Radio Access Network (RAN) virtualization in the context of WLAN systems

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Abstract

The demand for broadband network connectivity has been increasing continuously the last years. As a consequence, it is necessary to develop new ways to get this service to reach all users. 5th Generation (5G) mobile networks are under development with target to provide users with improved coverage, higher data rates and increased capacities. Software Defined Networking (SDN) and Network function virtualization (NFV) are two key technologies of 5G that allow the Network/RAN slicing that consists in separating the physical infrastructure into different virtual networks (slices). Based on it, this thesis is about the Radio Access Network (RAN) slicing techniques for WLAN systems. 5G-EmPOWER Test-Bed, which implements a resource sharing algorithm called Weighted Airtime Deficit Round Robin (WADRR) for implementing RAN slicing, has been used. In particular, the target of this project is to implement all the measurement and test related WADRR functions in order to extract the system bit rate information and analyze thoroughly the obtained results. Finally, some conclusions about the behaviour and performance of the users of WLAN in different environments are achieved based on experiments.
Resum

La demanda de connectivitat a la xarxa de banda ampla ha anat en augment en els últims anys. En conseqüència, cal desenvolupar noves formes d'aconseguir que aquest servei arribi a tots els usuaris. S'estan desenvolupant xarxes mòbils de cinquena generació (5G) amb l'objectiu de proporcionar als usuaris una cobertura millorada, velocitats de dades més altes i majors capacitats. *Software Defined Networking* (SDN) i *Network function virtualization* (NFV) són dues tecnologies clau del 5G que permeten el tall de Xarxa / RAN que consisteix en separar la infraestructura física en diferents xarxes virtuals (trossos). Basant-se en aquests conceptes, aquesta tesi tracta de les tècniques de tall de xarxes d'accés radioelèctric (RAN) per a sistemes WLAN. S'ha utilitzat el *5G-Empower Test-Bed* emprant l'algoritme de repartició de recursos radio denominat *Weighted Airtime Deficit Round Robin* (WADRR) en ell. En particular, l'objectiu d'aquest projecte és implementar totes les funcions de mesura i proba relacionades amb el algoritme WADRR per extreure la informació de la velocitat de transmissió del sistema, i analitzar a fons els resultats obtinguts. Finalment, es treuen conclusions sobre el comportament i rendiment dels usuaris de WLAN en diferents entorns a partir d'experiments.
Resumen

La demanda de conectividad a la red de banda ancha ha ido en aumento en los últimos años. En consecuencia, es necesario desarrollar nuevas formas de conseguir que este servicio llegue a todos los usuarios. Se están desarrollando redes móviles de quinta generación (5G) con el objetivo de proporcionar a los usuarios una cobertura mejorada, velocidades de datos más altas y mayores capacidades. Software Defined Networking (SDN) y Network function virtualization (NFV) son dos tecnologías clave del 5G que permiten el corte de Red/RAN que consiste en separar la infraestructura física en diferentes redes virtuales (troclos). Basándose en estos conceptos, esta tesis trata de las técnicas de corte de redes de acceso radioeléctrico (RAN) para sistemas WLAN. Se ha utilizado 5G-EmPOWER Test-Bed empleando el algoritmo de de repartición de recursos radio denominado Weighted Airtime Deficit Round Robin (WADRR) en él. En particular, el objetivo de este proyecto es implementar todas las funciones de medida y test relacionadas con el algoritmo WADRR para extraer la información de la velocidad de transmisión del sistema y analizar a fondo los resultados obtenidos. Finalmente, se obtienen conclusiones sobre el comportamiento y rendimiento de los usuarios de WLAN en diferentes entornos a partir de experimentos.
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1. **Introduction**

In the last years, the demand for broadband network connectivity is increasing continuously by the consumers. Due to this high demand, it is necessary to develop new technologies to get this service to reach all users.

5th Generation (5G) mobile networks are currently under development with target to provide users with improved coverage, higher data rates and increased capacities. 5G employs the concept of Heterogeneous Networks that combines a set of various technologies, such as WiFi and LTE. Therefore, there is the need for technologies that will allow a flexible management and modification/upgrade of the network. On that respect, Software Defined Networking (SDN) [1] and Network function virtualization (NFV) [2] have been introduced in the literature.

SDN and NFV are two key concepts in the context of the 5th Generation (5G) mobile networks. They allow network slicing with which it is possible to create different virtual networks (slices) under a common physical infrastructure. In this way, each Mobile Virtual Network Operator (MVNO) or tenant can apply the services and policies that match better the needs of its clients. Moreover, the use of slicing techniques at the Radio Access Network (RAN) part allows the available resources to be shared dynamically with target the more efficient utilization of them and the reduction of the operating (OPEX) and capital (CAPEX) expenditures.

In order to perform RAN slicing a hypervisor is required that not only provides the appropriate radio resource sharing, but it is also able to provide isolation among the different slices.

This project is carried out at the department of Signal Theory and Communications (TSC) of the Polytechnic University of Catalonia (UPC), and in particular in the GRCM - Mobile Communications Research Group. GRCM is currently working on a RAN slicing approach that employs a virtualized WiFi network hypervisor. This hypervisor employs a resource sharing algorithm, known as Weighted Air-Time Deficit Round Robin (WADRR) [3]. The proposed approach is implemented using the EmPOWER Test-Bed [4], which is a demonstrator of Mobile Operating System for SDN and NFV research and is built upon a single platform consisting of general purpose hardware and operating system (Linux). The hypervisor with the WADRR is able to follow the dynamicity of the traffic variations seen by the different tenants located to the network.

In that respect, the purpose of this project is, by using the EmPOWER Test-Bed, to experimentally study the so-called “performance anomaly” of the IEEE 802.11 standard and how this affects the performance of the hypervisor and the WADRR algorithm. Let us notice that the “performance anomaly” appears when the users of a WLAN do not have the same propagation (channel) conditions. In particular, one user can capture the channel for a long time because it transmits with lower bit rates, penalizing this way other users that can transmit with higher rates. In order to perform this evaluation, additional features in the Test-Bed functionalities must be introduced in order to perform several experiments.

1.1. **Objectives**

Based on the above, the main objective of the project is to study the “performance anomaly” in the EmPOWER Test-Bed and the impact it has in the performance of the hypervisor and the WADRR algorithm when considering various use cases. For this research is necessary:
• The communication mechanism between the AP and the controller must be studied, understood and, in case, upgraded.
• The exchange of messages related to the bit rate and other important parameters that give us information about the system performance and the algorithm behaviour will be analysed.
• The implementation and evaluation of different experiments in which are evaluated the communication capabilities between the controller and the Access Points or – as referred in the EmPOWER terminology - Wireless Termination Points (WTPs) (the physical devices handling the low-level communication with the users).
• Assess the results of the experimental tests. These are based on forcing channel conditions of the “performance anomaly” and study the behaviour of the system.

1.2. Project Plan

The proposed project plan is presented in the Gantt diagram of Annex 1. Project Plan Gantt Diagram. The first phase mainly deals with the collection of information related to the project, in particular the concepts of 5G, SDN-NFV and RAN slicing. Moreover, the required time for the installation and familiarization with the system has been taken into account. The next part of the plan consists in implementing and validating the related functions that will allow the communication between the controller and the WTP in order to exchange information about the bit rate. After testing the functionality of the whole system, the following part consists in carrying out several experiments in order to study the “performance anomaly” and analyze the obtained results with respect to the whole system and the WADRR algorithm performance. Finally, the last phase involves the writing of this document.

Let us notice that the initial time plan had to be extended due to some problems faced with respect to the installation process. In particular, the software had to be updated to the last version of the EmPOWER Test-Bed, creating some incompatibility issues with the version of the GRCM group. In order to address this problem, the GRCM version has been updated, requiring however additional time that was not taken into account in the initial time planning. Also another incidence happened during the implementation and validation of the functions that allow the exchange of information between the controller and the WTP. The new code implemented to the Test-Bed introduced a bug that didn’t allow the system to work as expected. For this reason, we needed to extend the Development and validation task one week in order to perform debugging process and resolve the problem.

Based on the above mentioned incidents, the first version of the Work Plan had to be adapted to include the additional time required for the Installation and Development and validation tasks. The installation process took one week more than expected. Due to this issue, the Development and validation task could not be started until the system was not completely updated in order to be functional. In addition, this work-package had to be extended one week more than the expected because of the second incident explained before. Consequently, this caused that the Experimental results and evaluation work-package to start a week later. However, the final report, which was the last planned task, started one week earlier (in parallel with the Experimental results and evaluation task) in order to compensate the extra time needed.
2. **State of the art of the technology used or applied in this thesis:**

The state of the art related to this project is presented in this chapter. First, the Software Defined Networking (SDN) and the Network Function Virtualization (NFV) concepts are explained. Then, the theoretical background behind the RAN Slicing framework of this work is presented thoroughly. Moreover, the architecture of the EmPOWER Test-Bed, which is the Test-Bed used for the implementation of this project, is described in detail. Finally, the performance anomaly is analysed.

