What to do With the Wi-Fi Wild West

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Abstract

This deliverable presents the final version of the Wi-5 architecture that integrates all the smart and cooperative functionalities developed over the course of the project. We start by further analysing the business models and use cases, and we then provide an improved definition of the stakeholders and their concerns identified in the initial architecture. Using the guidelines of the ISO/IEC/IEEE 42010 standard, we present the final description of the Wi-5 architecture to reflect the changes that have been made with regards to the stakeholders and concerns. Finally, we identify the interactions among different stakeholders and the interfaces necessary to enable these interactions, and the technical approach adopted to realise this architecture and its interfaces.

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Executive Summary

This deliverable presents the final version of the architecture that was developed by the Horizon 2020 Wi-5 (What to do With the Wi-Fi Wild West) project. This version updates the initial and intermediate versions according to the experiences gained through tighter coordination with the use case and business modelling tasks. It also embodies the feedback received from the technical work in developing smart and cooperative Access Points (APs) addressing radio spectrum interference and spectrum usage inefficiency, and from the integration and field trials executed in the final year of the project. The approach was chosen to provide the best technical solution to the issues of radio resource management, mobility, and Quality-of-Experience (QoE) along with a standardised reference for other groups developing similar platforms.

This version also provides an updated analysis of the Wi-5 approach to justify the technical direction adopted. Our analysis shows that traditional networking techniques would not be sufficient to meet our functional and business-related requirements. We therefore adopt the Software Defined Networking (SDN) paradigm and base our approach on the emerging concept of Software Defined Wireless Networking (SDWN). The SDWN concept can fulfil the requirements of a novel Spectrum Usage Broker role (i.e. a stakeholder that devises and maintains sensible spectrum sharing strategies between Local AP Managers in a cooperative context), with the SDN Controller as the main configuration point for the entire wireless network. The Wi-5 solutions are then implemented on top of the controller.

Following this, we provide an analysis of the Wi-5 use cases to identify the functional requirements in each scenario, which are then combined to identify how the Wi-5 functionalities map onto these deployment scenarios. Further, the Wi-5 business model analysis addresses how the *tragedy of the commons* problem can be overcome in this context, and introduces some additional constraints such as the need for cooperation. The analyses result in a detailed description of the Spectrum Usage Broker 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 optimised user experience.

Based on this analysis, the updated Wi-5 architecture is formally described according to the guidelines of the ISO-IEC-IEEE 42010 standard. Firstly, the key Wi-5 system stakeholders and their related concerns are identified and mapped. Secondly, a set of viewpoints that address these concerns for each stakeholder are presented. Then, in order to present this in a more tangible way, we describe the architecture in the use case of a dense apartment block to outline the role of the spectrum broker and the radio resource management functionality in context.

Finally, this deliverable presents an overview of our implementation of the Wi-5 architecture. First, the relevant interfaces are defined, both at the upper layer towards the service providers, and at the lower layer towards the Wi-Fi APs. From there, a high level summary of the current status of our implementation work is provided to show how we have improved and extended the Odin platform for our architecture based on state-of-the-art work in the field. In particular, we highlight our latest progress toward smart AP selection and mobility management, including vertical handover.

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 hand-over 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 final version of the detailed Wi-5 architecture specification that integrates the smart and cooperative functionalities as proposed in Wi-5. We start in section 2 by reviewing 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 and our initial approach. 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 D2.6, and the input obtained from the project's Expert and Operator Boards. We then present the Wi-5 architecture description according to standard ISO/IEC/IEEE 42010. In section 5 we give an example of how to use this description based on the Dense Apartment Building use case. We explain how this architecture is designed according to the SDN concept in section 6. Finally, we present our conclusions in section 7.

1.3 Relationship with other deliverables

The material in this document relates to the following deliverables.

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.

D2.5i: The intermediate Wi-5 architecture is presented in this deliverable. The final version of the architecture presented here updates the version in D2.5i, providing a better specification of the interfaces and a preliminary architecture of the brokering functionality. Given the results gained from other WPs, we also decided to reallocate the Autonomy and Cooperation concern from “Service Provider” to “Local AP Manager” and better align with the business model and implementations.

D2.6: The final Wi-5 architecture description is based on the stakeholders and business-related requirements identified in this deliverable. This is an extra deliverable that updates D2.1 and presents the Wi-5 business model based on the completed DAMIAN methodology.

D3.1 and D3.3: Deliverable 2.5 describes the architecture that integrates the smart functionalities specified in deliverables D3.1 and D3.3. D3.1 focusses on a description of the Wi-5 monitoring functionalities and D3.3 updates D3.2 to present how smart functionalities have been defined and implemented. In deliverable D3.4, which will be submitted in month M40, we will present the final version and testing results of the smart functionalities based on the platform as defined in this deliverable.

D4.2: Finally, Deliverable 2.5 describes the architecture that integrates the cooperative functionalities specified in deliverable D4.2. D4.2 updates D4.1 to describe how the Wi-5 algorithms have been developed and implemented. In deliverable D4.3, which will be submitted in month M40, we will present the final version and testing results of the cooperative functionalities based on the platform as defined in this deliverable.

1.4 Glossary

AP	Access Point
API	Application Programming Interface
ARP	Address Resolution Protocol
ATP	AP Talk Protocol
CLC	CROWD Local Controller
CROWD	Connectivity management for eneRgy Optimised Wireless Dense networks
CSA	Channel Switching Announcement
CWP	Coordination Wi-Fi Platform
DQCA	Distributed Queuing with Collision Avoidance
EVA	Estimated aVailable bAnd-width
FAMS	Flexible Access Management System
HCI	Human Computer Interface

ISM	Industrial Scientific Medical
ISO	International Organization for Standardization
LCCS	Least Congested Channel Search
LVAP	Light Vırtual Access Point
QoE	Quality of Experience
QoS	Quality of Service
RSS	Received Signal Strength
SDN	Software Defined Networking
SDWN	Software Defined Wireless Networks
SOHO	Small Office Home Office
STA	WLAN Station
SSID	Service Set IDentifier
TPC	Transmit Power Control
VA	Virtual Agent
VAM	VA Management
VAP	Virtual Access Point
WDTX	Wi-Fi datapath programmability

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 [62,63]. 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] focusses 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 their ranges 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. The authors have shown that this 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 to 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 whereas in bandwidth based algorithms [48], [49], the decision is instead based on the amount of available bandwidth which helps to achieve a higher 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 APs.

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. In [54], the authors propose 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 user mobility. The implementation of an efficient and scalable seamless mobility approach requires an intelligent and flexible network management platform similar to the one proposed by the Software Defined Networking concept [17].

2.3 Software Defined Networking

The Open Networking Foundation (ONF) [16], a non-profit consortium dedicated to the development, standardisation, and commercialisation 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 simplifies the development and deployment of network applications running on top of the controller. In addition, a global view of the network at the controller enables SDNs to provide more efficient configuration, deliver better performance, and offer 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, proprietary configuration, and management interfaces of typical networking devices give 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 operating expenses of running a network. In contrast, 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 [18], RCP [19] and 4D [20] 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 centralised control-plane and demonstrated the feasibility of operating a centrally managed network. Later, OpenFlow [21] was 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 [22], [23], [24], and [25]. A survey of SDN with a special emphasis on OpenFlow, currently the most commonly deployed SDN technology, can also be found in [26]. SDN in the context of wireless networks is surveyed in [27].

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. 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 virtualisation, etc.

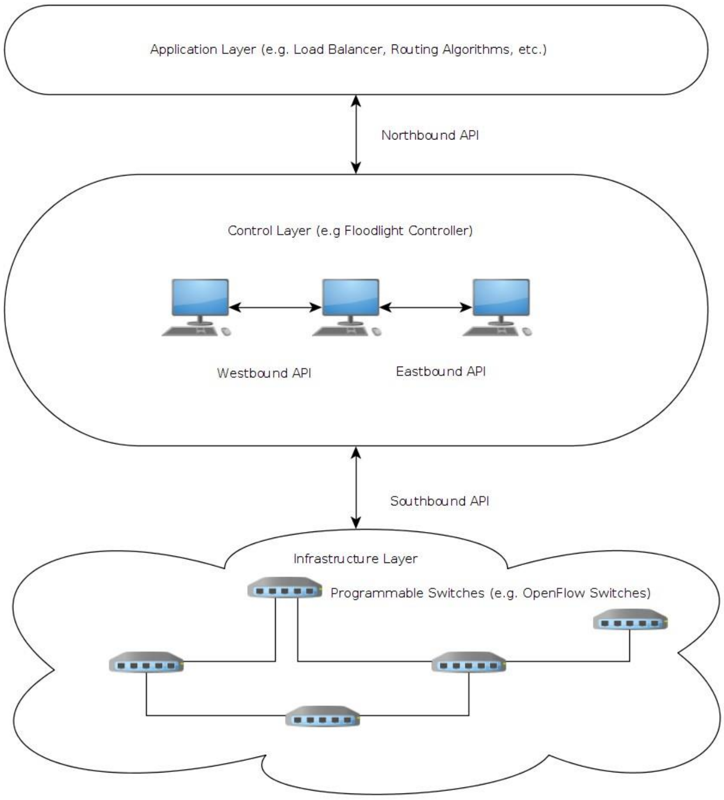

Figure 1: Layered View of an SDN Architecture

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 for 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 providing packet forwarding rules to switching devices.

Since multiple controllers can exist in a large administrative network domain, an "east-west" communication interface among the controllers is also needed for them 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 [22].

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 inserts the forwarding rules into the flow tables of each OpenFlow enabled switch. Depending on the rules installed by a controller, 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 therefore 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 yet emerged. 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.

2.4 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. 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 2. To describe this approach fully, we will discuss those concepts that will then be used to define the Wi-5 architecture in more detail below. The ISO/IEC/IEEE 42010 standard will be used to ***formally describe the 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.

