What to do With the Wi-Fi Wild West

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Abstract

The H2020 What to do With the Wi-Fi Wild West (Wi-5) project combines research and innovation to propose a Software Defined Networking (SDN) architecture based on an integrated and coordinated set of smart Wi-Fi networking solutions. The resulting system will be able to efficiently reduce interference between neighbouring Access Points (APs) and provide optimised connectivity for new and emerging services. The project approach is expected to develop and incorporate a variety of different solutions, which will be made available through academic publications, in addition to other dissemination channels.

In this document, we will present a description of the testbed to be used in the project and provide a definition of the tests to be done. First, the smart and cooperative solutions provided by the SDN based Wi-5 architecture will be briefly described. Next, we will define and explain the modular approach to be taken to model Wi-5 APs and the Wi-5 controller. According to this approach, we will describe the functionalities of both the Wi-5 AP that is modelled as a combination of the monitoring and network configuration modules, and the Wi-5 controller which is composed of the monitoring, decision, and network configuration modules. Then, we will define and explain the Wi-5 integration strategy that will be utilized to integrate the smart and the cooperative functionalities in terms of assembly of the modules utilized to model the Wi-5 AP and the Wi-5 controller.

Moreover, we will provide the definition of the performance metrics that will be utilized to evaluate and validate the performance of the monitoring, decision and network configuration modules with the use cases and performance requirements developed in Wi-5. This deliverable will focus on the definition and the explanation of the following two issues:

- Integration of the smart and cooperative functionalities provided by the SDN based Wi-5 architecture.
- Testing strategy to evaluate the performance of the Wi-5 architecture considering the use cases and requirements that focus on the selected scenarios.

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Glossary

AP	Access Point
API	Application Interface
CSA	Channel Switch Announcement
HT	High Throughput
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISO	International Organization for Standardization
LCC	Least Congested Channel
LVAP	Light Vırtual Access Point
MAC	Media Access Control
MCS	Modulation and Coding Size
QoE	Quality of Experience
QoS	Quality of Service
RF	Radio Frequency
RRM	Radio Resource Management
RSSI	Received Signal Strength Indicator
SDN	Software-Defined Network
SEBoK	System Engineering Body of Knowledge
SINR	Signal to Interference Ratio
SMB	Small Medium Businesses
SOHO	Small Office Home Office
SSID	Service Set Identifier
TPC	Transmit Power Control
VoIP	Voice over Internet Protocol
Wi-Fi	Wireless Fidelity

Executive Summary

The Wi-5 Project proposes a Software Defined Networking (SDN) based architecture to maintain seamless handover, smart wireless connectivity and cooperative Radio Resource Management (RRM) solutions. This document provides a definition of the tests to be conducted to evaluate and validate the performance of the Wi-5 architecture, and the description of the testbed that will be employed to execute the performance tests.

This deliverable focuses on the definition and explanation of two issues:

- Integration of the smart and cooperative functionalities provided by the Wi-5 architecture.
- Testing strategy to evaluate the performance of the Wi-5 architecture considering the use cases and requirements that focus on the selected scenarios.

First, we will define and explain the Wi-5 strategy which is being utilised to integrate the smart and cooperative functionalities in terms of assembly of the modules to model the Wi-5 AP and the Wi-5 controller. According to this approach, we will describe the Wi-5 AP that is modelled as a combination of the monitoring and network configuration modules, and the Wi-5 controller which is composed of the monitoring, network configuration and the decision modules. After explaining our integration approach, we will also briefly discuss the current status of the implementation of the Wi-5 functionalities.

In order to integrate the smart and the cooperative functionalities in terms of assembly of the modules outlined above, the Wi-5 integration strategy will be defined and explained. The Wi-5 integration strategy is implemented in three phases. In the first phase, we assemble the monitoring and the decision modules to obtain the control module –version 1 which we can use to verify the accuracy of the Wi-5 algorithms. In the second phase, we assemble the decision and the network configuration modules to get the control module – version 2. This process can be carried in parallel with integration- phase 1. If we do not conduct the second phase in parallel with the first phase, in the third phase, we assemble the control module- version 1 and the network configuration module to obtain the complete Wi-5 controller which we call the control module- version 3.

Next, we provide the definitions of the tests we will execute to assess and validate the performance of the monitoring, decision and network configuration modules. The key metrics for testing the monitoring module are scalability, delay and accuracy. The performance of the monitoring module will be evaluated by employing a testbed consisting of one Wi-5 controller and a range of both Wi-5 and legacy APs with SOHO, dense apartment building, airport/train station, pico-cell street and community Wi-Fi use cases. While evaluating and validating the performance of the monitoring module, we will consider the measurements directly taken from the field, measurements taken by employing the test-bed, and the measurements taken from simulations. We will evaluate the performance of the decision module by conducting MATLAB simulations whereas we will evaluate the performance of the network configuration module by applying the configuration determined by the decision module directly to the controlled testbed, field trials and the OPNET simulations with respect to the spectrum efficiency, saving energy and the Quality of Experience (QoE). After completing the testing of each module, we will gradually replace the simulations with the functionalities provided by the Wi-5 controller. For the last step, we will evaluate the performance of the Wi-5 controller and Wi-5 APs in realistic environments.

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 H2020 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 of the deliverable

This deliverable provides the definition of the tests that will be utilized to assess and validate the performance of the Wi-5 architecture, and the description of the testbed which will be employed to execute the performance tests. Wi-5 proposes a Software Defined Networking (SDN) based architecture to implement the seamless handover, smart wireless connectivity and cooperative Radio Resource Management (RRM) solutions. An overview of these smart and cooperative solutions will be provided along with a description of the Wi-5 APs and the Wi-5 controller that will constitute the Wi-5 SDN platform. This document will also include the definition and explanation of the integration strategy to integrate the smart and cooperative solutions that will be provided by the Wi-5 architecture. Moreover, the implementation strategy for these solutions will be defined, considering the modular approach that is taken to model the Wi-5 APs and controller. Finally, a testing strategy to evaluate the performance of the Wi-5 architecture with our use cases and requirements will be provided, that focuses on the selected scenarios and presents a description of the testbed that will be employed to execute the performance tests.

1.3 Document structure

After the introduction, a description of the Wi-5 SDN platform is provided in Section 2. Section 3 is devoted to a description of the integration approach that will be taken to model the Wi-5 APs and the Wi-5 controller. Next, we define and explain the Wi-5 integration strategy to integrate the smart and cooperative functionalities in detail, in terms of assembly of the modules utilized to model the Wi-5 APs and Wi-5 controller. In Section 5, we will first define the implementation strategy of the smart and cooperative functionalities that will be provided by the SDN based Wi-5 architecture. In addition, we will define the Wi-5 testing strategy which will be employed for going forward to assess and validate the Wi-5 architecture with use cases and requirements. This will focus on the selected scenarios and present a description of the testbed that will be employed to execute the performance tests. Finally, Section 6 concludes the document.

1.4 Relationship with other deliverables

The material in this document relates to the following deliverables.

D2.3: Use cases and requirements that focus on the selected Wi-5 scenarios, applications and services were defined in this deliverable. In the present document, we will provide a definition of the testing strategy to be utilized to assess and validate the Wi-5 architecture with the use cases and requirements defined in D2.3.

D2.5i: An updated version of the Wi-5 architecture presented in deliverable D2.5i "Interim Wi-5 architecture" provides a global view of the whole set of smart and cooperative solutions to be deployed. The architecture is described according to the ISO-IEC-IEEE 42010 standard, and the requirements are presented in the context of the business and stakeholders' requirements. In D5.1 we will provide a definition of the tests, along with the description of the testbed, which will be utilized to assess and validate the current Wi-5 architecture.

D3.1: In this deliverable, the Wi-5 monitoring functionalities are reported. This not only includes the features able to monitor the wireless environment, but also the tools for automatically detecting real-time services. The monitoring module defined in this document will utilize the functionalities defined in D3.1 to collect the monitoring information related to the status of the wireless network and to automatically detect real-time services.

D3.3: The second version of the specification for the mechanisms to be included in the Wi-5 APs to perform dynamic channel allocation, load balancing and power control is presented in this deliverable, along with the definition of the packet grouping policies between the AP and the end user device. In D5.1, the implementation and the testing strategies of the smart functionalities will be defined, considering the modular approach that is taken to model the Wi-5 APs and the Wi-5 controller.

D4.2: The Cooperative Functionalities being deployed in WP4 are explained in detail in Deliverable 4.2 "Specification of Cooperative Access Points Functionalities version 2". Like the smart functionalities, the implementation strategy of the cooperative functionalities will also be defined in the present deliverable, considering the modular approach that is taken to model the Wi-5 APs and the Wi-5 controller.

2 Description of Wi-5 SDN Platform

In this section, we present the summary of the Wi-5 SDN platform as a basis for our description of the integration work presented in sections 3 and 4. More detailed descriptions of this platform in terms of its specific functionalities can be found in deliverables D2.5i [1]**Error! Reference source not found.**, D3.3 [2], and D4.2 [3].

The SDN-based Wi-5 architecture relies on the decoupling of the control plane from the data plane in Wi-5 APs and the dynamic programmability of Wi-5 APs, which simplifies the development and deployment of network applications running on top of the Wi-5 controller. A global view of the Wi-5 SDN platform is depicted in Figure 1. According to Figure 1, the Wi-5 SDN Platform is composed of Wi-5 agents running in the APs and the Wi-5 controller.

