAIL_SPECTRUM_RESP_SLAVE | 1720 |
| SPECTRUM_USE_NOTIFY_SLAVE | 594 |
| SPECTRUM_USE_RESP_SLAVE | 78 |

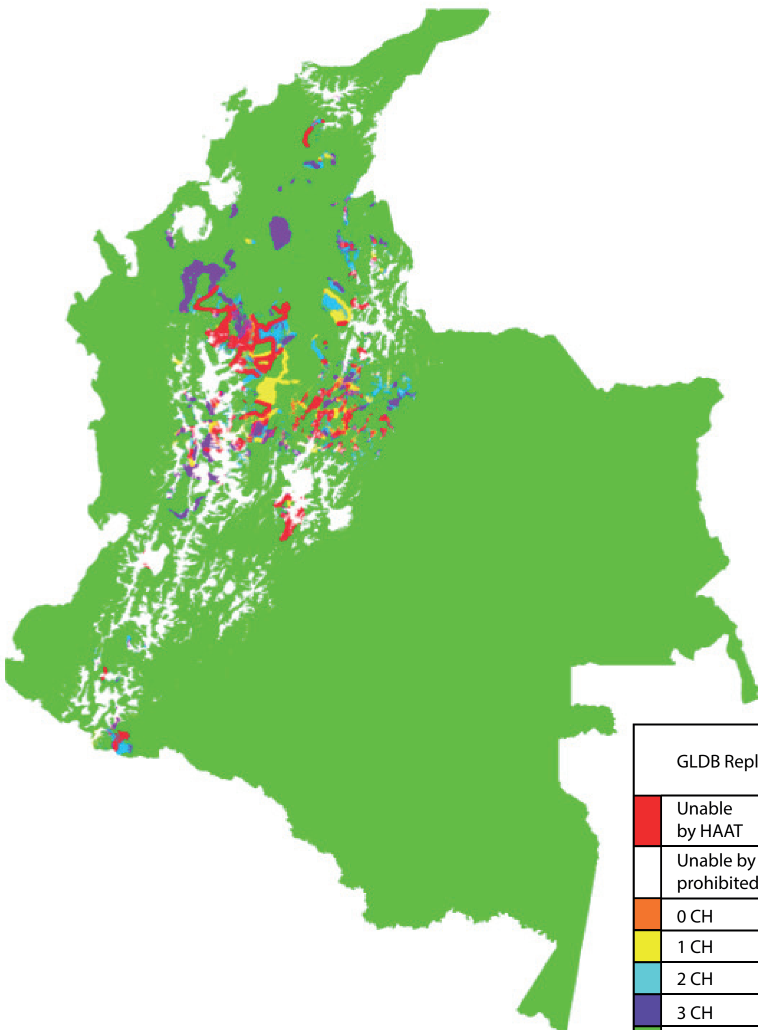
Tab. B.2.: Access Mechanism JSON Length

| Message | Maximum Bytes |
|---|---|
| BEACON | 43 |
| INIT-SD-RESP | 63 |

list of channels in the *service area*, MD serial number, and signals for positioning of the IoT devices. Moreover, in INIT-SD-RESP is sent SD serial number, the location, and spectrum-use of the SD. As shown in Table B.2.

C

# Heat map of TVWS available list of channels in Colombia



| | GLDB Reply | Percentage over the Colombian territory |
|---|---|---|
| (red) | Unable by HAAT | 0,63% |
| (white) | Unable by prohibited zones | 7,23% |
| (orange) | 0 CH | 1,6% |
| (yellow) | 1 CH | 0,93% |
| (cyan) | 2 CH | 0,85% |
| (purple) | 3 CH | 1,39% |
| (green) | ≥ 4 CH | 87,37% |

**Fig. C.1.:** TVWS available Channels in Colombian study case [75]

# D Other service areas

The main goal in this process is to improve the *service areas* with the same conditions of outage probability in Section 5.8.3 considering the optimization of the Triangle *service area*. In our results, we concluded that only Enneagon 1 had a ratio of more than 3 times in the shadowing case with respect to the reference case with one MD defined in Section 5.8.1. Therefore, we considered that this process is not suitable for the QoS constraints and the *service areas* maximization in our architecture.