2.1. **Software Defined Networking and Network Function Virtualization**

Software Defined Networking (SDN) [1] and Network Function virtualization (NFV) [2] are considered as key technologies for the 5G networks. As it has already been referred, due to the evolution of the mobile communications there is the need for new technologies that will allow the heterogeneous networks to be managed with flexibility and that would facilitate the modification and upgrade of them.

SDN is based on an emerging network architecture used to split up the data plane and the control plane as it is shown in Figure 1. It moves the control plane from the network devices to a central location, normally to the controller or to the Network Operation System (NOS) that are directly programmable and offers greater control of the network through programming. SDN works in the data plane elements using a programming interface. The main advantage is the flexibility achieved and as a consequence it endows the network with ease to be managed and allows defining isolated virtual networks. Instead of forwarding packets individually to a destination, SDN proposes to define flows of packets that fulfill a certain filter with a set of actions, so it is possible to unify the behaviour of different types of devices, such as routers or switches. Moreover, it pretends to decrease the costs of the whole system.

![Figure 1. SDN architecture](image)

On the other hand, the main idea of the NFV is to decouple the functions of the networks from the hardware network to software-based applications, as Figure 2 presents. These functions, named Virtualized Network Functions (VNF), are placed on independent physical devices without affecting their functionality. Applying it to the mobile networks, NFV uses the IT (Information Technology) virtualization and cloud
computing and applies them to telecommunication networks. With this technique it is possible to have more dynamic networks with better response to the services. The main benefits can be summarized as:

- Openness of platforms
- Scalability and flexibility
- Operating performance improvement
- Shorter development cycles
- Reduced CAPEX (capital expenditures) and OPEX (operational expenditures) investments

![Diagram](image)

**Figure 2. Network Function Virtualization**

Using the SDN and NFV techniques the Network Virtualization can be implemented. The latter is a framework of combining a set of network resources, making that each user has a unique and separate view of the network. This concept is explained in detail in the following section. Furthermore, the deployment of new applications and services can be quicker and different network functions can share the same resources.

The above mentioned implementation methods are running on the server, and the majority of the system is located inside the platform. In turn, SDN provides the connectivity to the NFV with optimized traffic. When SDN and NFV are combined they get better services, with the virtual functions managed by a controller that can be virtualized. Although SDN and NFV are complementary to each other, these techniques are based on different concepts for the system architecture and functions. NFV is a technique of implementing network functions in software, while the SDN concept consists in having a centralized controller and programmable network architecture, improving the connectivity.

To summarize, future wireless and mobile networks will rely on virtualized resources and on dynamic services. Both SDN and NFV play a key role in order to reach our objective, due to the fact that they provide the necessary flexibility and programmability. Besides, among other features, with SDN and NFV different control planes can be developed for the different slices. Hence, the resources can be configured as desired.
2.2. RAN Slicing

Network/RAN slicing [5] is defined as a concept for running multiple logical networks as independent business operations on a common physical infrastructure. Each network slice represents an independent virtualized end-to-end network and allows MVNOs, or also named tenants, to have different deployments in each slice, based on different architectures in parallel. So, each network is customized to best match to the needs of the tenants. In order to satisfy the diverse requirements imposed by future applications and services, tenants should be allowed to deploy custom applications within their network slice. Moreover, the system shall provide performance isolation between MVNOs and ensure efficient recourse utilization, because each tenant can have different resource requests in an Access Point (AP) depending on the traffic of the network. This technique permits that each tenant has a complete control of an isolated slice of resources with its own services.

In particular, RAN slicing is able to cope with the challenges imposed by the traffic demand in wireless networks. In most of the cases this traffic varies in time and is not following a homogeneous pattern. Moreover, to guarantee isolation between slices, a hypervisor must be introduced in the virtualization layer. In that respect, GRCM is currently working on a RAN slicing approach that employs a virtualized WiFi network hypervisor. This hypervisor employs a resource sharing algorithm known as Weighted Air-Time Deficit Round Robin (WADRR). Let us notice, that the need for the proposal of this algorithm resulted due to the fact that in a Wireless LAN (WLAN) the resources are mainly shared in time. As such, algorithms that handle packets or bytes, as they do the majority of algorithms in the literature, cannot be considered as ideal solutions. WADRR is based in the estimated transmission time of the packet, thus it consists an ideal candidate. The purpose of the algorithm is to adapt the resource allocation in each AP as instructed by a controller, presented later, conserving the Service Level Agreement (SLA) of each tenant when considering all the connected APs of the infrastructure. The resources (weights) are assigned according to the SLA.

2.2.1. Weighted Air-Time Deficit Round Robin

The WADRR algorithm (Weighted Air-Time Deficit Round Robin) [6], employed by the wireless hypervisor in the EmPOWER Test-Bed, has been created with purpose to cope with the challenge presented in WiFi networks with respect to the resource sharing. WADRR is based on the functionality of the Weighted Deficit Round Robin (WDRR), with the difference that instead of transmitted bytes, it considers the transmission time of a packet. As such, it is capable of sharing the resources in time. Another characteristic of the WADRR algorithm is that it performs the scheduling per tenant basis instead of users.
The input parameters used by the algorithm are the length of the packet and an estimation of the bit rate with which the packet will be transmitted. The Minstrel algorithm, implemented by the Minstrel element, provides this estimation. This is described in section 2.2.1.1.

The WADDR algorithm, presented in Figure 3 [7], considers an initial system quantum (Qs) that is common for all the tenants and it corresponds to the time needed to transmit the packet of maximum size at the lowest bit rate. Then, for an AP, each tenant is assigned a tenant quantum (Qi) resulting from the following equation:

$$Q_i = W_i \cdot Q_s$$  \hspace{1cm} (1)
The weights ($W_i$) indicate how the resources should be shared among the tenants. They are calculated by the Weight Compensation Algorithm (WCA), based on the tenants’ traffic at each AP. Details behind the WCA implementation are omitted since it is out of scope of this project. Moreover each tenant is assigned with a Deficit Counter ($DC_i$), whose value is initialized to the value of $Q_i$. The DC indicates how much time a tenant disposes for transmission. Finally, each tenant has a corresponding queue where its packets are stored.

Once all the values are initialized, the algorithm looks if the first tenant (e.g. $i$) has packets in its queue. If so, the system calculates an estimation of the transmission time ($t_p$) of the packet to be transmitted. Otherwise, if the queue is empty the $DC_i$ is set to 0. As equation (2) shows, the $t_p$ is computed by taking into account the length of the packet and an estimation of the bit rate ($R$) based on the Minstrel algorithm.

$$t_p = \frac{L \text{ [bits]}}{R}$$  \hspace{1cm} (2)

Then it checked if $t_p$ is greater or equal than the $DC_i$ of tenant $i$, and if it is the packet is transmitted, since this means that the tenant has not spent yet the time assigned to it for transmission. In the case that $DC_i$ is less than $t_p$, then the packet is not transmitted and the resource sharing process passes to the following tenant in turn. The $DC_i$ of tenant $i$ is re-calculated according to equation (3):

$$DC_i = DC_i - t_p$$  \hspace{1cm} (3)

If there are still packets in the queue of tenant $i$, the same procedure is repeated, otherwise the next tenant queue is considered for transmission. When all the tenants had the chance to transmit their packets, the process starts again and the $DC_i$ value is updated according to the following equation:

$$DC_i = DC_i + Q_i$$  \hspace{1cm} (4)

### 2.2.1.1. Minstrel

Minstrel [9] is a recently developed rate control algorithm that supports multiple rate retries, based on the throughput and the changes of the environment. The probability of success of sent packets between two or more users is an unknown function of variables (distance between devices, multipath effects, interference from other devices...). The radio can be used in any environment, where the relationship between these variables is unknown, so it is decided to get these values from experimentation, evaluation or by trial-and-error methods. Minstrel operation includes a programmable frequency resulting by a timer, based on which a statistics table is constructed. This table includes some important parameters as the throughput or the probability of success of a packet. Then, the success history of each rate is calculated and finally a decision is made according to the rate. It is important to notice that the frequency of the algorithm has to be lower than the TCP timeout. Minstrel is divided in three parts: the retry chain mechanism, the rate selection process and the statistic calculations.

