What to do With the Wi-Fi Wild West

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Abstract

This deliverable defines the initial specification of the Wi-5 architecture that integrates all the smart and cooperative functionalities. The architecture takes into account the functional requirements related to the environment where Wi-5 will be deployed as well as the stakeholders of the Wi-Fi systems and the business models that sustain them. The architecture is described according to ISO-IEC-IEEE 42010 standard, and the initial design approach is presented.

Wi-5 Consortium

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Executive Summary

This deliverable describes the initial version of the architecture that was developed by the Horizon 2020 Wi-5 (What to do With the Wi-Fi Wild West) project, which will provide a foundation for the technical work in developing smart and cooperative Access Points (APs) addressing radio spectrum interference and spectrum usage inefficiency. The approach was selected to provide the best technical solution to the issues of radio resource management, mobility, and Quality-of-Experience (QoE) and was designed in conjunction with, and using input from, the work to explore the Wi-5 business models and use cases. This architecture was refined as the technical work progressed and the initial version presented here embodies the feedback that was gathered through interaction with our Operator Board and Expert Advisors.

Our first step in designing the Wi-5 initial architecture was to consider these functionalities in the context of the use cases that the project has chosen to focus on (as outlined in Deliverable 2.3) and the business models and concerns that have been identified (as outlined in Deliverable 2.1). These, together with the architecture, represent the initial outcomes of Work Package 2 and embody the close interrelationship between technology, application, and utilisation that we strive for.

An analysis of the most relevant use cases helped to identify the functional requirements in each scenario, and were then combined to identify how the Wi-5 functionalities map onto these deployment scenarios. The business model analysis addressed the *tragedy of the commons* whereby competing interests aggressively claim a shared resource, ultimately resulting in lower overall performance for everyone. As such, a new role of the Spectrum Usage Broker has been developed within Wi-5 as our approach to enabling cooperation between competing entities whilst ensuring them a fair share of the resources, a minimal loss of autonomy, and an overall optimized user experience.

Following this analysis, the Wi-5 initial architecture was formally described according to the guidelines of standard ISO-IEC-IEEE 42010. Firstly, the key Wi-5 system stakeholders and their related concerns were identified and mapped. Secondly, a set of viewpoints that address these concerns for each stakeholder were presented.

The analysis also shows that traditional networking techniques would not be sufficient to meet the functional and business-related requirements. We therefore chose to adopt the Software Defined Networking (SDN) paradigm and base our approach on the emerging area of Software Defined Wireless Networking (SDWN). The SDWN concept can fulfil the requirements of the Spectrum Usage Broker, with the SDN Controller as the main configuration point for the entire wireless network. In the proposed architecture, the Wi-5 solutions are then implemented on top of the Controller. The configuration capabilities of access points are extended to support Wi-5 solutions.

The innovations introduced in the Wi-5 architecture result from the introduction of fine-grained control over the wireless spectrum resources in the access point, the flexible inter-operator deployment model that is enabled via the broker, and the close integration between the novel smart and cooperative functionalities that are implemented in the Wi-5 solutions. These include novel features such as dynamic channel assignment and power control, AP load balancing and packet grouping based on traffic type and requirements, support for smart handovers to optimise user QoE and seamless vertical handovers to maximise usage of the full wireless environment, and coordinated interference management to find the optimal wireless configuration.

1 Introduction

1.1 Wi-5 background

The last few years have witnessed a significant increase in the use of portable devices, especially smartphones and tablets thanks to their functionality, user-friendly interface, and affordable price. Most of these devices use Wi-Fi Access Points (AP) where possible, in addition to 3G/4G, to connect to the Internet due to its speed, maturity and efficiency.

Given this demand, Wi-Fi is facing mounting issues of spectrum efficiency due to its utilisation of non-licensed frequency bands, so improvements continue to be added to standards in order to improve performance and adapt it to new demands. For example, as Wi-Fi saturation increases in areas, such as business centres, malls, campuses or even whole European cities, interference between these competing APs can begin to negatively impact users' experience. At the same time, real-time interactive services have grown in popularity and are now used across a range of mobile devices. These share the same connection with "traditional" applications, such as e-mail and Web browsing, but are far more bandwidth intensive and require consistent network capacity to meet user Quality of Experience demands.

In this context, the Wi-5 Project (What to do With the Wi-Fi Wild West) proposes an architecture based on an integrated and coordinated set of smart solutions able to efficiently reduce interference between neighbouring APs and provide optimised connectivity for new and emerging services. Cooperating mechanisms will be integrated into Wi-Fi equipment at different layers of the protocol stack with the aim of meeting a demanding set of goals:

- Support seamless handover to improve user experience with real-time interactive services.
- Develop new business models to optimise available Wi-Fi spectrum in urban areas, public spaces, and offices.
- Integrate novel smart functionalities into APs to address radio spectrum congestion and current usage inefficiency, thus increasing global throughput and achieving energy savings.

1.2 Scope and structure of this deliverable

This deliverable describes the first version of the detailed Wi-5 architecture specification that integrates the smart and cooperative functionalities as proposed in Wi-5. We first start by reviewing in section 2 the contributions and concepts found in the literature which are related to the project and that have influenced some of the choices made during the design process of the architecture. In section 3 we present the Wi-5 functionalities that the proposed architecture integrates. In section 4, we present the architecture design requirements derived from the use case and requirement analysis presented in D2.3, the business models analysis presented in D2.1, and the input obtained from the project's Operator Board. We then present the Wi-5 architecture description according to standard ISO/IEC/IEEE 42010, and explain how this architecture is designed according to the SDN concept. Finally, we present our conclusions in section 6.

1.3 Relationship with other deliverables

The material in this document relates to the following deliverables.

D2.1: The Wi-5 architecture description is based on the stakeholders and business-related requirements identified in this deliverable.

D2.3: The Wi-5 architecture is based on the functional and performance requirements derived from the analysis of the use cases presented in this deliverable.

D3.2: Deliverable 2.4 describes the architecture that integrates the smart functionalities specified in deliverable D3.2. D2.4 also describes how these functionalities fit into the proposed architecture and how they interact with other functionalities and entities.

D4.1: Deliverable 2.4 describes the architecture that integrates the cooperative functionalities specified in deliverable D4.1. D2.4 also describes how these functionalities fit into the proposed architecture and how they interact with other functionalities and entities.

2 Literature Review

2.1 Radio Resource Management

Due to the limited number of orthogonal channels that the 802.11 standard supports, high levels of interference are expected, which in the end leads to a reduction in the network efficiency and therefore lower Quality of Service (QoS) and degraded Quality of Experience (QoE) for users. In this context, in recent years several channel assignment schemes for infrastructure-based WLANs have been proposed and a comprehensive survey can be found in [1]. Most of these works propose centralised algorithms that assume there is a network which belongs to one administrative domain [2], [3]. However, in most situations this is not the case for WLANs, which continuously evolve, generating heterogeneous scenarios where multiple WLANs are deployed by different owners and Wi-Fi access providers. In this scenario channel assignment algorithms, where the operating channels of the Access Points (APs) can be self-configured and their transmitted power level can be managed in order to minimise interference with adjacent APs, would be more appropriate.

For instance, Least Congested Channel Search (LCCS) is a common feature provided for channel auto-configuration in commercial APs [4]. With LCCS each AP scans all available channels, listens to the beacons transmitted by neighbouring APs and chooses the channel used by the least number of associated devices. In contrast, the authors of [5] introduce a channel assignment solution that exploits the gain of using partially overlapping channels relying on the SINR interference model, which considers the accumulative interference of the environment from the receiver point of view. They propose a heuristic algorithm able to assign overlapping channels to the APs in the system, which maximises the network throughput. Other studies provide solutions explicitly proposed for specific use cases such as high density networks [6] and areas with uncoordinated interfering network elements, one of the most challenging Wi-Fi deployments nowadays.

Transmission power control algorithms are also important in any wireless system. In WLANs, the devices typically transmit at their highest output power, and this results in high interference levels and a subsequent throughput reduction. Different power control methods have been proposed for 802.11 trying to reduce interference: in [7] an algorithm is presented, based on the link-quality estimation scheme defined for Transmit Power Control (TPC) of IEEE 802.11h. The WLAN station (STA) estimates the path loss between itself and the transmitter, updates the data transmission status, and then selects the proper transmission rate and transmit power for the current data transmission that attempts using a simple table look-up. The power control management method proposed in [8] focussed on minimisation of the interference level when different APs and WLANs are present in the same area. The APs on different WLANs are synchronised in order to avoid asymmetric links. At any instant of time, all APs in the network operate at the same power level to avoid link asymmetry. By using different power levels, the system achieves per-client power control to maximise spatial reuse. In [9] the authors propose a combination of power level control and rate adjustment for meeting the link quality requirements. Rate selection in WLANs is determined by an estimation of the channel conditions including packet loss, delivery ratio, throughput, or SINR estimation.

The optimisation of the associations of users to APs is also important to improve wireless performance. User devices are generally associated with APs within range either according to user policies or simply based on the Received Signal Strength (RSS), under the assumption that APs with a stronger signal will offer better performance. Other AP selection strategies can be defined with the aim of maximising the QoS of a particular user that tries to join a WLAN. This is the approach considered in [10], where an association metric called EVA (Estimated aVailable bAnd-width) is proposed, allowing a user to be allocated to the AP that provides the maximum achievable throughput. Authors have showed that the solution increases the per-station throughput, balances the load on the APs, and enhances the aggregate throughput. Other papers consider AP selections strategies relying on best throughput under frameworks based on game theory [11], [12], [13]. Finally, in [14] the authors described the handover processes for Distributed Queuing with Collision Avoidance (DQCA) in a multi-cell environment considering different AP selection mechanisms. These mechanisms are based either on a single metric such as the Signal to Noise Ratio (SNR), on the traffic load, or on a cross-layer design by combining the information from different layers.

2.2 Seamless Mobility and Handover

In addition to providing mechanisms to better manage the radio resources in Wi-Fi networks, Wi-5 also aims help exploit underused Wi-Fi or 3G/4G capacity by allowing users to leave and join any available Wi-Fi network or 3G/4G network without affecting their experience.

Traditionally, seamless mobility has always been addressed in cellular networks through Horizontal Handover solutions where the aim was to guarantee continuous connectivity. However, these solutions do not support mobility across heterogeneous networks with different radio resources and performances as is the case in wireless data networks.

This problem, usually referred to as Vertical Handover, has been addressed through a number of contributions [43], [44]. Most of the Vertical Handover solutions rely on the mobile terminal to trigger the process, and provide the performance metrics in order to assist the algorithm in choosing the most suitable AP to connect to when performing the handover. These performance metrics include: Received Signal Strength Indicator (RSSI), the network connection time, the available bandwidth, the power consumption and the transition cost. In RSS based algorithms [45], [46], [47] the decision to join a network is based on the RSS parameter. In bandwidth based algorithms [48], [49], the decision to join a network is based on the amount of available bandwidth which helps to achieve high throughput. Other contributions propose handover solutions that rely on functions that, in addition to RSS and available bandwidth, combine a number of other parameters such as: battery consumption, Connections QoS, and latency [50], [51].

These solutions, however, have been designed with the assumption that the heterogeneous networks are again under the same management entity. Moreover, the implementation complexity of these solutions makes them unsuitable for large infrastructure networks that consist of dozen to hundreds of access points.

More recent contributions have tried to address the problem through distributed mobility management approaches based on mobile agents and virtualisation [52], [53], [54]. In [52], the authors propose to deploy an agent on the Wi-Fi APs and the mobile terminal to assist the vertical handover algorithm. The agent reports monitoring information such as signal strength, network security, available bandwidth, network load, QoS and user preferences, etc. The agent also enables cooperation between APs and the mobile terminal to select the appropriate AP as well as executing seamless mobility. Although, these distributed approaches provide a more robust vertical handover solution, they do not scale well, especially when implementing seamless mobility in highly dynamic Wi-Fi networks characterised by increasing network usage and high users' mobility. In [54], the authors propose to address mobility in large wireless networks through the concept of virtual APs. According to this concept, the complexity of the mobility management is implemented within the network infrastructure, where Virtual AP are created and associated with wireless stations. This provides a centralised yet efficient mobility management framework that optimises the network resources.

Although, these distributed approaches provide a robust vertical handover solution, they do not scale well, especially when implementing seamless mobility in highly dynamic Wi-Fi networks characterised by increasing network usage and high users' mobility. The implementation of an efficient, and scalable seamless mobility requires an intelligent and flexible network management platform similar to the one proposed by the Software Defined Network concept [17].

2.3 Software Defined Networking

The Open Networking Foundation (ONF) [16], a non-profit consortium dedicated to the development, standardization, and commercialization of Software-Defined Networking (SDN), defines SDN as follows: *SDN is an emerging network architecture where network control is decoupled from forwarding and is directly programmable* [17].

The decoupling of the control plane from the data plane and the dynamic programmability of forwarding devices simplify the development and deployment of network applications running on top of the controller. In addition, the global view of the network at the controller enables SDNs to provide more efficient configuration, better performance, and higher flexibility to accommodate innovative network designs.

Current computer networks typically consist of a large number of vertically-integrated routers, switches and numerous types of middle boxes running many complex distributed control and transport network protocols. Individual network devices usually need to be configured separately using low-level and vendor-specific commands to achieve the desired high-level network policies. Furthermore, the lack of automatic reconfiguration and response mechanisms in the face of dynamic network conditions such as faults and load changes makes network management and performance tuning quite challenging. Finally, vertical integration and proprietary configuration and management interfaces of typical networking devices gives rise to vendor lock-in and restricts change and innovation.

As current and emerging network applications and services become increasingly more complex and demanding, the inertia and inflexibility of current networking infrastructures significantly increases the capital and operational expenses of running a network. SDN is an emerging networking paradigm that promises to simplify network management and facilitate network evolution.

The idea of programmable networks and decoupled control logic has been around at least since the mid-1990s. Early efforts in SDN such as Ethane [36], RCP [37] and 4D [38] attempted to extend network devices with the desired functionality as and when needed. Ethane introduced a flow based policy language to a network comprised of a simplified data plane and a centralized control-plane and demonstrated the feasibility of operating a centrally managed network. OpenFlow [39] built on this work by defining an open protocol that defines communication between the network controller and a network device such as a switch.

With these early efforts having laid the foundation for the current SDN paradigm, SDN has since received considerable attention from both academia and industry. As a result, many comprehensive literature surveys on SDN have been published recently. For example, see [18], [20], and [21]. A survey of SDN with a special emphasis on OpenFlow, currently the most commonly deployed SDN technology, can also be found in [22]. SDN in the context of wireless networks is surveyed in [23].

2.3.1 OpenFlow Protocol

The SDN model consists of three layers stacked over each other: an infrastructure layer, a control layer, and an application layer. A layered view of an SDN architecture is given in Figure 1. The infrastructure layer consists of switching devices such as switches, routers, etc. in the data plane. Switching devices are responsible for processing packets based on rules provided by a controller. In addition, they are also responsible for collecting network status, temporarily storing them in local devices and sending them on to controllers. The control layer bridges the application layer and the infrastructure layer. The control layer is based around one or more controllers and has the responsibility of establishing every flow in the network by installing flow entries on switch devices.