## D.1 Hexagon service areas based on the optimization of the triangle service area

We defined the hexagon according to Figure D.1. The term $\lambda$ is the distance between the center of mass of the triangle deployment and the middle point in one side of the triangle service area improvement, while $\mu$ is the factor of the distance between triangle service area and the hexagon vertex. For defining the hexagon vertices, we took into account the $\lambda$ distance reference and the triangle service area improvement.

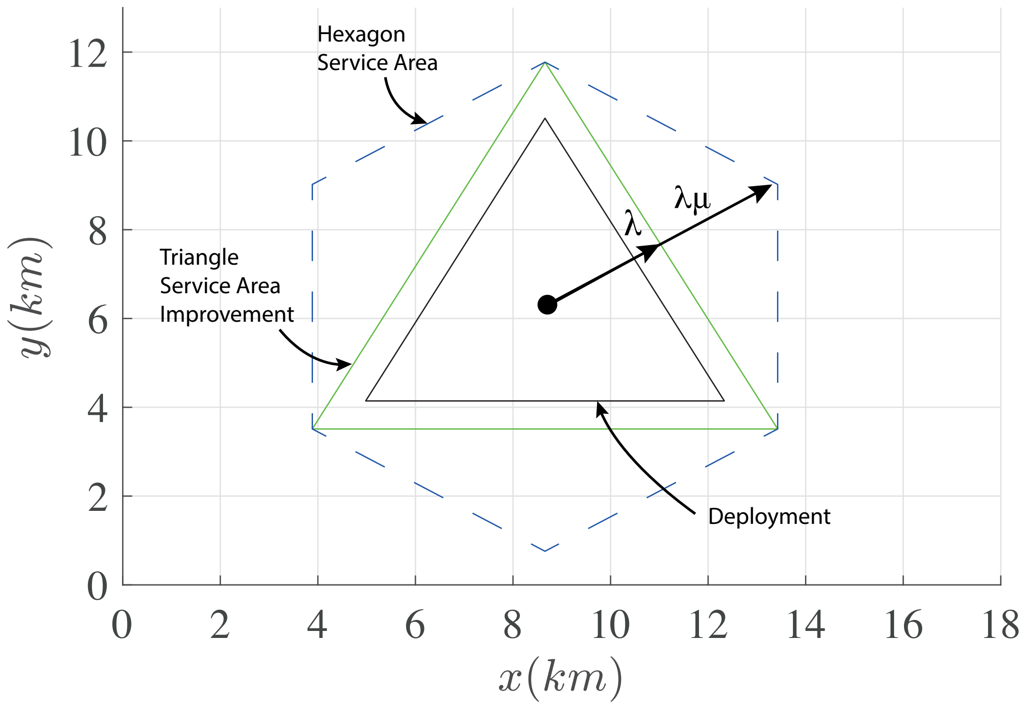



**Fig. D.1.:** Hexagon polygon

## D.2 Enneagon service areas based on the optimization of the triangle service area

We defined the enneagon according to Figure D.2. The term $\eta$ is the distance between one point of the triangle deployment side and one point located in one quarter of the triangle service area improvement side. Let $\Upsilon = \eta \times \mu$ be the the distance between the triangle service area improvement and the enneagon vertex.