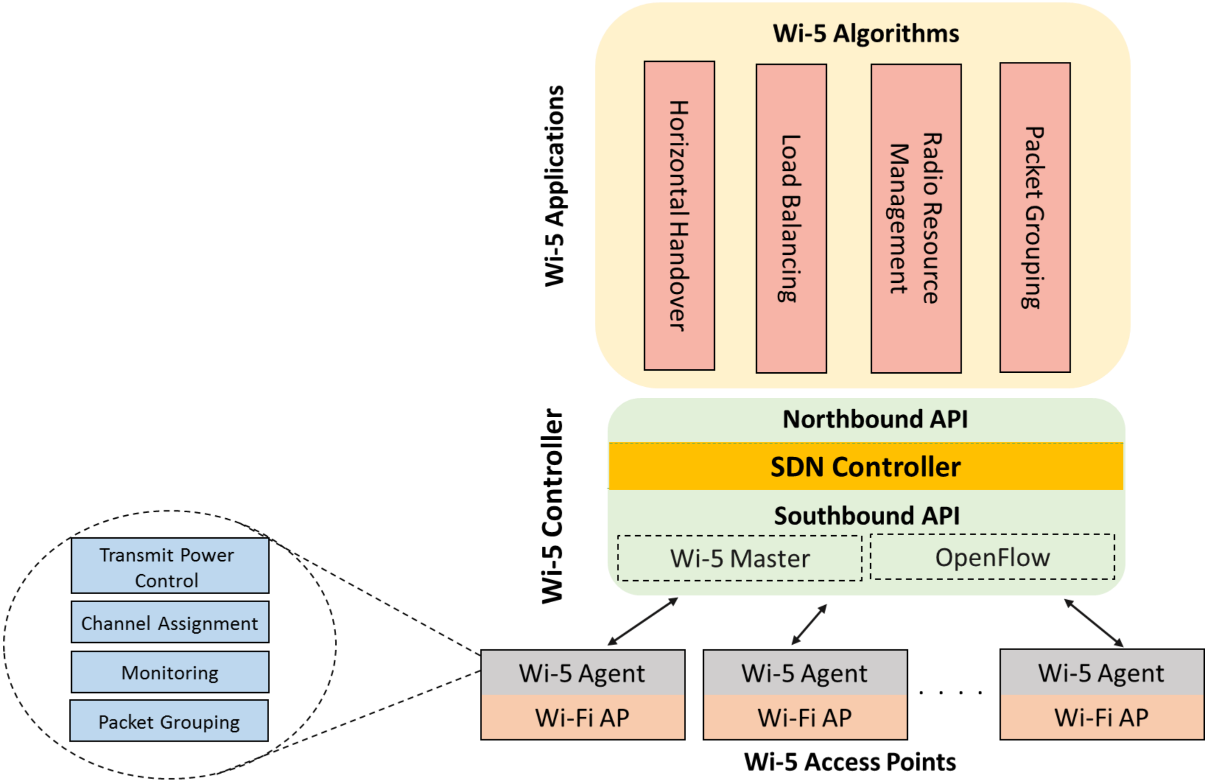

Figure 1: The global view of Wi-5 SDN platform

Wi-5 APs are responsible for processing packets based on rules provided by the Wi-5 controller. The Wi-5 APs and the Wi-5 controller communicate via the OpenFlow protocol. OpenFlow was developed by identifying common features in the flow tables of commercial Ethernet switches in order to facilitate vendors in providing a means to control their APs without exposing the code of their devices. In addition, Wi-5 agents deployed on each Wi-5 AP extend OpenFlow and are responsible for the configuration of the radio-specific parameters, monitoring of the wireless network status, and the SSID association process.

In the Wi-5 controller, the southbound API allows it to apply the necessary wireless network configuration generated by Wi-5 functionalities. In order to achieve this, an extension of the OpenFlow protocol, which is called Wi-5 master, is deployed to communicate to the Wi-5 agents. The Wi-5 master provides the controller with the following control functions: transmit power control, channel assignment, monitoring of the wireless network status and packet grouping configuration.

The northbound API of the Wi-5 controller provides a programmable interface to allow the implementation of the Wi-5 functionalities, such as horizontal handover, load balancing, radio resource management and packet grouping. Besides the implementation of these algorithms, this API also allows the management, processing and storage of the monitoring information that is necessary for implementation of the Wi-5 functionalities. A more detailed description of the overall architecture is presented in deliverable D2.5i [1].

The Wi-5 functionalities can be divided into two categories:

- Smart Functionalities aim at enabling the performance improvement of Wi-Fi networks by means of radio configuration capabilities and resource management algorithms, including dynamic channel assignment, load balancing and power control. The use of packet grouping is also considered here. These functionalities consider a scenario where all the APs are managed by a central controller.

- Cooperative Functionalities will enable cooperation between Wi-Fi networks under different management authorities, in cooperation with the smart functionalities. These functionalities improve interference management in Wi-Fi jungle scenarios (i.e. including a high number of devices in the same zone), and the realisation of seamless soft and hard handover.

Both smart and cooperative functionalities are briefly summarized in the following subsections.

2.1 Smart Functionalities

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

- **Dynamic Channel Selection and Transmit Power Control**: This functionality will enable Wi-Fi networks to dynamically adjust their 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 to make decisions on when not to accept new association requests, with the aim of maximising the aggregate data rate of these networks.

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

A detailed description of the Wi-5 smart functionalities is provided in deliverable D3.3 [2].

2.2 Cooperative Functionalities

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

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

A detailed description of the Wi-5 cooperative functionalities is provided in deliverable D4.2 [3].

3 Integration Approach of Wi-5

In order to integrate and implement the Wi-5 functionalities, we use a modular system. By using this approach, we model the Wi-5 architecture as a combination of the three different modules, namely the monitoring module, the network configuration module and the decision module, as illustrated in Figure 2.

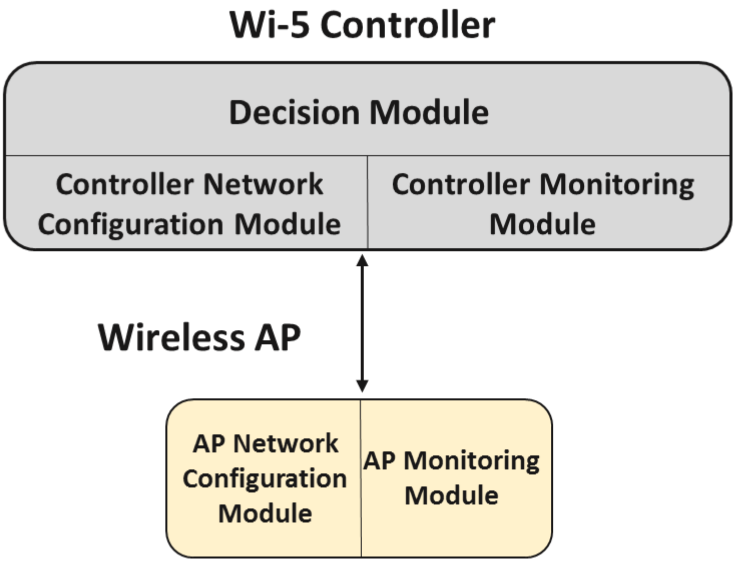

Figure 2: Diagram describing the modular implementation approach in Wi-5

The monitoring module will be responsible for monitoring the status of the network and providing this information with the QoS information related to users/flows to the decision module. This module will be located on both the Wi-5 controller and the AP.

The decision module will be responsible for processing the input provided by the monitoring module with respect to the Wi-5 algorithms such as interference management, smart AP selection, load balancing, seamless handover and packet grouping, and provide the output to the network configuration module. This module will be located in the Wi-5 controller.

The network configuration module will be responsible for the implementation of the configuration related functionalities such as switching the channel of an AP, moving a wireless client from one AP to another and the packet grouping. Similarly to the monitoring module, this module will be located on both the controller and the AP.

Before providing a description of these modules, we can summarise our strategy to implement the Wi-5 functionalities as shown in Figure 3.

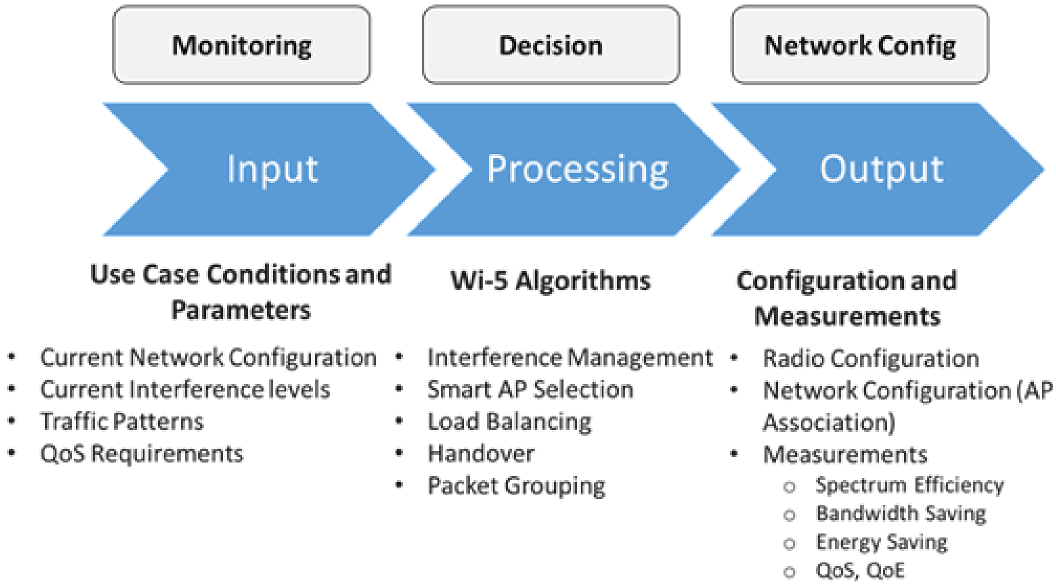

Figure 3: Wi-5 Implementation Strategy

This will be based around three stages as explained in the following:

- Current network configuration such as the channel assignment of the APs, the number of users/flows associated with each AP, traffic patterns showing the traffic distribution across APs, and QoS requirements in terms of the bit rate and latency requirements of user services will be provided to the decision module as an input. In the monitoring module, Wi-5 agents will track the interference levels sensed from each AP at the available channels in the considered frequency bands and will provide this information to the decision module.
- The decision module will trigger decisions for the execution of the Wi-5 algorithms with respect to the statistics and use case conditions and parameters provided by the monitoring module. These Wi-5 algorithms were developed to implement the smart functionalities such as load balancing and packet grouping, and the cooperative functionalities such as handover, smart AP selection and interference management.
- The output of the Wi-5 algorithms will be implemented in terms of configuring the radio and network. These configurations will be evaluated and validated by measuring the parameters such as the spectrum efficiency, saved bandwidth, saved energy, QoS and QoE of user services.

We currently implement the load balancing and horizontal handover utilizing the SDN based Wi-5 platform, whereas the smart AP selection and interference management functionalities are run in a MATLAB simulation environment.

Currently we are working on integration of the Wi-5 functionalities run in MATLAB on the SDN based Wi-5 platform. The integration of the Wi-5 functionalities to the Wi-5 SDN platform will be explained in forthcoming parts of this section.

More detailed information related to the status of the implementation of the smart and cooperative functionalities and first performance evaluation results are provided in deliverable 3.3 and 4.2 respectively.

3.1 Monitoring Module

In order to implement the smart and cooperative functionalities defined in Section 2, the monitoring module will provide the statistics gathered from a set of measurements taken from the Wi-5 APs in the network. The set of measurements should provide information on:

- Interference levels sensed from each AP at the available channels in the considered frequency bands.
- The number of users/flows associated with each AP.
- Bit rate and latency requirements of user services.

The monitoring module will consist of two parts: one part will reside in the controller and the other will reside in the Wi-Fi APs.

3.1.1 AP Monitoring Module

The monitoring information will be collected by the Wi-5 agents running on the Wi-5 APs. Wi-5 agents will supply monitoring information to the Wi-5 controller as an input to the implemented smart and cooperative algorithms, through the southbound API.

