“”

What to do With the Wi-Fi Wild West

Deliverable	D5.2
Title	Integration Results
Date	30 April 2018
Milestone	MS6
Authors	Omer TOPAL (AirTies, Editor), Jose Saldana (UNIZAR), Alessandro Raschella (LJMU), Jan de Nijs (TNO)
Reviewers	Salim Eryigit (AirTies) Faycal Bouhafs (LJMU), Michael Mackay (LJMU), Qi Shi (LJMU)
Approved by	General Assembly
Dissemination	Public

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.

In this document, we present the integration methodologies and provide the integration test results of the developed functionalities of Wi-5. The integration of the functionalities is being developed within Work Package 5. 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 applied in Wi-5 APs and the Wi-5 controller. According to this approach, we will describe the functionalities of both the Wi-5 APs that are 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. Following this, we will define and explain the Wi-5 integration strategy that was utilized to integrate the smart and cooperative functionalities in terms of assembly of the modules utilized to model the Wi-5 AP and the Wi-5 controller.

The integration approach and steps of the proposed functionalities are then given and the limitations that have been faced during the integration progress of the functionalities are clearly explained in each subsection. Moreover, the design criteria and possible evaluation approaches of such non-integrated functionalities are explicitly provided. During the integration process, coordinated work between WP3 and WP4 was carried out and, after the feedback was shared for WP5-WP3 and WP5-WP4, some novel innovations and contributions are introduced. The online integration approach for the channel assignment algorithm of the radio resource management solution is proposed, and integrated as a product of this mutual feedback. Also, the proactive handover application for seamless handover functionality is another product of this collaboration.

After the integration process, the test definitions and evaluation results of the integrated functionalities are presented. Also, the available test metrics and network deployments for each of the functionality tests are provided. The test results prove that the proposed functionalities perform well in meeting the design objectives. We observe that the Wi-5 solutions give the expected performance gains in most of the conducted test cases.

Wi-5 Consortium

LIVERPOOL JOHN MOORES UNIVERSITY	Liverpool John Moores University	2 Rodney Street Egerton Court Liverpool, L3 5UK United Kingdom
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek	Anna van Buerenplein 1 2595 DA Den Haag Netherlands
Universidad Zaragoza 1542	Universidad de Zaragoza	Calle Pedro Cerbuna 12 Zaragoza 50009 Spain
AirTies	AirTies Kablosuz İletişim San veDış. Tic. A.Ş	Mithat Uluünlü Sokak No:23 Esentepe, Şişli P.K 34394 İstanbul Turkey
PRIMETEL	PrimeTel PLC	The Maritime Center, 141 Omonia Avenue, 3045 Limassol, Cyprus

Contents

List of Figures

List of Tables

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

This document presents the integration approach and evaluation results of the whole Wi-5 solution. A collaborative process with WP3 and WP4 was performed to enhance all the developed functionalities. The integration model that is based on a modular approach to perform these functionalities is detailed in the document. The advantages of this modular approach are also explained in the related sections. The works carried out to integrate the radio resource management (RRM,) Seamless handover, Vertical Handover, Packet Grouping, Load Balancing and Smart AP Selection functionalities are explained in detail. The roles of the monitoring, decision and network configuration modules are given for each of the functionalities, and detailed information on the integration process of each functionality is explained using a stepwise approach. Moreover, the requirements and limitations for the integration of the functionalities are provided in each module explanation.

Several contributions to the Wi-5 project as a product of the collaborative works with WP3 and WP4, which are a proactive handover application and online integration of the channel assignment algorithm, are also explained in the document. The proactive handover algorithm was suggested during the evaluation of the existing handover application for seamless handover functionality. In the proactive handover, the motivation was to scan the environment periodically rather than requiring a trigger event as in the reactive handover application. The handover decisions are made after each scan operation is performed. As a result, this new approach provides a better decision mechanism. The online integration of the channel assignment algorithm was suggested once the offline channel assignment algorithm was already evaluated. In the previous application, the data between the monitoring and decision modules was transferred manually via text files. In other words, the data is manually imported into the MATLAB code so that the algorithm works. However, while this earlier approach was sufficient for testing, it brings high delays and impracticality to take place in a realistic setting. Moreover, our motivation, integration approach, advantages and performance enhancements of this new approach are explicitly discussed in the document.

After the integration work, the evaluation results of all the functionalities are presented. The tests were carried out mostly in Airties' Mecidiyeköy test house, which provides a centrally controlled platform for the Wi-5 project. The definitions of the tests are re-created and designed as functionality-specific process according to the design objectives of each functionality. During the tests, throughput, delay and RSSI measurements were used in the performance evaluations of the functionalities. Each of the test definitions is evaluated against the deployment schemes and the expected outcomes in order to achieve a better understanding of the design objectives of the Wi-5 solutions.

Finally, the integration results demonstrate that the Wi-5 solutions provide massive performance improvements in many different challenging conditions where a traditional Wi-Fi may suffer in terms of data rates, delays and connectivity.

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 utilization of non-licensed frequency bands, so improvements continue to be added to the standards in order to improve performance and adapt it to increasing demand. For example, as Wi-Fi saturation increases in areas, such as business centers, 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 that are able to efficiently reduce interference between neighboring APs and provide optimized 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 optimize 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 logical integration steps and performance evaluation results of the proposed Wi-5 solutions. 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 an explanation of the integration steps of the smart and cooperative solutions that are provided by the Wi-5 architecture. Moreover, the implementation strategy for these solutions will be explained, considering the modular approach that was taken to model the Wi-5 APs and controller. Finally, the performance of the proposed Wi-5 solutions is evaluated with the help of tests conducted within the integrated testbeds and simulation environments.