This algorithm is used in this project for the calculation of the bit rate estimation and the throughput in order to allow the WADRR to estimate the transmission time of a packet. Specifically, the bit rate parameter is analysed in this thesis. It is defined as the
number of bits that are conveyed or processed per unit of time and it is quantified using the bits per second (symbol: “bit/s”). The rate adaptation is an optimization problem; if the rate is too high, many of the packets will be dropped due to bit errors, however if the rate is too low, the wireless channel will not be fully utilized. High data rates transmit data faster than lower data rates, however higher data rates are more susceptible to bit errors, resulting in higher packet loses and degradations of the quality of the wireless channel.

The first step of Minstrel is the retry chain mechanism that enables to react in front of the variations of the channel quality. At the beginning a packet is transmitted with a certain rate and a number of defined attempts. If these attempts are not successful, Minstrel transmits the packet with lower rates, setting another number of attempts for each possible rate. This process continues until, either the packet is successfully transmitted or later discarded after a decided number of unsuccessful transmission attempts. There are two categories of transmission summarized in Table 1 [9]:

- Normal transmission: occurs 90% of the time. The first rate is set to the rate that achieves the highest expected throughput, the following rate is the second highest expected throughput, the third one is the rate with the highest probability of success, and the final one is set to the lowest available data rate.
- Sampling transmission: corresponds to the remaining 10% of the packets. Minstrel relies on having accurate statistics about the success rate of transmissions for each data rate. To achieve this objective, in these type of data frames a random rate not currently in the retry chain is chosen to sample. The higher rate between the best rate and the random one is selected as the first try and the other as the second one. Then, the third is the rate with the best probability, and finally is set to the lowest available data rate.

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<tr>
<td>2</td>
<td>Best rate</td>
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</tr>
<tr>
<td>4</td>
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</table>

Table 1. Minstrel Retry Chain Table

In addition, the algorithm calculates the probability of success and the expected throughput for each possible data rate, based on the Exponential Weighted Moving Average (EWMA) [8]. The EWMA is a type of infinite impulse response filter that applies weighting factors, decreases exponentially and never reaches to zero according to equation (5). The latter calculates the probability of successful transmission for each possible rate based on the historical success rate of packet transmissions, so that a success rate can be calculated for each of the data rates. This probability is used to estimate the throughput of each possible rate. Also, a weight is defined, which means how much the new probability depends on the old one, and consequently the impact of old results on the choice of the ideal rate.

\[
P_{\text{success}}(t+1) = R_s \cdot (1 - \alpha) + P_{\text{success}}(t) \cdot \alpha
\]  

(5)
Defining the previous expression, $P_{\text{success}}$ is the probability of a successful transmission, $R_s$ is the historical observation of packets successes and failures, $\alpha$ is used to know the weight and $t$ represents the time scale.

Then, Minstrel calculates an expected throughput, for each data rate according to equation (6):

$$Th = \frac{P_{\text{success}} \cdot B}{t}$$

where $Th$ is the throughput, $B$ the bits transmitted, $t$ the time for one try of one packet to be sent and $P_{\text{success}}$ the probability of a successful transmission. The results are based on the station’s previous observations of the proportion of packets that have been successfully transmitted at this data rate. The system should record the successfulness of all transmitted packets and other parameters. From this data, it has sufficient information to decide which rates are more successful than others and these values are stored in a table like the one in Annex 2. Table of loss/success rates for each data rate. With these measures, Minstrel can then determine which rate is most likely to achieve the best throughput and use this information to start the retry chain again with the following packet.

Let us notice that the elements of the AP used in this project don’t show the bit rate directly on the screen, because they work with a rate information vector. As such, for each studied bit rate the rate value of the vector is related according to Table 2 [10].

<table>
<thead>
<tr>
<th>Index</th>
<th>Rate</th>
<th>Bit rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>108</td>
<td>54</td>
</tr>
<tr>
<td>10</td>
<td>96</td>
<td>48</td>
</tr>
<tr>
<td>9</td>
<td>72</td>
<td>36</td>
</tr>
<tr>
<td>8</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>7</td>
<td>36</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. Relation between index, rate and bit rate

2.3. **EmPOWER Test-Bed**

EmPOWER Test-Bed [4], developed by the FuN team of the research centre Create-Net in Italy, is an open Mobile Network Operating System (MNOS) for SDN and NFV research. As such, this Test-Bed has been chosen for the implementation of the RAN Slicing approach, and consequently this project. Moreover, the EmPOWER Test-Bed is characterized by scalability, flexibility, and ease of use. In particular, it has flexible architecture and includes high-level programming APIs that allow the fast prototyping of novel services and applications. In this way, the traffic coming from the users can be monitored in real time by the experimenter. Finally, EmPOWER permits network virtualization to be performed, guaranteeing isolation between the various network slices (tenants).
2.3.1. EmPOWER Architecture

The EmPOWER system architecture [11] is composed of a controller and multiple agents running in each Access Point (AP). The controller has a global view of the network in terms of users, flows, and infrastructure, while the Agent provides the interface for the radio part and is responsible for the communication with the controller. The Agent is implemented with the Click Modular Router, which is a software implementation of a router. More details for each of the components are given in the following sections.

EmPOWER builds upon a single platform consisting of general purpose hardware (x86) and operating system (Linux) in order to deliver three types of virtualized network resources: forwarding users, packet processing, and radio processing.

Figure 4 presents the EmPOWER architecture [4]. As it can be seen from the figure, it is comprised of Wi-Fi Access Points, known as Wireless Termination Points (WTPs), and the LTE eNodeB(s) called Virtualized Base Stations (VBSs). These consist the physical Radio Access Nodes that handle the low level communication with the user and support virtualized radio processing capabilities. In addition, the Test-Bed can include Click Packet Processors (CPPs) that are the packet processing nodes with forwarding capabilities. Finally, the controller simplifies the network management and introduces seamless mobility support.

![EmPOWER's architecture](image)

**Figure 4. EmPOWER's architecture**

2.3.1.1. Controller

The EmPOWER Controller [4] is responsible for the Light Virtual Access Point (LVAP) and Light Virtual Network Functions (LVNF) deployment on the network devices. The LVAP concept [12] is that each Agent is given the illusion of having a dedicated AP to each user, it is explained in detail in the next subsection. Otherwise, the LVNFs are in charge of receiving and processing the traffic. Network applications run on top of the Controller and utilize primitive means through either a REST API or a native Python API. The Controller ensures that Network Apps are just presented with a view of the network related to its slice. Some of the main features of these concepts are:
- Soft State: The information stored at the controller is related to user authentication methods and the lists of the network slices currently defined. As a consequence, the Controller can communicate with other instances without affecting the active users.
- Modular Architecture: Every task supported by the Controller is implemented as a plug-in that can be loaded while the system is running, excepting the logging subsystem.
- Slicing: It supports multiple tenants on the top of the physical infrastructure.

2.3.1.2. WTPs

The term Wireless Termination Points (WTPs) [13] is used to refer to the physical devices that form the Radio Access Network (RAN) providing users with wireless connectivity. They are essential WiFi Access Points running the EmPOWER Agent. In the EmPOWER implementation the routing capabilities are extended in order to add functions such as the LVAP handling and the rate control algorithm.

Figure 5 shows the logical diagram of the WTP. EMPOWER0 interface is responsible for getting the traffic outside the WTP in order to perform the communication between the Controller and the Agent, while MONI0 interface is responsible for the ACK and data frames exchange between the WTP and the users.

In the GRCM implementation WTPs are deployed in PCEngines Alix running the OpenWRT [14] operating system based on GNU/Linux distribution for embedded devices. OpenWRT provides an integrated framework for compiling the software, allowing to generate a customize firmware image to be loaded into the wireless router. Therefore, this operating system allows building an application without having to build the complete firmware. These characteristics permit the configuration of the routing capabilities of the WTP.

The LVAP concept, referred previously, simplifies the association/authentication method in the WiFi network. This abstraction is giving to each user the illusion of having a dedicated AP. As a result, the time spent when a user wants to re-associate due to a handover process is significantly reduced. In particular, every user attempting
to join the network will trigger the creation of a new LVAP. Specifically, the implementation of this method is the following:

If there are more than one WTPs, the first that receives the probe request will be the one who will advertise the network. When the user requests the LVAP, it receives a BSSID (LVAP ID), which results from the combination of the networks’ SSID (network ID) and the user’s MAC Address. This way the user is assigned a “virtual WTP”. More in detail, abstracting the association state of a users’ connection from individual physical WTPs, LVAPs achieve a form of wireless network virtualization, where each user sees a logical WTP unique and independent from the real one with which it is connected. Once a user is associated with a WTP, the only protocol level requirement is that the user gets ACK frames for the data frames that it generates. As such, each WTP will host as many LVAPs as the number of wireless users that are currently under its control. Removing a LVAP from a WTP and change it to another one, has as a result a handover. The controller can also decide whether the network has sufficient resources left to handle the new user and might suppress the generation of the LVAP. For these reason, the WTPs’ EmPOWER Agent has the responsibility of communicating with the controller, receiving the commands and executing them in order to manage the LVAP.