Wi-5 agents will run on top of the Wi-5 AP network interface running in the monitor mode, to receive all frames including both management frames and data frames, along with per-frame reception information exposed using a special header, named *radiotap* header. The *Radiotap* header format is a mechanism to supply additional information about frames from the driver to userspace applications such as the Click modular router, and from a user space application to the driver for transmission. The *Radiotap* header includes detailed information on each packet, like the signal strength or the data rate of the captured packet. Detailed information on the fields of a *radiotap* header can be found in [4].

The information used to measure the quality of the wireless link will include the signal strength of the reception, the bit rate or the Modulation and Coding Size (MCS) of the transmitted frame and the noise. Wi-5 agents will save this information on a per source basis, and will also keep track of the timestamps for each source.

3.1.2 Controller Monitoring Module

The monitoring module in the Wi-5 controller will gather the information collected by the Wi-5 APs and store them. The monitoring module will be able to access the information through the SDN southbound API.

Currently, the monitoring module in the Wi-5 controller is able to store the statistics given below:

- Initial and final timestamps: All the statistics are collected during an interval between initial and end time, both in seconds.
- Number of packets received/sent during the interval.
- 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 airtime this packet has consumed, i.e. the product of the length in bits by the rate.

More detailed information regarding the monitoring functionalities of the Wi-5 architecture can be found in deliverable D3.1 [5].

3.2 Decision Module

The decision module will be responsible for triggering decisions using the Wi-5 algorithms with respect to the statistics provided by the monitoring module. These Wi-5 algorithms are designed in order to implement the Wi-5 functionalities such as horizontal handover, load balancing, packet grouping, smart AP selection, and interference management. The processing mechanisms of these functionalities are briefly summarized in the following subsections and more detailed information regarding these functionalities can be found in D3.3 [2] and D4.2 [3].

3.2.1 Horizontal Handover

Horizontal handover considers the case where the STA is steered from one AP to the other AP due to mobility of the STA throughout the network. In the Wi-5 framework, the Light Virtual Access Point (LVAP) concept, which is described in detail in deliverable D3.3 [2], is utilized to support this. In summary, the Wi-5 controller creates an LVAP (which includes a specific MAC) for each terminal, which is dynamically assigned to the physical AP where the STA is located at each moment. Each time the STA needs to be moved between Wi-5 APs, its LVAP will be transferred from the previous AP to the new one.

The horizontal handover decision is triggered by the decision module, when the Received Signal Strength Indicator (RSSI) level of the STA measured by the monitoring module in the associated Wi-5 AP is decreased due to the mobility of the STA throughout the network.

In the current testbed, we consider the case where the two Wi-5 APs operating on different channels are connected to the network. The decision module executes this functionality regarding the timestamp and RSSI values extracted from the packets measured by the monitoring module in the STA's associated Wi-5 AP denoted as AP1 in Figure 4. The decision module calculates the difference between the RSSI values and timestamp values of the last heard packet and the first heard packet, respectively. In order for the decision module to trigger a handover decision, the difference between the timestamps of the last heard and the first heard packets should be greater than a configurable hysteresis threshold to prevent the so called ping-pong effect [4] and the decrease in the RSSI value should be greater than a configurable received power level threshold.

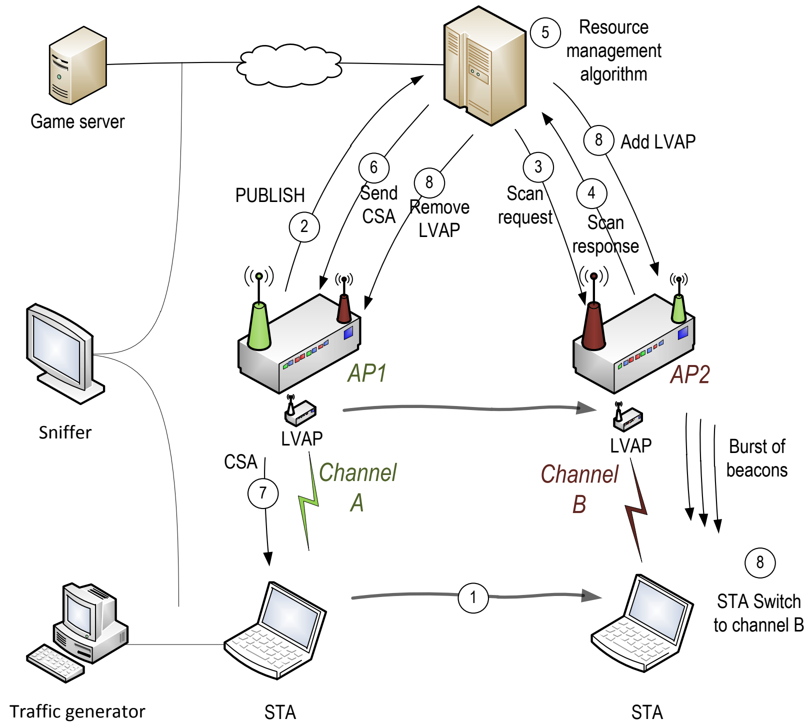

Figure 4: Description of the handover testbed used in Wi-5 integration and testing

Currently, we are working on extending the number of Wi-5 APs in the testbed and extending the smart AP selection functionality towards the inclusion of the horizontal handover functionality.

3.2.2 Load Balancing

Load Balancing functionality will enable Wi-5 networks to make decisions on association or roaming requests of the STA's, with the aim of maximising the aggregate data rate of these networks.

This functionality is triggered by the decision module either reactively or proactively. The reactive case covers the situation when a new STA wants to connect to the Wi-5 network or an existing STA wants to switch to another application implying a new flow with different QoS requirements. The proactive case corresponds to the case where this functionality is triggered periodically.

In the reactive case, the association request of a new STA or switching request of the existing STA is delivered to the monitoring module in the Wi-5 controller by the monitoring module in the Wi-5 AP which receives the request of the new STA or the monitoring module in the Wi-5 AP which the existing STA is associated. The monitoring module in the Wi-5 controller also provides the map of Wi-5 agents and the corresponding connected STAs including the RSSI values, MAC and IP addresses of the STAs to the decision module. The decision module exploits this information to accept or reject the joining request of the new STA or switching request of the existing STA.

Currently, if the association request of the new STA is accepted, a simple round robin algorithm is run by the decision module to assign a Wi-5 AP to the STA. In the 3rd year of the project, we will extend the smart AP selection functionality towards the inclusion of the load balancing functionality. So, if the association request of the new STA or switch request of the existing STA is accepted, it will be associated to an AP depending on the result of the smart AP selection algorithm which is triggered by the decision module.

3.2.3 Smart AP Selection

Smart AP selection process implements an algorithm based on the Fittingness Factor (FF) in charge of associating a Wi-5 AP to each new STA/flow considering the bit rate requirements. This algorithm extends the Network Fittingness Factor metric introduced in [9] and [10], which efficiently addresses the QoS requirements of both a flow joining the network and other flows active in the network. The more detailed information about this functionality is provided in deliverable 4.2 [3].

The smart AP selection algorithm is triggered by the decision module when either a new user joins the network, or an existing user switches to another application implying a new flow with different QoS requirements. After the association request of a new STA or AP switching request of an existing STA is delivered by the monitoring module in the controller, the decision module collects the available information from the monitoring module in the controller. This information includes the bit rate provided by the each Wi-5 AP connected to the network depending on the radio environment and required bit rate of the connection requesting STA, determined by the flow detection tool employed by the monitoring module in the Wi-5 APs. Then, the decision module uses this information to calculate a FF metric for each AP according to the service it can provide for the new flow. Based on this information, the decision module determines the most suitable AP for each new flow/STA or the flow/STA requesting an AP switch, characterised by the Network Fittingness Factor.

3.2.4 Interference Management

The interference management functionality implements an RRM algorithm to address interference in Wi-5 networks by combining both channel assignment and transmit power adjustment techniques.

The channel assignment process considered in our RRM algorithm is based on an objective function which reduces the magnitude of the interference in the whole Wi-5 network. This strategy allows the Wi-5 controller to select the optimised channel configuration in terms of interference for the different APs in a network based on the Wi-Fi system properties (e.g. IEEE 802.11's standard channel characteristics), the logical network topology (the AP distribution throughout the network), and the desired resource management criteria (the assigned channels, interference related QoS, or handover requirements). The channel assignment algorithm is triggered by the decision module either periodically in a proactive manner, or when either a new user joins the network or an existing user switches to another application implying a new flow with different QoS requirements.

If the channel assignment is triggered periodically by the decision module, the monitoring module in the controller provides the interference levels measured by each Wi-5 AP in the network, in terms of path loss values inferred from the RSSI measurements of the other APs gathered from the monitoring module in each AP through the southbound API. Then, the decision module determines the best channel configuration for the APs in the network utilizing the path loss values provided by the monitoring module in the controller.

Channel assignment can also be triggered after an AP is selected for a new STA joining the network or an existing STA switches to another application. Here, the channel assignment is triggered by the decision module as explained above after an AP is selected for the flow if the deviation of the accumulated interference level throughout the network provided by the monitoring module in the controller is above a configurable threshold as explained in detail in deliverable 4.2 [3].

The Power adjustment process considered in our RRM algorithm provides the capability of setting the transmission power of the APs such that the QoS requirements of the flows are satisfied and the level of interference in the network is maintained close to its optimal value defined through the Channel assignment process.

The power level adjustment process is triggered jointly with the smart AP selection process either when a new user joins the network, or an existing user switches to another application to address minimisation of interference in the Wi-Fi network and the QoS requirements of the users. The decision module adjusts the power based on the provided bit rate of the each Wi-5 AP connected to the network and required bit rate of the connection requesting STA gathered by the monitoring module in the Wi-5 controller collected from the monitoring tool in the Wi-5 AP through the southbound API.

3.3 Network Configuration Module

The role of this module is to apply the radio and network configurations provided by the decision module. This configuration can consist of a range of parameters that should be enforced by the identified Wi-5 APs, including channel switching, setting the transmit power, controlling the transmission rate, triggering of packet grouping, etc. Therefore, this module is split into two parts with one part residing in the controller to communicate this to the AP, and another residing in the Wi-5 AP to enforce it. Below, we will first provide brief descriptions of the functionalities of the network configuration module in the Wi-5 controller and the Wi-5 AP respectively. Then we will discuss how the radio and network configuration will be implemented by per AP and per packet base respectively.

3.3.1 Controller Network Configuration Module

The controller network configuration module programmes the wireless network parameters of the Wi-5 APs such as channel configuration, transmit power and the transmit rate of the Wi-5 APs depending on the configuration information provided by the decision module. The Wi-5 APs expose a number of tools to the Wi-5 controller which can be used in order to configure certain parameters. This section will describe how they can be used in relation to channel switching, setting the transmit power, and controlling the transmission rate of the Wi-5 APs.