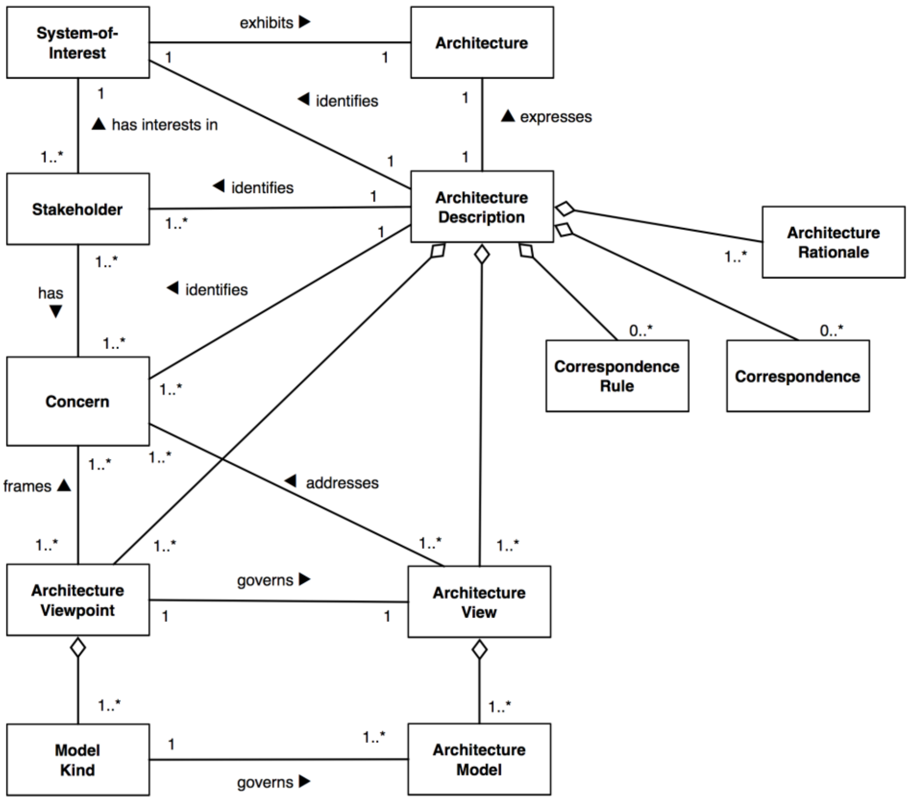

Figure 2: ISO-IEEE 42010 Architecture Description Model

2.4.1 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.

2.4.2 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.

2.4.3 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 deliverables D3.1 and D3.3.

- 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 handovers (typically horizontal) and hard handovers (typically vertical). These functionalities are developed by Work Package 4 and their specification is described in deliverable D4.2.

The Wi-5 architecture relies 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 the Wi-5 functionalities, and the approach adopted in this project to design the Wi-5 architecture. A description of the architecture using the ISO/IEC/IEEE 42010 standard is presented in the next section.

3.1 Wi-5 Smart Access Point 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-grained 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 follows:

- **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 a significant overhead reduction and bandwidth and energy savings.

3.2 Wi-5 Cooperative Access Point 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 is 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 requirements 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.

3.3 Wi-5 Architectural Approach – Software Defined Wireless Networks

When considering how to approach the combination of smart and cooperative functionalities described above, it is clear that while Wi-5 is focussed on optimising Access Points, the need for broader local cooperation means that a coordinated approach is necessary. As such, the concepts introduced by SDN provide a good fit here as they allow for very fine grained and coordinated management of network configurations over an entire network. However, unlike wired networks, wireless networks are highly dynamic, and must provide additional control operations such as managing mobility, authentication, etc. As such, developing SDNs to manage wireless networks introduces significant complexities and, in the context of Wi-Fi networks specifically, a software defined network must also support fundamental IEEE802.11 functions such as managing SSIDs and network associations. Nevertheless, researchers have started to consider SDN as a more efficient approach to address the challenges of managing wireless networks, and Software Defined Wireless Networks (SDWN) [37] are now an active research field in their own right.

In [28], OpenRoads proposes OpenFlow Wireless, which is built on top of OpenFlow. Their main focus is to virtualise the network by using the FlowVisor [29] which virtualises the datapath, and SNMPVisor which virtualises the configuration. They also give users the ability to opt-in to experiments.

Yamasaki et al [30] 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.

In [31], 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 take care of network functions requiring global visibility, such as mobility management and load balancing.

In [33], an energy programmable Wi-Fi networking framework named Thor is proposed with the aim to cluster clients around APs in an energy-efficient manner. This framework is a combination of Energino [34], 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.

Odin [35], [36] 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 separate virtual AP.

OpenSDWN [32] utilises the LVAP abstraction and extends Odin with three new features: i) Wi-Fi datapath programmability (WDTX) for fine grained wireless datapath transmission control, ii) a unified abstraction for virtualised middleboxes and APs to migrate the per client state, and iii) a participatory interface to allow for the sharing of network control.

The EmPOWER platform 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 again 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 be built on top of other SDN frameworks.

In [38], a software-defined real-time power consumption monitoring framework named Joule is proposed, this framework is built on top of EmPOWER. 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 APs.

In [39], 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 controller: 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 [40] relies on an OpenFlow based SDN architecture that supports traffic engineering in heterogeneous mobile networks. This architecture supports resource on demand provisioning in a centralised control plane and hides the technology specifics from the controller through the use of abstractions.

CloudMAC [41] 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 [42], 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 virtualisation of wireless networks in order to extend the SDN concept to allow the programmability of wireless APs.

Wi-5 builds on the work presented above to develop our own SDWN-based architecture to implement the functionalities we require for the fine-grained management of Wi-Fi networks.

4 Wi-5 Final Architecture

Wi-5 architecture integrates all the functionalities developed in WP3 and WP4, as described earlier, into a single system. In addition, the architecture considers the requirements and limitations set by the Use Cases, identified in deliverable D2.3, and the Wi-5 Business Model described in deliverable D2.6.

As shown in Figure 3, both the Business Model and Use Cases influence the architecture design process. Firstly, the business model defines the use cases that can be considered in the Wi-5 system such that all these use cases can be operated with the same Business Model, and their limits. Secondly, the Use Cases define the functional requirements that need to be considered in the architecture design process. The limits set by the business model on the use cases are also considered as requirements in the architecture design process.

By respecting these Use Cases and the defined Business Model, 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 as presented in section 2.4. Following this standard, the Wi-5 architecture description will oblige to the concerns of each system stakeholder and their viewpoints.

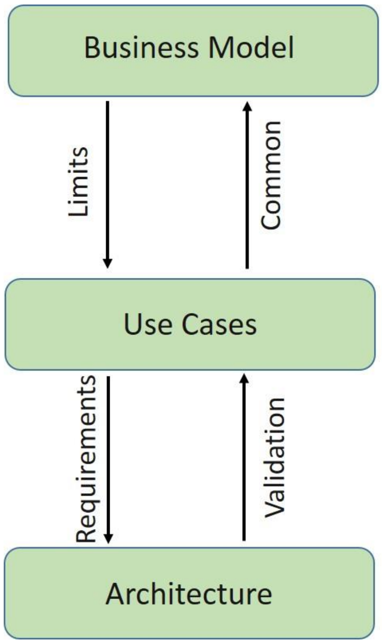

Figure 3: Interaction between Business Model, Use Cases and Architecture

4.1 Use Cases 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 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 as 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 APs. This deployment scenario is characterised by radio interference between Wi-Fi APs and a 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 an existing residential and Small- and Medium Business 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 all 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 quality of service 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 QoS required by their applications such as VoIP, Online Gaming, etc.

- **Self-Configuration**: In all use cases there is also 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 case of dense apartment buildings, the network will need to find a radio configuration that achieves optimal performance for all while minimising interference levels. In the Wi-Fi pico-cell deployment, the spectrum should be allocated fairly among users but take 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 Model 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 emphasise 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 for the current deployment models but they are not future proof. Due to its rapidly growing popularity, Wi-Fi networks are currently suffering from spectral congestion 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. In D2.6 "*Regulatory and game-theoretical considerations regarding the Wi-5 business model*", we completed our analysis using the DAMIAN methodology to refine the business roles and present the generic Wi-5 business model.

In particular, while we identified the need for cooperation among operators to break the tragedy of the commons in D2.1, D2.6 examined the limitations that must be considered in the context of regulatory frameworks in Europe. We showed that current regulations for spectrum usage and anti-trust do not pose fundamental limitations to AP operators collaborating. While the Wi-5 business models seem to violate anti-trust laws at first sight, exceptions can be made in order to improve the quality of the common good, provided that the monopolist (in our case the Spectrum Usage Broker, or the collaborating Spectrum Usage Brokers) is tightly controlled and regulated. However, the existing regulations also cannot prevent third parties to enter the space and interfere with their own APs and devices. The challenge for the collaborating entities will therefore be to present the incoming third party with a positive business case for entering the collaboration.

In addition to the need for a spectrum usage brokering functionality, the architecture design requirements that were derived from the business model analysis and discussion can be summarised as follows:

- **Autonomy**: Although many AP 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 a 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 for cooperation between AP operators.

4.3 Architecture Description

In this project we have chosen to follow the formal architecture description of ISO/IEC/IEEE 42010 described in section 2.4. In this approach, we start by systematically aggregating the above commonalties and requirements obtained from the analysis of the use cases, business models study and discussion with the project's Operator Board, into a limited number of stakeholders and concerns. The Wi-5 architecture viewpoints and the concerns and stakeholders within each viewpoint are then presented. Then, for each viewpoint, architecture views are defined and described.

4.3.1 Stakeholders

The following stakeholders have been identified:

- **Service Provider:** This role provides, manages, and controls the Wide Area Network (WAN) connectivity and service access for the wireless access networks. This connectivity and service access may be provided by fixed or mobile 3G/4G access networks, backhaul networks, and associated service architectures. Every Service Provider manages a single managed domain. The Wi-5 architecture must enable the Wireless User to have access to multiple Service Providers.

- **Local AP Manager:** This role is responsible for managing wireless APs that operate in the ISM bands of concern. It includes Community network operators, Office IT departments, Shop Owners, House Users, and Public Spaces IT managers (Airports, Train Stations, etc.), which correspond to the Airport/Train Station, SOHO, and Community Wi-Fi use cases. The Wi-5 architecture must be able to support optimisation of multiple APs belonging to multiple Local AP Managers.

- **Wireless User:** This can be any user who connects to a wireless network through a wireless terminal. This includes connecting to a Wi-Fi hotspot, or a fixed broadband subscriber accessing the broadband service via the wireless in-home network in the dense apartment building scenario. In the Wi-5 architecture, an AP must be able to serve multiple Wireless Users simultaneously.

- **Wi-5 System Operator**: This stakeholder is in charge of developing, implementing, and operating the technology needed to execute the Wi-5 spectrum sharing strategies as devised by the Spectrum Usage Broker. This includes functionalities such as: QoS Awareness, Interference Management, Mobility, etc. In the Wi-5 architecture, there is only one Wi-5 System Operator.

- **Spectrum Usage Broker:** This stakeholder, also referred to in this document simply as Spectrum Broker, devises and maintains sensible spectrum sharing strategies between Local AP Managers in a cooperative context, as described above. This may include a pricing agreement. This role treats the spectrum as a scarce resource to be shared by the Wireless User according to the pricing agreement. Ideally, the Quality-of-Experience (QoE) is optimised such that the number of complaints (help desk calls) to Service Providers is minimised. In the Wi-5 architecture, there is only one Spectrum Usage Broker.

4.3.2 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 Wireless 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 Wireless 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 stakeholders concerned.
- **Spectrum Usage Optimisation:** This concern is related to managing the wireless spectrum to provide fair utilisation between Wireless Users and managing interference.
- **AAA:** This concern is related to authenticating a Wireless 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 Local AP Managers while limiting their autonomy of management as little as possible.