2.3.1.2.1. Click Modular Router

Click Modular Router [15] is a software architecture for building flexible and reconfigurable routers. Its architecture is focused on small components, called elements, which are interrelated or linked between them. The main features [16] of Click Modular Router are:

- Modular architecture: The architecture of Click is based on the definition of elements that each one individually implements simple router functions, such as packet classification, queuing, scheduling, and interfacing with network devices. The elements are linked to each other resulting in a Click configuration, which corresponds to a directed graph with elements. A set of fundamental (default) elements is already implemented, however new ones can be created to serve the current needs of the router implementation.
- Declarative language: Each element is defined as a C++ class using an extensive support library.
- Programmability and flexibility: The Click system guides the user to create modular router and element designs by making modularity easy to achieve.

Based on the above, Click Modular Router is an extensible toolkit for writing packet processors. Each element is a software component representing a unit of router processing. Therefore, each link represents a possible path for packet transfer. The elements have the following common properties:

- Element class: Specifies the data layout and behaviour.
- Ports: Each element has a variable number of input and output ports. The connection links are from an output port to an input port of another element.
- Configuration string: Additional arguments can be passed to the element.
- Method interfaces: Each element imports methods of other elements.
- Handlers: Methods exported to the user rather than to other elements.

The Click programming language describes Click router configurations. More specifically, there are declarations creating elements and connections connecting
elements together. The connections are defined syntactically by an arrow. The goal of Click programming language is to create a declarative and simple language. To achieve this objective, every element class must include the elements’ configuration strings and the input/output ports that can be push or pull. Let us notice that push connections refer to the connections that the source element passes the packet to the destination element, while pull refers to the connections where the destination element asks for the packet.

Focusing on this project, Click Modular Router is being used to implement the WTP and LVAP frame exchange. The element Socket is responsible for the communication with the controller establishing a TCP connection with it, while the element LVAPManager takes care of the interpretation of the commands. Let us point out that for the configuration of the system operation there are additional elements responsible for the process of the management and data frames. For example, the element FromDevice receives the packets in the uplink direction from the WTP interface. The WiFiDupeFilter discards duplicated frames, while Minstrel uses the feedback frames in order to calculate the most adequate data rate with which packets will be transmitted. In addition, there are elements dedicated to the authentication and the association of users.

A frame to be sent to the downlink (DL) direction is encapsulated to include the RadioTap header. This header includes the possible rates to be tested and a number of retransmissions for each possible rate. After sending the frame (or not in the case that all the rates fail), the card sends a feedback frame to the Agent. This frame includes the number of retransmissions (for each rate) and is used by Minstrel to select the next rate. Actually, all the frames, data, management and feedback reach the Minstrel and after, either they are sent to their destination or they are discarded. Finally, the packets are received for the element FromHost and they follow the path as the data frames that are destined to the network.

2.4. Identified Problems – Performance Anomaly

The performance anomaly [17] in the IEEE 802.11 networks appears when the users connected to the network have different transmission rates in the same access point. The users might experience the same throughput, despite the fact that their transmission rates are different. This is because each WLAN provides the same probability of channel access, but it does not guarantee the equal use of the wireless channel among the users. As such, throughputs tend to be aligned with the one of the slowest user in the network. In particular, this happens when a user with poor link quality is monopolizing the air-interface.

The IEEE 802.11 standard defines the specification for two types of access methods: the Distributed Coordination Function (DCF), which uses CSMA/CA to allow for contended access to the wireless media; and the Point Coordination Function (PCF), which provides collision-free access. The DCF method [18], adopts an exponential back off scheme. At each packet transmission, the back off time is uniformly chosen in a range defined by the contention window (CW), which it is used for congestion control. This counter is decremented as long as the channel is sensed idle. A user wishing to transmit packets using the channel waits the back off time and then transmits if the medium is still free.
If the packet is correctly received, it sends an ACK frame after letting pass another fixed period of time. If the transmitting user does not receive this ACK frame, a collision is assumed to have occurred. The system defines several transmission rates in the case of temporal degradation of the wireless channel. When it is bad, the sender changes the sending rate to a lower one. When a sender misses four consecutive ACKs, it drops the sending rate by changing the modulation or channel coding method. In contrast, when the timer expires or 10 consecutive ACKs are received successfully, transmission rate is upgraded to the next higher data rate. This timer has to be bigger than the sum of the round trip time of the packet and the delay that the system enters in the signal processing. The system overlooks the fact that actually not the sender but the receiver estimates the channel condition. Consequently, in wireless communications if a user moves to a location with bad radio characteristics, other users communicating with it may experience transmission failures.

The main challenge happens when a user experiences lower channel quality. It degrades his bit rate, and as result all the users connected to the same wireless AP experience the same throughput regardless the transmission rate. The principal reason for this is that the DCF does not provide the same probability to use the channel, while guaranteeing that all the users connected to the same AP have the same probability to access the channel. Consequently, the user with the higher bit rate has a longer transmission than the user that has a lower bit rate, resulting in inefficient channel utilization. Furthermore, a user transmitting at a lower bit rate than the other faster users forces them to drop down to a bit rate lower than its own. For example, if N users are transmitting at 11Mb/s and one user transmitting at 1Mb/s, all the users can only transmit at a bit rate lower than 1 Mb/s.

To analyse the anomaly theoretically, is necessary to derive expressions from the useful throughput. The Department of Computer Science and Engineering of Korea University validated the mathematical expressions by means of simulations and compared with several performance measurements. In the results presented in [18], the throughput experienced by each user is the same although the data rate is different. The expression giving the throughput of user s is as follows:

\[ X_s = X_f = \frac{S_d}{(N - 1)T_f + T_s + P_c(N) \times t_{jam} \times N} \]  

(7)

where \( X_f \) is the throughput at the MAC layer of each of the N-1 fast user, \( X_s \) is the throughput at the MAC layer of the slower user, N is the total number of users, and \( T_f \) and \( T_s \) is transmission time for fast users and slow users, respectively per packet. Moreover, \( P_c(N) \) is the probability of collision, \( S_d \) is the frame size and \( t_{jam} \) is the delayed time due to collisions. Equation (7) assumes that the channel is always busy and there are no multiple successive collisions. The throughput is not related to the sending rate of a user, because all the users have the same transmission time and the same frame size.

In a WLAN, the transmission rate depends on the distance between the communicating terminals or between terminals and an AP. Generally, the larger the distance is, the lower the preferable transmission rate is. Therefore, when there is high distance between a user and the AP, the channel condition will be poorer. If one or more users are moving, then the bit rate of the other users can also be affected. As a
result, a constant bit rate cannot be assumed for the fixed users. Finally, interference among the different users can also have impact in the others.

The LPI6 Laboratory from University of Paris [19] has been doing some simulations to validate this behaviour. The following picture shows an example.

![Two users in mobility behaviour and bit rate degradation](image1.png)

![The throughput degradation according to bit rate in two users](image2.png)

**Figure 6. Measurement Performance Anomaly experiment**

In the graph of Figure 6, at the beginning only one user is active with 11Mbps bit rate and 6Mbps as useful throughput. After 10 seconds another user arrives with 11Mbps as bit rate, and the useful throughput decreases to 3Mbps. Then the second user starts to move away from the AP, which corresponds in experiencing poor channel conditions. As such, the user minimizes its useful throughput and the bit rate decreases to 2Mbps. In this instant, the other user also decreases drastically the throughput. This behaviour verifies that the bit rate degradation of one user imposes the degradation of the other and monopolizes the wireless system. Later, the second user comes close to the AP and the system runs as normal. Overall, it confirms the behaviour of the “performance anomaly”; the throughput gets lower when users have different conditions and this is much smaller than the nominal bit rate.

Based on the above and having in our disposal the bit rate information of the Minstrel, the “performance anomaly” of the IEEE 802.11 can be studied, as well as the impact it can have in the behaviour of the WADRR resource sharing algorithm.
3. **Methodology / project development:**

The main objective of this project is to study the behaviour of the users of a WLAN in different environments. To do so, various metrics need to be analysed. Some of these metrics are already implemented, while some others, such as the bit rate information resulting from the Minstrel, are not available. Based on the above, this chapter focuses on the details of the implementation of the additional feature added to the Test-Bed, in order to monitor periodically, in real time, the bit rate of the users. In particular, both the WTP Agent and the Controller have been modified using C++ and Python 3 programming languages, respectively.

Despite the fact that the controller is characterized by a modular architecture giving the possibility to create various Apps on top of it, in order to introduce the additional feature there was the need for modifications in the core of the controller and the WTP. These changes are located in the empower-runtime (the Python-based controller) and the empower lvap-agent (the EmPOWER WiFi Agent).