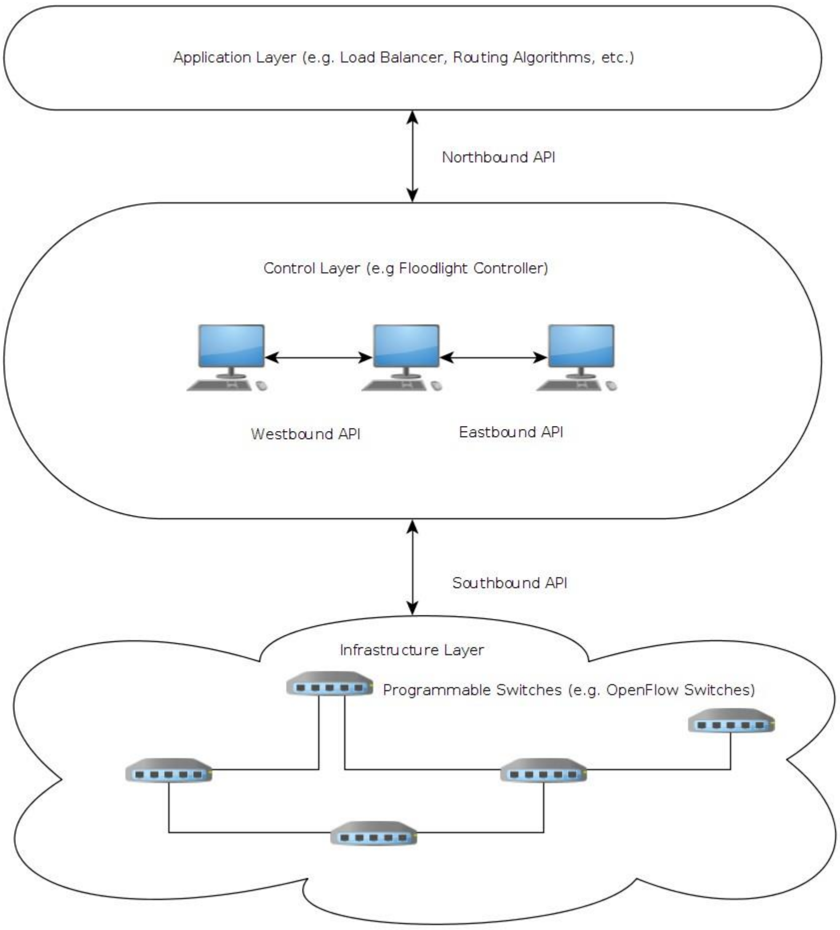

Figure 1: Layered View of an SDN Architecture

The south-bound interface of the control layer with the infrastructure layer enables access to the functions provided by switching devices such as network status reporting and importing of packet forwarding rules. The north-bound interface of the control layer with the application layer provides access to network services through an Application Programming Interface (API). SDN applications can access network status information reported from switching devices through this API, make system tuning decisions based on this information, and carry out these decisions by setting packet forwarding rules to switching devices using this API.

Since multiple controllers can exist in a large administrative network domain, an “east-west” communication interface among the controllers is also needed for the controllers to share network information and coordinate their decision-making processes. The functions of the eastbound and westbound interfaces are to import data between controllers, to implement algorithms for data consistency models, and to monitor and notify capabilities of controllers [18]. The application layer contains SDN applications developed to manage network functionalities by programming the controller's capabilities. Through the programmable platform provided by the control layer, SDN applications are able to access and control switching devices at the infrastructure layer. Examples of SDN applications include dynamic access control, seamless mobility and migration, server load balancing, network virtualization, etc. The most notable example of the south-bound interface is OpenFlow which was initially deployed in academic campus networks.

The OpenFlow protocol was developed by identifying common features in the flow tables of commercial Ethernet switches in order to facilitate vendors providing a means to control their switches without exposing the code of their devices. The industry has embraced SDN and OpenFlow as a strategy to increase the functionality of the network while reducing costs and hardware complexity.

An OpenFlow enabled switch has one or more tables of packet-handling rules. Each rule in the flow tables matches a subset of the traffic and performs actions such as dropping, forwarding, modifying, etc. on the traffic. An important SDN characteristic is that the forwarding decisions are flow-based, instead of destination-based.

The network controller dictates the forwarding rules into the flow table of each OpenFlow enabled switch. Depending on the rules installed by a controller application, an OpenFlow switch can behave like a router, switch, firewall, or perform other roles such as load balancer, traffic shaper, etc. By logically centralizing the network intelligence in software-based controllers, network devices become simple packet forwarding devices that can be programmed via an open interface.

While OpenFlow is the most widely used interface between the data and control planes, others exist such as OVSDB, ForCES, etc. along with protocol plugins (e.g., SNMP, BGP, NetConf) which are adapted to control the network devices.

Although there is now a currently accepted standard for the southbound interface, a common northbound interface has not emerged yet. The northbound interface is mostly a software ecosystem in contrast to the southbound interface. NVP NBAPI, SDMN API, and others derived from several SDN programming languages are used to maintain the communication between the control and application layers.

2.3.2 SDN in Wireless Networks

The SDN paradigm and the OpenFlow protocol have so far been used mostly to manage and control wired networks. However, with the rapid growth of mobility and cloud services, the wireless LAN is becoming the primary access method. Tablets, smartphones and laptops will also be joined by billions of Internet of Things devices in the near future. Unified management of the wired and wireless LAN through open and standards-based interfaces and the ability of an SDN-enabled network to dynamically respond to changing policies and traffic loads will greatly simplify network operations and lower costs. Since the Wi-5 project focuses on effective management and control of the Wi-Fi network, the remainder of our short survey puts more emphasis on the literature on adaptation of SDN and OpenFlow concepts to wireless networks.

SDN provides an opportunity to effectively allocate wireless resources, manage scarce bandwidth and interference, implement efficient handover mechanisms, and perform load balancing between the access points. Wireless communication takes place on an unreliable shared medium with implications like higher packet loss and hidden or exposed terminals [18]. As a result, the abstractions proposed by the wired SDN approach are not yet sufficient to perform the aforementioned actions to control the wireless network. In order to maintain the proper control of a wireless network, design challenges such as variable link characteristics, mobility of nodes, quality of service of the links, and location of the users should also be taken into account.

A simplified example of a wireless SDN architecture is given in Figure 2. According to this figure, wireless network is controlled by the SDN controller using the monitoring information of users provided by AP's. This information is used as an input to the algorithms, implemented in the Radio Resource Management Block through the API's, where each API corresponds to a different interface for a different algorithm.

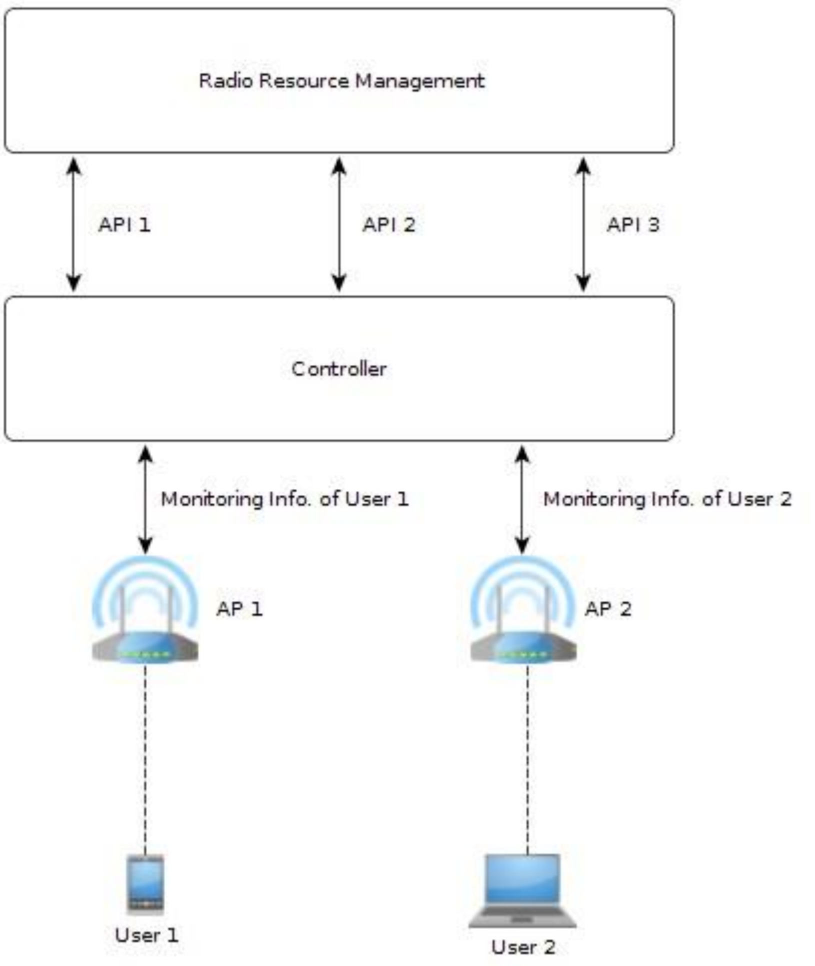

Figure 2: A Simplified Overview of a Wireless SDN architecture

In the following, we will give some brief information on the methods and architectures proposed to optimize the performances of wireless networks by using the SDN approach.

The survey of SDN in the context of wireless networks in [23] provides a review of recent SDN efforts in WLANs, cellular networks, and wireless mesh and sensor networks.

In [30], OpenRoads proposes OpenFlow Wireless, which is built on top of OpenFlow. Their main focus is to virtualize the network by using the FlowVisor [31], which virtualizes the datapath, and SNMPVisor which virtualizes the configuration. They also give users the ability to opt-in to experiments.

Yamasaki et al [27] propose an access management system named Flexible Access Management System (FAMS) for campus WLAN networks. FAMS manages communication access by virtual group ID (GID) using an OpenFlow controller.

Odin ([28] and [29]) is an architecture that uses SDN concepts to manage the client mobility. In order to transparently migrate clients among APs, Odin introduces the Light Virtual Access Point (LVAP) concept, whereby every client is assigned to a single virtual AP. Since we intend to use the Odin architecture as a starting point in this project, a detailed description of Odin is provided in Section 2.5.

In [24], a two-tier approach is proposed for the design of a wireless SDN control plane. The lower tier includes the Near Sighted Controllers that are responsible for setting per client or per flow transmission parameters. The upper tier is composed of Global Controllers that takes care of network functions requiring global visibility, such as mobility management and load balancing.

OpenSDWN [33] utilizes the LVAP abstraction and extends Odin with three new features: i) WiFi datapath programmability (WDTX) for fine grained wireless datapath transmission control, ii) a unified abstraction for virtualized middleboxes and APs to migrate the per client state, and iii) a participatory interface to allow for the sharing of network control.

In [40], an energy programmable Wi-Fi networking framework named Thor is proposed with the aim to cluster clients around access points in an energy-efficient manner. This framework is a combination of Energino [41], which is an open real-time energy consumption monitoring toolkit, with the Odin SDN framework for WLANs. The system architecture is composed of two main components: the Energy Manager and the Mobility Manager. The Energy Manager handles the energy management in the network, while the Mobility Manager is responsible for handing over new clients to one of the available APs.

The EmPOWER platform, which is proposed in [34], consists of a single master and multiple agents running on each AP. The master is implemented on top of the Floodlight controller which has a global view of the network in terms of clients, flows, and infrastructures. The agents use the LVAP concept to assign every client to a single virtual AP. Network applications run on top of the controller and can either exploit the embedded Floodlight REST interface or can be built on top of other SDN frameworks.

In **Error! Reference source not found.**, a software-defined real-time power consumption monitoring ramework, named Joule is proposed. This framework is built on top of EmPOWER, an SDN platform for research and experimentation on programmable wireless and mobile networks. There are two applications running within the same slice, namely the Virtual Power Meter and the Mobility Manager. The Virtual Power Meter collects the network statistics to estimate the consumed power by the AP in a given observation period. The Mobility Manager is then responsible for handing over the new clients to one of the available AP's.

In [25], an architecture named Connectivity management for eneRgy Optimised Wireless Dense networks (CROWD) is proposed to manage and control very dense and heterogeneous wireless networks. Their structure is composed of two types of controllers: i) the CROWD regional controller (CRC), which is responsible for taking long time scale decisions with a broader but coarse grain scope, and ii) the CROWD local controller (CLC), which is responsible for taking fast, short time scale decisions with a limited but fine grain scope.

The OFTEN (OpenFlow framework for Traffic Engineering in mobile Networks with energy awareness) framework [35] relies on an OpenFlow based SDN architecture that supports traffic engineering in heterogeneous mobile networks. This architecture supports resource on demand provisioning in a centralized control plane and hides the technology specifics from the controller through the use of abstractions.

CloudMAC [26] is a distributed architecture, in which the Wi-Fi MAC functionality, such as the processing of MAC data and management frames, is implemented in data centers on virtual machines, which are called virtual access points (VAPs), connected by an OpenFlow controlled network. In this architecture, APs are simple forwarding devices that forward MAC frames between VAPs and mobile clients via an OpenFlow controlled network.

In [32], an SDN based 802.11 network architecture named Ethanol is proposed to manage and control dense wireless networks. This architecture provides an API for QoS, security, mobility and virtualization of wireless networks in order to extend the SDN concept to allow the programmability of wireless APs.

2.4 Odin WLAN Management Framework

Unlike wired networks, wireless networks are highly dynamic, and must provide other control operations such as managing mobility, authentication, etc. In the context of Wi-Fi networks, a software defined network must also support IEEE802.11 functions such as managing SSIDs, network associations, etc.

Odin, [28], was among the first WLAN management solutions to adopt a software defined networking approach. ODIN allows operators to implement wireless network management policies through the creation of light virtual access points (LVAPs) that act as an abstraction of the physical access points, as illustrated in figure 3. In Odin, a wireless device will be associated with an LVAP through which will be perceived as a regular Wi-Fi access point.

To address the lack of IEEE802.11 control functionality in OpenFlow, ODIN uses a software agent that runs on each controlled wireless access point, which should be OpenFlow enabled. The ODIN architecture consists of two logical entities:

- **Odin Controller**: Built on top of Floodlight OpenFlow controller, the controller allows the programming of control applications through a northbound API and their execution at wireless access points through the southbound API. By interacting with an Odin agent, the controller extends the OpenFlow protocol to support IEEE 802.11 functions such as managing SSIDs and clients association.

- **Odin Agent**: Deployed on each wireless AP, Odin agents offer the necessary interfaces for the controller to manage the wireless network and gather monitoring information through the southbound API. This monitoring information includes signal strength of the reception, the bit-rate or Modulation Coding Scheme for 802.11n at which the frame was transmitted by the source, and the noise. When an LVAP is migrated and a new data-path is used for forwarding a client's traffic, the transport network can issue an ARP request for the client's IP address (since the physical AP runs as a bridge). Again, with the goal of client transparency in mind, the agents intercept ARP requests for the client's IP, and use the LVAP information to answer with the appropriate ARP responses themselves.

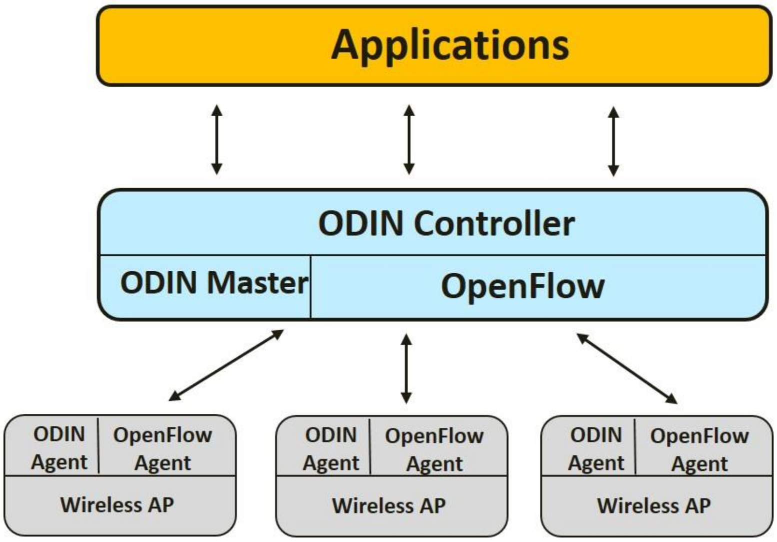

Figure 3: Odin Framework

Using this architecture, Odin can implement both proactive applications such as Load Balancing, and reactive applications such as seamless handover. However, although Odin provides a flexible and programmable platform to manage wireless networks through its SDN approach, it is still very limited and cannot help to address the Wi-5 requirements.

2.5 Architecture Description Using ISO/IEC/IEEE 42010

Although the architecture of software differs from one domain to another, software architectures still share some common design principals and conventions. The standard IEEE 1471 [55] was the first standard to recognise this feature and the importance of defining the best practices to describe a software architecture. Through the introduction of architecture viewpoints, the IEEE 1471 standard defines a conceptual model of architecture description.

This standard has since been adopted by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC). Subsequently a revised standard ISO/IEC/IEEE 42010 [56] was published in 2007. ISO/IEC/IEEE 42010 defines a standardised way to describe system, software and enterprise architectures. In its architecture description model, the standard specifies architecture viewpoints, architecture frameworks and architecture description languages that may be used in architecture descriptions, as depicted in Figure 4. To describe this approach fully, we will discuss those concepts that will be used to define the Wi-5 architecture in more detail below. The ISO/IEC/IEEE 42010 standard will be used to ***formally describe Wi-5 system architecture*** to ensure that our work conforms to current approaches to software description and can be more easily understood and utilised beyond the scope of Wi-5.