3.3.2 AP Network Configuration Module

The AP network configuration module in Wi-5 APs will be responsible for implementing the network configuration determined by the decision module and provided by the network configuration module in the Wi-5 controller through the southbound API.

Implementation of the network configuration functionality includes manipulating the channel switch, transmit power setting and transmission rate settings of the Wi-5 AP. Besides the configuration of the parameters in the Wi-5 AP, the network configuration module in the Wi-5 AP configures some packet level parameters such as the per packet transmit power control and the per packet rate control.

3.3.3 Configuration of the Network Parameters per AP

Channel Switching

According to IEEE 802.11-2012, an AP shall inform associated STAs that the AP is moving to a new channel and maintain the association by advertising the switch using Channel Switch Announcement elements in Beacon frames, Probe Response frames, and Channel Switch Announcement frames until the intended channel switch time. This is implemented in the wireless driver employed in Wi-5 APs that adopts cfg80211 Linux 802.11 configuration API, and is exposed to user space tools, such as hostapd or wpa_supplicant.

The OpenWRT running Wi-5 APs utilizes hostapd as user space authenticator. It maintains a command line tool called hostapd_cli to interact with the hostapd daemon. The channel switch of an AP from the network configuration module in the Wi-5 controller is handled using the “chan_switch” function of the “hostapd_cli” command line tool. This can be achieved by running the following command:

chan_switch<numberofchannel><frequencyofchannel>

Transmit Power

iw is a nl80211 based command line configuration utility for wireless devices. Transmit power of an AP can be set from the Wi-5 controller by utilizing an iw command line tool in OpenWRT running Wi-5 APs. This can be handled by using either the interface name of the wireless device or the corresponding name of the physical interface as illustrated in the following example:

iw dev <devname> set txpower<auto|fixed|limit> [<tx power in mBm>]

iwphy<phyname> set txpower<auto|fixed|limit> [<tx power in mBm>]

Note that, mBm corresponds to millibel-watts and power in mBm equal to 100 * <power in dBm>.

Transmission Rates

The iw tool also supports modifying both legacy transmit bitrates and HT MCS rates. We can set preference for transmitting using only certain legacy bitrates as shown in the following example:

iw<devname> set bitrates legacy-2.4 12 18 24

We can set the preference for transmitting using MCS rates, which is achieved by specifying the band and MCS rate by executing the following command in the Wi-5 controller:

iw dev <devname> set bitrates mcs-<bandname><mcs>

3.3.4 Configuration of the Network Parameters per Packet

Transmit Power Control

Per packet power transmission control can be used to enhance the performance at multiple layers of the network stack. In order to control the network topology, TPC can be combined with routing and to minimise the interference it can be combined with the MAC layer.

A Click modular router will provide a status information structure in the form of “packet annotations” associated with each packet. These annotations will then be transferred with each packet between the modules that will be responsible for performing functions in separate network layers. The transmission power per packet can be changed as one such annotation. When a packet is ready to be sent, the information about transmission power can be encapsulated into radiotap headers by the encapsulation module of Click and injected into the ath9k driver operating in the monitor mode. The wireless NIC then will transmit the frame with the output power as specified in the radiotap headers.

In order to control the transmission power per packet utilizing Click’s packet annotation, the TPC register should be enabled. The debug filesystem of ath9k driver could be used to handle this issue.

Rate Control

Per packet rate control can also be enabled utilizing Click’s packet annotation structure. Unlike the case where the power is controlled per packet, per packet rate control can be implemented without any driver modification.

4 Wi-5 Integration Strategy

According to the SEBoK (System Engineering Body of Knowledge), "*system integration consists of taking delivery of the implemented system elements which compose the system-of-interest (SoI), assembling these implemented elements together, and performing the verification and validation actions (V&V actions) in the course of the assembly*". We can extend this process to any kind of product, service and enterprise systems.

Mainly, there are 3 purposes of system integration which can be summarized as below:

- Assemble the implemented system elements to ensure that the individual system elements function properly as a whole.
- Show that the integrated elements perform as expected and meet the performance requirements.
- Detect the defects and failures related to design and assembly process through the verification and validation actions.

A predefined integration strategy is needed to integrate the implemented system elements. The integration strategy is defined based on the system architecture and it relies on the way the system architecture has been designed.

In Wi-5, the system architecture has been designed using SDN, a concept that relies on the decoupling of the control plane from the data plane in Wi-5 APs and the dynamic programmability of Wi-5 APs, which simplifies the development and the deployment of network applications running on top of the Wi-5 controller.

Wi-5 APs and the Wi-5 controller are modelled using a modular approach, having the goal of facilitating construction of the system by decomposing it into independent, interchangeable modules, such that each contains everything necessary to execute only one aspect of the desired Wi-5 functionality.

In this section, we will define and explain the Wi-5 strategy to integrate the smart and cooperative functionalities in terms of assembly of the modules utilized to model the Wi-5 controller. Our integration strategy can be implemented in three phases. In the first phase, we can assemble the monitoring and the decision modules to obtain the control module – version 1 and then we can verify the accuracy of the Wi-5 algorithms again. In the second phase, we can assemble the decision and the network configuration modules to get the control module – version 2. This process can be carried out in parallel with the integration - phase 1. If we do not carry the second phase in parallel with the first, in the third phase we can assemble the control module – version 1 and the network configuration module to obtain the complete Wi-5 controller which we call the control module – version 3.

The detailed definition and explanation of the Wi-5 integration strategy will be given in the following subsections.

4.1 Integration Strategy: Phase 1 (Control Module version 1)

In order to trigger the decisions for the Wi-5 algorithms, the decision module will rely on the statistics that are gathered from a set of measurements conducted on the Wi-5 APs. These statistics are provided by the monitoring module in the Wi-5 controller. The monitoring module in the Wi-5 controller retrieves these statistics from the Wi-5 APs through the southbound API.

Control module – version 1, which will be responsible for both monitoring the network status and the triggering the decisions for Wi-5 algorithms, will be assembled by interfacing the monitoring and the decision modules. After assembling these two modules, the Wi-5 controller is composed of two modules as illustrated in **Error! Reference source not found.**, namely the control module and the network configuration module. In this configuration, Wi-5 algorithms employed by the control module will determine the suitable network configuration based on information supplied by the monitoring information and the network configuration module will apply this configuration to the network that will be provided by the control module.

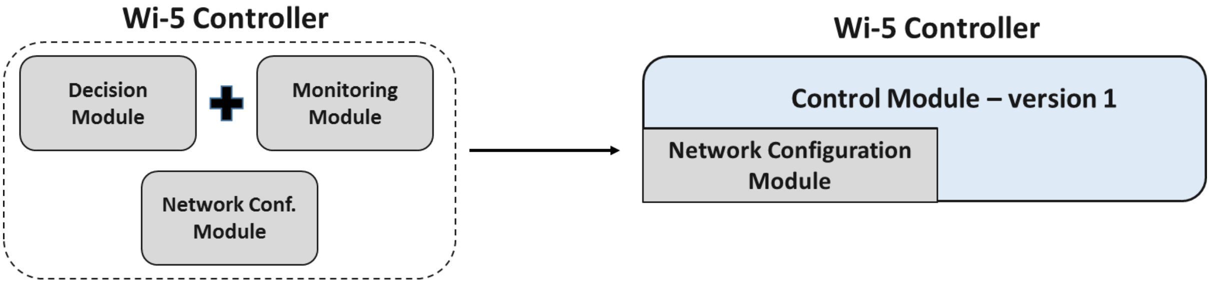

Figure 5: Wi-5 Integration Strategy: Phase 1

In the following section, the integration of channel assignment will be briefly explained as an example of the implementation of the integration strategy phase 1. The more detailed information related to the channel assignment algorithm can be found in deliverable D4.2 [3].

4.1.1 Integration of Channel Assignment Functionality: Phase 1

Our proposed analytical model for channel assignment is taking advantage of a quantity which we call interference impact. This embodies the contribution of a source signal in the experienced interference throughout the network. Below, we will try to clarify this quantity and explain the way it indicates the network-wide interference status. Each AP is assumed to be a source of a signal with a specific power level and also an assigned RF channel. This AP provides the main signal strength for its associated STAs and makes interference for other Aps and their associated STAs.

We will need just one type of measurement here which is the signal strength of an AP measured at the other APs as illustrated in Figure 6.

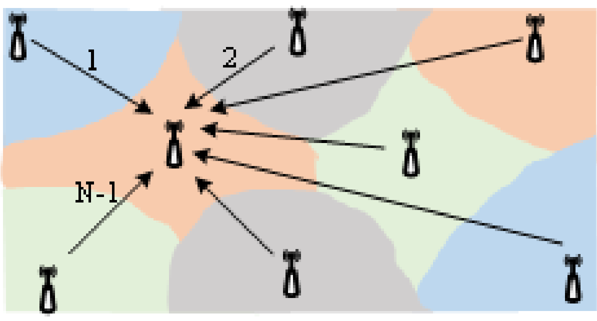

Figure 6: APs as the evaluation agents for assessing the reception combination at various locations in the network

After measuring the received power at each AP, we will define a matrix called $M^{(N-1)x(N-1)}$ as given in Equation 1. The numbers of rows and columns of this matrix M correspond to the number of APs connected to the network, except the AP where the measurement is executed. Matrix M is constructed in such a way that each element of the matrix, m_{ij}, represents the path loss between AP_i and AP_j. The element m_{ij} is calculated by subtracting the received power Rx_i measured at AP_i from the transmit power of AP_j which is equal to Tx_j.

$$\boldsymbol{M} \in \{\mathbb{R}\}^{(\boldsymbol{N-1})\times(\boldsymbol{N-1})} \rightarrow \boldsymbol{m_{ij}} = \boldsymbol{Tx_j} - \boldsymbol{Rx_i} \qquad (1)$$

Once we obtain the matrix M, we can consider the offline and online integration methods for assembling the monitoring module and the decision module to obtain the control module version 1. At this stage, we just consider the offline integration which will be explained in the following. On-line integration methods will be considered in the future documents.

Currently, we implement the channel assignment functionality as outlined below:

1. Each AP will collect the RSSI levels of the other APs connected to the network utilizing the iw command line tool in OpenWRT running Wi-5 APs.
2. Once the RSSI level of each link is obtained, the corresponding path loss values will be determined using Equation 1. These values will be stored in a text file where the extension of the file is ".txt".
3. The text files containing the path loss values will be delivered to the Wi-5 controller through the secure copy protocol (SCP), where the channel assignment functionality will be triggered by the decision module in the MATLAB environment.
4. After parsing these text files with MATLAB's *textscan* function, the elements of the matrix *M*, denoted by m_{ij}, will be obtained by averaging a sufficient number of path loss samples. The required number of samples, that provides a sufficiently accurate estimate of m_{ij}, is determined utilizing the confidence interval concept. The details about this concept can be found in [6].
5. In the decision module, channels are assigned to each AP based on the Wi-5 channel assignment algorithm and the Least Congested Channel (LCC) algorithm [7] seperately.
6. The two channel configurations are provided to the network configuration module and applied to the network using the "chan_switch" function of "hostapd_cli" as also mentioned in section 3.3.3, through the southbound API utilizing the OpenFlow protocol.