Before proceeding to the implementation details, let us give a brief description of the signalling that takes place between the Controller and the Agent. As Figure 7 shows, first the controller and the EmPOWER Agent launch the EmPOWER/Runtime and the LVAP-Agent processes, respectively. Then a Hello message is send by the Agent to initialize (and later on to keep alive) the connection with the controller. When the communication is carried out correctly, the user can execute the applications created by GRCM for the WiFi RAN Slicing as presented in [6]. In particular, one application is used to request periodically (from the Controller to the WTP) the transmission times of each of the tenants, while the second one processes the results. After receiving the related requests, the WTP responds with the corresponding information.

The bit rate request and process have been added in the above mentioned applications. Moreover, based on the previous description, one can notice that the message exchange consists in requests-responses. As such, the implementation of the project has been divided into two logical parts, the request and the response.

The process starts with a function implemented in the controller that sends periodically to the WTP a “bit rate request” for a particular tenant. This request is carried out through a “request” packet that includes the SSID (network name) of the tenant. When the WTP receives the “request” packet, it calls the function to access the bit rate information for this particular tenant and then in turn, it sends a “response” message to the controller that includes this information (bit rate). Finally, once the controller receives the “response packet”, it prints the received bit rate appearing in the terminal during its execution. In the following points the whole process is explained with more details.
3.1. **Signalling between Controller – WTP**

A list of the controller’s modules related to this implementation, which are the ones that have been modified in order to allow the exchange of the bit rate information, is given in the following:

- `lvappconnection.py`: Defines the handling of the packets (messages) according to the EmPOWER protocol used for the communication with the WTPs.
- `__init__.py`: Defines the structure of the packets according to the EmPOWER Protocol.
- `wadrrdata.py`: Application that requests the transmission times of the tenants, as well as the number of transmitted packets.
- `weightapp.py`: Application to handle the received information.
- `wtp.py`: Defines the characteristics of the WTPs. It includes vectors that map the WTPs with their defined tenants and store the received information.

The WTP’s elements related to this implementation that have been modified in order to allow the exchange of the bit rate information are listed below:

![Diagram showing signaling between controller and agent](image-url)
- `empowerlvapmanager.cc/empowerlvapmanager.hh`: Is the element responsible for the communication with the controller, and the handling of the controller’s instructions.
- `empowerfairbuffer.cc`, `empowerfairbuffer.h`: This element implements the wireless hypervisor employing the WADRR algorithm.
- `empowerpacket.hh`: This header file defines the *EmPOWER protocol*, including the packet structure.
- `minstrel.cc`, `minstrel.hh`: This element implements the minstrel algorithm.

Notice that in order to apply any code modification, the WTP software has to be re-compiled (in a common PC). This is carried out using a script file (known as `build-empower.sh`) created by the developers of CreateNet. Once recompiled, the new software is uploaded to the WTP. The new code can be tested either using the normal execution mode, or using the GNU Project Debugger (GDB) in cases that debugging has to be carried out for the identification of errors that might occur during the code development. GDB offers the possibility of modifying the execution of a program. The user can control and alter the values of the program's internal variables. Finally, it is worth pointing out that the controller’s code changes are not necessary to be re-compiled; any changes are applied just by re-launching it.

### 3.2. Packet structure

The *EmPOWER protocol* defines the following packet structure:

- **Header**: Includes the version (i.e. *EmPOWER protocol*), the type of the message (e.g. bit rate request/response), as well as the packet length.
- **WTP**: Includes the WTP MAC address (from/to which the packet is send).
- **Data**: The variable amount of data to be send.

For the implementation of this project there was the need to create four types of packets:

- **Bit rate request** (Controller side): Is used to do the request from the controller to the WTP. This message is constructed as:
  - *EmPOWER protocol*
  - Type of message: *bit rate request*
  - Packet length
  - Packet sequence
  - WTP MAC address
  - Tenant SSID

- **Bit rate request** (WTP side): Is used to receive (identify) the request from the controller. It includes the same information as the request of the controller part.

- **Bit rate response** (WTP side): Is send from the WTP as a response to the controller’s request. This message is constructed as:
  - *EmPOWER protocol*
  - Type of message: *bit rate response*
  - Packet length
  - Packet sequence
  - WTP MAC address
  - Bit rate information
  - Tenant SSID
- **Bit rate response** (Controller side): This packet is used in the second part of the cycle to send the bit rate and other data from the Agent to the controller. Specifically: the type of the packet, the length, the sequence of the packet, the MAC address of the WTP, the bit rate and the SSID of the tenant. It is important to define the type of the packet so that the controller can receive (identify) it and handle it correctly.

### 3.3. Send request function – Controller part

First, the controller sends a request to ask the WTP to send the bit rate information. Since the bit rate is related to the users of each tenant, there is the need to include in each message the tenant’s SSID. The SSID (Service Set Identifier) is a sequence of 0-32 octets (most of the characters alphanumeric) included in all packets of a wireless network to identify them as part of that network.

As Figure 8 presents, the send request function is called for each WTP and SSID (tenant). Before performing any action, the function first checks if the WTP is indeed connected or if any error has occurred. If the validations are carried out successfully, the function creates the bit rate request packet using the structure described in section 3.2. Finally, the packet is send using the TCP connection established between the controller and the WTP. This process is executed in loop.

![Figure 8. Bit rate Request – Controller part](image)
3.4. Handle request function – WTP part

The WTP receives the packets through the TCP connection using the Socket element. Upon each packet reception, a check is carried out in order to discard erroneous packets, as Figure 9 indicates. When a packet is received, the lvapmanager.cc checks the type of the message and calls the corresponding function to handle the message. As such, a handle_bitrate_request function has been created in order to handle the Bit rate request messages. It is responsible for extracting the SSID parameter from the packet and calling the function that gets the bit rate information from the Minstrel element with purpose to call the corresponding function, known as send_bitrate to send it to the controller.

![Diagram](image)

Figure 9. Bit rate Request and Response – WTP part

In particular, the send_bitrate function gets the bit rate information from the Minstrel element (let us remind that the Minstrel element is based on the Minstrel algorithm and it calculates the bit rate for each packet to be send) and creates a packet of type bit rate response that includes the tenant’s SSID, the WTP MAC address and the bit rate information.
3.5. **Handle rate Function – Controller part**

When a *bit rate response* packet arrives at the controller through a *bit rate response* message, the system automatically calls the “handle_bit_rate” function. Following the diagram of Figure 10, the purpose of this function is to check that the SSID of the arrived packet matches with the ones stored in the controller’s database. Then, the bit rate information is stored in the corresponding WTP-Tenant vector and the result is printed on the log of the controller.

![Diagram](image)

**Figure 10. Bit rate Request Response – Controller part**
4. **Experimental Results**

In this chapter the experiments and their results are presented and analysed in detail. The main objective is to study the performance of the WTP with two tenants in different scenarios, and see how the WADRR algorithm and bit rate behave. The different scenarios include a tenant with a user in a fixed position and a tenant with a user whose distance from the WTP is varied. The latter results in varying the channel conditions of the user based on the distance.

4.1. **Experiment Description**

To study the impact that has the performance anomaly on the WADRR algorithm the experiment are carried out in a real environment using the EmPOWER Test-Bed. In particular, the experiments consider the average bit rate in which the packets are transmitted, the average packet losses and the resource sharing as results from the wireless hypervisor (with the WADRR algorithm). Especially for the resource sharing it is necessary to estimate the transmission time of the packets according to the following formula used on Click [20]:

\[
T_{\text{transmission}} = \text{DIFS} + \text{Backoff time} + \text{Header time} + t_p + \text{SIFS} + \text{ACK}
\] (8)

where \( T_{\text{transmission}} \) correspond to the transmission time, DIFS (DCF Inter-Frame Space) period refers to the time spent in the controls access to the physical medium, Back off time is defined as the multiplication of the time slot and CW, the Header transmission time, \( t_p \) is referred as the time spent on the packet according to the length and the rate of Minstrel, SIFS (Short Inter-Frame Space) is the propagation delay and finally the ACK has been explained before.

Whenever an attempt to transmit a packet fails, a number of retransmissions is scheduled, unless the retry limit is reached. Focusing on the CW, for the first transmission attempt of a packet, CW sets to the minimum one, but is increased with the number of retransmissions. Once the retry limit is reached, the packet is dropped, and the CW is reset. If the packet transmission is successful, CW value is initialized too. As such, the experiments are studied under various retransmissions in order to see the impact in the way the WADRR algorithm shares the resources to each of the Tenants.