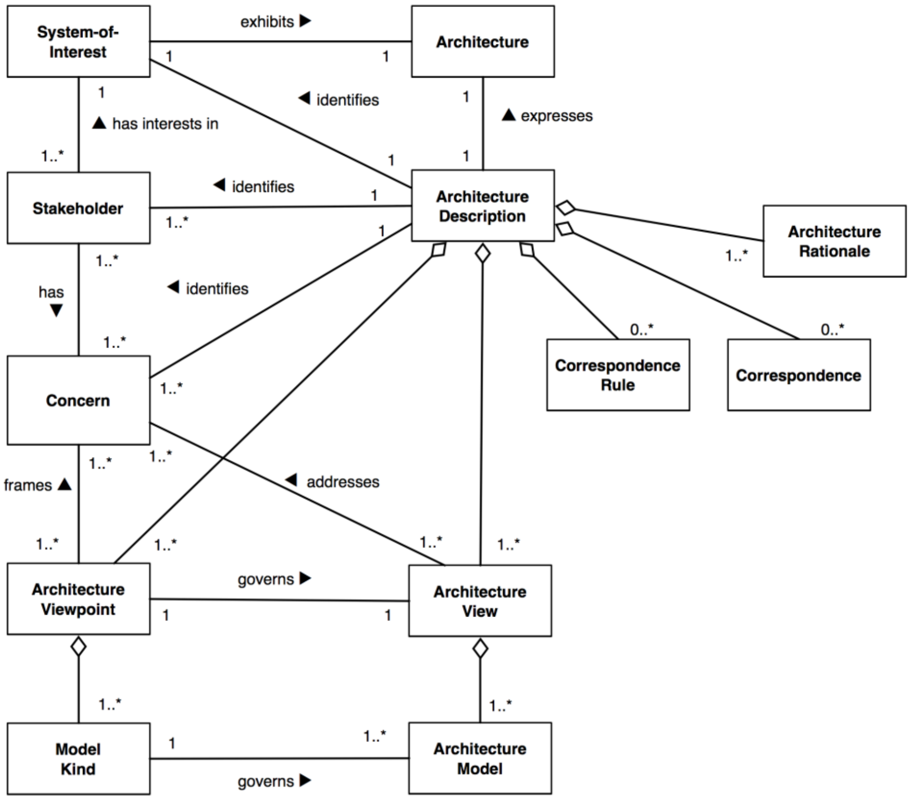

Figure 4: ISO-IEEE 42010 Architecture Description Model

2.5.1 Architecture Stakeholders

An architecture description shall identify the system stakeholders which might be individuals, groups or organisations. In the ISO/IEC/IEEE 42010 architecture description model, a system stakeholder can be one of the following:

- Users of the system.
- Operators of the system.
- Acquirers of the system.
- Owners of the system.
- Suppliers of the system.
- Developers of the system.
- Builders of the system.
- Maintainers of the system.

2.5.2 Architecture Concerns

In addition to the system stakeholders, the architecture description should also define the concerns considered fundamental to the architecture of the system. These concerns represent the areas of interest of the stakeholders, and the architecture description should associate each identified concern with the identified stakeholders having that concern. The ISO/IEC/IEEE 42010 standard defines a set of concerns that need to be considered, and identified where applicable in the architecture description:

- The purposes of the system;
- The suitability of the architecture for achieving the system’s purposes;
- The feasibility of constructing and deploying the system;

- The potential risks and impacts of the system to its stakeholders throughout its life cycle;
- Maintainability and evolvability of the system.

2.5.3 Architecture Views and Viewpoints

In compliance with ISO/IEC/IEEE 42010, the architecture description should also define Architecture Views and Architecture Viewpoints. An Architecture View, in the architecture description model, defines the architecture of the system of interest from the perspective of one or more stakeholders to address a specific concern.

An Architecture Viewpoint is a set of conventions for constructing, interpreting, using and analysing one type of Architecture View. An Architecture Viewpoint can be operational, systems, technical, logical, deployment, process, or information.

3 Overview of Wi-5 Functionalities

The Wi-5 project objectives are to address radio spectrum interference and spectrum usage inefficiency by providing flexible and fine-grained management of the wireless network through the integration of the AP-based control functionalities. These functionalities can be divided into two categories:

- Smart Access Point Functionalities: The aim of these functionalities is to enhance the flexibility and adaptability of Wi-Fi networks by introducing fine-grain radio configuration capabilities and performance management functions, such as packet grouping for efficient bandwidth usage and load balancing. These functionalities are developed by Work Package 3 and their specification is described in deliverable D3.2.

- Cooperative Access Point Functionalities: These functionalities will enable cooperation between Wi-Fi networks regardless of their management authority, using the smart access point functionalities. These functionalities will help Wi-Fi networks to address issues related to interference management, including faultless execution of seamless soft and hard handover. These functionalities are developed by Work Package 4 and their specification is described in deliverable D4.1.

Wi-5 architecture will rely on a strong element of integration between the two categories of functionalities and on the use of a common monitoring functionality. In this section we will provide more details about Wi-5 functionalities, the approach adopted in this project to design the Wi-5 architecture, and a description of the architecture using the ISO/IEC/IEEE 42010 standard.

3.1 Wi-5 Smart Functionalities

These functionalities will equip Wi-Fi networks with the necessary capabilities that allow them to better manage the wireless spectrum and adapt to changing conditions. Fine-grain radio resource configuration is among the functionalities that will be introduced in Wi-5. The improved Wi-Fi networks will have the capability to adjust their transmission range, change their transmission frequency, or both, according to the observed spectrum utilisation, and the bandwidth requirements. Another contribution of these functionalities is to optimise the utilisation of the spectrum through packet grouping. These smart functionalities can be summarised as following:

- **Dynamic Channel Selection and Transmit Power Control**: This functionality will enable Wi-Fi networks to dynamically adjust the radio configuration including changing the transmission channel within the network and the transmit power between an AP and a wireless device.

- **Monitoring**: This functionality will allow Wi-5 to gather information about the state of the Wi-Fi network, its environment, operational parameters, and performance.

- **Load Balancing**: This functionality will enable Wi-Fi networks to make decisions on when not to accept new association requests, with the aim of maximising the aggregate data rate of these networks.

- **Packet Grouping**: This functionality will enable packet grouping between the Wi-Fi AP and the wireless device, which should result in significant overhead reduction and bandwidth and energy savings.

3.2 Wi-5 Cooperative Functionalities

Enabling cooperation between Wi-Fi networks is critical to achieve efficient spectrum usage and flexible management. For instance, wireless networks need to be able to share their spectrum with STAs from a different provider in order to provide seamless mobility. Interference management is another topic that can benefit from cooperative wireless networks. An optimal radio configuration that can minimise the effects of interference while maximising the network capacity, can only be achieved if the operators of the interfering networks can cooperate together. The need for a cooperative environment in wireless networking will be reflected in Wi-5 through a set of functionalities that can be summarised as following:

- **Seamless Vertical Handover**: This functionality will allow devices to join and leave wireless networks without affecting the user experience, hence, exploiting any underused Wi-Fi or 3G/4G capacity.
- **Smart Connectivity (Soft Handover)**: This functionality will assist wireless devices in choosing the most suitable connection according to the application running on the device. It takes into account the QoS requirement of the application, the quality of the link, and the network capacity.
- **Interference Management**: In this functionality, APs will cooperate to find an optimal radio configuration that reduces the effect of interference on the QoS of following traffics while trying to maximise the network throughput.

4 Wi-5 Initial Architecture

The smart and cooperative functionalities described above, which are developed in WP3 and WP4 respectively, require a global architecture that integrates these functionalities into a single system. This architecture should meet the functional requirements (concerns) of the Wi-5 system stakeholders.

In deliverable D2.3 we have defined the use cases and the requirements that are considered in Wi-5, including relevant network services, with a special emphasis on those emerging from real-time requirements (*e.g.* VoIP, video conference, online games). This deliverable provides the functional and performance requirements needed to design the Wi-5 architecture.

The architecture design needs to meet the expectations of the system stakeholders and respect the environmental constraints and limitations imposed. These requirements are not only related to the performance of the system, but also focus on other needs of its future users and beneficiaries, such as: ease of use, flexibility, adoption in the market, etc. In this context, Wi-5 aims to identify additional business related requirements through the work presented in deliverable D2.1. This deliverable provides an analysis of the business models to make Wi-5 adopted in the market and identifies the requirements that need to be met by the architecture in order to achieve this objective. In addition to the business related requirements defined in D2.1, we rely on input from the project's Operator Board to obtain the remaining architecture design requirements. The Wi-5 Operator Board, which acts as an industrial advisory board, consists of a number of companies that operate public or semi-public networks, hence representing the typical Wi-5 stakeholders, and will help to identify other requirements such as deployment requirements, operational requirements, etc.

Note that although the use cases analysis as well as the business model analysis and Operator Board are currently used to identify the main design requirements for Wi-5 architecture, these entities will be used later to validate the soundness of the architecture, as illustrated in Figure 5.

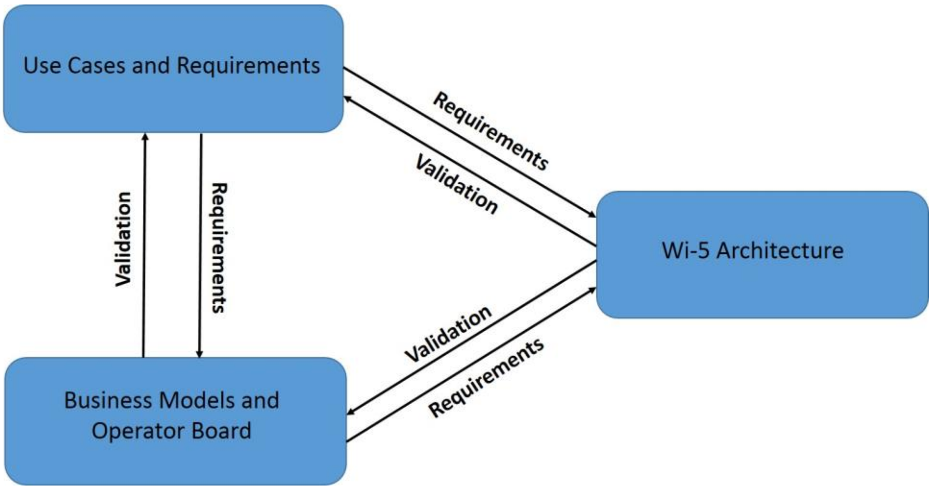

Figure 5: Identifying Requirements and Validation in Wi-5

By respecting the different functional and stakeholder requirements mentioned above, we aim to provide an architecture description that can be transferred and reused within the wireless telecommunication community. Consequently, we have decided to describe the Wi-5 architecture according to the ISO-IEEE 42010 standard already presented in section 2.5. Following this standard, the Wi-5 architecture description will oblige to the concerns of each system stakeholder and their viewpoints.

4.1 Functional Requirements

The use cases presented in Deliverable 2.3 “Use Cases and Requirements” focus on a selected set of scenarios. The choice of these scenarios is based on a thorough analysis of on-going work in the IEEE and Wi-Fi Alliance to identify the most pressing usage models, as well as the interests of the project partners and the members of the Operator Board. These use cases can be summarised as follows:

- **Airport/Train Station**: This use case focuses on the deployment and utilisation of large Wi-Fi networks in public areas, where the users are characterised by nomadic and there is a need to support the use of real-time applications.
- **Dense Apartment Building**: This use case focuses on the dense and uncoordinated deployment, operation and utilisation of Wi-Fi access points. This deployment scenario is characterised by radio interference between Wi-Fi APs and lack of coordinated control over the wireless networks.
- **Pico-cell Street Deployment**: In this use case, we consider outdoor users initially connected to a cellular network and then switch to a Wi-Fi network that has been deployed by the mobile operator to off-load data.
- **Large Home/SOHO**: This represents a common scenario where the usual single AP deployment within a home or an office is extended to provide extra coverage and improve the user’s Quality of Experience.
- **Community Wi-Fi Network**: This use case focuses on an emerging service where the network operators offer Wi-Fi network access to their on-the-go subscribers through existing residential and SMB Wi-Fi infrastructure.

The analysis of these uses cases focused on the functional and performance requirements that need to be met by the Wi-5 architecture, while the Wi-Fi access network is seen as the bottleneck to deliver the required services and QoS. Although each use case has been analysed separately, the functional requirements described below are shared between the use cases:

- **Seamless Mobility**: There is an emphasis on the need for seamless mobility in all the use cases studied. This requirement means that the user can roam within a single network or across many networks without service interruption.
- **QoS Awareness**: Similarly to Seamless Mobility, there is an emphasis on QoS awareness in all uses cases studied in this project. Users in the scenarios considered need the network to deliver the necessary performance to maintain the quality of service required by their applications such as: VoIP, Online Gaming, etc.
- **Self-Configuration**: In all use cases, there is a requirement that the network should be able to self-configure and maintain itself with minimal user input. For instance, in the case of high interference levels caused by a neighbouring Wi-Fi network, the network should be able to detect the interference and apply a radio configuration that appeases the level of interference and its effect on the network users.
- **Spectrum Usage Optimisation**: This requirement is emphasised in several of the use cases studied in the project. In the case of dense apartment buildings, the network will need to find a radio configuration that achieves optimal performance while minimising interference levels. In the Wi-

Fi pico-cell deployment, the spectrum should be allocated fairly among users but taking into account the network capacity of each operator in an area. In the large home/SOHO scenario, the network should be able to adapt the infrastructure to maximise Wi-Fi coverage whilst optimising wireless resource utilisation.

- **Authentication, Authorisation and Accounting**: In the dense apartment building use case and large home/SOHO use case, there is an emphasis on the necessity to authenticate users so that only authorised users may join the network. In the community Wi-Fi use case, the network is also required to control the service level that is provided to the individual hosts and visitors while taking into account the applications being used, the traffic conditions and the service subscription conditions contracted.

4.2 Business and Stakeholders Requirements

The design of the Wi-5 architecture also needs to take into account other factors that extend beyond the functional requirements described above. These factors should cover all the constraints under which Wi-5 will be operating and the nature of the environment within which it will be used.

First, it is important to emphasize the importance of business models, as without a viable business model it will become very difficult to deliver the Wi-Fi network services demanded by the future market. Current Wi-Fi business models are obviously viable. However, they are not future proof. Due to its rapidly growing popularity, Wi-Fi networks are currently suffering from spectral congestion. This situation is caused by the absence of a cooperative attitude of the current stakeholders and a lack of a centralised or a coordinated spectrum management technology enabling such cooperation. In Deliverable 2.1 "*Viability of business models for multi-operator Wi-Fi coordination platforms"*, we addressed this issue, and we discussed the conceivable remedies from a business perspective. The study presented in that deliverable concluded that a spectrum usage broker role (and enabling technology) is needed to grant the available frequency spectrum to the different users in a fair and optimized manner.

Although the telecommunication market is very competitive, cooperation between operators is sometimes necessary, as is the case with roaming and interconnection operations. This type of cooperation is implemented based on the concept of federation; the technology is standardized, and each provider has its own autonomous platforms that are interconnected. Moreover, operators deliver mutual services (peering, interconnection, termination, etc.) on an economic basis and on their own conditions. Members of the project's Operator Board have agreed on the need for inter-operator cooperation to achieve the Wi-5 functionalities and the presence of a spectrum usage broker as part of this. However, the operators preferred to have the spectrum usage broker as part of their own control system, rather than as a third party, hence emphasising on the need to maintain autonomy in decision-making. In the view of the Wi-5 team, cooperation and full autonomy are mutually exclusive though. Either they cooperate to some level, or the tragedy of the commons will hold. Wi-5's ambition is to provide them with a platform to bring this cooperation in effect while minimizing the loss of autonomy.

The architecture design requirements that are derived from the business models analysis and discussion with the project's Operator Board can be summarised as following:

- **Spectrum Usage Broker**: The spectral congestion in Wi-Fi networks, which Wi-5 aims to address, will require the introduction of this business role in order to implement coordinated spectrum management strategies. The presence of this role and its interactions with different stakeholders needs to be considered in the Wi-5 architecture.

- **Autonomy**: Although the operators agree on the need for a Spectrum Usage Broker role to achieve better spectrum utilisation and reduce interference, the control mechanisms proposed in Wi-5 and the introduction of the Spectrum Usage Broker should limit their autonomy of management as little as possible.

- **Cooperation**: In order to implement many of the future services and functionalities proposed in Wi-5, the architecture will need to allow cooperation between operators.

4.3 Wi-5 Initial Architecture Description

In this project we have chosen to follow the formal architecture description of ISO/IEC/IEEE 42010 described in section 2.5. In this approach, we start with systematically aggregating the above commonalties and requirements obtained from the analysis of the use cases, business models study and the discussion with the project's Operator Board, into a limited number of stakeholders and concerns. The initial architecture description thus includes the following:

- Wi-5 system stakeholders and concerns.
- Wi-5 architecture viewpoints and the concerns and stakeholders within each viewpoint.
- For each viewpoint, architecture views are defined and described.