In the 3rd year of the project, we are planning to integrate this functionality to the Wi-5 SDN platform and implement offline integration as illustrated in Figure 7. The steps are provided below:

1. Wi-5 agents in each AP will measure the RSSI levels of the other APs connected to the network utilizing the iw command line tool.
2. Once the RSSI levels of each link is obtained, the monitoring module in Wi-5 APs will deliver this information to the monitoring module in the Wi-5 controller through the southbound API.
3. The monitoring module in the Wi-5 controller will calculate the path loss values corresponding to each link by utilizing Equation 1 and will store these values in a suitable structure.
4. The elements of the matrix *M*, denoted by m_{ij}, will be obtained by averaging a sufficient number of path loss samples.
5. *M* will be constructed by using the path loss value of each link and will be put into a ".txt" text file and saved in a folder shared between the monitoring module and the decision module.
6. The ".txt"text file containing *M* will be provided to the decision module by calling MATLAB's textscan function and given as an input to the channel assignment algorithm run by MATLAB, by parsing this file utilizing MATLAB's *textscan* function. Therefore, the *textscan* function will work as an interface that will be used to assemble the monitoring and decision modules.

7. Channels will be assigned to each AP triggering the Wi-5 channel assignment algorithm and LCC algorithm seperately and applied to the APs connected to the Wi-5 network as an output of the control module using the "chan_switch" function of "hostapd_cli" through the southbound API utilizing the OpenFlow protocol.
8. After applying the assigned channels to the network, the performance analysis of the channel assignment algorithms will be performed.

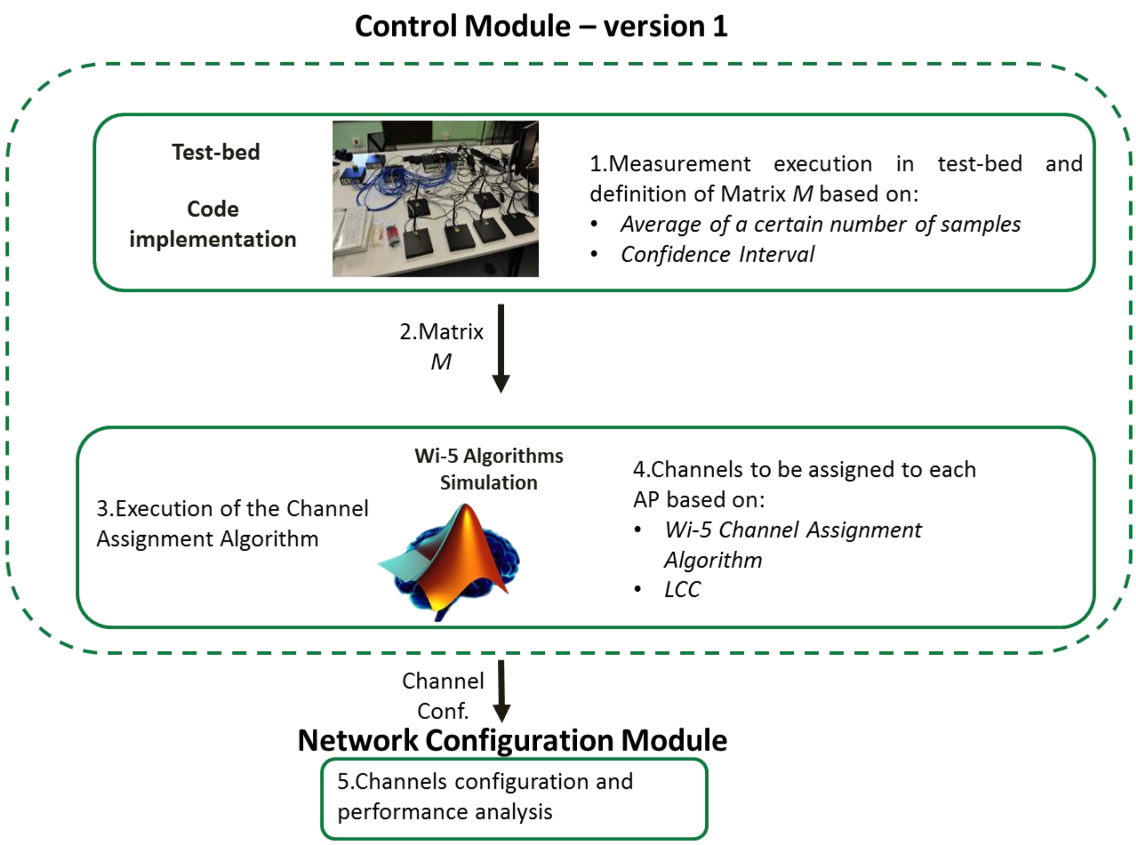

Figure 7: Integration of Channel Assignment: phase 1

It must also be mentioned that the channel assignment process is not needed to be executed continuously or too frequently. However, the measurements are supposed to be maintained and updated continuously. APs are doing such a measurement during their own idle time periods and these time periods are not synchronized together. Subsequently, the updating process in practice won't be smooth and well correlated. Furthermore, there will be some gaps and missing updates every now and then. These are some issues which can degrade the validity and correlation between collected information. We can neglect these issues for the time being and address them later.

4.2 Integration Strategy: Phase 2 (Control Module – version 2)

Control module – version 2 will be responsible for both triggering decisions for the Wi-5 algorithms and configuring the network according to the output of the Wi-5 algorithms. It will be assembled by interfacing the monitoring and the decision modules. This control module can be assembled in parallel with integration phase 1, where we will assemble the monitoring and the decision modules.

After assembling these two modules, the Wi-5 controller will be composed of two modules as illustrated in Figure 8, namely the control module and the monitoring module. In this configuration, the Wi-5 algorithms employed by the control module will determine and apply the suitable network configuration based on the monitoring information provided by the monitoring module.

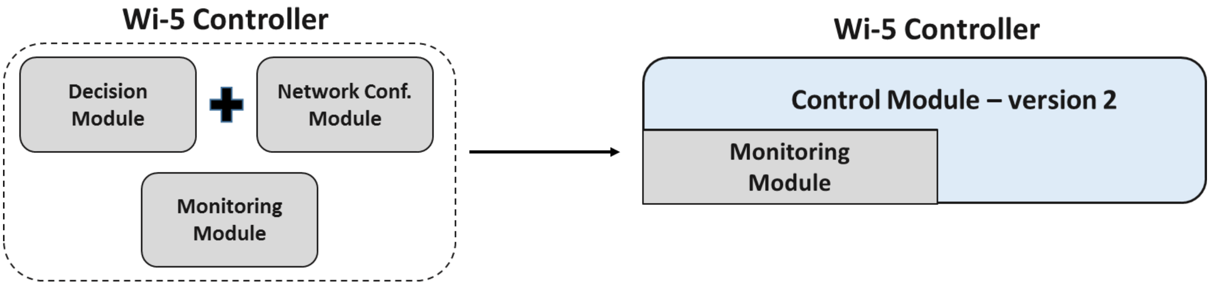

Figure 8: Wi-5 Integration Strategy: Phase 2

The integration of the decision and network configuration modules to obtain the control module can be carried out in parallel with integration – phase 1. In the following, the integration of the channel assignment functionality performed in the second phase will be briefly explained as an example.

4.2.1 Integration of Channel Assignment Functionality: Phase 2

We provide the integration strategy of the channel assignment functionality in phase 2 in Figure 9 as follows:

1. The monitoring module will construct matrix *M* according to the procedure defined for the integration of channel assignment phase 1 in section 4.1.1, following the steps 1-5 provided therein.
2. The ".txt" text file containing *M* will be provided to the decision module by calling MATLAB's textscan function and given as an input to the channel assignment algorithm run by MATLAB, by parsing this file utilizing MATLAB's *textscan* function.
3. In the decision module, channels will be assigned to APs connected to the Wi-5 network by triggering the Wi-5 channel assignment algorithm and LCC algorithm seperately. These channel configurations will be applied to the APs by the network configuration module, as an output of the decision module using the "chan_switch" function of "hostapd_cli" through the southbound API utilizing OpenFlow. Here, the OpenFlow protocol will be utilized to communicate the outcomes of the decision module to the network configuration module.
4. After applying the assigned channels to the network the performance analysis of the channel assignment algorithms will be performed.