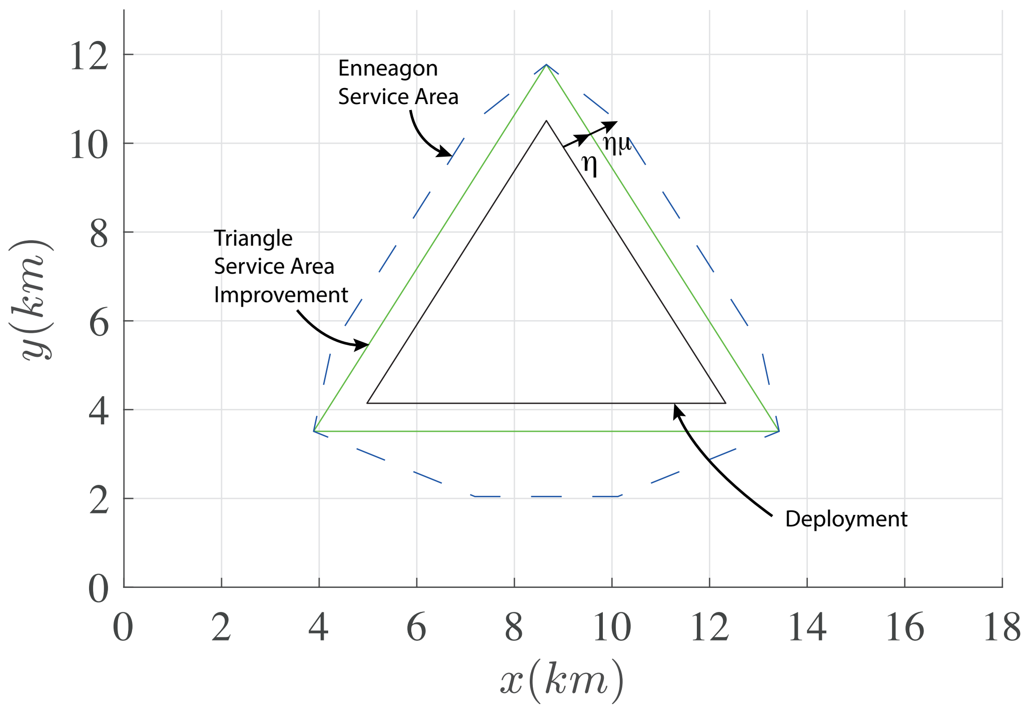



**Fig. D.2.:** Enneagon polygon

# QoS constrains

# E

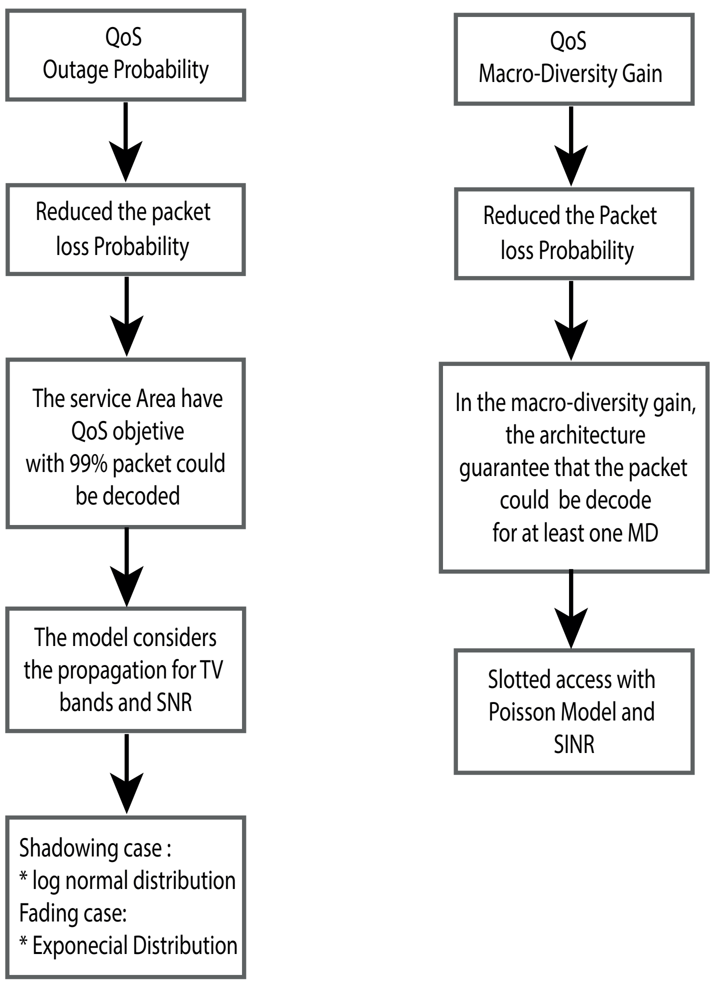



Fig. E.1.: QoS constraints

# Colophon

This thesis was typeset with $\LaTeX\,2_\varepsilon$. It uses the *Clean Thesis* style developed by Ricardo Langner. The design of the *Clean Thesis* style is inspired by user guide documents from Apple Inc.

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# Declaration

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*Bogotá, Colombia, June, 2021*

Mónica Espinosa Buitrago