4.3.1 Wi-5 Stakeholders

The following stakeholders have been identified:

- **Operator:** This is typically a commercial operator that owns and manages the wireless access network and that provides wireless connectivity to the customers through Wi-Fi hotspots or 3G/4G networks, manages the backhaul network that support other wireless access networks as a broadband service provider, or both. In addition, an operator can own the Wi-Fi APs and 3G/4G networks. This role best matches with a combination of the core network provider, Internet service provider, and network service packager in D2.1.

- **Manager:** This is typically a wireless access network manager that only manages the Wi-Fi APs and does not necessarily own or manage the backhaul network behind them. It includes Community network operators, Office IT departments, Shop Owners, House Users, and Public Spaces IT managers (Airports, Train Stations, etc.), which corresponds to the Airport/Train Station, SOHO, and Community Wi-Fi use cases. This role matches with the access network provider in D2.1.

- **Wireless User:** This can be any user who connects to a Wi-Fi network through a wireless terminal or a broadband subscriber with a Wi-Fi AP in the dense apartment building scenario. This matches with what is called "end user" in D2.1.

- **Wi-5 System Designer**: This stakeholder is in charge of developing and implementing the Wi-5 management algorithms that address the functional requirements identified above such as: QoS Awareness, Interference Management, Mobility, etc. In D2.1 this matches loosely with "end device manufacturers", but here in D2.4 it more explicitly also includes system and platform designers and manufacturers.

- **Spectrum Usage Broker:** This stakeholder has been identified as a business role in D2.1, required to devise sensible spectrum sharing strategies between operators in a cooperative context, as described above.

4.3.2 Wi-5 Concerns

The following concerns have been identified. They follow from the requirements as formulated in section 4.1:

- **Mobility**: This concern is related to allowing the user to move within a single network or across many networks without service interruption.
- **Quality of Service Awareness**: This concern is related to providing the quality of service required by the application or quality of experience perceived by the user and reducing the effect of spectrum congestion and interference.
- **Flexibility and Self-Configuration**: This concern is related to providing a scalable, extendible wireless management system that requires minimal intervention from the Operator or Manager.
- **Spectrum Usage Optimisation:** This concern is related to managing the wireless spectrum to provide fair utilisation between users and managing interference.
- **AAA:** This concern is related to authenticating a user when requesting a connection to the wireless network and identifying the corresponding service.
- **Cooperation and Autonomy:** This concern is related to enabling cooperation between operators while limiting their autonomy of management as little as possible.

4.3.3 Wi-5 Concern–Stakeholder Traceability

The above concerns and stakeholders have been mapped into the table provided below:

	Operator	Manager	Wireless User	Wi-5 System Designer	Usage Spectrum Broker
Mobility	X	X	X		
Quality of Service Awareness	X	X	X		
Flexibility and Self-Configuration				X	
Spectrum Usage Optimisation	X	X	X		X
AAA	X	X			
Cooperation and Autonomy	X				X

Table 1: Concern-Stakeholder Traceability in Wi-5 Architecture

4.3.4 Operator Viewpoint

The operator maintains the whole wireless network asset such as Wi-Fi APs, the 3G/4G network, and the core network behind them. This viewpoint exposes technology related operations in Wi-5 such as ensuring network connectivity, as well as business related operations such as data roaming and cooperation with other operators. From this viewpoint, the Wi-5 architecture addresses the following concerns:

- **Mobility**: This concern is related to allowing the user to move within a single network or across many networks without service interruption.
- **Quality of Service Awareness**: This concern is related to providing the quality of service required by the application or quality of experience perceived by the user and reducing the effect of spectrum congestion and interference.
- **Spectrum Usage Optimisation:** This concern is related to managing the wireless spectrum to provide fair utilisation between users and managing interference.
- **AAA:** This concern is related to authenticating a user when requesting a connection to the wireless network and identifying the corresponding service.
- **Cooperation and Autonomy:** This concern is related to enabling cooperation between operators while limiting their autonomy of management as little as possible.

The Operator Viewpoint consists of the following views: Mobility View, QoS Management View, Interference Management View, AAA Management View and Cooperation and Autonomy View, which are described in Figure 6, Figure 7, Figure 8, Figure 9 and Figure 10, respectively.

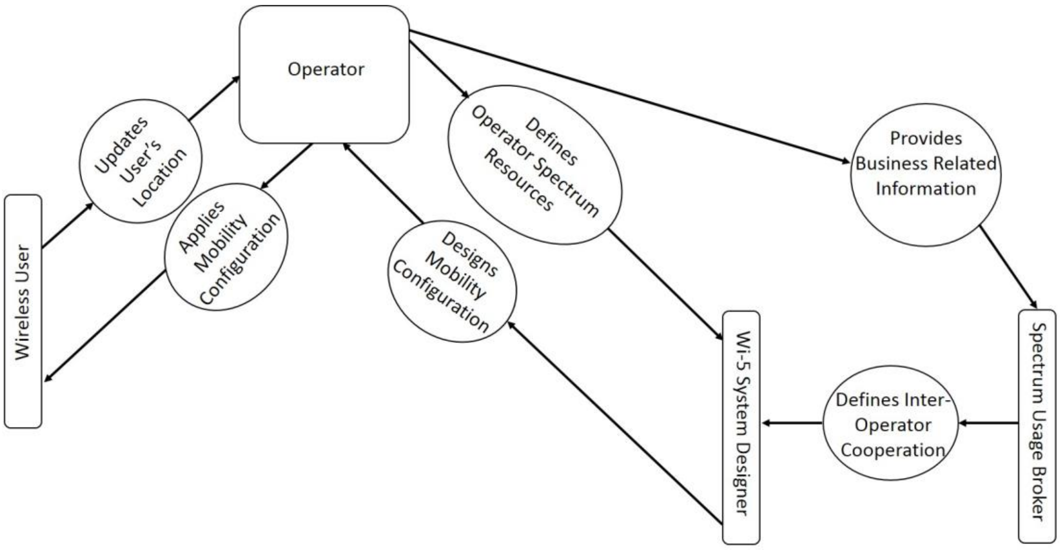

Figure 6: Mobility Management View in Operator Viewpoint

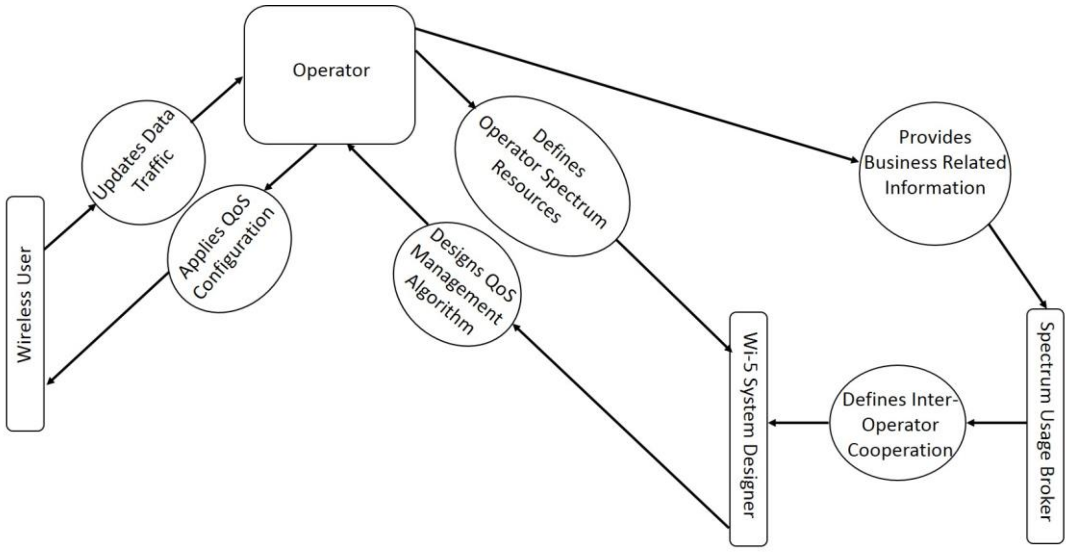

Figure 7: QoS Management View in Operator Viewpoint

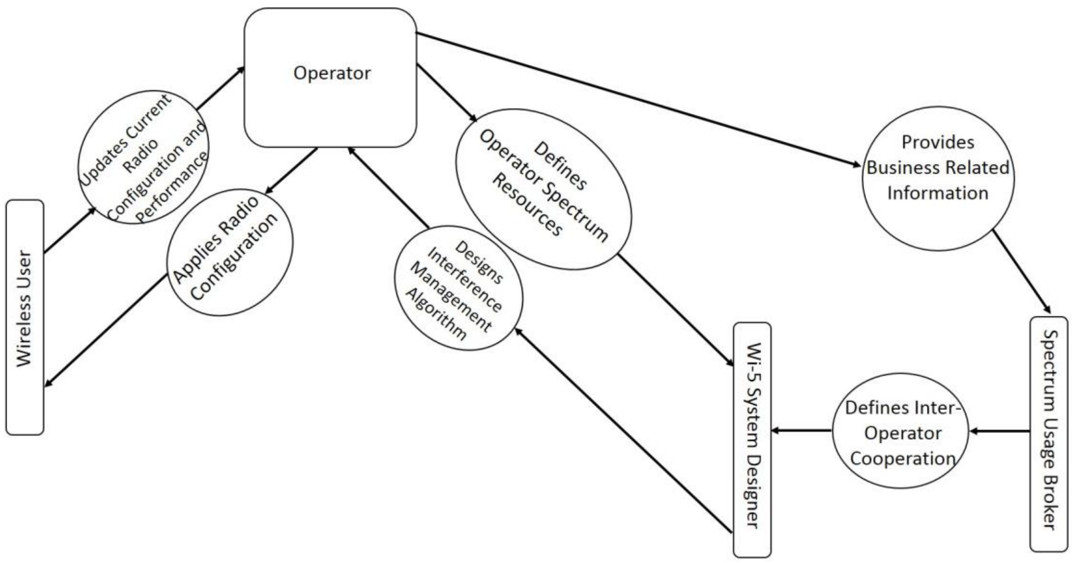

Figure 8: Spectrum Usage Optimization View in Operator Viewpoint

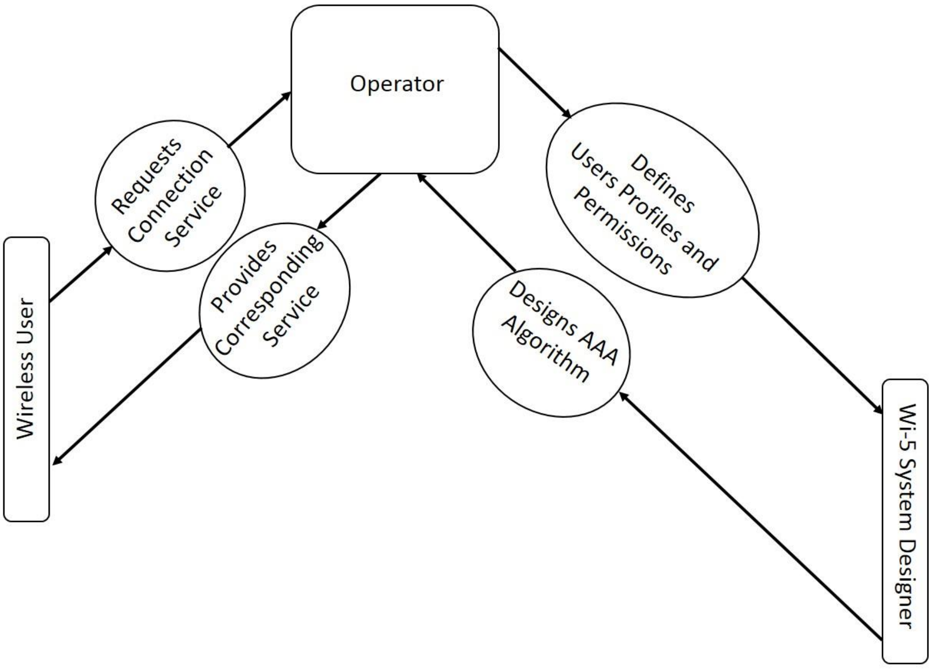

Figure 9: AAA Management View in Operator Viewpoint

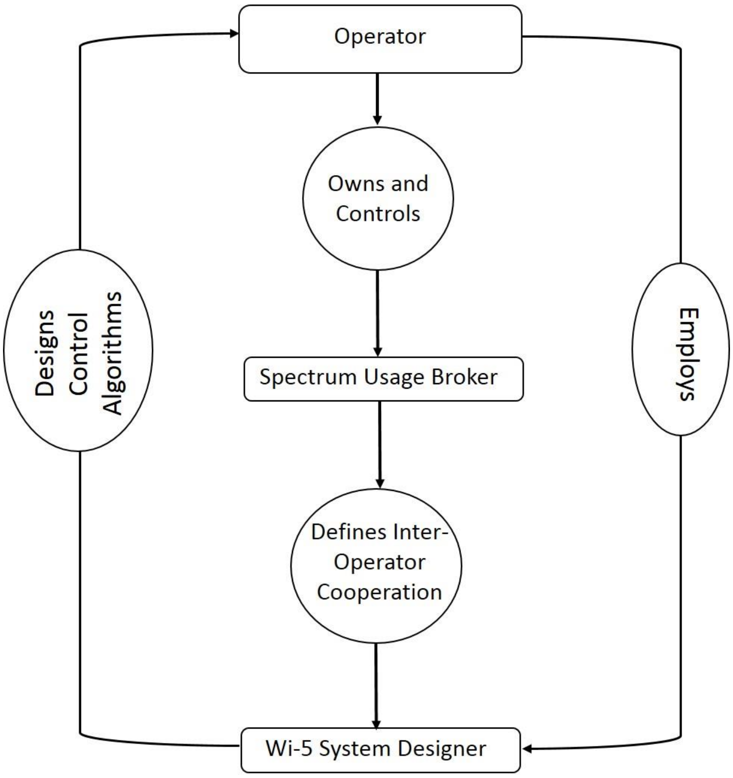

Figure 10: Cooperation and Autonomy View in Operator Viewpoint

4.3.5 Manager Viewpoint

This Viewpoint takes into account the technology related operations and Wi-Fi network related assets managed and maintained by the manager stakeholder. Typical stakeholders in this viewpoint are: Office IT departments, Public Space IT managers (Airports, Train Stations, etc.), Business Owners (Shops, Cafeterias, Restaurants, etc.), households with broadband connection and Wi-Fi APs. From this viewpoint, the Wi-5 architecture addresses the following concerns:

- **Mobility**: This concern is related to allowing the user to move within a single network or across many networks without service interruption.
- **Quality of Service Awareness**: This concern is related to providing the quality of service required by the application or quality of experience perceived by the user and reducing the effect of spectrum congestion and interference.
- **Spectrum Usage Optimisation:** This concern is related to managing the wireless spectrum to provide fair utilisation between users and managing interference.
- **AAA:** This concern is related to authenticating a user when requesting a connection to the wireless network and identifying the corresponding service.

The Manager Viewpoint consists of the following Views: Mobility Management View, QoS Management View, Spectrum Management View and AAA Management View, which are described in Figure 11, Figure 12, Figure 13 and Figure 14, respectively.