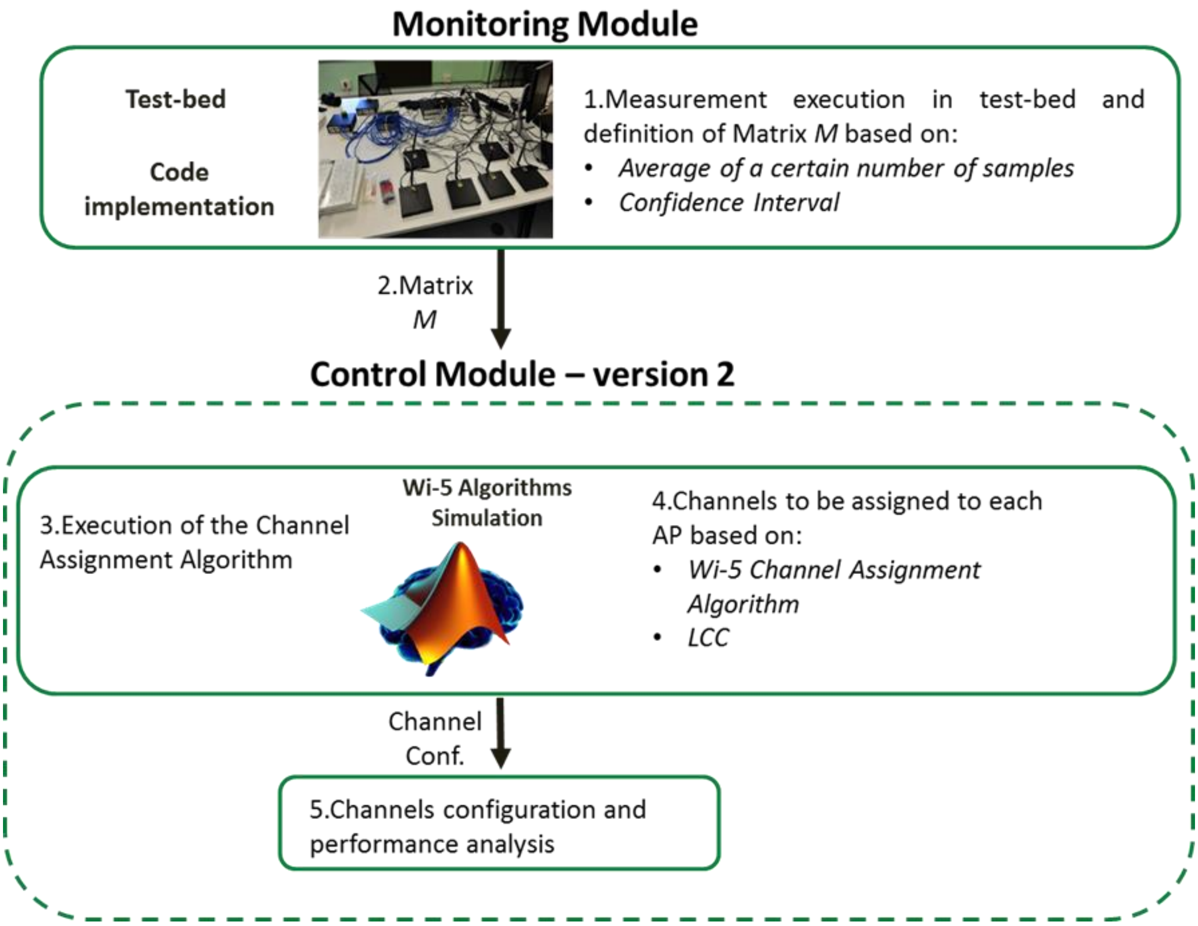

Figure 9: Integration of Channel Assignment: Phase 2

4.3 Integration Strategy: Phase 3 (Control Module – version 3)

Control module – version 3 will be responsible for triggering the decisions for Wi-5 algorithms according to the monitoring information collected by the Wi-5 agents and then configuring the network according to the output of Wi-5 algorithms. It will be assembled by interfacing the network configuration module and the control module-version 1, where the control module-version 1 will be assembled according to section 4.1. After assembling these two modules, the Wi-5 controller will be a complete module as illustrated in Figure 10, namely the control module. In this configuration, Wi-5 algorithms employed by the control module will determine and apply the suitable network configuration based on the monitoring information provided by the monitoring module.

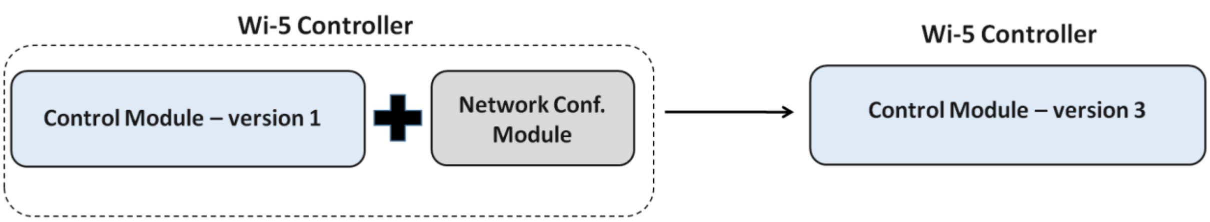

Figure 10: Wi-5 Integration Strategy: Phase 3

In the following, the integration of the channel assignment functionality performed in the third phase will be briefly explained as an example.

4.3.1 Integration of Channel Assignment Functionality: Phase 3

We provide the integration strategy of the channel assignment functionality for phase 3 in Figure 11 as follows:

1. Control module – version 1 will determine the channel configurations for the APs connected to the Wi-5 network which will be determined utilizing Wi-5 channel assignment algorithm and LCC respestively as explained in section 4.1.1.
2. The network configuration module will apply these configuration using the "chan_switch" function of "hostapd_cli" through the southbound API utilizing the OpenFlow protocol. Here, the OpenFlow protocol will be utilized to communicate the outcomes of the decision module to the network configuration module.
3. After applying the assigned channels to the network, the performance analysis of the channel assignment algorithms will be performed.

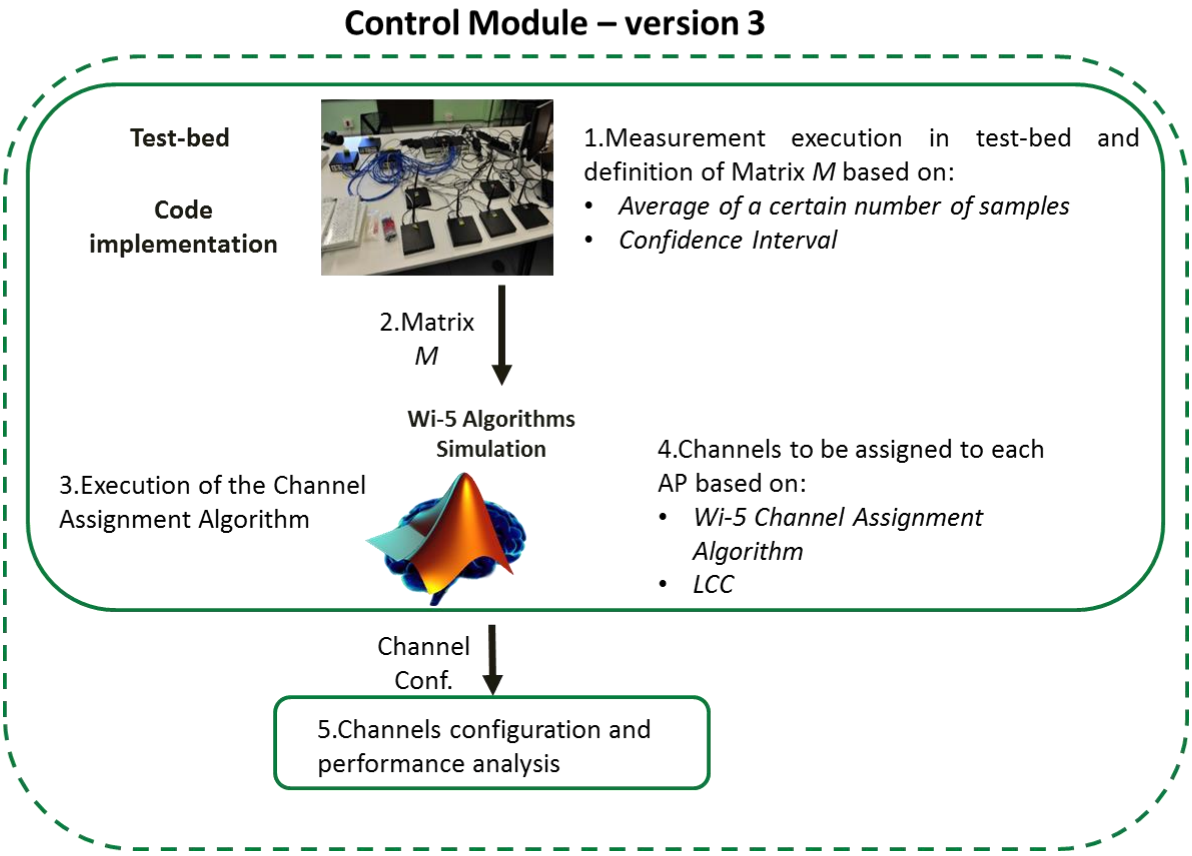

Figure 11: Integration of Channel Assignment: Phase 3

5 Wi-5 Testing Strategy

In order to evaluate and validate the proposed SDN based Wi-5 architecture, and the resource management algorithms developed to implement the smart and the cooperative functionalities, performance tests will be required. Since we adopted a modular approach to model the Wi-5 controller and the Wi-5 APs, we will assess the performance of the Wi-5 architecture and the Wi-5 functionalities by testing each module separately. The details of this approach and the corresponding modules were explained in detail in section 3, where we described the Wi-5 controller and the Wi-5 AP separately. Before explaining our performance testing strategy for each module, we will outline the selected use cases and requirements that we will utilise to validate the Wi-5 architecture.

5.1 Use Cases and Requirements

The use cases presented in Deliverable 2.3 [9] focus on a selected set of scenarios. The choice of these scenarios is based on a thorough analysis of on-going work in the IEEE and Wi-Fi Alliance to identify the most pressing usage models, as well as the interests of the project partners and the members of the Operator Board. In order to quantify the benefits achieved by means of inclusion of the Wi-5 functionalities, we will consider to evaluate the dense apartment building, large home office/SOHO environment, community Wi-Fi, pico-cell street and airport/train station use cases.

The use cases that will be evaluated for the testing scenarios considered by the Wi-5 project can be briefly described as follows:

- **Airport/Train Station**: This use case focuses on the deployment and utilisation of large Wi-Fi networks in public areas, where the users are characterised by nomadic and there is a need to support the use of real-time applications.

- **Dense Apartment Building**: This use case focuses on the dense and uncoordinated deployment, operation and utilisation of Wi-Fi APs. This deployment scenario is characterised by radio interference between Wi-Fi APs and lack of coordinated control over the wireless networks.

- **Pico-cell Street Deployment**: In this use case, we consider outdoor users initially connected to a cellular network and then switch to a Wi-Fi network that has been deployed by the mobile operator to off-load data.

- **Large Home/SOHO**: This represents a common scenario where the usual single AP deployment within a home or small office is extended to provide extra coverage and improve the user’s QoE.

- **Community Wi-Fi Network**: This use case focuses on an emerging service where the network operators offer Wi-Fi network access to their on-the-go subscribers through existing residential and Small Medium Businesses (SMB) Wi-Fi infrastructure.

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

- **Seamless Mobility**: There is an emphasis on the need for seamless mobility in all the use cases studied. This requirement means that the user can roam within a single network or across many networks without service interruption.

- **QoS Awareness**: Similarly to Seamless Mobility, there is an emphasis on QoS awareness in all uses cases studied in this project. Users in the scenarios considered need the network to deliver the necessary performance to maintain the QoS required by their applications such as: VoIP, Online Gaming, etc.

- **Self-Configuration**: In all use cases, there is a requirement that the network should be able to self-configure and maintain itself with minimal user input. For instance, in the case of high interference levels caused by a neighbouring Wi-Fi network, the network should be able to detect the interference and apply a radio configuration that appeases the level of interference and its effect on the network users.

- **Spectrum Usage Optimisation**: This requirement is emphasised in several of the use cases studied in the project. In the case of dense apartment buildings, the network will need to find a radio configuration that achieves optimal performance while minimising interference levels. In the Wi-Fi pico-cell deployment, the spectrum should be allocated fairly among users but taking into account the network capacity of each operator in an area. In the large home/SOHO scenario, the network should be able to adapt the infrastructure to maximise Wi-Fi coverage whilst optimising wireless resource utilisation.