4.3.3 Concern–Stakeholder Traceability

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

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

	Service Provider	Local AP Manager	Wireless User	Wi-5 System Operator	Spectrum Usage 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

4.3.4 Model Kind

According to the architecture description standard ISO/IEC/IEEE 42010, the views need to be described according to a defined Model Kind. The Model Kind used in the Wi-5 architecture description is based on a Data Flow Diagram (DFD) data representation approach that consists of: Actors, Data Flows, and Processes.

A. *Actor*

In this Model Kind, any of the Wi-5 stakeholders described above are considered as an Actor, where it will either provide data to the Wi-5 system or receive data from it. Actors are represented with rounded circles, with the description of the actor (stakeholder) inside the circle.

B. Process

Any inter-actor interactions that generate data or include manipulation of data before transfer from one actor to another is considered a process. A process is represented with a square, with the name and description of the process inside the square.

C. Data Flow

This is an arrow line that represents the path that data takes through the system. The arrowed line has an actor (stakeholder) and a process as either its source or destination. An example of how actors, processes and data flows are used in this Model Kind, is presented in Figure 4.

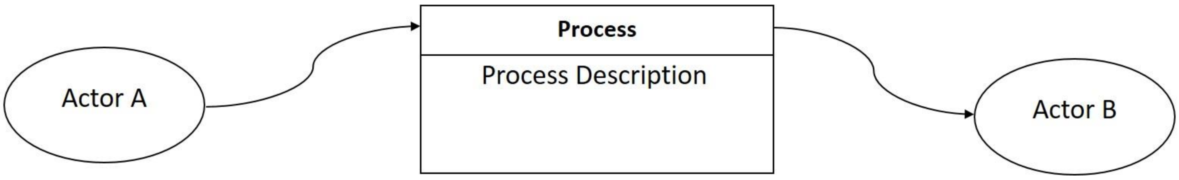

Figure 4: Example of Model Kind in Wi-5 Architecture Description

4.3.5 Service Provider Viewpoint

The Service Provider 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, Quality of Service Awareness, Spectrum Usage Optimisation, and AAA.

The Service Provider Viewpoint consists of the following views: Mobility View, QoS Awareness View, Spectrum Usage Optimisation View, and AAA Management View are described in Figure 5, Figure 6, Figure 7, and Figure 8, respectively.

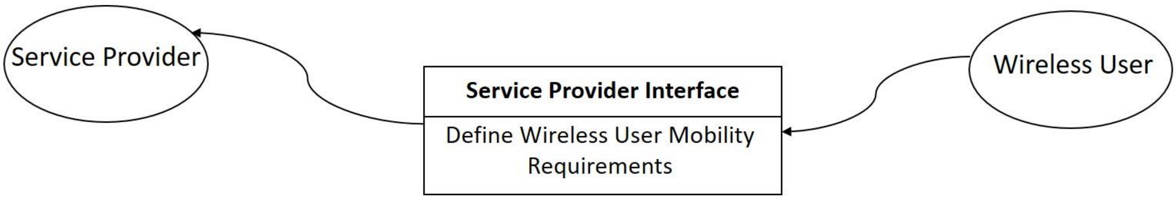

Figure 5: Mobility View in Service Provider Viewpoint

Figure 6: QoS Awareness View in Service Provider Viewpoint

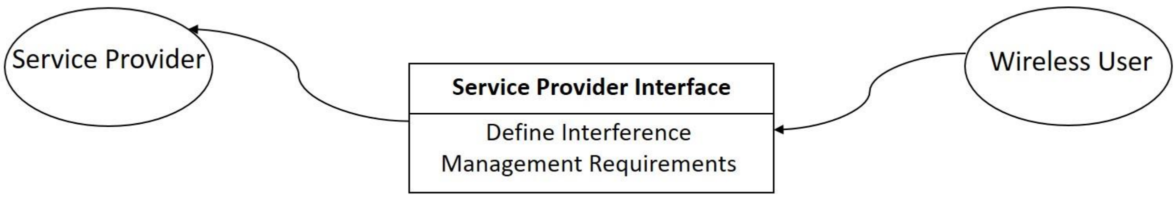

Figure 7: Spectrum Usage Optimisation View in Service Provider Viewpoint

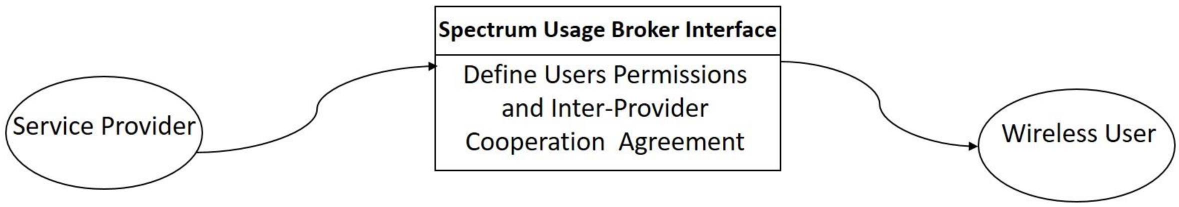

Figure 8: AAA Management View in Service Provider Viewpoint

4.3.6 Local AP 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. Also traditional telecom operators operating APs in a Wi-Fi hotspot network or in many home networks fall in this category. From this viewpoint, the Wi-5 architecture addresses the following concerns: Mobility, Quality of Service Awareness, Spectrum Usage Optimisation, AAA, and Cooperation and Autonomy.

The Local AP Manager Viewpoint consists of the following Views: Mobility Management View, QoS Awareness View, Spectrum Usage Optimisation View, AAA Management View, and Cooperation and Autonomy View which are described in Figure 9, Figure 10, Figure 11, Figure 12, and Figure 13, respectively.