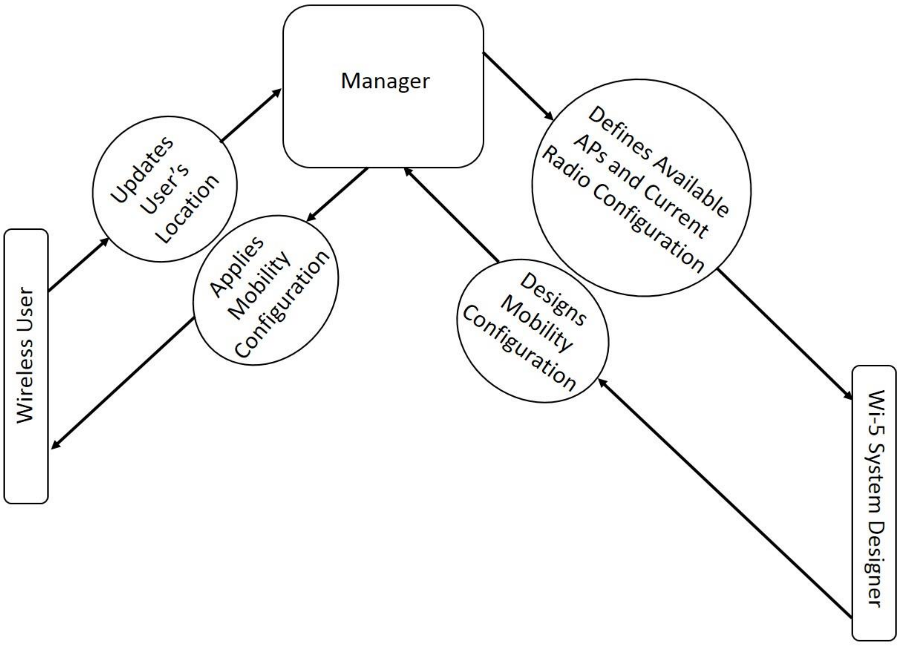

Figure 11: Mobility Management View in Manager Viewpoint

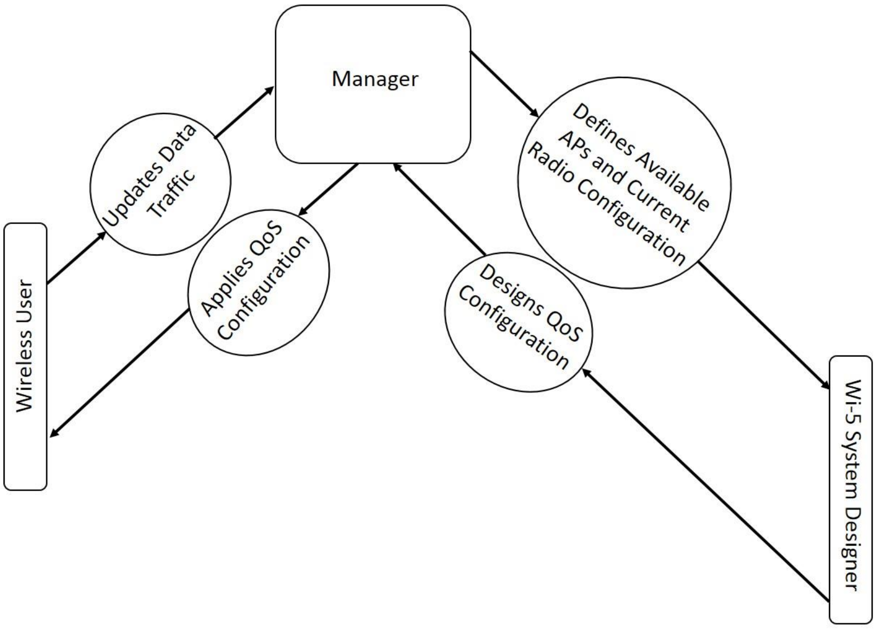

Figure 12: QoS Management View in Manager Viewpoint

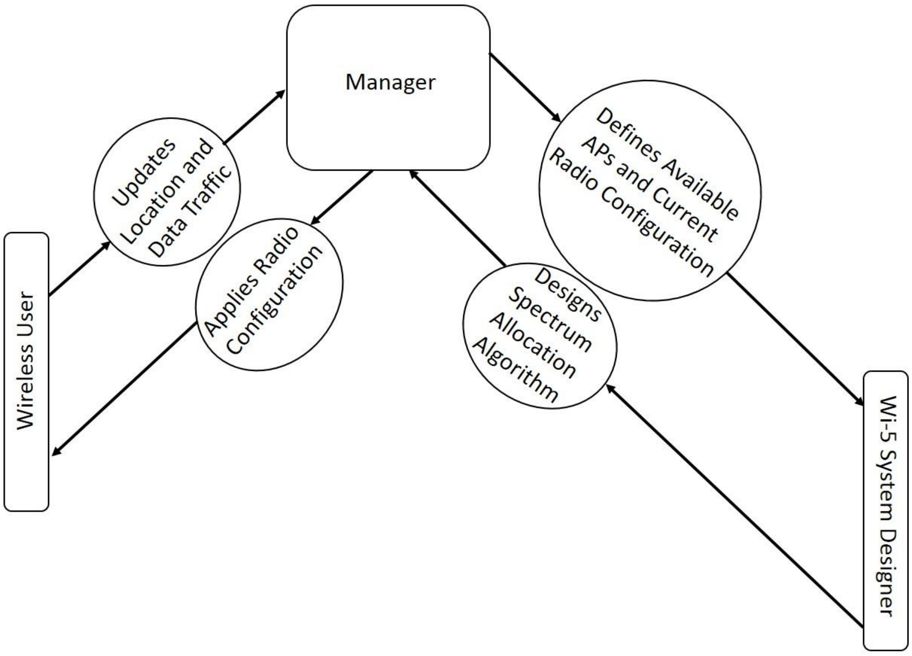

Figure 13: Spectrum Optimization View in Manager Viewpoint

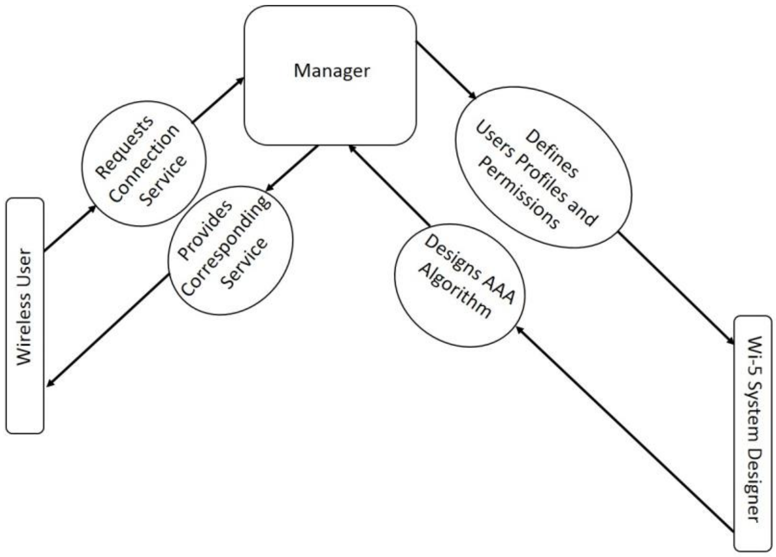

Figure 14: AAA Management View in Manager Viewpoint

4.3.6 Spectrum Usage Broker Viewpoint

This Viewpoint covers the technology-related operations and concerns of the Spectrum Usage Broker described above, which has the role to enable cooperation between operators to provide coordinated spectrum management strategies. From this viewpoint, the Wi-5 architecture addresses the following concerns:

- **Cooperation and Autonomy**: This concern is related to enabling inter-operator cooperation while limiting their autonomy of management as little as possible.
- **Spectrum Usage Optimisation:** This concern is related to guaranteeing optimal and fair spectrum allocation among users.

The Spectrum Usage Broker Viewpoint consists of the following Views: Cooperation View and Spectrum Management View, which are described in Figure 15 and Figure 16 respectively.

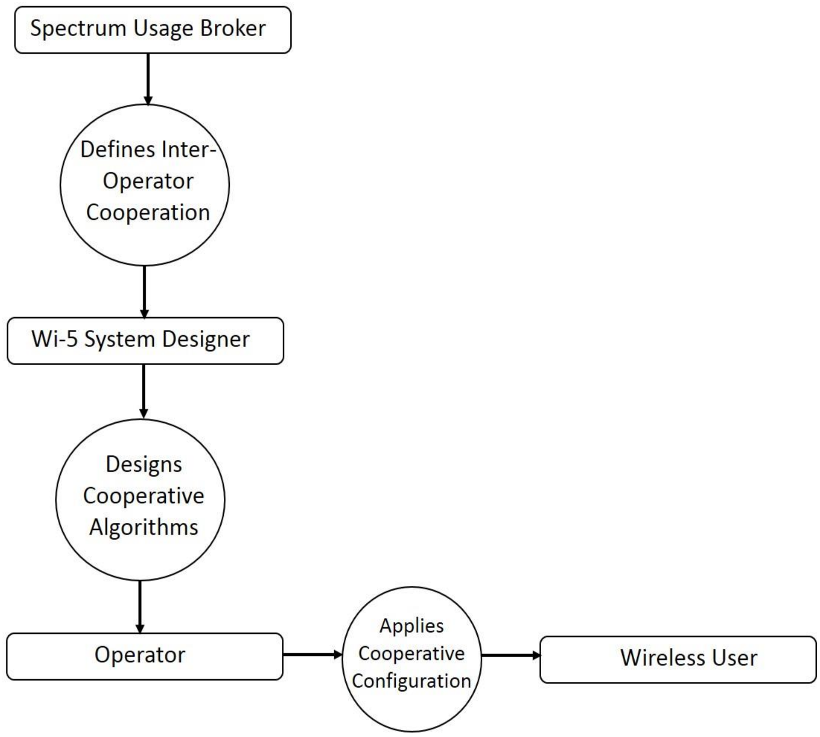

Figure 15: Cooperation and Autonomy View in Spectrum Usage Broker Viewpoint

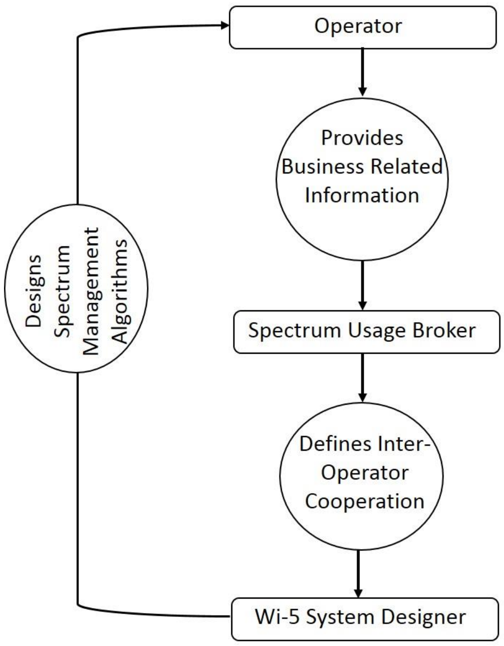

Figure 16: Spectrum Usage Optimization View in Spectrum Usage Broker Viewpoint

4.3.7 Wireless User Viewpoint

This Viewpoint covers the concerns of a user through a wireless terminal, or a broadband subscriber with a Wi-Fi AP. These concerns are as follows:

- **Mobility**: This concern is related to allowing the user to move within a single network or across many networks without service interruption.

- **Quality of Service Awareness**: This concern is related to providing the quality of service required by the application or quality of experience perceived by the user and reducing the effect of spectrum congestion and interference.

- **Spectrum Usage Optimisation:** This concern is related to managing the wireless spectrum to provide fair utilisation between users and managing interference.

The Wireless User Viewpoint consists of the following Views: Mobility View, QoS View and Radio Coverage View which are described in Figure 17, Figure 18 and Figure 19 respectively.

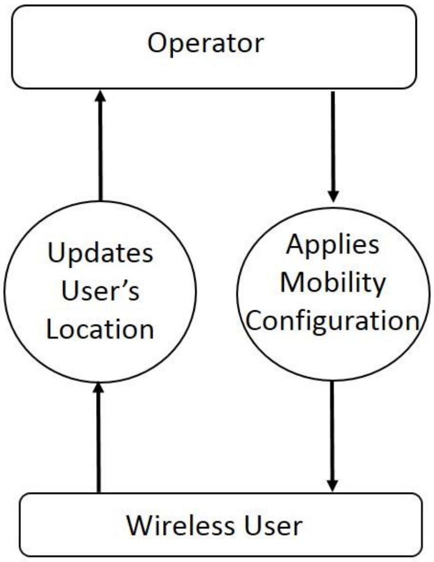

Figure 17: Mobility View in Wireless User Viewpoint

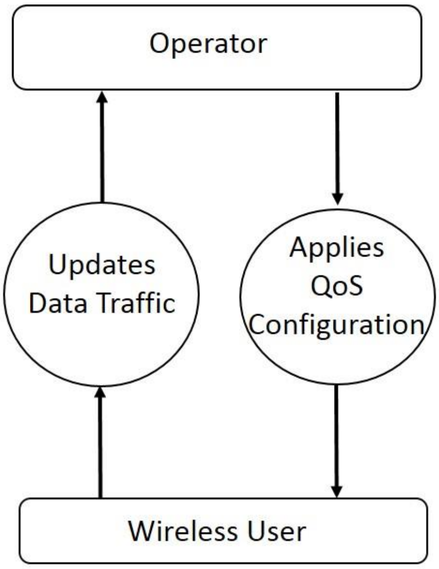

Figure 18: QoS View in Wireless User Viewpoint

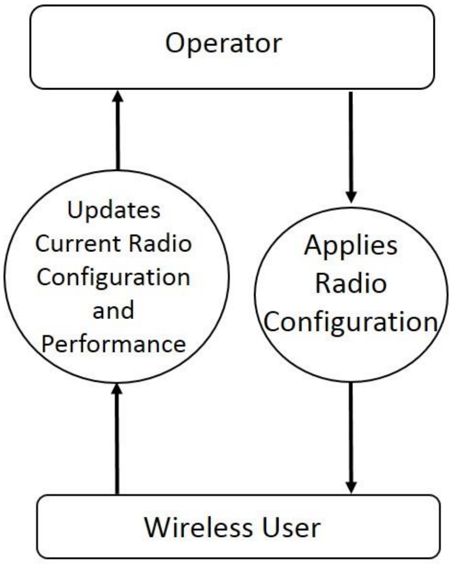

Figure 19: Spectrum Usage Optimization View in Wireless User Viewpoint

4.3.8 Wi-5 System Designer Viewpoint:

This Viewpoint covers the concerns of the Wi-5 System Designer with regards to flexibility and self-configuration when interacting with a Manager or an Operator stakeholder, described above. These concerns are the following:

- **Wi-5-Operator Flexibility and Self-Configuration**: This concern is related to providing a scalable, extendible wireless management system that requires minimal intervention from the Operator

- **Wi-5-Manager Flexibility and Self-Configuration**: This concern is related to providing a scalable, extendible wireless management system that requires minimal intervention from the Manager

The Wi-5 System Designer Viewpoint consists of the following Views: Wi-5-Operator Flexibility and Self-Configuration View and Wi-5-Manager Flexibility and Self-Configuration View which are described in Figure 20 and Figure 21, respectively.

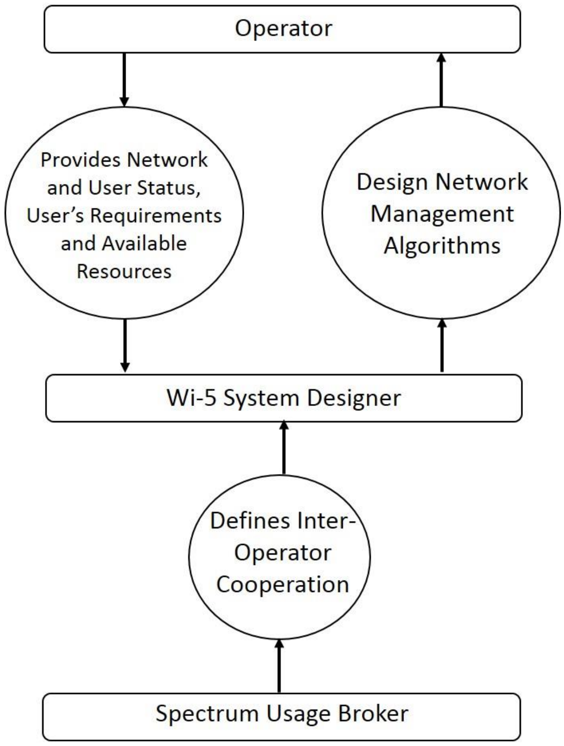

Figure 20: Wi-5-Operator Flexibility and Self-Configuration View

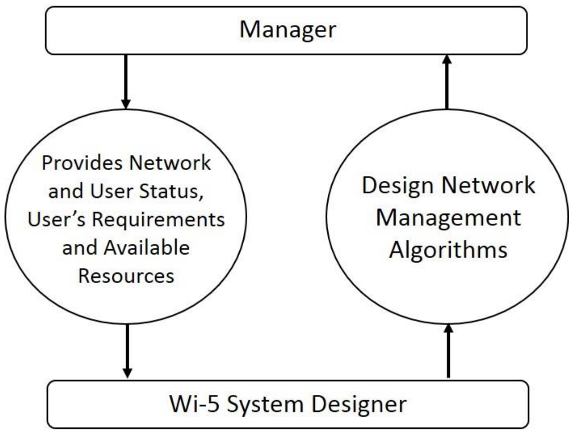

Figure 21: Wi-5-Manager Flexibility and Self-Configuration View

4.4 SDN-Based Design Approach

The architectural description presented above matches well with the Software Defined Networking (SDN) concept introduced in section 2.3. Following an SDN concept, the control plane of the Wi-Fi access points is decoupled from the data plane. We define a Wi-5 controller as the main control entity that interacts with OpenFlow enabled Wi-Fi APs, and the Wi-5 solutions will be implemented by the Wi-5 System Designer on top of the Wi-5 Controller, as illustrated in Figure 22.