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

The more detailed analysis of the uses cases focused on the functional and performance requirements is provided in deliverable 2.3 [9].

5.2 Performance Testing Strategy

In this section, we will provide the information related to the tests which we will execute to assess and validate the performance of the monitoring, decision and network configuration modules. First, we will define and describe the metrics and testbed for testing the monitoring module. Then we will explain how to assess the performance of the Wi-5 algorithms that were designed and developed to implement the smart and cooperative functionalities. Finally, we will describe how we plan to test the network configuration module.

5.2.1 Testing the Monitoring Module

The monitoring module will be responsible for tracking the status of the wireless network and providing this information as an input to the decision module, which executes the Wi-5 algorithms to implement the Wi-5 functionalities. While evaluating and validating the performance of the monitoring module, we will consider the measurements directly taken from the field, measurements taken by employing the testbed, and the measurements taken from simulations as depicted in Figure 12.

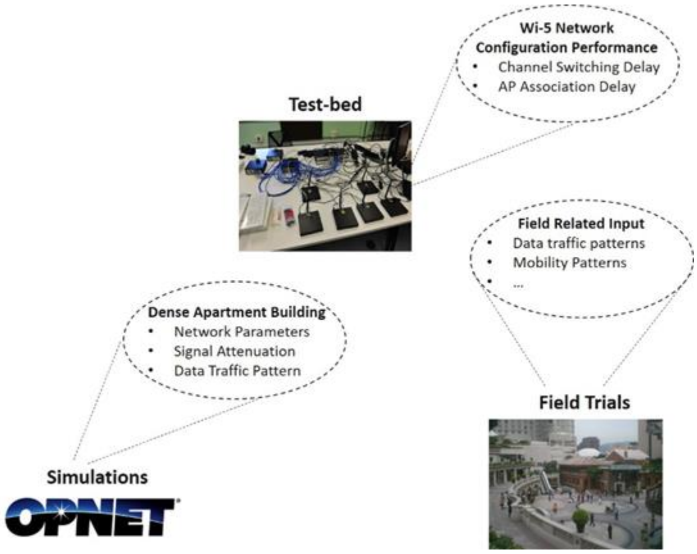

Figure 12: Evaluation of the monitoring module

The main objective of testing the monitoring module is to ensure that the Wi-5 controller obtains the network status and QoS information. In order to achieve this aim we will test that:

- Monitoring data can be sent and stored at the controller.
- Monitoring data can be updated.
- The Wi-5 controller can detect traffic classes and QoS requirements.

In the following, we will provide and explain the performance measurement metrics and the utilized testbed for testing the performance of the monitoring module. The testbed description and testing metrics of the corresponding use cases for testing the monitoring module are provided in Table 1, Table 2 and Table 3, Table 4 and Table 5 respectively.

Table 1: Evaluation of SOHO use case for testing the monitoring module

Testbed Description	Testing Metrics
• One Wi-5 Controller • 10 Wi-5 APs • 8 non-Wi-5 AP’s • 10 STAs	• Scalability • Delay • Accuracy

Table 2: Evaluation of dense apartment building use case for testing the monitoring module

Testbed Description	Testing Metrics
• 3 Wi-5 Controllers • 15 Wi-5 APs • 12 non-Wi-5 APs • 45 STAs	• Scalability • Delay • Accuracy

Table 3: Evaluation of airport/train station use case for testing monitoring module

Testbed Description	Testing Metrics
• One Wi-5 Controller • 25 Wi-5 APs • 20 non-Wi-5 APs • 60 STAs	• Scalability • Delay • Accuracy

Table 4: Evaluation of pico-cell street use case for testing the monitoring module

Testbed Description	Testing Metrics
• 3 Wi-5 Controllers • 15 Wi-5 APs • 12 non-Wi-5 APs • 45 STAs	• Scalability • Delay • Accuracy

Table 5: Evaluation of community Wi-Fi use case for testing the monitoring module

Testbed Description	Testing metrics
• 3 Wi-5 Controllers • 15 Wi-5 APs • 12 non-Wi-5 APs • 30 STAs	• Scalability • Delay • Accuracy

According to Table 1, Table 2, Table 3, Table 4 and Table 5 in order to evaluate and validate the performance of the monitoring module, our testing metrics are:

- Scalability: to test whether the Wi-5 controller can monitor and manage a maximum number of APs,
- Delay: to test whether monitoring data is updated,
- Accuracy: to test whether the Wi-5 controller can detect the traffic classes and QoS requirements.

For testing these metrics, we will measure the monitoring data size, the acceptable frequency of monitoring updates and the accuracy of the QoS information respectively. We have determined the testbed settings for evaluating each use case considering the processing capabilities of the host which we will use as Wi-5 controller, the bandwidth of the link between the Wi-5 APs and the Wi-5 controller and the corresponding AP and STA densities of each case.

For considering scalability of the tests, we do this by means of the processing capabilities of the controller and the bandwidth of the backhaul link between the controller and the AP's, we have set the maximum number of APs as 25. Also, in order to encounter the effect of the interference, by considering the airtime utilized by the beacons, we have set the number of interfering non-Wi-5 APs as 80% of the number of Wi-5 APs.

In order to evaluate the SOHO use case, where the low density of APs and STAs is considered, we set the number of Wi-5 APs as 10 and STAs as 10. We consider 15 Wi-5 AP's to evaluate the use cases dense apartment building, pico-cell street, and the community Wi-5 where medium density of AP's is considered. We will evaluate the airport/train station use case by accommodating 25 Wi-5 APs, to mimic a high density of APs. We will employ 45 STAs to evaluate the dense apartment building and the pico-cell street use case, 30 STAs to evaluate the community Wi-Fi use case and 60 STA's to evaluate the airport/train station use case, respectively.

Number of the controllers accommodated for evaluating each use case has been determined by considering the management domain of each use case. We set the number of Wi-5 controllers to 3 where the multiple management domain is considered whereas we set this to 1 where the single management domain is considered.

5.2.2 Testing the Decision Module

The decision module will be responsible for triggering the decisions for the Wi-5 algorithms by considering the monitoring input provided by the monitoring module as explained in Section 3.2. In order to evaluate the performance of the decision module, we will inject the input provided by the monitoring module into the Wi-5 simulation code. This monitoring information could be in terms of measurement information taken from the field trials or from the indoor test-bed or the simulation input provided by the simulation tool such as OPNET as depicted in Figure 13. We will then build simulation scenarios using the input data from the field trials, the indoor test-bed and the OPNET simulation tool.

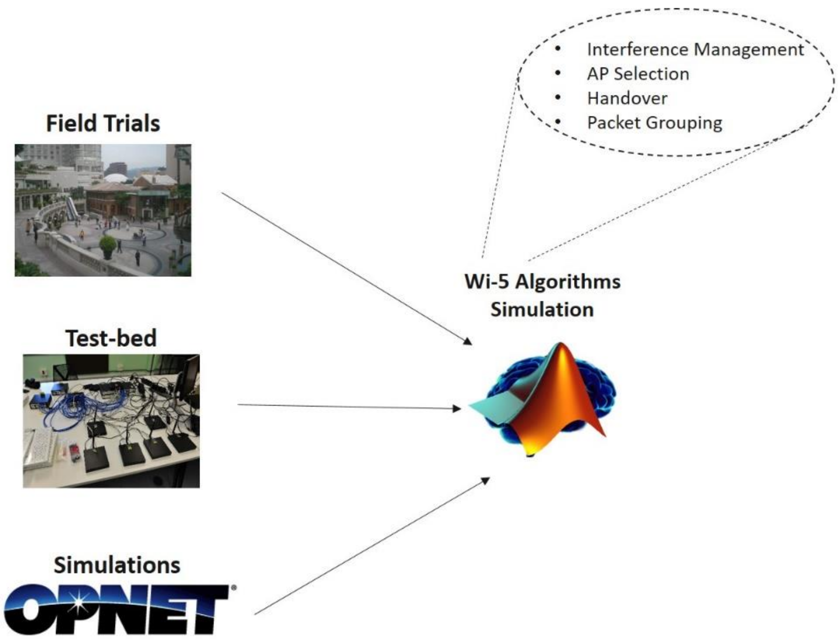

Figure 13: Evaluation of the decision module

Then, we will evaluate the Wi-5 functionalities such as smart AP selection, interference management and handover algorithms through the simulations based on the following performance metrics tabulated in Table 6:

- ***Average Number of Dropped Connections***: This is the average number of denied flow connections, which decrease the average satisfaction (defined below) of the selected AP, which is guaranteed to the connected flows by a certain percentage.
- ***Average Provided Data Rate***: This metric represents the data rate in terms of kbps achieved by each new flow trying to join the network and averaged for all the flows.

- ***Average User's Satisfaction***: This is the average percentage of flows connected to the network with their served data bit rates higher than or equal to its given requirement. This percentage is updated each time a new flow is associated to an AP of the network.

- ***Average Interference Levels***: This is the average interference level throughout the network, due to the channel assignment configuration of the APs.

- ***Average SINR***: This is the average Signal to Interference plus Noise Ratio (SINR) value measured at the STA which evaluates the STA's signal based on the interference plus thermal noise being seen. In this definition, an interference value corresponds to the total signal power being seen at the station received from the all APs connected to the network except the STA's associated AP.

- ***Spectral Efficiency (bits/sec/Hz)***: This value represents the assessment of the spectrum utilization at the physical layer in terms of the achievable rate per unit of the employed bandwidth, (bits/sec/Hz).

We will model indoor office testing, home environment and indoor public area scenarios to test the above Wi-5 functionalities utilizing the corresponding evaluation test metrics provided in Table 6.

Table 6: The performance evaluation tests for the decision module

Wi-5 Functionality Tested	**Evaluation Metrics**
• Smart AP Selection	• Average User's satisfaction • Average provided data rate • Average number of dropped connections
• Interference Management	• Average Interference Levels • Average SINR • Spectral Efficiency (Bits/sec/Hz) • Average User's Satisfaction
• Handover Algorithm	• Average User's satisfaction • Average provided data rate • Average number of dropped connections

We will conduct MATLAB simulations to evaluate the performance of the Wi-5 functionalities, by utilizing the evaluation metrics provided in Table 6. We will evaluate the performance of the decision module regarding the use cases provided in section 5.1, as we also consider this for testing the monitoring module. The first results related to the performance of these functionalities have been provided in D4.2 [3].

5.2.3 Testing the Network Configuration Module

The network configuration module will be responsible for configuring the network according to the output of the Wi-5 algorithms as explained in Section 3.3. The output of the Wi-5 algorithms, in terms of network configuration, can be directly applied to:

- Controlled testbed
- Field Trials
- Simulations

This process is depicted in Figure 14.