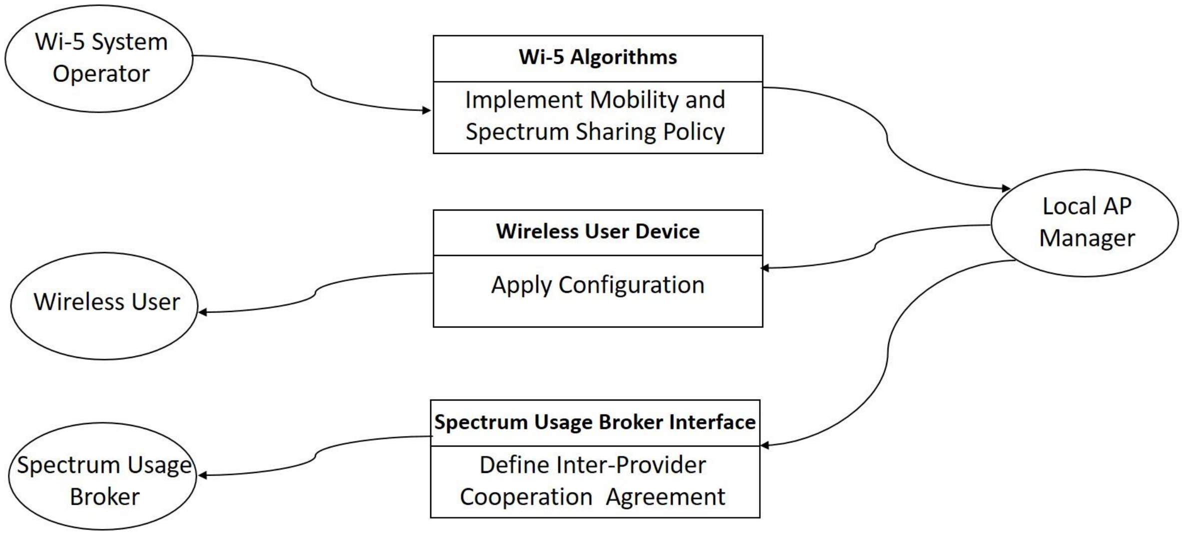

Figure 9: Mobility Management View in Local AP Manager Viewpoint

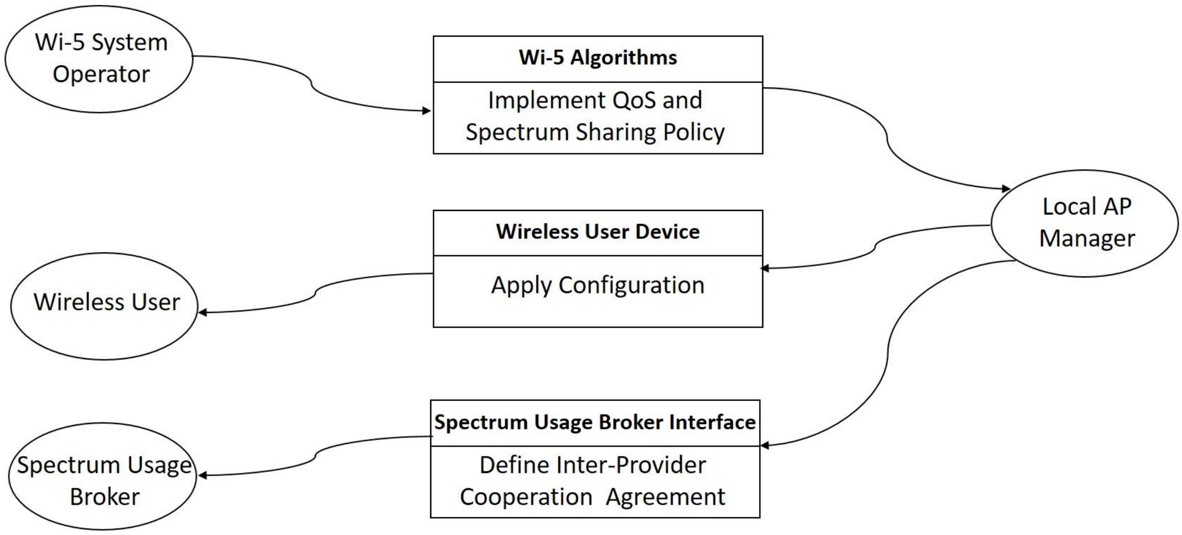

Figure 10: QoS Awareness View in Local AP Manager Viewpoint

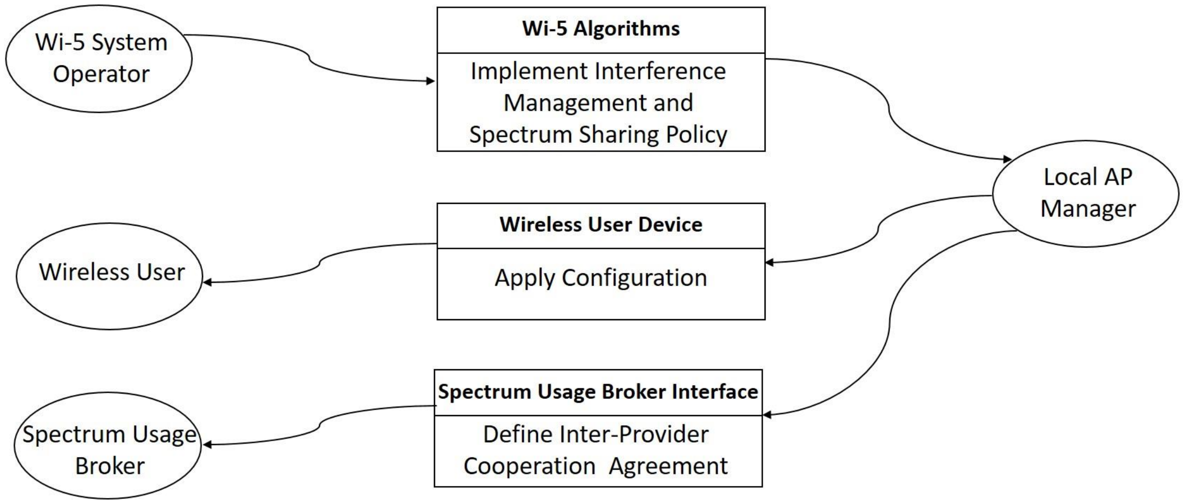

Figure 11: Spectrum Usage Optimisation View in Local AP Manager Viewpoint

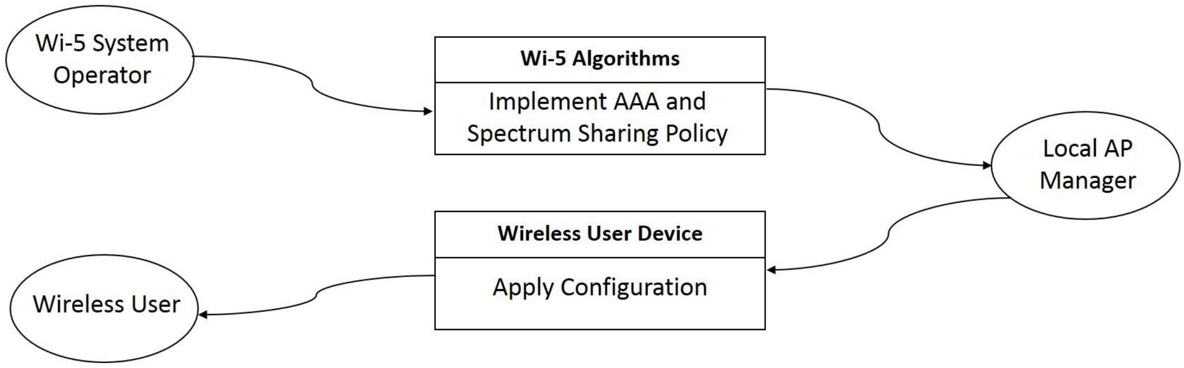

Figure 12: AAA Management View in Local AP Manager Viewpoint

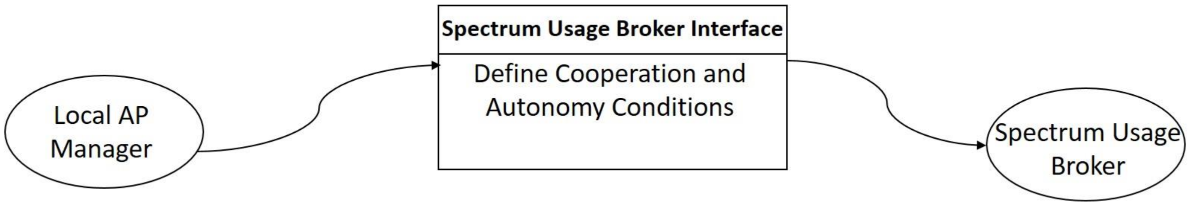

Figure 13: Cooperation and Autonomy View in Local AP Manager Viewpoint

4.3.7 Wireless User Viewpoint

This Viewpoint covers the concerns of a Wireless User through a wireless terminal. These concerns are as follows: Mobility, Quality of Service Awareness, and Spectrum Usage Optimisation.

The Wireless User Viewpoint consists of the following Views: Mobility View, QoS Awareness View and Spectrum Usage Optimisation View which are described in Figure 14, Figure 15, and Figure 16 respectively.

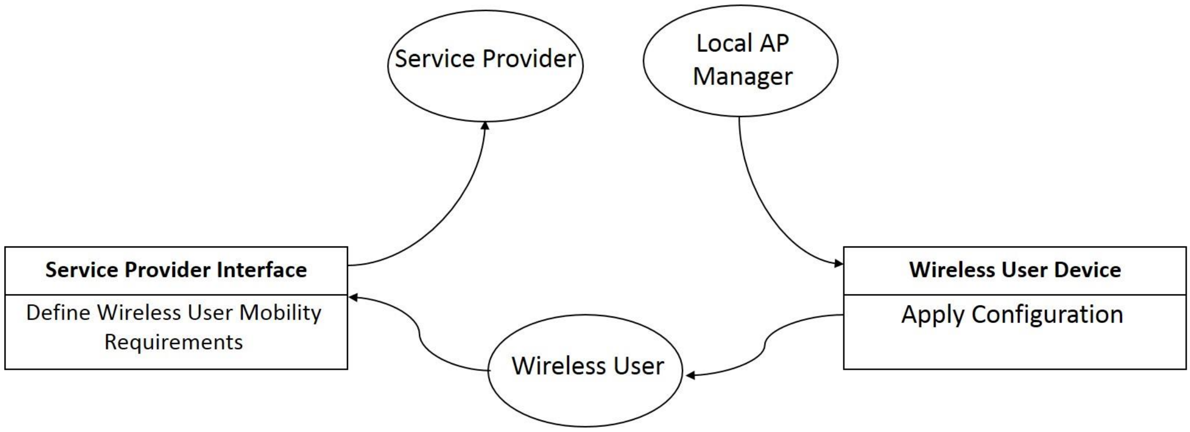

Figure 14: Mobility View in Wireless User Viewpoint

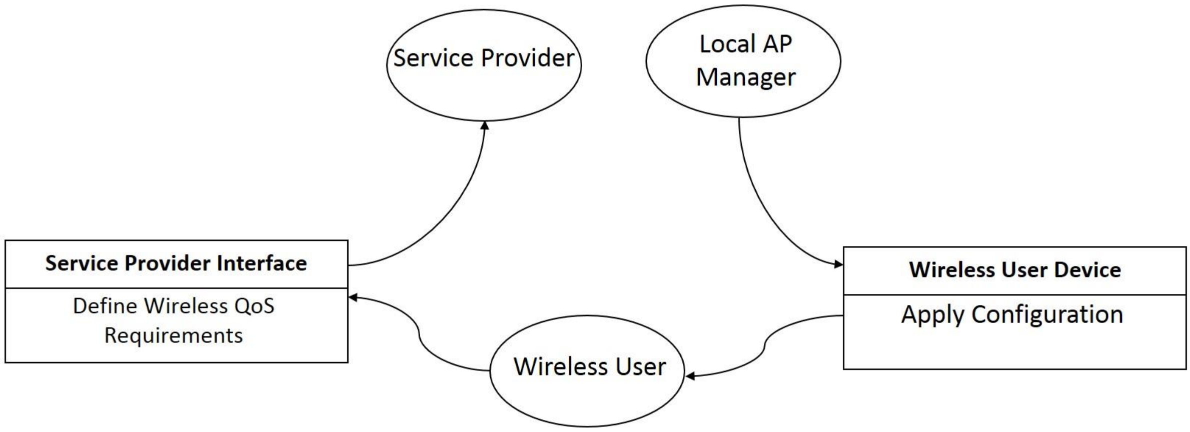

Figure 15: QoS Awareness View in Wireless User Viewpoint

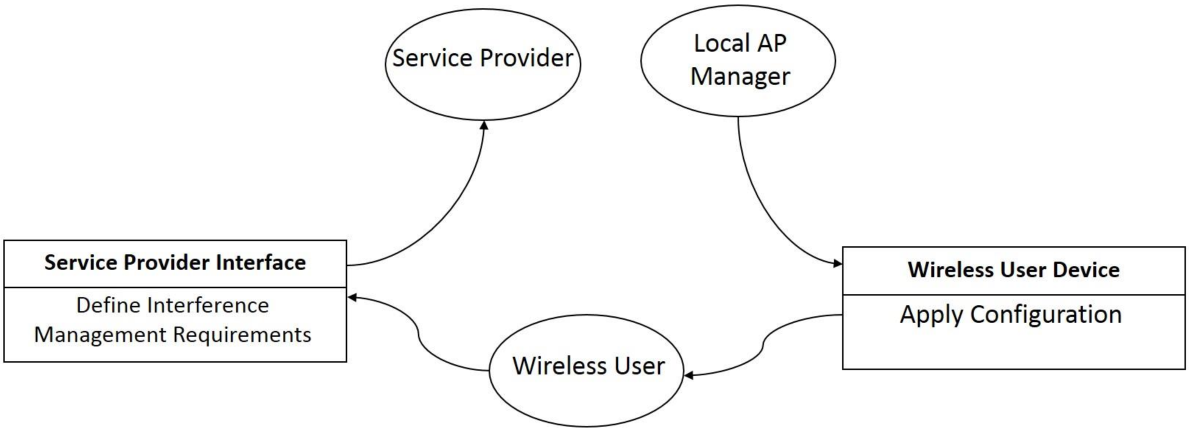

Figure 16: Spectrum Usage Optimisation View in Wireless User Viewpoint

4.3.8 Wi-5 System Operator Viewpoint

This Viewpoint covers the concerns of the Wi-5 System Operator with regards to Flexibility and Self-Configuration when interacting with other stakeholders, as described above. The Wi-5 System Operator's Flexibility and Self-Configuration View is described in Figure 17.

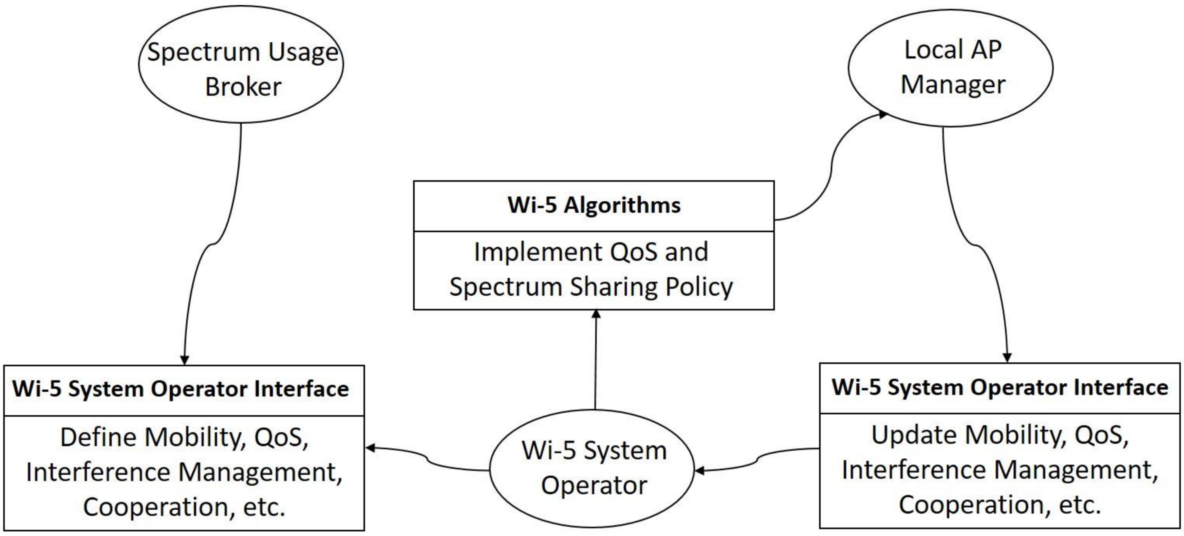

Figure 17: Flexibility and Self-Configuration View in Wi-5 System Operator Viewpoint

4.3.9 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, and Spectrum Usage Optimisation.