The Wi-5 controller will be owned and managed by the entity managing the wireless network, whether it is an Operator, as it is the case in Dense Apartment Buildings and Pico-cell Street use cases, or a Manager as it is the case in Airport/Train Station and SOHO use cases.

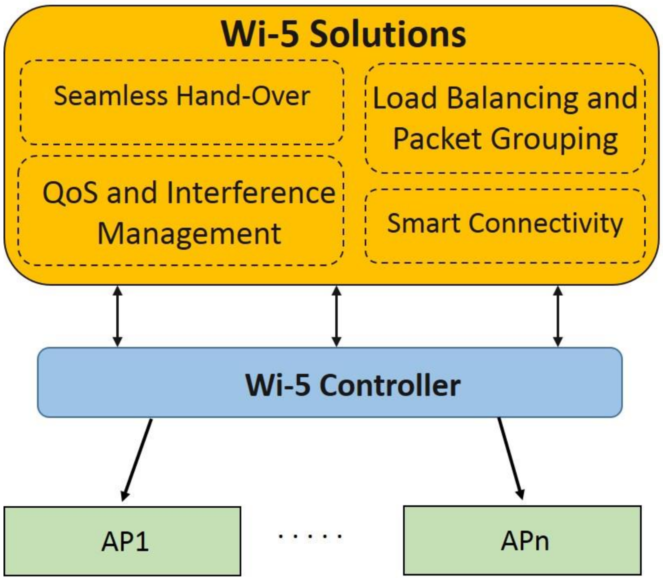

Figure 22: SDN-based Design of Wi-5 System

Dynamic Channel Selection and Transmit Power Control presented in section 3.1 are implemented as part of the southbound API of the Wi-5 controller, in the form of an entity called the Wi-5 master, and also on the Wi-Fi APs in the form of entities called Wi-5 agents. Wi-5 agents interact with the controller through the Wi-5 master which acts as an interface between the Wi-5 controller and the APs, as illustrated in Figure 23.

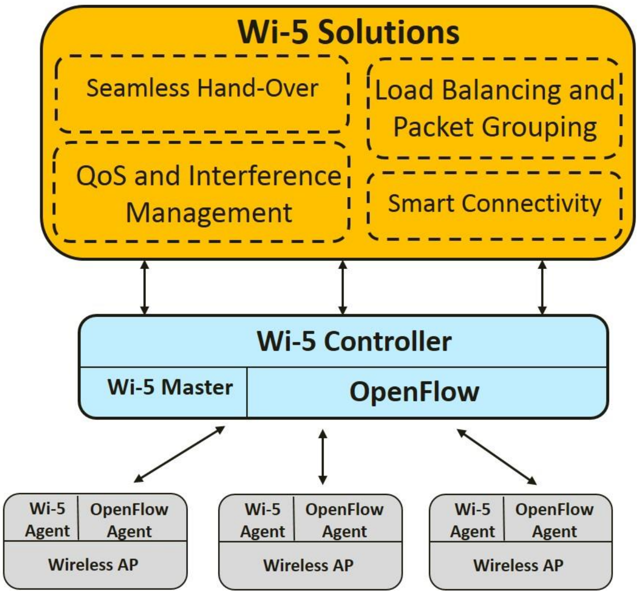

Figure 23: Wi-5 Controller Southbound API

Unlike conventional network virtualisation techniques, where a control plane has to be created with its instance, in SDN all virtual instances, called slices are managed by the controller. Wi-5 exploits this property by slicing the wireless network into Virtual SSIDs that are managed by the controller, as illustrated in Figure 24. In this section, we will show how these SDN features help to fulfil the Wi-5 architecture design requirements according to the design viewpoints and views described previously.

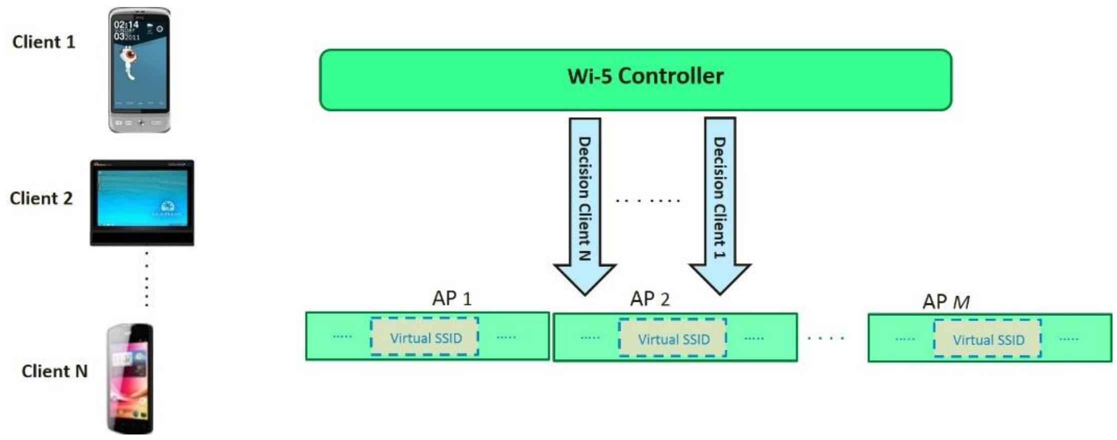

Figure 24: Virtualisation in and Slicing in SDN-Based Wi-5

4.4.1 Mobility Management

Mobility management is implemented in the Wi-5 architecture through the slicing concept mentioned above. Following this concept, a mobile STA is associated with a virtual SSID. When a mobile STA moves away from the range of AP1 and enters the range of AP2, the controller moves the virtual SSID from AP1 to AP2, thus creating a seamless handover and removing the management complexity and delay resulting from the de-association and re-association processes. This process is shown in Figure 25.

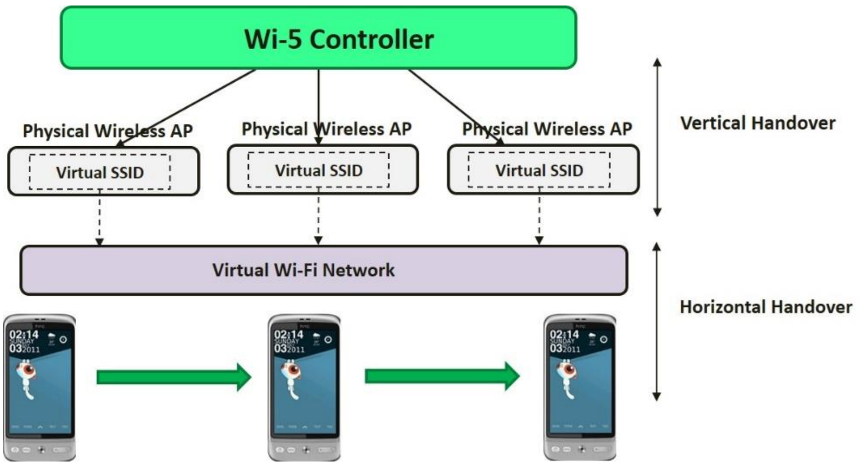

Figure 25: Achieving Seamless Mobility in Wi-5 Architecture

4.4.2 Spectrum Usage Optimization and QoS Management

Wi-5 addresses the dual problem of QoS management and spectrum usage optimization by looking at data flows separately and implementing appropriate flow management policies, which involve AP selection and radio resource configuration such as selecting the appropriate channel or adjusting the transmit power of the AP. For each class of traffic, a policy is implemented within the wireless network to reach the required QoS by configuring the radio resources while minimising the interference as much as possible. SDN is compatible with this approach as it provides the necessary flexibility and fine granularity to implement Wi-5 flow management policies. SDN allows us to implement both proactive and reactive flow management policies. In proactive flow management, the controller populates the data plane switches with rules that apply to each flow. In reactive mode, however, the data plane switches have to consult the controller each time a new traffic passes through a switch.

In its first version, Wi-5 architecture adopts proactive flow management whereby we define a set of traffic classes and the controller implements the management policies that correspond to each class of traffic, as shown in Figure 26. The proactive flow management is realised in Wi-5 through a publish-subscribe model, where the QoS management and Interference Management application subscribe to a per-flow event. When a STA connected to the wireless networks starts receiving a flow from the AP, the application is triggered and tries to find the best radio configuration that satisfies the QoS requirements of the flow and reduce the interference effects.

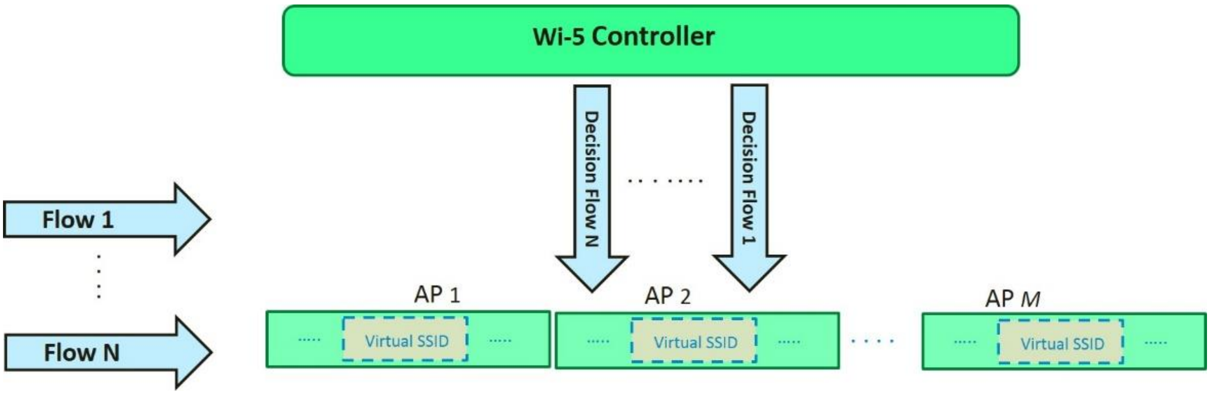

Figure 26: Flow Management in Wi-5 Architecture

The slicing concept is also used in Wi-5 to implement QoS related functionalities, such as Smart Connectivity. In Wi-5, an STA running an application with specific QoS requirements will be associated with a virtual SSID created on an AP that satisfies these requirements. If the AP can no longer satisfy the STA QoS requirements, the controller identifies another AP that can and, if found, the virtual SSID is moved to the new AP, as illustrated in Figure 27.

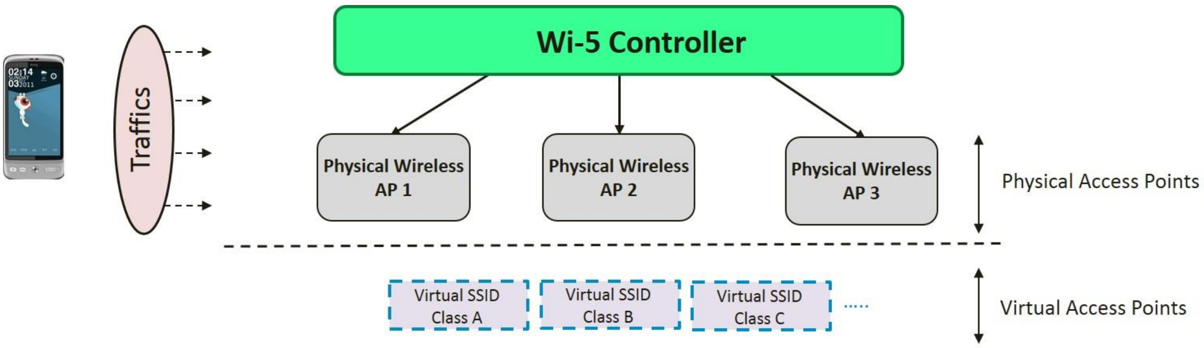

Figure 27: Slicing in Wi-5 Architecture to Achieve Smart Connecivity

Finally, Wi-5 uses the slicing concept to configure radio parameters of the AP by creating customised virtual SSIDs. In the case of QoS and interference management functionality, once an optimal solution is found, the controller will create a virtual SSID with a customised radio configuration (channel, transmit power) that implements the solution, as shown in Figure 28.

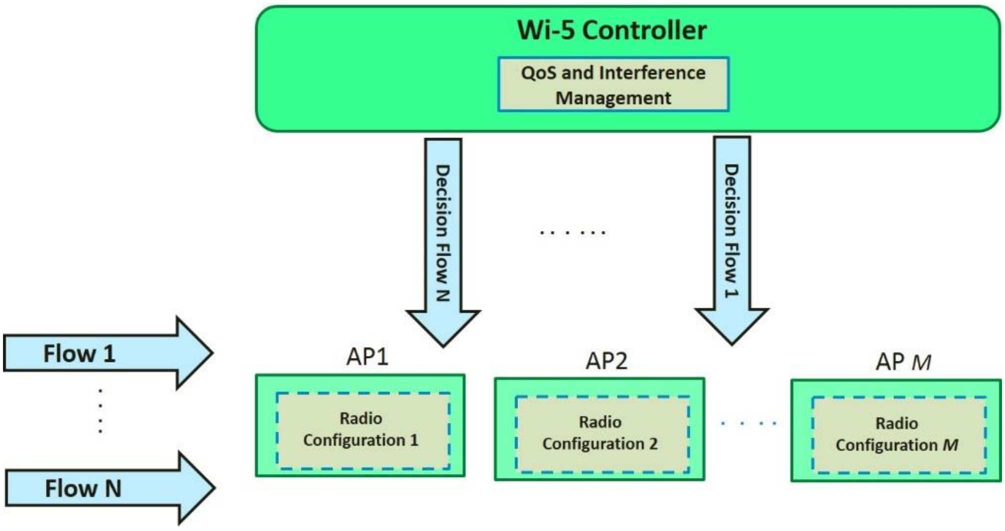

Figure 28: Slicing in Wi-5 to Achieve QoS and Spectrum Usage Optimization

4.4.3 Flexibility and Self-Configuration

By adopting an SDN approach, the Wi-5 architecture will address the flexibility requirement by simplifying the execution of control operations across the whole Wi-Fi network and offering a global view of the network state. This will also allow the Wi-5 system design to implement the different control algorithms as modules hence offering a scalable and extendible design solution, as illustrated in Figure 29.

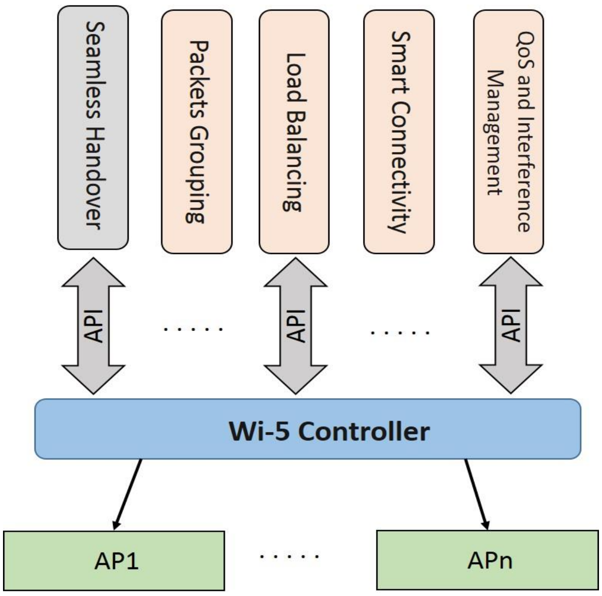

Figure 29: Wi-5 Architecture Design Approach

Note that through the Openflow protocol as well as the monitoring agents that are deployed on the Wi-Fi APs and wireless STAs, the Wi-5 controller will be continuously updated on the status of the network, the quality of the wireless channel, the QoS requirements of the traffic, and any other relevant performance related reports, as illustrated in Figure 30. These reports will help the Wi-5 controller to trigger the adequate control application, hence requiring no intervention from the network manager or operator.