Figure 11 depicts the employed scenario. As it can be seen from the figure, there is one WTP with two tenants and one user each of them. Following the scheme of Figure 11, User 1 is located below the WTP with a distance (d1) of approximately 2.5 meters (the WTP is located in the ceiling) and stays fixed in this position. User 2 changes its position and consequently its distance (d2) from the WTP according to each experiment.
Figure 11. Experiment scheme

Figure 12 presents the map of the first floor of the D4 building of Campus Nord – Universitat Politècnica de Catalunya where the experiments have been carried out. The user connected to Tenant 1 is located together with the WTP in front of the office 107, which corresponds to position 1 on the map of the Figure 12. Then, 5 positions are defined for the user of Tenant 2:

- 2: In front of office 108 \( (d_2 = 5.6 \text{ m}) \)
- 3: In front of office 110 \( (d_2 = 12.25 \text{ m}) \)
- 4: inside office 108 \( (d_2 = 6 \text{ m}) \)
- 5: inside office 111 \( (d_2 = 14.3 \text{ m}) \)
- 6: inside office 110 \( (d_2 = 12.7 \text{ m}) \)

Figure 12. Floor 1 of D4 building map
Let us notice, that in each of the experiments not only $d_2$ is changing, but also the signal of the WTP has to go through various obstacles to reach the user. As such, the positions are ordered from the best case to the worst by taking into account the channel conditions and the distance. It is clear that position 2 and position 3 are the best ones, followed by the fourth. The worst cases are the fifth and sixth position with the sixth being the worst one. Although it may seems that in office 110 (position 6), the signal should arrive better than in office 111 (position 5) due to the proximity to the WTP, the signal in office 111 enters directly through the door and then it is reflected on the walls until it reaches the user. On the other hand, in office 110 the signal is reflected (bounced off) before entering the room. Therefore, in this last position, the signal gets even weaker and consequently this is the worst case scenario studied.

As mentioned previously, this experiment involves performing measurements taking into account various retransmission attempts in the calculation of the transmission time according to WADRR algorithm. In particular, we consider 0,1,3 and 4 retransmissions. In each case, the 5 possible locations of the User of Tenant 2 will be considered keeping the User of Tenant 1 in its fixed position, with target to study how the changes in the user position and channel conditions (performance anomaly) affect the overall system performance. The final result is the average of 10 experiments of 1 minute duration each. To create a flow of packets sent from the WTP to the tenants, iPerf [21] has been used. It is a tool for active measurements of the maximum achievable bandwidth on IP networks. The value of the bandwidth has been chosen to 8.3 Mb/s because it was found that the EmPOWER has a limitation in the total capacity of approximately 8 Mb/s. Moreover, another study has been made, concluding that the ideal values to work are: 1500 Byte packets for both tenants, 2.6 Mb/s of bandwidth for Tenant 1 and 5.7 Mb/s for Tenant 2 and maximum losses of around 12%. If these values are exceeded, the system may have large packet losses due to the software. On the other hand, the WADRR algorithm requires a full buffer in the tenant queues in order to be able to achieve the results that could be properly analysed. As such, the values must be set accordingly so that the WADRR will reach its maximum performance while keeping the packet losses in very low levels. Finally, the weights (resource sharing) have been set to 30% for Tenant 1 (with the user closer to the WTP) and 70% for Tenant 2.

4.2. Results analysis

The metrics analysed in this experiment are: the percentage of time assigned to each tenant according to the WADRR algorithm, the real average speed, the bit rate and the percentage of the total losses. It is important to note that the bit rate is the number of bits per unit of time available from the channel, specifically in wireless connections on the air interface. Meanwhile, the available bandwidth is the speed that the connected users are observing.
Figure 13 depicts the graphs for the case of considering 0 retransmission attempts (in the calculation of the packet transmission time), depending on the position of the tenants. Let us notice that the detailed tables including all the experimental results can be found in Annex 3. 0 retransmissions.

---

**Figure 13. a) %Time, b) Bandwidth, c) Bit rate and d) Loss – 0 Retransmissions**

It is important to remind that the controller shows a set of rates, but the real results are taken from the relationship of Table 2 presented in chapter 2.2.1.1. First, it is clear that the results are close to the theoretical ones (presented in green line in the graphs). In graph a) (% time) the trend line is to have 30 % of the time assigned to the tenant with the user located closest to the WTP and 70 % to Tenant 2. Moreover, looking at the typical deviation represented on the same chart, the most experiments work as expected, except for some concrete cases in the losses. On the other hand, in the door of office 108 there is the worst case of % time (figure a) and bandwidth (figure b). The explanation is that near that position there is another AP working and there are occasional cases with high interference. Overall, it is clear that even though the bit rate of User 2 (of Tenant 2) is degrading with the distance, the resource allocation performed by the WADRR algorithm is as instructed by the weights, thus it can be stated that there is no negative impact in its performance. Finally, let us notice that the maximum losses observed are in the office 110 with a value of the order of 12%.
Figure 14 presents the average values of the experiments considering 1 retransmission. The detailed results can be found in Annex 4. 1 retransmissions. The effect of interference at the door of office 108 is observed as in the previous case. Also, it is confirmed that the office 110 is the worst case, because the signal makes a lot of bounces before it reaches User 2 (of Tenant 2), as explained before. These trends are followed in the 4 cases of the experiment. Furthermore, the fluctuations in general are higher than the previous case, there are more losses and worse bit rate. The bandwidth also is lower than the ideal one due to the losses. These factors occur because at the time of testing, there were many people working in the building that produced a higher level of traffic on the routers and therefore more interference. This is reflected in the performance of the WADRR were there is a small declination from the resource instructed by the selected weights (30-70%).

![Graphs showing performance metrics](image-url)
Figure 15 presents the graphs of the four parameters analysed with 3 retransmissions per packet, based on the tables of Annex 5. 3 retransmissions. The principal difference with the cases explained before, is that the bit rate has improved and the order of losses has been decreased based on a factor of 12. This behaviour indicates that the interference during the execution of these experiments was lower. In the particular case of the Tenant 2 situated in 108 office, the bit rate did not decrease significantly, but it can be see that the standard deviation quite high. So, the bit rate average is lower because there is a wider range of values to average. Finally, observing figure a) it is obvious that the impact it has in the performance of the WADRR is minimal, since the resource allocation performed by the algorithm is very close to the desired one.

Figure 15. a) %Time, b) Bandwidth, c) Bit rate and d) Loss – 3 Retransmissions
Then, Figure 16 shows the results of the test concerning 4 retransmissions according to Annex 6. As it is expected, the % time and the bandwidth are maintained close to the theoretical values. Even though there are slightly more losses than in the previous case, the rest of the differences are negligible caused by the level of interference of that day. Therefore, it can be considered that it follows the expected behaviour, especially with respect to the WADRR performance.

![Graphs showing % Time, Bandwidth, Bit Rate, and Loss for 4 Retransmissions](image)

Figure 16. a) %Time, b) Bandwidth, c) Bit rate and d) Loss – 4 Retransmissions.

The expected behaviour of the system is to have better results as the retransmissions increase, since when more retransmissions are considered in the estimation of the packet transmission time, closer to the real one. In spite of this, in Annex 7, %Time, Bandwidth, Bit rate and Loss 0,1,3 and 4 Retransmissions there are all the previous graphs superimposed in the same graph and there are no big changes between the results of different retransmission cases, confirming that the WADRR algorithm works as it is expected even under adverse channel conditions, although it improves when you have less distance from the WTP. So, the conclusion is that the various channel environments do not affect in high degree the performance of the WADRR algorithm. In particular, the algorithm works correctly up to a minimum distance of 14.3 meters and poor channel conditions, with a maximum of 7% error in average. In addition, it is observed that even though in all the results User 2 is under adverse state in the connection, it does not affect the bit rate of User 1 as it is always maintained at 54 Mb/s approximately.
Figure 17 presents a histogram of the bit rate obtained in all the results of the experiment coming from both tenants. This information in numerical format can be found at Annex 8. Number of each Bit Rate. Finally, for the result analysis it can be said that the resource allocation is performed correctly in all the cases and that the system works correctly. As expected, there's a slight improvement as the considered retransmissions go up and it can be said that 84% of the experiments have the users transmit with very high bit rate.

Figure 17. Bit rate histogram
5. **Budget**

This project corresponds to 18 ECTS credits, which are 540 hours of dedicated work. Taking into account that the salary of a junior engineer is around 18€ per hour the total Cost is 9720€ according to equation (9). In Annex 9. *Decomposition cost of Junior engineer’s project* there is the decomposition of the cost of the Junior engineer’s project for each task.

![Equation](#)

\[ \text{Junior engineer Cost} = 18 \left( \frac{\text{€}}{\text{hour}} \right) \cdot 540 \left( \text{hours} \right) = 9720,0 \text{€} \]  

(9)

5.1. **Software**

The software used in this project is open-source developed by the Wireless and Networked Systems (WiN) research unit at CREATE-NET, or GRCM’s property. So it doesn’t suppose an additional cost to the project.