The Spectrum Usage Broker Viewpoint consists of the following Views: Cooperation and Autonomy View and Spectrum Usage Optimisation View, which are described in Figure 19 and Figure 18 respectively.

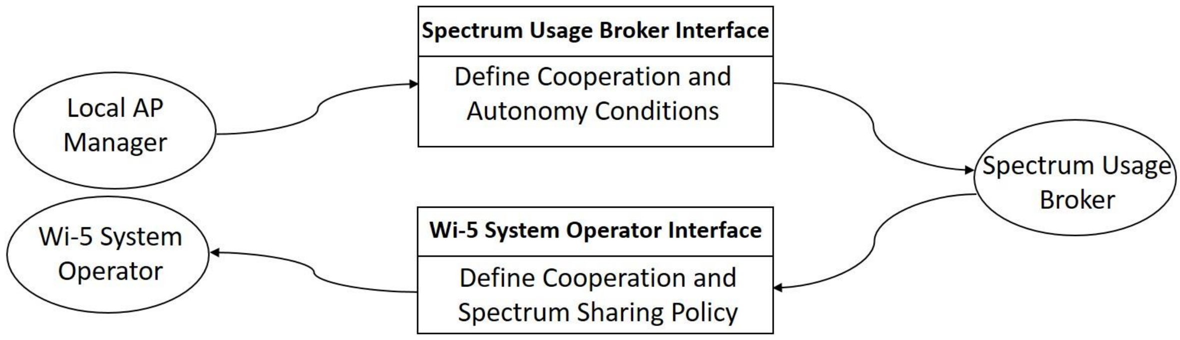

Figure 18: Cooperation and Autonomy View in Spectrum Usage Broker Viewpoint

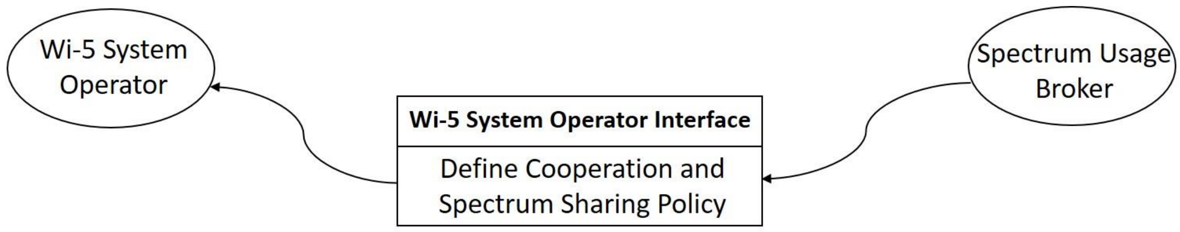

Figure 19: Spectrum Usage Optimisation View in Spectrum Usage Broker Viewpoint

5 Wi-5 System examples corresponding to the Dense Apartment Building use case

5.1 Radio Resource Management

To create a better understanding of the architecture of the Wi-5 system, we consider the example of a dense deployment, where three Wi-Fi APs are serving three different Wireless Users with their respective wireless devices, which are close to each other. This example corresponds to the Dense Apartment Building use case in D2.3, and is illustrated in Figure 20. Via the Wi-Fi APs, the Wireless Users are connected to various Service Providers. The Wi-Fi APs are managed by three different Local AP Managers, which could be residents and/or broadband access network operators. There is no coordination among the Local AP Managers, which results in the APs interfering with each other as a result of operating on the same channel. Such interference among Wi-Fi APs could affect the quality of connection served to the wireless devices, and thus the perceived QoS.

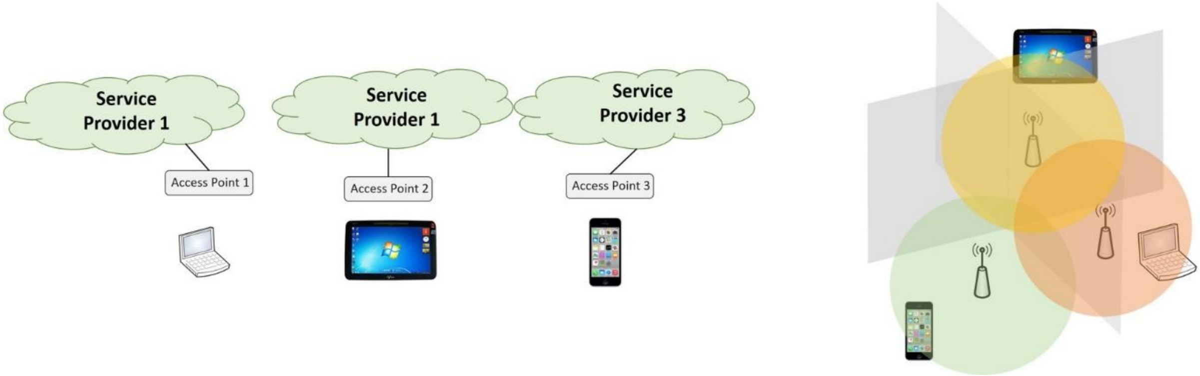

Figure 20: Depiction of the Example Considered in this Section

As mentioned in section 4.3, QoS Awareness is a concern for the following stakeholders: Service Provider, Local AP Manager, and Wireless User. The necessary interactions among different stakeholders to address this concern are depicted in the views presented in Figure 6, Figure 10, and Figure 15. These views involve the Spectrum Usage Broker and the Wi-5 System Operator as they allow Wi-5 to devise and then implement cooperation and spectrum sharing policies that will alleviate the radio interference among Wi-Fi APs.

In the context of the dense deployment scenario considered in this example, these interactions could be described in four steps, as follows:

- First, each Wireless User has to agree with his Service Provider on the QoS requirements of the service to be consumed, (for example, if a Wireless User has an HD subscription with Netflix, he/she has obviously agreed with Netflix that they should be able to consume the service with HD quality). This can be done explicitly, where the Wireless User defines certain performance related metrics, most notably the required bandwidth, or implicitly where the Service Provider identifies the QoS requirements by recording and analysing the traffic pattern of the user.

- Second, Local AP Managers collect the QoS requirements of their Wireless Users, and passes them on to the Spectrum Usage Broker to devise a cooperation and spectrum sharing policy that can alleviate the interference situation, as illustrated in Figure 211.

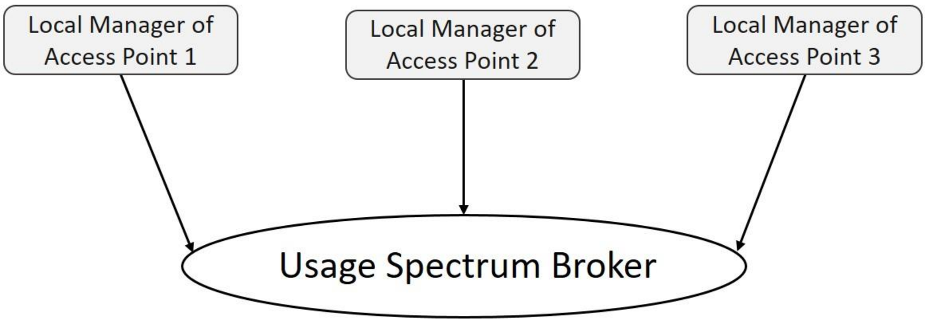

Figure 21: Local AP Managers Interacting with the Spectrum Broker

- Third, the Spectrum Usage Broker passes the cooperation and spectrum sharing policy to the Wi-5 System Operator, which then applies a combination of one or more Wi-5 algorithms running on the Controller. In this case, the interaction between the Spectrum Usage Broker and Wi-5 System Operator will result in triggering the Radio Resource Management algorithm, as illustrated in Figure 222.

- Finally, the radio configuration output of the Radio Resource Management Algorithm is then applied through the southbound interface of the Controller which allows the interaction between the Wi-5 System Operator and the Wi-Fi APs. The radio configuration output might consist of a new channel assignment among the APs, a change of transmit power of one or more APs, or a combination of the two.

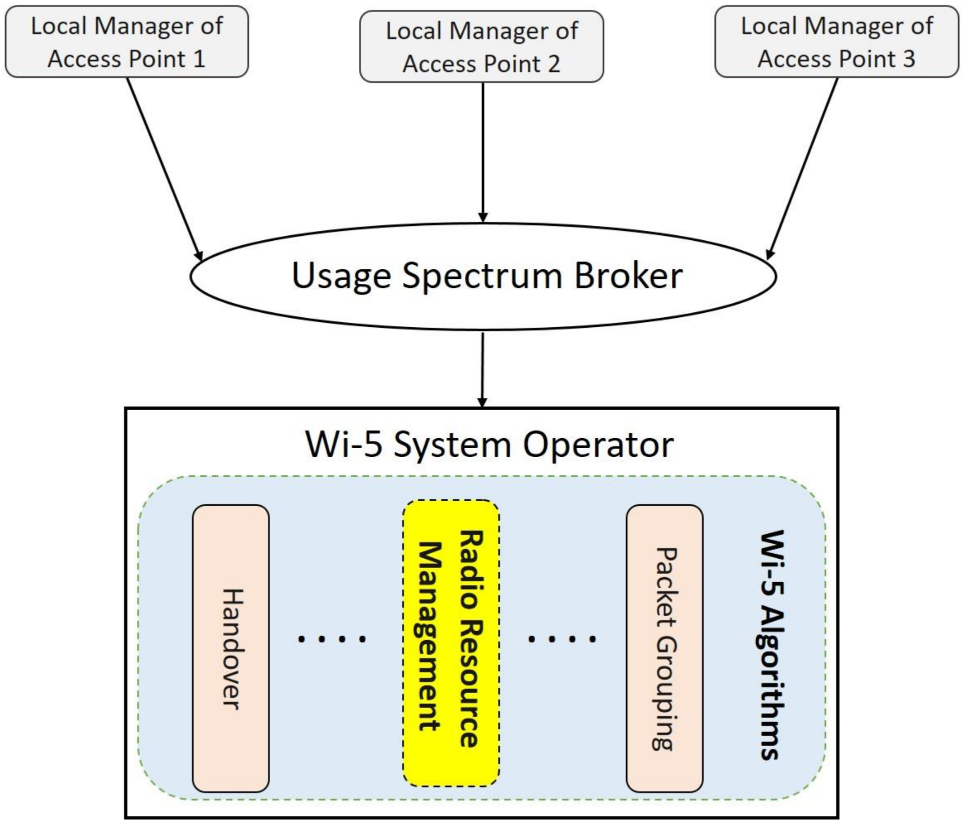

Figure 22: Wi-5 System Operator Translates the Agreement into Wi-5 Algorithms

5.2 Handover

In section 5.1, the spectrum sharing policy as devised by the Spectrum Usage Broker is implemented by the Wi-5 System Operator by executing the Radio Resource Management application on the Wi-5 Controller. Similarly, it could have chosen to execute the Handover application, or a combination of these (or other) applications. The Handover application is typically executed when Radio Resource Management alone is not enough to achieve the desired result, and performing handovers in addition would help.