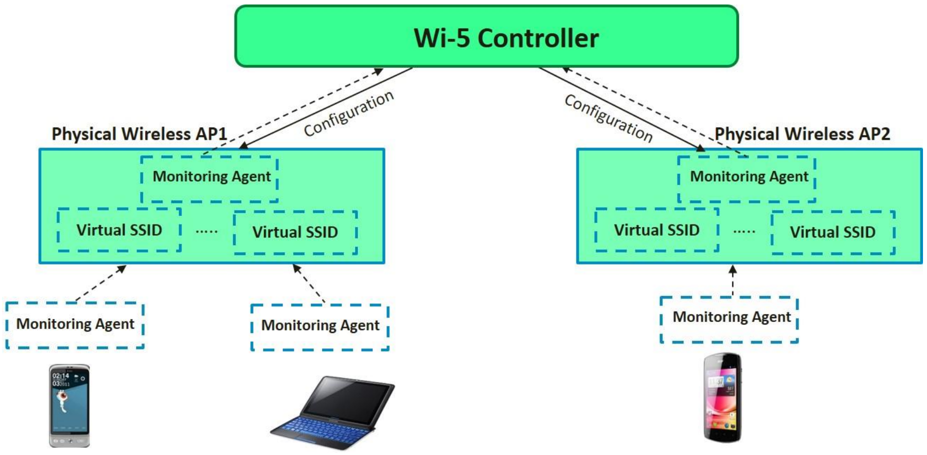

Figure 30: Monitoring in SDN-Based Wi-5

4.4.4 Implementing Spectrum Usage Broker

The spectrum usage broker identified above performs an important role to enforce fair and coordinated spectrum allocation and management policies between operators. It will interact with the Wi-5 system through the control (northbound) API by implementing the spectrum usage broker application on top of the controller, as illustrated in Figure 31.

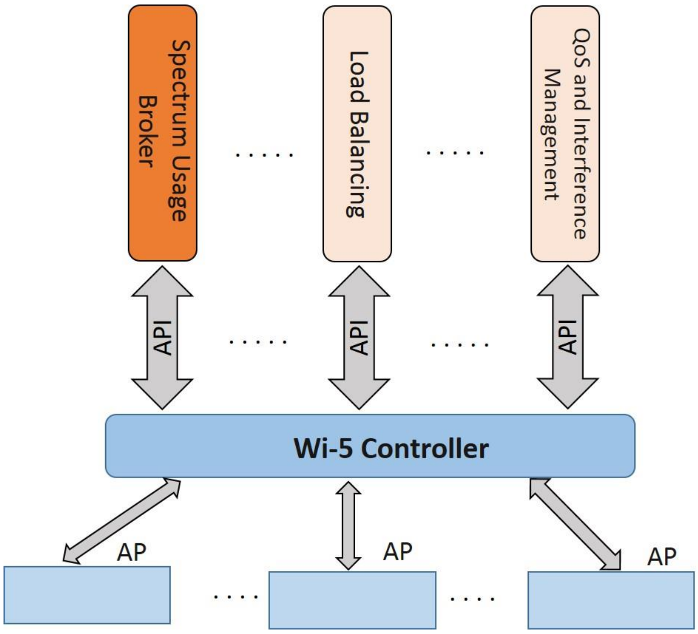

Figure 31: Spectrum Usage Broker as part of Wi-5

4.4.5 Cooperation and Autonomy

According to the SDN concept, the cooperation concern, identified above, is implemented at the control layer, i.e. between SDN Controllers, as illustrated in Figure 32. Following this SDN-based approach, the Spectrum Usage Broker application will run on each Operator Wi-5 controller, which will offer a reliable and direct inter-operator (East-West) cooperation platform, while limiting their autonomy of management as little as possible.

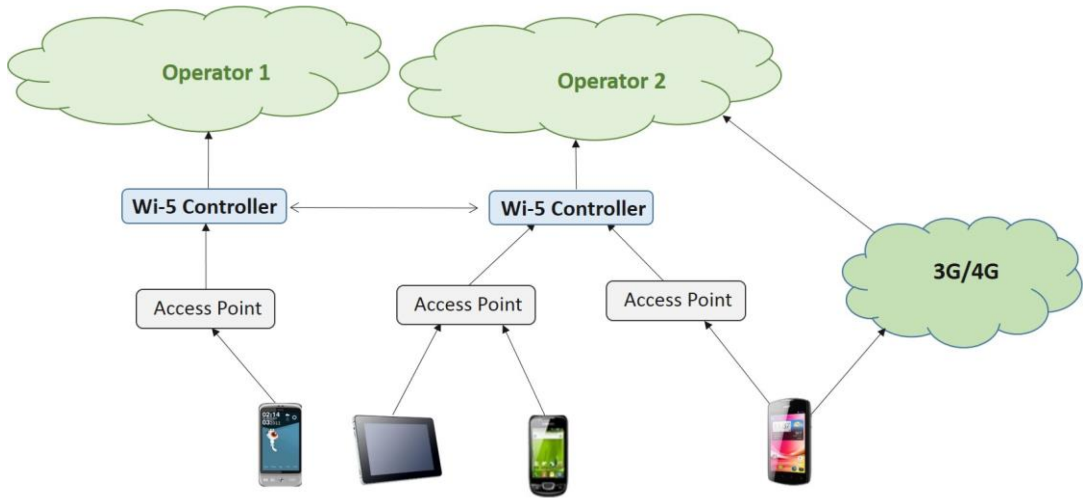

Figure 32: Direct Inter-Operator Cooperation in SDN-Based Wi-5

Note that although operators prefer to own and manage their own spectrum usage broker, the current architecture also allows us to implement this role as a third party on top of an SDN controller similar to the previous approach, as illustrated in Figure 33.

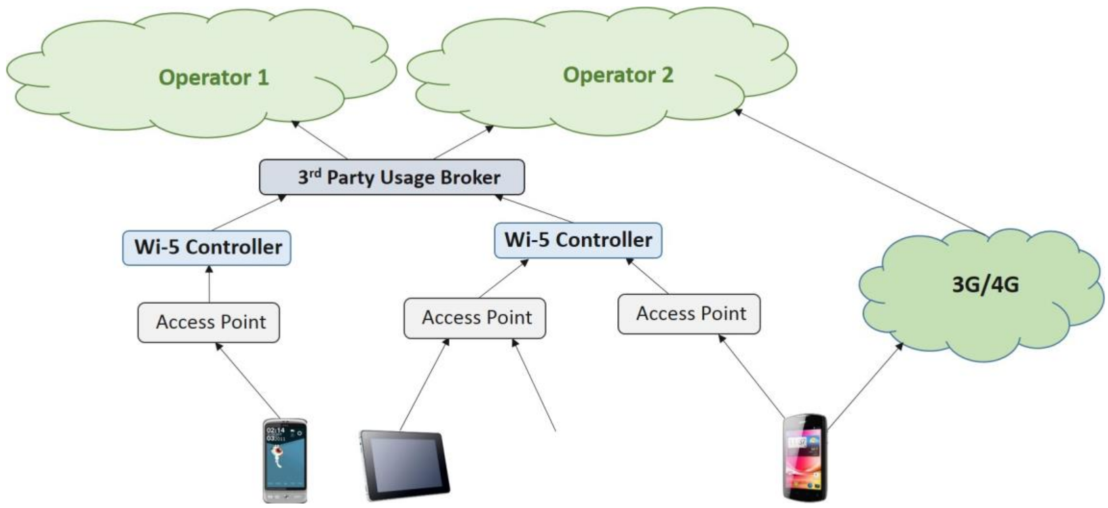

Figure 33: Inter-Operator Cooperation through a Third Party in SDN-Based Wi-5

5 Implementation of Wi-5 Architecture

5.1 Introduction to the selected approach: Odin

Despite the simplicity and flexibility of the SDN approach adopted in Wi-5, OpenFlow currently does not support IEEE 802.11 control functions. Odin, described in section 2.4, offers an SDN framework that uses a controller to manage infrastructure WLANs. Its design simplicity as well as its Open Source availability were important factors in choosing Odin to implement the Wi-5 architecture and its functionalities. In this section we present a technical analysis of the Odin framework, including its system design, its current capabilities, and its limitations. We will also present our initial tests of this framework and our plans to extend it in order to support Wi-5.

Odin uses the LVAP (Light Virtual Access Point) abstraction which is created by the controller for each user terminal (client), making it *see* the whole WLAN as a single AP. For that aim, the AP, instead of sending the frames with its own MAC address, uses a MAC specifically created for the client. If the client moves to another AP, the controller moves the LVAP accordingly, so the user terminal does not notice the AP change. The use of LVAPs makes it possible to hide the handover between APs from the terminal, thus avoiding the delay produced by re-association. In fact, the handover is totally transparent for Layer 3.

Two resource management algorithms were defined as applications in Odin which run on top of the Floodlight OpenFlow controller:

1. **Odin Mobility Manager**: This is a reactive application that manages the handover of an STA when the user is moving towards a new AP. First, the controller adds a `SUBSCRIPTION` to each AP: as a consequence, if an AP hears a new client with a signal strength higher than a threshold, it reports the event to the controller (`PUBLISH` message). If an event is triggered, the application then moves the LVAP corresponding to the STA from the origin to the destination AP. This is illustrated in Figure 34**Error! Reference source not found.**: first, a “Subscription” is added to each AP (1). When a client moves (2), the destination AP detects a radio signal power increase, and publishes a message (3). The controller may decide to handover the client, and the LVAP accordingly (4).

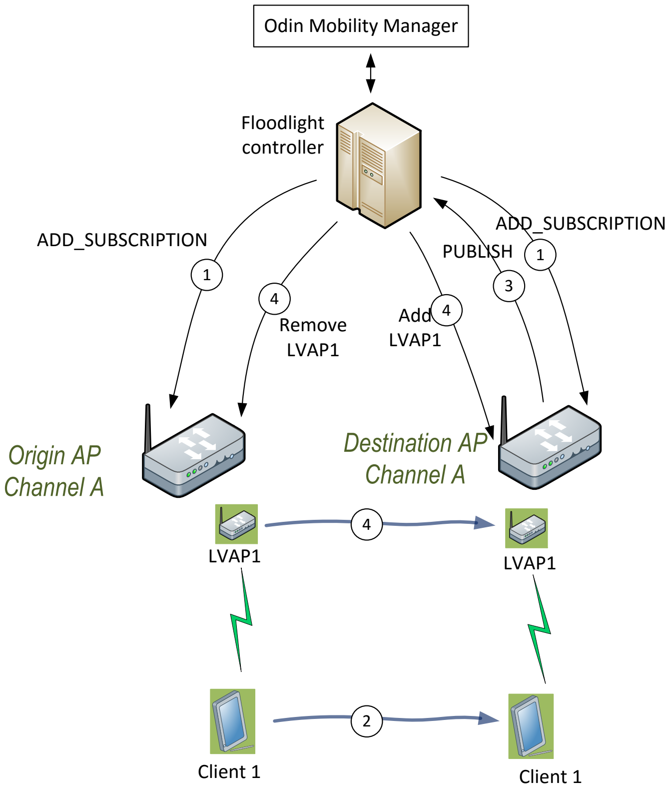

Figure 34: Odin Mobility Manager

2. **Simple Load Balancer**: This is a proactive load balancing application, which can be run periodically (every 60 seconds by default). As shown in Figure 35, the controller first queries every AP (1) in order to know all the STAs it is able to *hear*. Once the statistics have been gathered (2), a simple round robin algorithm is run, and the STAs are assigned to one of the APs (3).

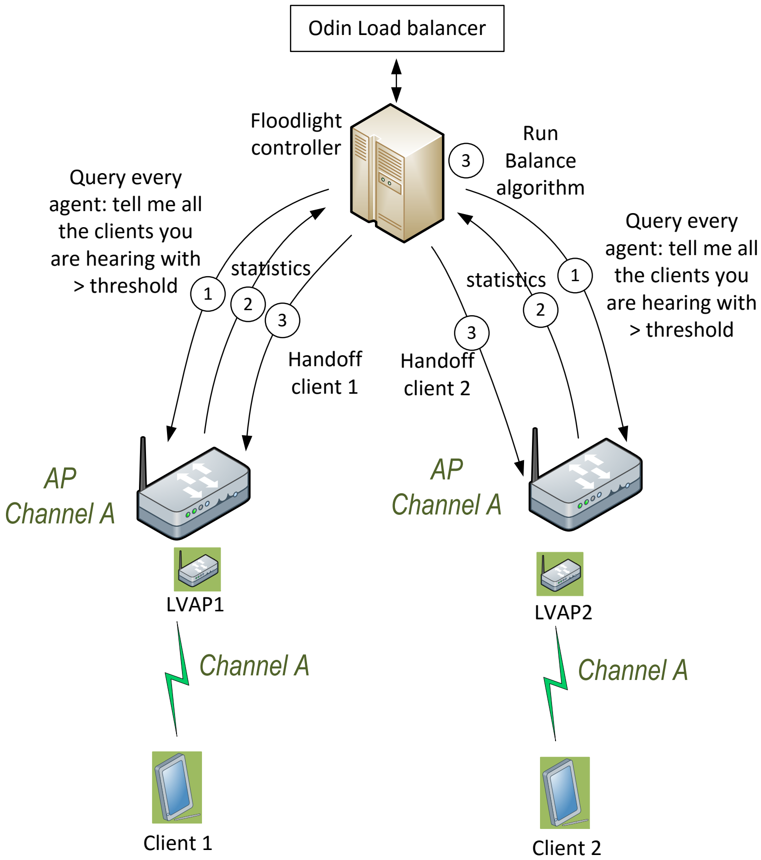

Figure 35: Odin Simple Load Balancer

5.2 Extensions required in Odin for supporting the Wi-5 Architecture

Although Odin is able to extend the SDN concept to wireless network management, it does not offer the necessary fine-grain control mechanisms to implement all the Wi-5 functionalities. Odin does not support QoS flow management policies, radio parameters configuration, and inter-controller cooperation, which are all very important in Wi-5. **Error! Reference source not found.**6 shows our approach to extending the Odin framework to support the proposed Wi-5 architecture. The Wi-5 API will extend the Odin controller northbound API to support Wi-5 functionalities. The Odin controller will also be extended to support inter-controller cooperation, necessary to implement the cooperative functionalities in Wi-5. The southbound API of Odin's controller will also be extended to support fine-grained radio parameter configuration. Finally, the Wi-5 agent, will extend the existing Odin agent to support the programming of radio resources on the wireless APs.

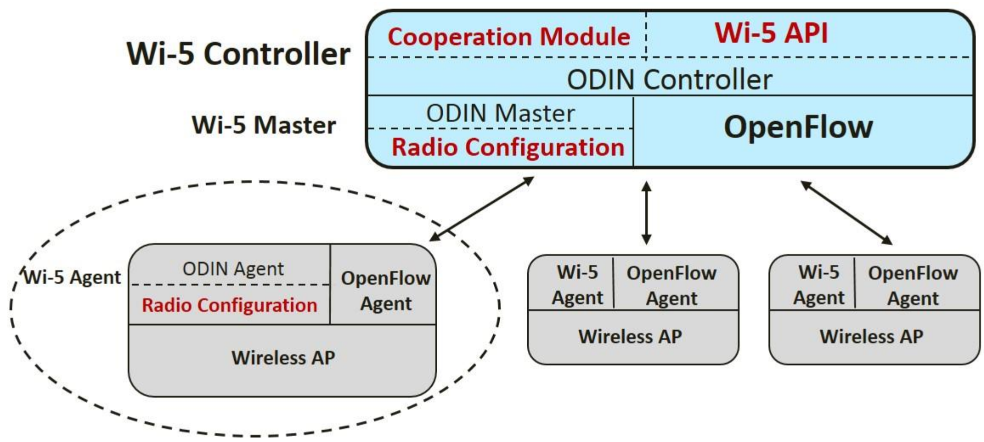

Figure 366: Implementing Wi-5 Architecture Using Odin Framework

5.3 Testbed and Initial Experiments with Odin

In order to perform the preliminary tests, and to establish a platform where we can add new functionalities to Odin, we have installed it in a controlled laboratory environment, using the publicly available implementation. The scheme is depicted in Figure 37.