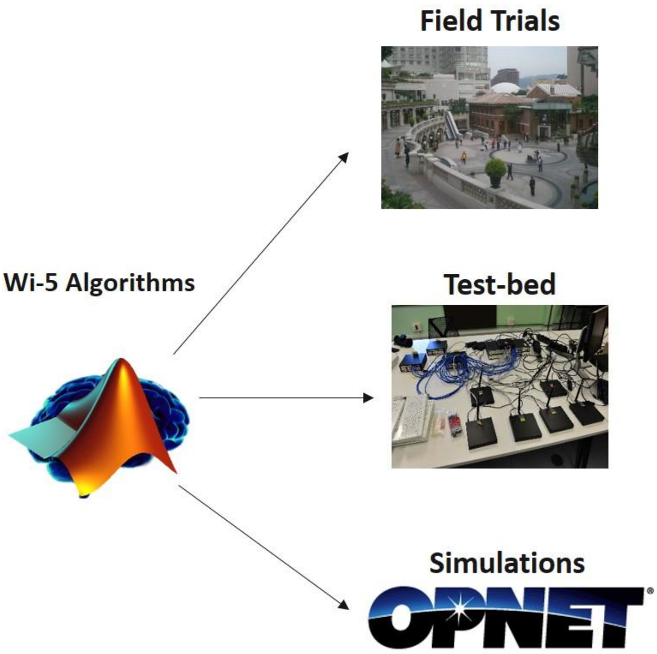

Figure 14: Evaluation of the network configuration module

Table 7, Table 8, Table 9, Table 10 and

Table 11 specify the network performance evaluation metrics and the tested Wi-5 functionalities for the five use cases, namely the SOHO, dense apartment building, airport/train station, pico-cell street, and community Wi-Fi respectively.

Table 7: Evaluation of SOHO use case for testing the network configuration module

Testbed Description	Wi-5 Functionality	Evaluation Metrics
• One Wi-5 Controller • 10 Wi-5 APs • 8 non-Wi-5 APs • 10 STAs	• Interference Management • AP Selection • Handover • Packet Grouping	• Spectrum Efficiency • Energy saving • QoE

Table 8: Evaluation of dense apartment building use case for testing the network configuration module

Testbed Description	Wi-5 Functionality	Evaluation Metrics
• 3Wi-5 Controllers • 15 Wi-5 APs • 12 non-Wi-5 APs • 45 STAs	• Interference Management • AP Selection • Handover • Packet Grouping	• Spectrum Efficiency • Energy saving • QoE

Table 9: Evaluation of airport/train station use case for testing the network configuration module

Testbed Description	Wi-5 Functionality	Evaluation Metrics
• One Wi-5 Controller • 25 Wi-5 APs • 20 non-Wi-5 APs • 60 STAs	• Interference Management • AP Selection • Handover • Packet Grouping	• Spectrum Efficiency • Energy saving • QoE

Table 10: Evaluation of pico-cell street use case for testing the network configuration module

Testbed Description	Wi-5 Functionality	Evaluation Metrics
• 3 Wi-5 Controllers • 15 Wi-5 APs • 12 non-Wi-5 APs • 45 STAs	• Interference Management • AP Selection • Handover • Packet Grouping	• Spectrum Efficiency • Energy saving • QoE

Table 11: Evaluation of community Wi-Fi use case for testing the network configuration module

Testbed Description	Wi-5 Functionality	Evaluation Metrics
• 3 Wi-5 Controllers • 15 Wi-5 APs • 12 non-Wi-5 APs • 30 STAs	• Interference Management • AP Selection • Handover • Packet Grouping	• Spectrum Efficiency • Energy saving • QoE

We will evaluate the performance of the network configuration module after applying the output Wi-5 algorithms to the controlled testbed, field trials and simulations based on the following performance metrics tabulated in: Table 7, Table 8, Table 9, Table 10 and

Table 11. The testbed settings are determined according to the same conditions that have been considered to evaluate the performance of the monitoring module, as explained in section 5.2.1.

- ***Spectrum Efficiency***: This parameter represents the maximum number of flows per AP that can be served while maintaining an acceptable QoS level, which is measured through the service parameters such as packet loss rates or average throughput.

- ***Energy Saving***: This parameter represents the decrease of power consumption in the network after configuring the network according to the outputs of Wi-5 algorithms, while maintaining an acceptable QoS level to the STA's.

- ***Quality of Experience (QoE)***: This parameter measures the satisfaction rate of a user service after applying the new network configuration with respect to the output of the Wi-5 algorithms.

5.2.4 Testing the Wi-5 System

After completing the testing of each module, we will gradually replace the simulation algorithms with the functionalities that will be provided by the Wi-5 controller. Then, we will assess the performance of the Wi-5 controller and Wi-5 APs in realistic environments by considering the SOHO, dense apartment building, pico-cell street, airport/train station and community Wi-Fi cases, according to the details of each use case provided in Section 5.1. This process will be handled as depicted in Figure 15, where we consider to evaluate the performance of the Wi-5 system, utilizing the field trials and the testbed.

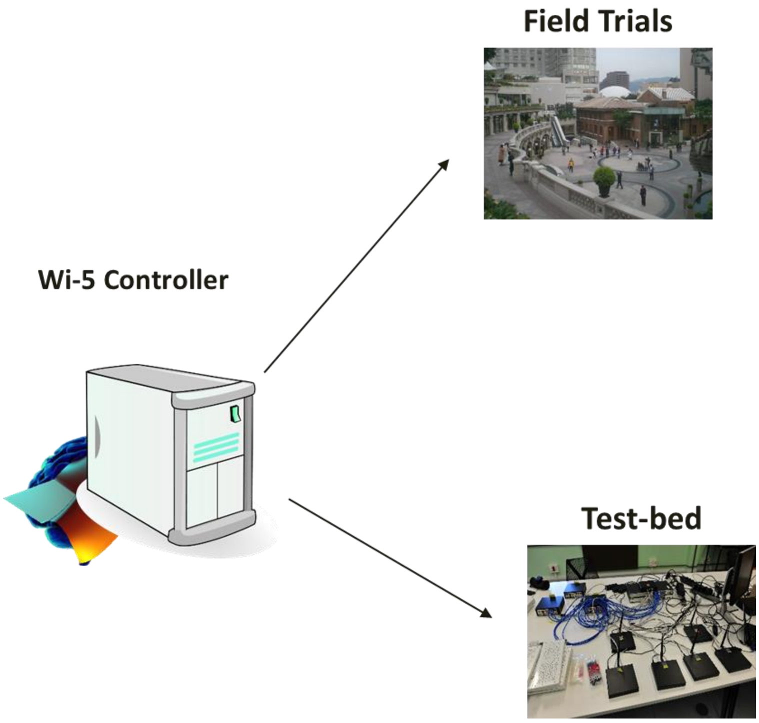

Figure 15: Evaluation of the performance of the whole Wi-5 system.

We will evaluate the performance of the Wi-5 controller by considering the scalability, delay and accuracy metrics. The testbed settings and the use cases will be the same with the ones provided to evaluate the performance of the monitoring module.

Finally, we will evaluate the network performance of our complete Wi-5 system, considering the spectrum efficiency, energy saving and the QoE performance metrics, by utilizing the same testbed settings that will be utilized to measure the performance of the network configuration module.

More detailed information regarding the testing of the complete Wi-5 system will be provided in future documents.

6 Conclusions

This document has presented the definition of the tests to be executed to assess and validate the performance of the SDN based Wi-5 architecture and the description of the testbed which will be employed to execute the performance tests.

The Wi-5 SDN platform has been briefly summarized with the smart and cooperative functionalities provided by the SDN based Wi-5 architecture. The descriptions of the Wi-5 APs and the Wi-5 controller have also been provided by considering the modular approach that is taken to model them. The Wi-5 APs and Wi-5 controller are modelled using a modular approach having the goal of facilitating construction of the system by decomposing it into independent, interchangeable modules, such that each contains everything necessary to execute only one aspect of the desired Wi-5 functionality.

After describing the Wi-5 APs and Wi-5 controller, we have defined the implementation strategy of the Wi-5 functionalities. Specifically, Wi-5 APs are modelled as a combination of elements of the monitoring module and the network configuration module, whereas the Wi-5 controller is composed of elements of the monitoring module, the decision module, and the network configuration module. The monitoring module is responsible for monitoring the status of the network with the real-time service types of users/flows. The decision module processes the input provided by the monitoring module and triggers decisions for the Wi-5 algorithms such as interference management, smart AP selection, load balancing, seamless handover, packet grouping. Then the decision module provides the configuration that is determined by the Wi-5 algorithms to the network configuration module. The network configuration module implements the configuration in terms of as switching the channel of an AP, handing over the client from one AP to the other, and the grouping of the packets to efficiently utilize the airtime.

In order to integrate the smart and the cooperative functionalities in terms of assembly of the modules outlined above, Wi-5 integration strategy has been defined and explained. Wi-5 integration strategy is implemented in three phases. In the first phase, we assemble the monitoring and the decision modules to obtain control module –version 1 and we can then verify the accuracy of the Wi-5 algorithms. In the second phase, we assemble the decision and the network configuration modules to get the control module – version 2. This process is can be carried in parallel with the integration- phase 1. If we do not conduct the second phase in parallel with the first phase, in the third phase, we assemble the control module- version 1 and the network configuration module to obtain the complete Wi-5 controller which we call control module- version 3.

Finally, we have provided definitions of the tests we will execute to assess and validate the performance of the monitoring, decision and network configuration modules.

The metrics for testing the monitoring module are scalability, delay and accuracy. The performance of the monitoring module will be evaluated by employing a testbed consisting of one Wi-5 controller and a changing number of Wi-5 and legacy APs with SOHO, dense apartment building, airport/train station, and pico-cell street use cases. While evaluating and validating the performance of the monitoring module, we will consider the measurements directly taken from the field, measurements taken by employing the test-bed, and measurements taken from simulations.

In order to evaluate the performance of the decision module, we will inject the input provided by the monitoring module into the Wi-5 simulation code. This monitoring information could be in terms of measurements information taken from the field trials or from the indoor test-bed or the simulation input provided by the simulation tool such as OPNET. We will evaluate the performance of the Wi-5 functionalities utilizing the evaluation metrics such as the average user satisfaction, average provided data rate, average number of dropped connections, average interference levels, average SINR and spectral efficiency.

The performance of the network configuration module will be evaluated after applying the output of Wi-5 algorithms to the controlled test-bed, field trials and simulations based on spectrum efficiency, energy saving and the QoE with the use cases that are considered for the evaluation of the monitoring module.

After completing the testing of each module, the performance of the whole Wi-5 system will be evaluated gradually by replacing the simulation algorithms with the functionalities provided by the Wi-5 controller and Wi-5 APs in realistic environments with respect to the spectrum efficiency, energy saving and QoE performance metrics.

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