Two varieties of the Handover application exist: Horizontal Handover and Vertical Handover. Both Horizontal Handovers and Vertical Handovers can be executed within a single managed domain or between multiple managed domains. They are discussed individually below.

5.2.1 Single domain Horizontal Handover

This is the simplest type of handover. A wireless device is handed over from one Wi-Fi AP to another Wi-Fi AP, both operating within a single managed domain, i.e. being managed by a single Local AP manager. With SDWN, this can be implemented using the concept of LVAPs as will be explained in section 6.2. The use of LVAPs here facilitates seamless handovers. If the handovers stay within a single managed domain, no additional arrangements need to be made among Local AP Managers regarding responsibilities and accountability for e.g. the content of the traffic being handled.

5.2.2 Multi-domain Horizontal Handover

Here, a wireless device is handed over from a Wi-Fi AP managed by one Local AP Manager to another Wi-Fi AP managed by another Local AP Manager. Technically, the same solution as for a single domain Horizontal Handover can be applied, which also means that the handover can be seamless. However, additional procedural (e.g. legal) and technical arrangements need to be made to release the receiving Local AP Manager from responsibilities regarding e.g. the content of the traffic that would otherwise be handled by the other Local AP Manager. For both the legal and the technical side, the methods as currently used by FON (www.fon.com) could be adopted.

5.2.3 Single domain Vertical Handover

Here, a wireless device is handed over between two technologically different networks, where both networks are managed by the same Local AP Manager. For instance, a smartphone is handed over from a Wi-Fi AP to a 4G network, both being operated by a public network operator. LVAP technology cannot be used now so other technologies need to be applied, of which the simplest form is for the Wi-5 Controller to temporarily black-list the Wi-Fi MAC address of the wireless device, after which the device automatically performs a handover to the 4G network (assuming that the device is configured as such). To make such a handover seamless requires additional technologies to be deployed in the Local AP Manager's network, such as SIP (Session Initiation Protocol) and/or Mobile IP.

Two possibilities exist here to manage the handover: the 4G network is part of the Wi-5 system (i.e. the Wi-5 controller is part of the 4G network, which actually makes it a 5G network) or the 4G connection by-passes the Wi-5 controller (which would be the most typical implementation with today's technology). In the first case, an integrated QoS monitoring system can be deployed, which makes the decision on when to perform a handover. In the second case, the Wi-5 controller has to make an intelligent estimate of the expected user performance on both networks, e.g. using technologies as described in [57].

5.2.4 Multiple domain Vertical Handover

The most complicated case is where a device is handed over between two technologically different networks, where both networks are managed by different Local AP Managers. An example is a smartphone that is handed over from a Wi-Fi AP managed by a local resident to a 4G network operated by a public network operator.

As above, the handover may be triggered in a simple fashion by temporarily black-listing the device MAC address. However, it will be hard in this case to make the handover seamless, as the local AP Managers must have the same technologies deployed in their networks to support this (Mobile IP, etc.), and there must be roaming agreements and technology in place. In theory this could all be achieved if both Local AP Managers agree to have their APs (in 4G that would be the base station and the e-NodeB) controlled by a single Wi-5 controller. However, the chance of a public operator allowing their infrastructure to be managed by a 3rd-party Wi-5 System Operator is negligible, due to a lack of trust in such an operator and/or the lack of a suitable legal/procedural framework for handing over such management responsibilities. Alternatively, the resident could handover the management responsibility of its Wi-Fi AP to the 4G operator, which would reduce this use case to the one described in section 5.2.3.

A similar reasoning holds for how to determine the potential performance in both networks to trigger the handover. In the unlikely case of both Local AP Managers agreeing on having their APs controlled by a 3rd party Wi-5 System Operator, an integrated QoS monitoring system can be deployed, which makes the decision on when to perform a handover. Compared to the integrated case as described in section 5.2.3, this QoS monitoring has limited capabilities, though: Only QoS parameters determined by the radio access network can be monitored, whereas if both APs belong to the same (5G) network, a more end-to-end approximation of QoS could be obtained. Therefore it is advised that in either case (both APs controlled by the same controller or not), the Wi-5 controller controlling the AP to which the device is attached at a given moment has to make an intelligent estimate of the expected performance on both networks by using technologies, e.g. as described in [57].

6 Architecture Design and Implementation Approaches

In theory, the Wi-5 functionality can be implemented with existing remote management and control techniques, such as those being used in enterprise Wi-Fi networks. However, these techniques are closed, too expensive, and too inflexible for massive deployment and dynamic automated control in multiple-operator consumer environments, governed by a set of optimisation algorithms.

We, therefore, propose to use the emerging concept of Software Defined Wireless Networking (SDWN) to implement the Wi-5 architecture, where the control plane of the Wi-Fi AP is decoupled from the data plane. Accordingly, the SDN controller configures the internal switches of the Wi-Fi APs, and the algorithms run on top of the controller, as illustrated in Figure 233.

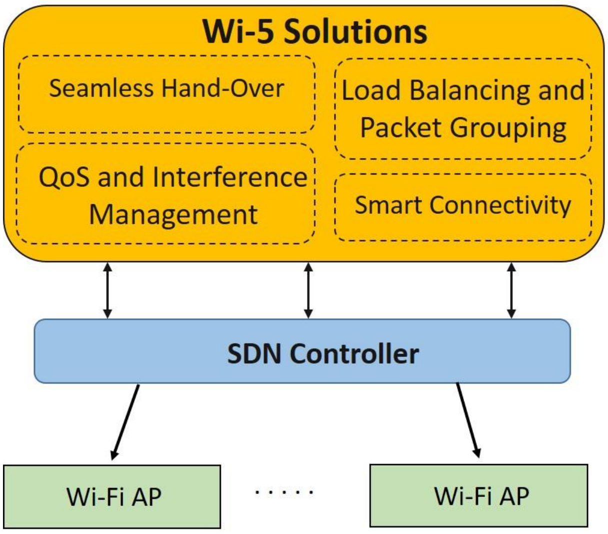

Figure 23: SDN-based Design of Wi-5 System

6.1 Wi-5 Architecture and Interfaces

The architecture description presented in the previous section shows the necessity to enable interactions among different stakeholders to fulfil the requirements of each stakeholder as illustrated in Figure 244. The Wi-5 architecture as presented here stacks a number of platforms vertically, where each platform is operated by the stakeholders mentioned to the right of the platforms.

Maybe contrary to what the reader may expect, the fact that the platforms are stacked vertically does not mean that each platform has direct interfaces to the platforms directly adjacent at the top and the bottom. Interfaces are only dictated by the need for *automated* interaction between platforms. That is:

1. the business model in D2.6 shows that the related stakeholders need to interact with each other, *and*
2. the interaction between these stakeholders is best to be automated, for instance for reasons of complexity and scalability.

For instance, Figure 24 shows the Service Platform at the top of the Wi-5 system, which seem to interact with the Brokering Platform. However, having Service Providers (e.g. Netflix) directly interacting with Spectrum Brokers (e.g. an apartment block corporate) is not realistic: the number of different Service Providers per apartment block may be very high, as well as the number of relevant Spectrum Brokers per Service Provider. Instead, the Service Providers only interact with Wireless Users, in the traditional manner as described in section 5. The Brokering Platform then obtains its information via an automated interface, e.g. as described in [58], or via papers and a HCI (Human Computer Interface) of some kind, to find a suitable spectrum sharing and cooperation policy. Once the Brokering Platform devises a spectrum sharing policy to be shared among the Local APs, it translates this policy into a combination of Wi-5 algorithms implemented on top of the Wi-5 SDN controller. Finally, the Wi-5 SDN controller applies the Wi-5 algorithm configurations to the Wi-Fi APs using the controller's southbound interface.

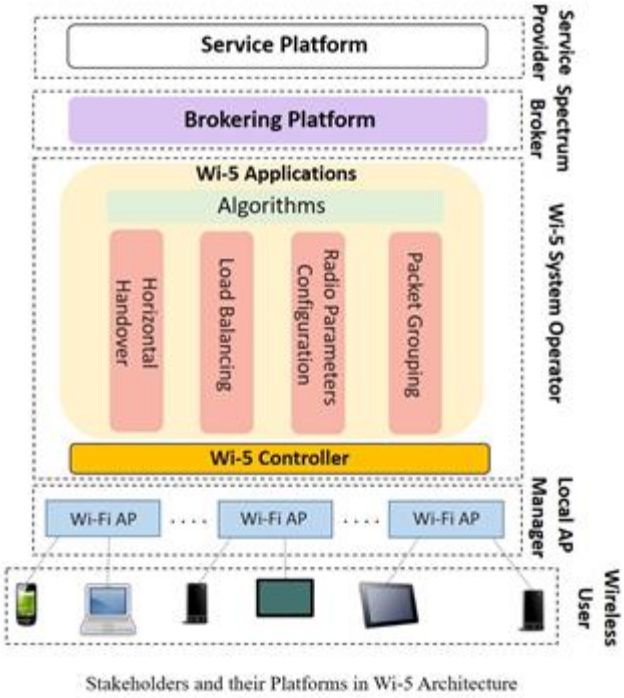

Figure 24: Diagram describing the Wi-5 Architecture and related stakeholders

6.1.1 Service Platform – Wireless User Device Interface

This is a traditional interface between a device and a Service Provider's platform, as described in the first bullet of section 5. The data plane of this interface typically goes via the Wi-Fi network, the Wi-Fi AP, and the wider Internet. QoS negotiations may be done via an inband control interface (i.e. also via the Wi-Fi network) or out-of-band control interface, e.g. by telephoning the Service Provider or using a control app on a smart phone.

6.1.2 Wi-5 Controller – Local AP Interface

The interaction between the Wi-5 Controller and the Local APs includes all the configurations that need to be applied to Wi-Fi APs directly through the controller's southbound interface, as illustrated in Figure 255. Protocols like OpenFlow could be used for that. OpenFlow itself, however, does not include primitives that support the management of Wi-Fi networks. The limitations of the OpenFlow protocol are currently being addressed by WP3 in Wi-5, and this is elaborated further in section 6.2. The Wi-5 Controller must have access to all the relevant Wi-Fi APs via this interface.