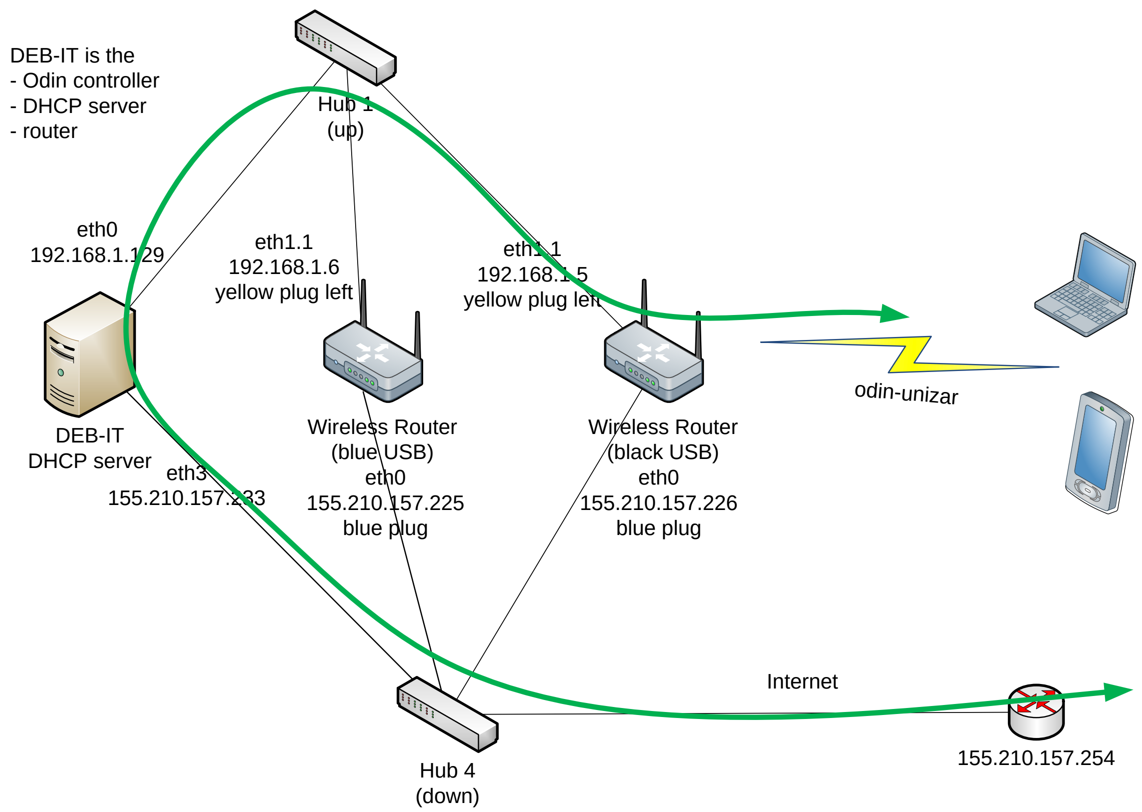

Figure 377: Wi-5 Testbed using Odin Framework

These are the characteristics of the machines used:

- Two TP-Link1043NDv2 APs are used, both configured in channel 6 (2.4 GHz band). New routers in 5 GHz band are being added currently.

- The controller (named *DEB-IT)* is a commodity PC running Linux Debian 8. It also includes the *router*, *NAT* (Network Address Translation) and *DHCP server* functionalities
- The STA *miniPC1* and STA *miniPC4* are connected to the 802.11 SSID "odin-unizar"
- The test traffic (e.g. game traffic) is generated with D-ITG traffic generator, which includes an option for generating *Quake3* (a popular First Person Shooter game) traffic.

The green arrow specifies the path followed by packets using the 802.11 network to access the Internet. As can be seen, all the traffic goes through the *DEB-IT* machine. This is just an option we have taken, but this functionality does not necessarily have to run in the same machine as the Odin controller.

5.4 Preliminary tests performed with the developed testbed

Once we completed our Odin setup, our next step was to run some tests in order to evaluate its suitability for the accomplishment of Wi-5 objectives, especially the support of real-time services with good quality. For that aim, we have selected a First Person Shooter game, which represents a good example of a service with tight real-time requirements.

The two questions to be answered are:

- Can this Wi-Fi WLAN support seamless handovers between different APs? In this case, "seamless" means that the player of a First Person Shooter, usually considered the game genre with the tightest real-time constraints, must experience a good quality.
- Should the fact of having a player in an AP be considered as an input for the resource management algorithms?

In the first test, a single machine is connected to the Odin Wi-Fi SSID, and it generates a *Quake3* traffic flow. No other machines are connected to that SSID. The mobility application has been configured to handover the client every 3 seconds from one AP to another. Figure 38 presents the delay of each packet during 24 seconds (8 handovers). It can be observed that the delay does not significantly increase after the handover, and it is usually below 15ms. The jitter (delay standard deviation) is 5.5ms and the packet loss rate is 3.25%.

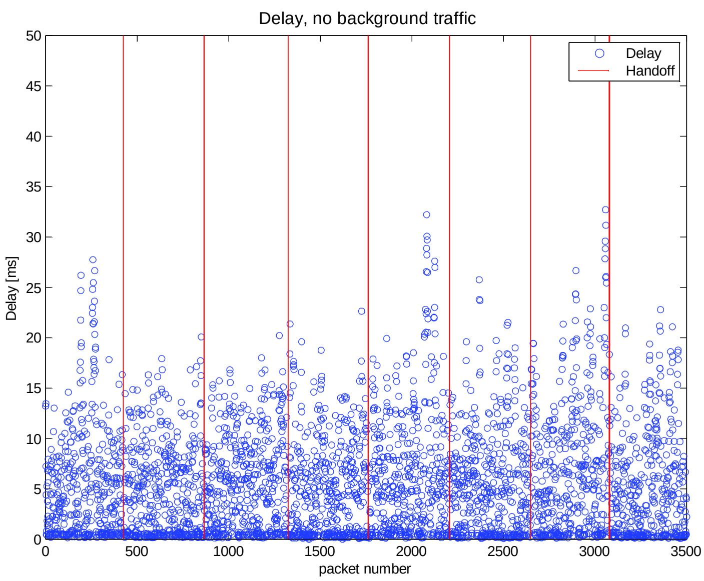

Figure 388: Delay of *Quake 3* packets when no background traffic is present

A subjective quality estimator, based on delay and jitter, has been used to obtain the results shown in Table 2. Different values of Round Trip Time (typical intra and inter-region values) have been added, in order to consider the time required to reach the game server, taking into account that in our setup all the machines are in the same LAN. The value of MOS (Mean Opinion Score) ranges from 1 *(bad quality)* to 5 *(excellent)*. If the MOS scale of VoIP is used, it is considered acceptable above 3.5. However, some works consider that a value of 3 can be good, but gamers will exchange to another server if MOS is roughly 2 [57]. In our case, MOS values above 3 can be obtained. Please note that this model was developed for *Quake 4*, but we are using it for *Quake 3*, so the results are only estimative.

In the second test, a similar testbed is deployed where an extra STA is downloading a big file (a Debian ISO image) from the Internet using the Odin SSID. From the results shown in Figure 399, it can be observed that the delay increases significantly (following a pattern similar to the sawtooth TCP rate increase of the FTP download), making the game unplayable. In addition, many packets are lost. There are some moments where a correlation between handovers and delay is observed (see e.g. a delay increase after the handover corresponding to packet number 1740), but the delay increase caused by the handover is not significant. Long bursts of lost packets appear.

Scenario	**G-Model Subjective Quality Estimator[a]**		
	Delay (Round Trip Time)	***Jitter***	***MOS***
LAN	5 ms	5.5 ms	3.73
Intra-region	20 ms	5.5 ms	3.58
Inter-region	80 ms	5.5 ms	3.04

Table 2: Subjective Quality Estimation depending on Network Delay

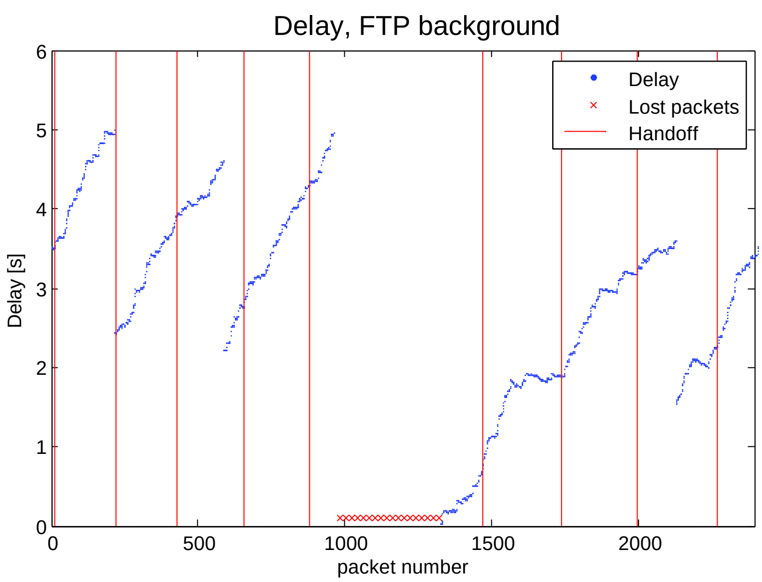

Figure 399: Delay of *Quake 3* packets when coexisting with a FTP background flow

We will now try to answer the two questions raised above. First of all, we can conclude that the solution based on LVAPs is able to support seamless handovers of online game traffic. It has been shown that the delay added to the packets after a handover is not significant.

Regarding the second question, the results set clear that the coexistence of an online game and an FTP download produces a significant delay increase in the real-time application. Therefore, if the resource management algorithms were aware of the presence of a real-time flow in an AP, they would be able to distribute the terminals in such a way that avoids this coexistence. This result encourages us to include monitoring tools able to detect real-time flows in the architecture, and to consider this factor as an important input for the resource management algorithms.

The results of these experiments show that it is possible to maintain an acceptable subjective quality level during the handover, in a scenario where an end device moves between different APs while generating game traffic. Therefore, the choice of this LVAP-based approach seems to be a good selection for the implementation of Wi-5 functionalities.

As far as resource management algorithms are concerned, it is set clear that the fact of having a real-time flow (e.g. a game flow) in the AP should be taken into account by the algorithms, in order to provide a better quality: the results have shown that the coexistence of real-time traffic and FTP in the same AP may harm the QoE of the player, so perhaps these flows should be attended by different APs.

5.5 Demonstration of the testbed in a research conference

A portable version of this testbed has been used for running some tests, which results were submitted to NetGames 2015, *The 14th International Workshop on Network and Systems Support for Games* (In co-operation with ACM SIGCOMM and ACM SIGMM, Technically co-sponsored by IEEE Communications Society). This workshop is organised every year, and the Technical Program Committee brings together the world’s experts on network support for online games. An article was accepted for publication and was presented by Unizar researchers as a Demo in Zagreb on 3-4 December 2015 [15].

The demonstration was implemented with two servers:

- A game server of the popular *Counter Strike* (1.6 version) in a Windows 8.1 machine
- The Wi-5 Controller (Intel NUC 5i3RYH, i3-5010U 2.1 GHz and 8 Gbytes) running a router, a DHCP server and the Odin Controller.

In addition, two Wi-Fi access points (TP-Link1043NDv2) were used in order to create the wireless network in channel 6 (2.4 GHz band). The servers and the access points are connected through a 100Mbps hub for the corresponding communication, while two different laptops are used as mobile devices connected to the wireless network, in which a *Counter Strike* client is running.

Figure 40: Demonstration testbed scheme

presents the scheme of the portable testbed. The Odin Controller includes some Wi-5 improvements and an application which switches (handover) one mobile device from one AP to the other one every 3 seconds, while the others devices are permanently connected to the corresponding AP. In this scenario, the difference on the QoS and the QoE between a switching-device and a non-switching-device can be observed. Figure 4 shows a photograph of the actual setup during the workshop in Zagreb.

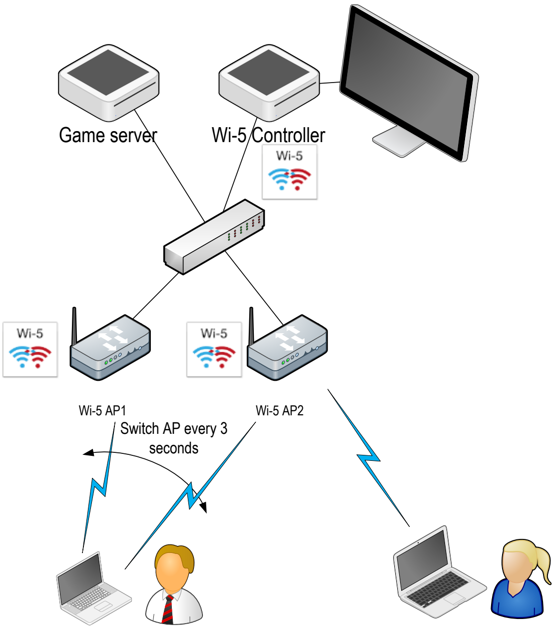

Figure 40: Demonstration testbed scheme

Figure 41: Demonstration testbed photograph

All in all, this section has summarised the reasons for selecting this LVAP-based solution, and the performed tests have shown promising preliminary results. However, Odin requires a number of extensions in order to fulfil the requirements of the Wi-5 architecture. Our next objectives will include the development of these extensions as part of WP3 and WP4, which will be tested in our lab deployment.

6 Conclusions

The Wi-5 project addresses the issues related to Wi-Fi network congestion and the inefficient usage of wireless spectrum through a set of functionalities and solutions focused on Wi-Fi Access Points. The realisation of these solutions, however, depends on the availability of an architecture that can effectively integrate them into a single system. This architecture should meet the functional requirements (concerns) of the Wi-5 system stakeholders.

We analysed the business models presented in Deliverable D2.1, the use cases as described in D2.3, and we took on board the input from the project's Operator Board. This analysis helped us identify the key stakeholders and concerns to be considered, which are important to describe the architecture according to the guidelines of the ISO/IEC/IEEE 42010 standard. Five stakeholders were identified based on the business model analysis that each play a role in the Wi-5 architecture:

- Operator who owns the backhaul network
- Manager who operates a local wireless network
- Wireless User who interacts with the wireless network
- Wi-5 System Designer to develop and implement Wi-5
- Spectrum Usage Broker to enable cooperation between operators

The following concerns were then defined and mapped to the relevant stakeholders:

- Mobility
- Quality of Service Awareness
- Flexibility and Self-Configuration
- Spectrum Usage Optimisation
- AAA
- Cooperation and Autonomy

In this deliverable, a set of viewpoints are presented for the Operator, Manager, Spectrum Usage Broker, Wireless User and Wi-5 System Designer to model each of their concerns in the Wi-5 architecture.

The initial Wi-5 architecture can be matched well on the SDN concept that defines Access Points being managed using OpenFlow by a Wi-5 Controller responsible for the configuration of every Access Point owned by a single operator. The Wi-5 solutions are then implemented on top of the Controller to provide interference management and support seamless handover, smart connectivity, and load balancing based on the use case. Agents are deployed inside the Access Points to allow the policies from the Wi-5 Controller to be enforced and they support instances or Virtual SSIDs tailored to individual users to be created, reconfigured, moved, or removed dynamically. In this way, the Wi-5 solutions for mobility, QoS and spectrum management can be implemented by controlling the configuration and deployment of these Virtual SSIDs. Monitoring agents within the access network will allow the controller to seamlessly gather state information about the wireless environment, allowing the system to self-configure and optimise itself based on the density of the spectrum usage and the number of users supported at any point in time. This approach is designed to enable the fine-grained wireless configuration that is required to optimise the spectrum while, at the same time, providing a scalable and flexible platform that can be applied to a wide range of use cases. To support cooperation between domains within the same local wireless environment, the Wi-5 Controller will be able to interact with its peers, either directly or through a 3rd party broker, so states and configurations can be exchanged.

As such, the individual domains are still able to fully control their network but can also engage with the cooperative approach pioneered by Wi-5.

For future work, we will further investigate the technical implications of the different cooperation options described above, on the design of the SDN system, especially the controller. We will study the different inter-controller cooperation options proposed in the literature and we will analyse the advantages and drawbacks of each approach with regards to the requirements identified during our initial architecture design process. Our analysis can also be used to refine the Wi-5 business models. Our next step is then to validate the proposed architecture with regards to these business models and use cases through research and a set of discussions with the project's Operator Board and the Expert Board. Finally, we will experimentally validate the architecture using the Odin framework while extending Odin's capabilities as needed.

In summary, the Wi-5 architecture considers the current state of the art in Software Defined Wireless Networking and has applied these to the business and use case requirements of our project to propose the overall approach. The innovations introduced here result from the introduction of fine-grained control over the wireless spectrum resources in the access point, the flexible inter-operator deployment model that is enabled via the broker, and the close integration between the smart and cooperative functionalities that are implemented in the Wi-5 solutions. These include truly novel features such as dynamic channel assignment and power control, AP load balancing and packet grouping based on traffic type and requirements, support for smart handovers to optimise user QoE and seamless vertical handovers to maximise usage of the full wireless environment, and coordinated interference management to find the optimal wireless configuration.

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