5.2. **Hardware**

Table 3 shows the analysis of the hardware elements’ depreciation calculated from equations (10) and (11), taking into account that the hardware has been used for 130 days.

![Equation](#)

\[ \text{Price per year (€)} = \text{Price (€/years)} \cdot \text{Life time (years)} \]  

(10)

\[ \text{Depreciation (€)} = \frac{\text{Price per year (€)} \cdot \text{Time used (days)}}{\text{Time of a year (days)}} \]  

(11)

<table>
<thead>
<tr>
<th>Hardware elements</th>
<th>Price</th>
<th>Life time (years)</th>
<th>Depreciation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laptop</td>
<td>600.00 €</td>
<td>4</td>
<td>53.42 €</td>
</tr>
<tr>
<td>WTP</td>
<td>200.00 €</td>
<td>3</td>
<td>32.70 €</td>
</tr>
<tr>
<td>Mobile 1</td>
<td>150.00 €</td>
<td>4</td>
<td>13.36 €</td>
</tr>
<tr>
<td>Mobile 2</td>
<td>150.00 €</td>
<td>4</td>
<td>13.36 €</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1.100.00 €</strong></td>
<td><strong>4</strong></td>
<td><strong>112.84 €</strong></td>
</tr>
</tbody>
</table>

Table 3. Hardware depreciation
6. **Environment Impact**

The environment impact of this project is low due to the fact that it is implemented in software. It does not include many hardware devices; such as the harmful effects are degraded. Furthermore, the energy consumed by the platform (controller PC and WTP) can be considered negligible.

The final objective of the project is to exploit the SDN and NFV concepts. As it has been explained before, these technologies permit us to perform the implementations in software instead of hardware devices. Therefore, any required modification can be implemented through a software update of the device, rather than substituting the old device by a new one. This results in a significant decrement of hardware residues.

Based on the above it can be concluded that the environment impact of this project is negligible.
7. **Conclusions and future development:**

The main goal of this project was to implement and experimentally validate the measurement and test related functions of the resource sharing algorithm WADRR, algorithm implemented in the context of WiFi RAN slicing. In particular, the project was able to extract the bit rate information of the rate selection algorithm included in the APs, known as Minstrel algorithm, monitor it in the controller and analyse thoroughly the obtained results extracted from various experiments. The implementation of the proposed and developed algorithms and functions has been carried out using real-time Test-Bed with SDN and NFV capabilities, known as EmPOWER. The final purpose of the work was to study the “performance anomaly” under different channel conditions, the performance of the WADRR algorithm under these scenarios and draw in general conclusions about the behaviour of the users of the WLAN in different environments.

The development of functions for the extraction of the user bit rate and the integration with the whole system has been successfully deployed thanks to a detailed analysis of the characteristics and the architecture of the system. In particular, the software of the EmPOWER Test-Bed, both Controller and AP (Agent) parts, has been studied thoroughly, as well as the communication between them (i.e. EmPOWER protocol and signalling). Furthermore, for the validation of the functions it was important to get familiarized with the debugging process.

After the implementation was validated, various tests have been carried out extracting all the necessary information in order to analyse the system performance. The WADRR algorithm has been found to work well even when the channel conditions were not ideal. The algorithm shared the available resources based on weights that reflected the traffic demand in each virtual network (slice). Moreover, it has been shown that the system achieves very high bit rates in the channel transmissions. Therefore, although theoretically the number of retransmissions influences the calculations and the final result, it has been observed that in total it does not have a significant impact in the WADRR performance.

Regarding the future development, there are many ways to explore this project and the EmPOWER Test-Bed in order to study more aspects related to the RAN slicing:

1. Instead of performing an estimation of the transmission time using the Minstrel bit rate, the feedback frames of the WTP can be used in order to extract the actual bit rate information and calculate with more precision the packet transmission time.
2. Study similar scenarios but with multiple APs, Tenants and users to better analyse the behaviour of the system. For example by experimenting with more than one user connected to a tenant, having it with clearly more traffic than another tenant.
3. Study the impact that the handover can have on system performance.
Bibliography:


Appendices:

Annex 1. Project Plan Gantt Diagram

This Annex shows the plan Gantt diagram followed in the project.

Figure 18. Project Plan Gantt diagram
Annex 2. Table of loss/success rates for each data rate

In this Annex there is an example of a table of loss/success rates for each bit rate [8]. The values of this table change depending on the scenario where Minstrel is running. In this case, there is the performance for two users in close proximity, one beside each other. The columns *bit rate*, *throughput* and *ewma prob*, indicate the rates with the highest throughput, the throughput measured for a packet given the probability of success and the EWMA probability, respectively. Moreover, *this prob* reports the success change from the last time interval. Then *succ/attempt* inform of how many packets were sent (and number of successes). Finally, two last columns are the number of success and attempts.

<table>
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<th>bit rate</th>
<th>throughput</th>
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<th>this prob</th>
<th>this succ/attempt</th>
<th>success</th>
<th>attempts</th>
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<td>P1</td>
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<td>100</td>
<td>0(0)</td>
<td>106</td>
<td>111</td>
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<td>2</td>
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<td>1</td>
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<td>1</td>
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<td>11</td>
<td>1.1</td>
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<td>0(0)</td>
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<td>2</td>
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<tr>
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<td>10</td>
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<tr>
<td>54</td>
<td>16.2</td>
<td>91.1</td>
<td>91.2</td>
<td>115(126)</td>
<td>96429</td>
<td>109032</td>
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</table>

Total packet count: ideal 5756 | lookahead 641

*Table 4. Loss/success rates for each data rate*
Annex 3: 0 retransmissions results

This annex presents the average values of the tests carried out, in particular the experiment 1 with 0 retransmissions in the 5 different cases of Tenant 2’s position. It is important to notice that the green cells are the theoretical values, while the blue ones are those obtained.

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<td>Distance</td>
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<td>108 door</td>
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<tr>
<td>Bandwidth (Mb/s)</td>
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</tr>
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<td>Time (s)</td>
<td>7877980.8</td>
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<tr>
<td>% Time</td>
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<td>108</td>
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<tr>
<td>Bit rate real (MB/s)</td>
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<td>54.00</td>
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Table 5. 0 Retransmissions a) 108 door, b) 108 desk

Table 6. 0 Retransmissions a) 110 door, b) 110 desk

Table 7. 0 Retransmissions 111 desk
Annex 4. 1 retransmissions results

This annex presents the average values of the tests carried out, in particular the experiment 1 with 1 retransmissions in the 5 different cases of Tenant 2’s position. It is important to notice that the green cells are the theoretical values, while the blue ones are those obtained.

Table 8. 1 Retransmissions a) 108 door, b) 108 desk

Table 9. 1 Retransmissions a) 110 door, b) 110 desk

Table 10. 1 Retransmissions 111 desk
Annex 5. 3 retransmissions results

This annex presents the average values of the tests carried out, in particular the experiment 1 with 3 retransmissions in the 5 different cases of Tenant 2’s position. It is important to notice that the green cells are the theoretical values, while the blue ones are those obtained.

Table 11. 3 Retransmissions a) 108 door, b) 108 desk

Table 12. 3 Retransmissions a) 110 door, b) 110 desk

Table 13. 3 Retransmissions 111 desk
Annex 6. 4 retransmissions results

This annex presents the average values of the tests carried out, in particular the experiment 1 with 4 retransmissions in the 5 different cases of Tenant 2’s position. It is important to notice that the green cells are the theoretical values, while the blue ones are those obtained.