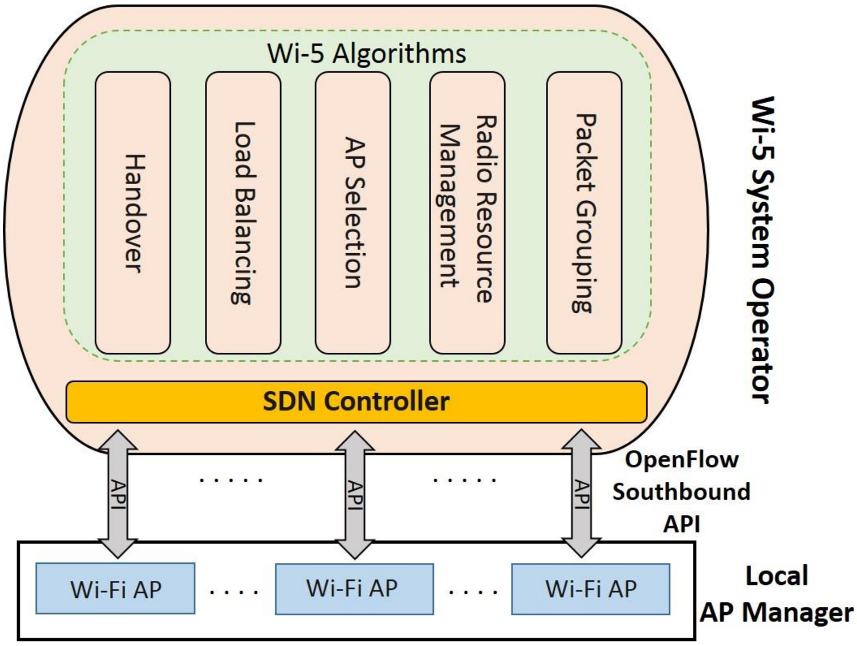

Figure 25: Openflow as Local AP Manager Interface

6.1.3 Brokering Platform – Wi-5 Controller Interface

In the Wi-5 architecture, the Wi-5 controller will be owned and managed by the Wi-5 System Operator and will interact with the Brokering Platform to implement the cooperation and spectrum sharing policy the Spectrum Broker has devised. This interface could very well be virtual, i.e. the Broker informs the Wi-5 System Operator manually of the spectrum sharing policies to be implemented. If this type of interaction becomes too complicated or frequent, it could be automated through an interface between the Brokering Platform and Wi-5 Controller, as illustrated in Figure 266. This interface could be implemented using a simple scripting language that calls the Wi-5 algorithms, such as Python and its Jython implementation version [59].

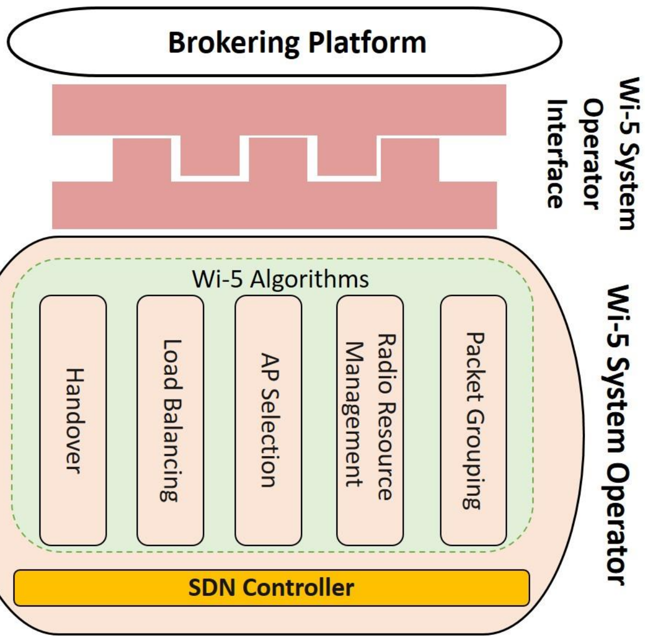

Figure 26: Wi-5 System Operator Interface

6.1.4 The Brokering Platform

In its simplest form, the Brokering Platform is virtual, i.e. the Brokering Platform contains the non-automated facilities (pen, paper, etc.) the Spectrum Broker uses to cement a deal between the Local AP Managers. Both interfaces of the Brokering Platform with the Local APs and the Wi-5 Controller are then virtual also.

Alternatively, the Brokering Platform is an IT platform which automates negotiation, in which the Local APs with their requirements and offers are represented by agents. The agents then barter a deal, e.g. using a negotiating algorithm as described in D2.6 and [60]. An excellent example of how the architecture of such a Brokering Platform could look like has recently been published in [58]. We present that architecture in Figure 27 below.

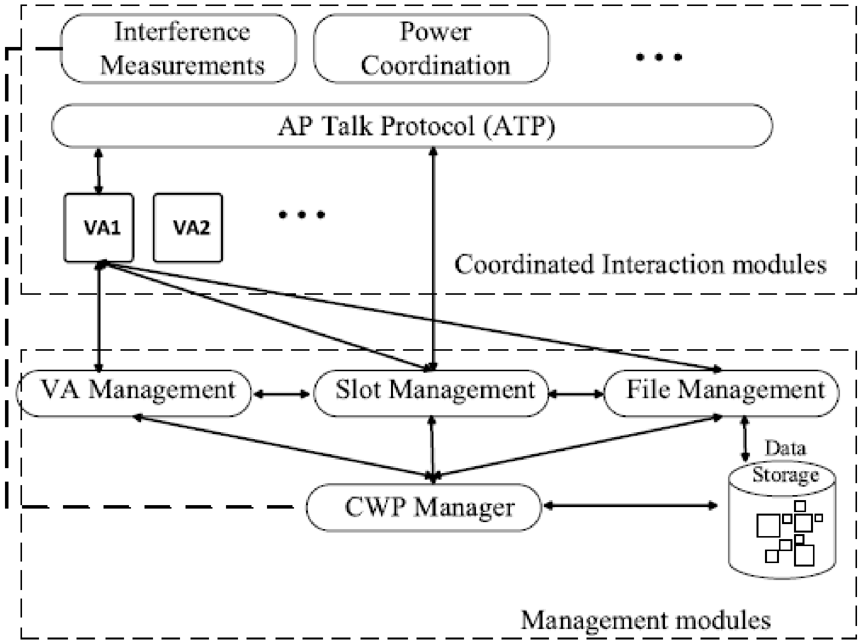

Figure 27: Broker Platform architecture as shown in [58], called Coordination Wi-Fi Platform (CWP)

[58] describes a Brokering Platform, there called “Coordination Wi-Fi Platform” (CWP), which talks directly to the APs, without having a flexible and intelligent Wi-5 controller in between. The APs and CWP exchange information using a novel AP Talk Protocol (ATP) and the APs are represented in CWP as Virtual Agents (VAs). The Interference Measurement module corresponds to our own monitoring module. The Power Coordination module is where negotiation between VAs happens, here using Nash bargaining. This is different from our model [60], because in [58] the participation of APs in the negotiation scheme is mandatory. Also, CWP only optimises transmission power without considering the other aspects such as channel assignment or AP selection. Then there are a number of management modules, one for managing the VAs (VA Management), one for time synchronisation (Slot Management), defining the heartbeat of the system, and one for managing the data being received and held in the Data Storage part of the CWP (File Management). These management modules are managed with the CWP Manager module.

Our Brokering Platform could be largely based on the CWP architecture, except that we need a simple procedure call protocol (some open API) between the Brokering Platform and the Wi-5 Controller, instead of the AP Talk Protocol. This API may work in two directions: providing the Brokering Platform with information about the APs, as well as providing the Wi-5 Controller with the resulting policy to be applied. Also, the Power Coordination module of the CWP needs to be extended with other parameters to be negotiated, including e.g. channel selection, and the negotiation needs to be based on a novel combination of cooperative and non-cooperative game theory as described in D2.6 and [60].

6.2 Architecture Implementation

6.2.1 Odin WLAN Management Framework

Odin 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 APs. In Odin, a wireless device will be associated with an LVAP through which it will be perceived as a regular Wi-Fi AP.

To address the lack of IEEE 802.11 control functionality in OpenFlow, Odin uses a software agent that runs on each controlled wireless AP, which should be OpenFlow enabled. The Odin architecture consists of two logical entities (Figure 28):

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

- **Odin Agent**: Deployed on each wireless AP, Odin Agents offer the necessary interfaces for the Odin Controller to manage the wireless network and gather monitoring information through the southbound interface. This monitoring information includes signal strength at reception, the bit-rate, 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 agent intercepts ARP requests for the client's IP, and uses the LVAP information to answer with the appropriate ARP responses themselves.

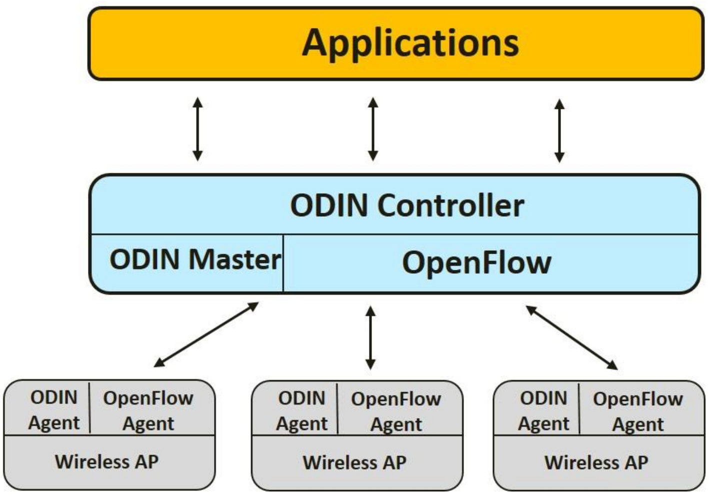

Figure28: Odin Framework

Using this architecture, Odin can implement both proactive applications such as Load Balancing, and reactive applications such as Seamless Handover.

6.2.2 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-grained control mechanisms to implement all the Wi-5 functionalities. For example, Odin does not support QoS flow management policies and radio parameters configuration, which are necessary to implement Wi-5. Figure 29 shows our approach to extending the Odin framework to support the proposed Wi-5 architecture.

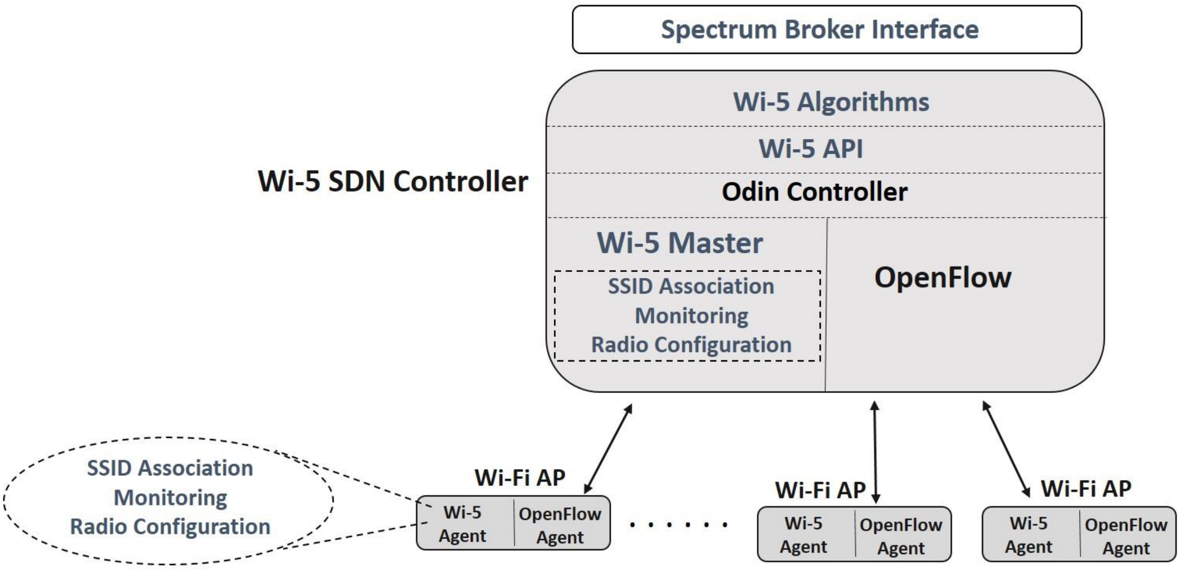

Figure 29: Implementing Wi-5 Architecture Using Odin Framework

First, although the internal switches of many Wi-Fi APs today can be OpenFlow enabled (e.g. with Open vSwitch[1]), they still lack certain control functions, such as configuration of the radio parameters, monitoring of the wireless network status, and SSID association. These functions can be developed as a Wi-5 agent running on the Wi-Fi AP.

Second, the controller southbound interface needs to be extended in order to allow the controller to apply the necessary fine-grained wireless network configuration generated by the Wi-5 algorithms, as the current OpenFlow protocol does not support these functions. To achieve that, we aim to develop a further extension to the OpenFlow protocol, called the Wi-5 Master. The Wi-5 Master will provide the controller with the following control functions: radio configuration, SSID association, and managing monitoring information.

Third, the northbound API of the SDN controller needs to be extended to allow the implementation of the Wi-5 algorithms, such as: Interference Management, Handover, etc. This also includes the management, processing, and storage of monitoring information necessary for most of the Wi-5

[1] As explained in the Open vSwitch web page (http://openvswitch.org/), "*Open vSwitch is a production quality, multilayer virtual switch licensed under the open source Apache 2.0 license. It is designed to enable massive network automation through programmatic extension, while still supporting standard management interfaces and protocols.*"

algorithms. The base implementation in Odin is very limited in this regard, providing only very limited functionality for mobility and scheduling.

6.2.3 Implementation Progress

The whole Wi-5 implementation process is managed using repositories on GitHub, a suitable platform for building software projects in a collaborative manner. The web-based Git hosting service provides distributed revision control and source code management functionalities. A GitHub "organisation" called Wi-5 (see https://github.com/Wi5) has thus been created, in order to coordinate the software development. This also allows other people not directly involved in the Wi-5 project to contribute and propose their improvements as "outside collaborators". The organisation includes a number of repositories:

- **odin-wi5.** This is the main repository, providing a general description of the solutions being developed by the Wi-5 Project. It includes a description of the scenarios, an explanation of the different features, and a wiki[2] where different experiences are summarised. It also includes:
  - A patch for the ath9k driver required to run Odin.
  - A script to automatically build the firmware to be flashed in the AP.
- **odin-wi5-controller.** Includes the software for the Odin Controller, which consists of an extended Floodlight OpenFlow controller , enhanced with the Wi-5 applications. The code of the wi-5 controller is written in Java.
- **odin-wi5-agent.** This is the software that runs in the agents. It mainly consists of an element called *odinagent*, to be added to Click Modular Router. The code is in C++, as is Click Modular Router. In addition, a Python script for building the Click script to run in the Agent is included. Finally, a number of Linux scripts allowing the starting of the Agent are provided.
- **odin-wi5-flow-detection.** This is a software module that allows the integration of any software-detection tool within the Odin framework. It takes packets, classifies them into flows (characterised by a 5-tuple including IP addresses, protocol and ports) and sends periodic reports to the controller about the presence of these flows in the AP network. The code is in C++.
- **wi5-aggregation.** This is an implementation of 802.11 A-MPDU frame aggregation. It works in a Linux machine, and creates a *fake* Access Point, in order to make an STA connect and send/receive aggregated frames. The code is in C.

Two of the repositories, namely **wi5-odin-controller** and **wi5-odin-agent**, are tightly related as many of the developed solutions are applied simultaneously in both repositories. Thus, when a new functionality is to be added, a new software branch is created on each of these repositories, and they are tested simultaneously. A number of functionalities have already been added:

- **Collecting statistics in the AP and sending them to the Controller.** The branch *statistics* of both repositories has been used for this aim. The objective is to make it possible for the AP to collect more detailed and combined statistics from the STAs, and to send them to the Controller, which stores them in suitable data structures. These are the statistics currently available[3]:
  - Initial and final timestamps: All the statistics are collected during an interval between initial and end times, both in seconds.
  - Number of packets received/sent during the interval.

[2] https://github.com/Wi5/odin-wi5/wiki

[3] More detailed information can be found in the wiki: https://github.com/Wi5/odin-wi5/wiki/STA-Statistics-measured-by-the-Agents-and-sent-to-the-Controller

  - Average rate of the packets received/sent during the interval.
  - Average signal level of the packets received/sent during the interval.
  - Average length (at IP level) of the packets received/sent during the interval.
  - Air time consumed by these packets received/sent during the interval. It gives an idea of the air time this packet has consumed, i.e. the product of the length in bits by the rate.

  All the statistics about each connected STA are gathered by each of the agents and forwarded to the controller. An example application has been built in the Controller, ShowStatistics.java, which shows all the statistics obtained. Both downlink and uplink statistics are gathered. A function for the controller to request the tx/rx statistics of all the STAs associated to an AP has been built.

- **Mobility Manager.** This functionality extends the handover initially included in Odin, which considered that all the APs were operating in the same channel. Different functions have been included in both the Controller and the Agent in order to permit:
  - Setting the channel of an AP from the controller.
  - Reading the channel of an AP from the controller.
  - Sending a number of Channel Switch Announcements (CSAs) in order to make the STA switch its channel.
  - Sending a burst of beacons in the AP (in the new channel) in order to make the STA aware of the channel switch.
  - An application *MobilityManager* has been built in the Controller, which uses all the above features to effectively perform a horizontal handover including a channel switch. This function has been used in order to run the tests and measurements of the multichannel handover. It follows a reactive approach: when the AP feels that the STA is going away, it reports this to the controller which instructs other APs in the neighbourhood to scan for it. It finally moves the STA to the best suited AP.
  - To perform a vertical handover, the Controller is able to black-list MAC addresses of attached STAs. Such an STA can then perform a vertical handover to e.g. 4G if it is so enabled.

- **Smart AP Selection.** This is a proactive application that is in charge of handovers. It performs periodical scans, gets the information and, if needed, hands off STAs between APs. It uses the auxiliary wireless interface of each AP to scan in the channels used by Odin APs. It creates a database with the heard STAs and their associated wireless parameters seen from each Wi-5 AP. Once the data is processed, it decides if any STA needs to be handed off to another AP. For performing vertical handovers, this function may be extended with technologies as described in [57].

- **Separation of data and control planes.** In order to avoid any conflict, data and control planes are separated. In addition, a set of SDN rules are automatically added to the APs by the controller, in order to improve the way the Controller manages the network.

Finally, we have developed a small testbed of this architecture which was first demonstrated by the UNIZAR team in Zagreb on 3-4 December 2015 [15]. Some results were obtained with the testbed, which were published in [61].

Our implementation is a proof-of-concept of some of the most important concerns as given in the architecture description in section 4.3.2. In a market-ready implementation, concerns such as AAA should also be addressed. This is left for future work.

7 Conclusion and Future Work

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 APs. 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 also meet the functional requirements (concerns) of the Wi-5 system stakeholders.

In the previous deliverable D2.5i, we thoroughly analysed the business models as presented in D2.1 and D2.6, and the use cases as presented in D2.3, and provided an improved definition of the stakeholders and their concerns, compared to D2.4. In this final deliverable D2.5, we:

- provided a better separation between the stakeholders' roles and the platforms they may use to execute their roles,
- reallocated the Autonomy and Cooperation concern to the Local AP Manager,
- provided a better description of the various interfaces (including the Brokering Platform – Wi-5 Controller interface),
- included a preliminary architecture for the Brokering Platform, and
- included an illustrative example to explain how the architecture works in practice.

Using the guidelines of the ISO/IEC/IEEE 42010 standard, we presented the final description of the Wi-5 architecture which allows us to identify the interactions among different stakeholders and the interfaces necessary to enable these interactions.

An important improvement made is the addition of a preliminary architecture of the Spectrum Broker's Brokering Platform, including a definition of its interfaces. The interface between the Spectrum Broker and local APs is needed to enable the Spectrum Broker to devise a suitable spectrum sharing policy among APs. The interface takes as input the spectrum sharing preferences of the APs, such as Quality of Service Awareness and Spectrum Usage Optimisation.

Second, the interactions between the Wi-5 System Operator, which operates the Wi-5 algorithms, and the Spectrum Broker have been identified. An interface is therefore needed to allow the Spectrum Broker to translate the spectrum sharing policies into a combination of Wi-5 algorithms, such as Handover and Interference Management.

Finally, we identified the necessity to develop an interface that allows the Wi-5 Controller to interact with the Local APs in order to apply the wireless network configuration that will implement the spectrum sharing policy communicated by the Spectrum Broker. In this context, we adopted the Software Defined Networking paradigm as a suitable approach to implement the Wi-5 Controller. Due to its flexibility and centralised management nature, the adoption of SDN principles will facilitate the interaction between the Wi-5 Controller and the Brokering Platform on one hand, and between the Wi-5 Controller and the Local APs on the other.

The realisation of the Wi-5 architecture requires the extension of current SDN controller capabilities on both the northbound and southbound interfaces. It also requires extending the capabilities of Wi-Fi APs to support network configuration functions that will allow the implementation of Wi-5 management policies. Wi-5 addresses these limitations using the Odin Wi-Fi Management Framework, by extending the functionalities offered by its SDN controller, as well as enhancing the capabilities of Wi-Fi APs.

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