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<th>a)</th>
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</tr>
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</tr>
<tr>
<td>Distance</td>
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<td>108 desk</td>
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<tr>
<td>Bandwidth (Mb/s)</td>
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<td>5.7</td>
</tr>
<tr>
<td>Time (s)</td>
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<td>Bandwidth (Mb/s)</td>
<td>2.49</td>
<td>5.42</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>0.86</td>
<td>3.6</td>
</tr>
<tr>
<td>Rate</td>
<td>106.8</td>
<td>108</td>
</tr>
<tr>
<td>Bit rate real (MB/s)</td>
<td>53.40</td>
<td>54.00</td>
</tr>
</tbody>
</table>

Table 14. 4 Retransmissions a) 108 door, b) 108 desk

<table>
<thead>
<tr>
<th>a)</th>
<th>Tenant 1</th>
<th>Tenant 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weights</td>
<td>30%</td>
<td>70%</td>
</tr>
<tr>
<td>Distance</td>
<td>close</td>
<td>110 door</td>
</tr>
<tr>
<td>Bandwidth (Mb/s)</td>
<td>2.6</td>
<td>5.7</td>
</tr>
<tr>
<td>Time (s)</td>
<td>87854774.9</td>
<td>184925304.9</td>
</tr>
<tr>
<td>% Time</td>
<td>32.21%</td>
<td>67.79%</td>
</tr>
<tr>
<td>Bandwidth (Mb/s)</td>
<td>2.55</td>
<td>5.38</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>0.25</td>
<td>3.61</td>
</tr>
<tr>
<td>Rate</td>
<td>108</td>
<td>108</td>
</tr>
<tr>
<td>Bit rate real (MB/s)</td>
<td>54.00</td>
<td>54.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>b)</th>
<th>Tenant 1</th>
<th>Tenant 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weights</td>
<td>30%</td>
<td>70%</td>
</tr>
<tr>
<td>Distance</td>
<td>close</td>
<td>110 desk</td>
</tr>
<tr>
<td>Bandwidth (Mb/s)</td>
<td>2.6</td>
<td>5.7</td>
</tr>
<tr>
<td>Time (s)</td>
<td>103642859.4</td>
<td>199582402.0</td>
</tr>
<tr>
<td>% Time</td>
<td>34.18%</td>
<td>65.82%</td>
</tr>
<tr>
<td>Bandwidth (Mb/s)</td>
<td>2.56</td>
<td>5.38</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>0.18</td>
<td>3.76</td>
</tr>
<tr>
<td>Rate</td>
<td>108</td>
<td>100.8</td>
</tr>
<tr>
<td>Bit rate real (MB/s)</td>
<td>54.00</td>
<td>50.40</td>
</tr>
</tbody>
</table>

Table 15. 4 Retransmissions a) 110 door, b) 110 desk

<table>
<thead>
<tr>
<th>a)</th>
<th>Tenant 1</th>
<th>Tenant 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weights</td>
<td>30%</td>
<td>70%</td>
</tr>
<tr>
<td>Distance</td>
<td>close</td>
<td>111 desk</td>
</tr>
<tr>
<td>Bandwidth (Mb/s)</td>
<td>2.6</td>
<td>5.7</td>
</tr>
<tr>
<td>Time (s)</td>
<td>87041298.3</td>
<td>187698364.2</td>
</tr>
<tr>
<td>% Time</td>
<td>31.68%</td>
<td>68.32%</td>
</tr>
<tr>
<td>Bandwidth (Mb/s)</td>
<td>2.55</td>
<td>5.49</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>0.02</td>
<td>1.89</td>
</tr>
<tr>
<td>Rate</td>
<td>108</td>
<td>102</td>
</tr>
<tr>
<td>Bit rate real (MB/s)</td>
<td>54.00</td>
<td>51.00</td>
</tr>
</tbody>
</table>

Table 16. 4 Retransmissions 111 desk
Annex 7. %Time, Bandwidth, Bit rate and Loss 0,1,3 and 4 Retransmissions

In the following graphs it is seen the results of the different experiments represented. Each one contains the cases of the two tenants, combined with the number of retransmissions. They are plot according to each metric and the distance of the tenant two from the WTP ($d_2$). Each point represented of each line is the average of the 10 tests performed.
Figure 19. a) %Time, b) Bandwidth, c) Bit rate and d) Loss – 0,1,3 and 4 Retransmissions.
Annex 8. Number of each Bit Rate

This annex presents the number of times that each bit rate has been used in the performed experiments. It is disclosed through the retransmissions.

<table>
<thead>
<tr>
<th>Bit rate (Mb/s)</th>
<th>Number of times</th>
<th>Bit rate (Mb/s)</th>
<th>Number of times</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>84</td>
<td>54</td>
<td>84</td>
</tr>
<tr>
<td>48</td>
<td>16</td>
<td>48</td>
<td>10</td>
</tr>
<tr>
<td>36</td>
<td>0</td>
<td>36</td>
<td>6</td>
</tr>
<tr>
<td>24</td>
<td>0</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>0</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td><strong>100</strong></td>
<td><strong>TOTAL:</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bit rate (Mb/s)</th>
<th>Number of times</th>
<th>Bit rate (Mb/s)</th>
<th>Number of times</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>94</td>
<td>54</td>
<td>88</td>
</tr>
<tr>
<td>48</td>
<td>4</td>
<td>48</td>
<td>12</td>
</tr>
<tr>
<td>36</td>
<td>1</td>
<td>36</td>
<td>0</td>
</tr>
<tr>
<td>24</td>
<td>0</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>0</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td><strong>100</strong></td>
<td><strong>TOTAL:</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Table 17. Number of each bit rate a) 0 Retrans, b) 1 Retrans, c) 3 Retrans, d) 4 Retrans
Annex 9. Decomposition cost of Junior engineer’s project

The following table shows the breakdown of the hours invested in the project and the cost involved.

<table>
<thead>
<tr>
<th>Task</th>
<th>Hours</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information research</td>
<td>33</td>
<td>594 €</td>
</tr>
<tr>
<td>Study of 5G</td>
<td>11</td>
<td>198 €</td>
</tr>
<tr>
<td>Study of SDN and NFV</td>
<td>11</td>
<td>198 €</td>
</tr>
<tr>
<td>Study of Network/RAN slicing</td>
<td>11</td>
<td>198 €</td>
</tr>
<tr>
<td>Installation</td>
<td>27</td>
<td>486 €</td>
</tr>
<tr>
<td>Empower</td>
<td>13</td>
<td>234 €</td>
</tr>
<tr>
<td>Controller</td>
<td>9</td>
<td>162 €</td>
</tr>
<tr>
<td>Others</td>
<td>5</td>
<td>90 €</td>
</tr>
<tr>
<td>Familiarization with software and hardware</td>
<td>108</td>
<td>1.944 €</td>
</tr>
<tr>
<td>WTP</td>
<td>28</td>
<td>504 €</td>
</tr>
<tr>
<td>WTP software (C++)</td>
<td>44</td>
<td>792 €</td>
</tr>
<tr>
<td>Controller software (Python)</td>
<td>36</td>
<td>648 €</td>
</tr>
<tr>
<td>Development and validation</td>
<td>155</td>
<td>2.790 €</td>
</tr>
<tr>
<td>Algorithm</td>
<td>45</td>
<td>810 €</td>
</tr>
<tr>
<td>Implementation</td>
<td>80</td>
<td>1.440 €</td>
</tr>
<tr>
<td>Debugging / Verification</td>
<td>30</td>
<td>540 €</td>
</tr>
<tr>
<td>Experimental results and evaluation</td>
<td>127</td>
<td>2.286 €</td>
</tr>
<tr>
<td>Whole system validation</td>
<td>45</td>
<td>810 €</td>
</tr>
<tr>
<td>Implementation of experiments</td>
<td>46</td>
<td>828 €</td>
</tr>
<tr>
<td>Results analysis</td>
<td>36</td>
<td>648 €</td>
</tr>
<tr>
<td>Writing and oral presentation</td>
<td>90</td>
<td>1.620 €</td>
</tr>
<tr>
<td>Final report</td>
<td>60</td>
<td>1.080 €</td>
</tr>
<tr>
<td>Pressentation approval</td>
<td>30</td>
<td>540 €</td>
</tr>
<tr>
<td>TOTAL</td>
<td>540</td>
<td>9.720 €</td>
</tr>
</tbody>
</table>

Table 18. Cost of the Junior engineer’s project for each task
Glossary

ACK: Acknowledgement
AP: Access Points
BSSID: Basic Service Set Identifier
CAPEX: CApital EXpenditures
CPP: Click Packet Processors
CPU: Central Processing Unit
GRCM: Mobile Communications Research Group
CREATE-NET: Center for REsearch And Telecommunication Experimentation for NETworked communities
CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance
DC: Deficit Counter
DF: Distributed Coordination Function
DIFS: DCF Inter-Frame Space
DL: DownLink
EWMA: Exponentially Weighted Moving Average
GDB: GNU Project Debugger
IT: Information Technology
LTE: Long Term Evolution
LVAP: Light Virtual Access Point
LVNF: Light Virtual Network Function
MAC: Media Access Control
MNOS: Mobile Network Operating System
MVNO: Mobile Virtual Network Operator
NFV: Network Function Virtualization
NOS: Network Operating System
OPEX: OPerating EXpense
PCF: Point Coordination Function
RAN: Radio Access Network
SDN: Software Defined Networking
SIFS: Short Inter-Frame Space
SSID: Service Set Identifier
TCP: Transmission Control Protocol
TSC: Signal Theory and Communications
UPC: Universitat Politècnica de Catalunya
VNF: Virtualized Network Functions
WADRR: Weighted Air-Time Deficit Round Robin
WCA: Weights Compensation Algorithm
WDRR: Weighted Deficit Round Robin
WIN: Wireless and Networked Systems
WLAN: Wireless Local Area Network
WTP: Wireless Termination Point
5G: 5th-Generation Wireless Systems