1.3 Document structure

After the introduction, a description of the Wi-5 SDN platform is provided in Section 2. Section 3 describes 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 terms of assembly of the modules utilized to model the Wi-5 APs and Wi-5 controller. In Section 4, we will give the details of the integration process and the performance evaluation results of the smart and cooperative functionalities. Finally, Section 5 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 the integration process to be utilized to assess and validate the Wi-5 architecture with the use cases and requirements defined in D2.3.

D2.5: The final version of the Wi-5 architecture was presented in deliverable D2.5 "Final Wi-5 architecture" which 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 the present deliverable, we will provide the integration approach and the performance evaluations of the proposed Wi-5 solutions.

D3.1: In this deliverable, the Wi-5 monitoring functionalities are reported. This not only includes the features that are 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 D5.2, the accomplished steps and limitations of the integration processes of the functionalities are mentioned, most of which are in closer relation with D3.3.

D3.4: The final specification for the Smart AP Selection and Packet grouping functionalities is included in this deliverable. In addition, the initial measurements of the functionalities are provided here. In D5.2, we will refer to some of the work done here, especially for Packet Grouping and Smart AP selection functionalities, since the most of the work is described in detail in D3.4.

D4.2 and D4.3: The Cooperative Functionalities being deployed in WP4 are explained in detail in Deliverable D4.2 "Specification of Cooperative Access Points Functionalities version 2" and Deliverable D4.3 "Final Specification of Cooperative Functionalities". Like the smart functionalities, the implementation and integration steps of these 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.

D5.1: The initial integration strategies which define a modular approach, along with the definitions of the testing and test metrics are included in this deliverable. D5.2 is an extension of D5.1, therefore, it utilizes the structure for a modular approach, testing strategy and testbed definition given in D5.1 [1].

2 Description of Wi-5

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. A more detailed description of this platform in terms of its specific functionalities can be found in deliverables D2.5 [21], 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 these APs, which simplifies the development and deployment of 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 Wi-5 controller which has a number of algorithms making decisions on the configuration of the Wi-Fi network.

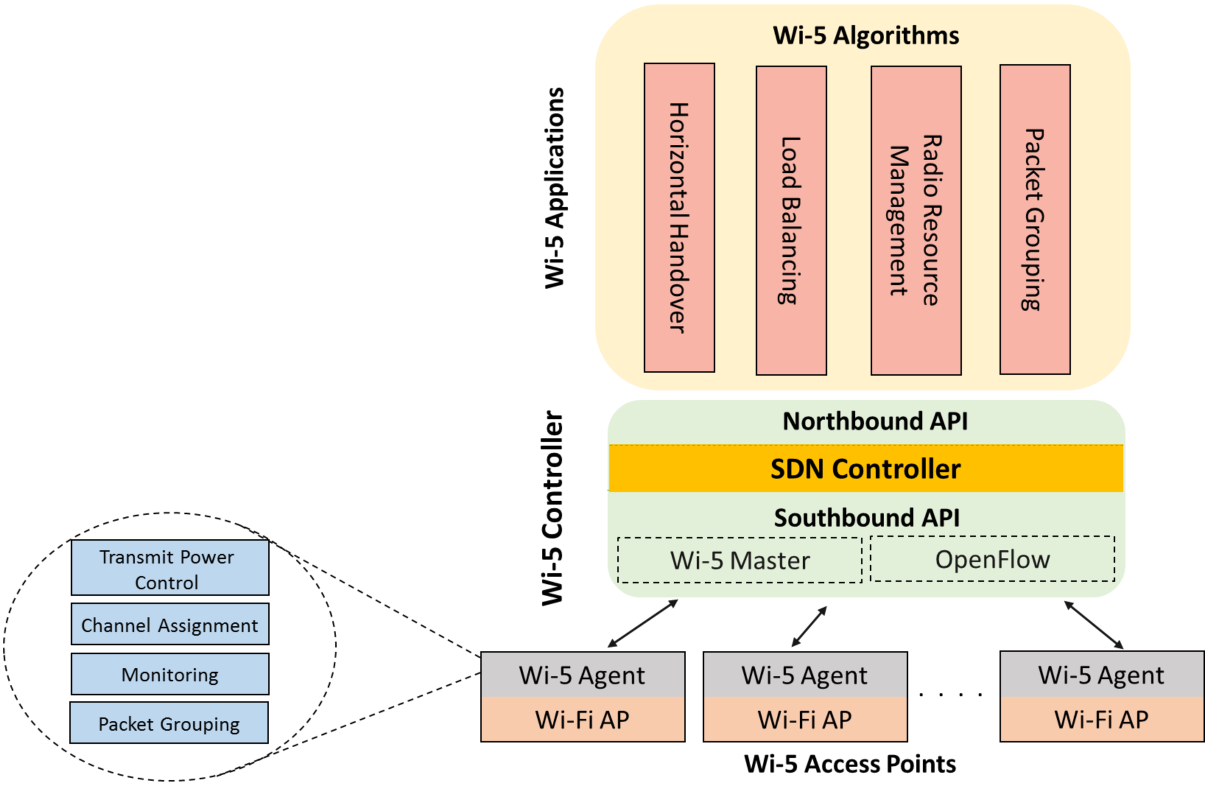


Figure 1: The global view of Wi-5 SDN platform

The 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 configuration of the radio-specific parameters, monitoring of the wireless network status, and the Service Set Identifier (SSID) association process.

The southbound API allows the Wi-5 controller to apply the necessary wireless network configuration generated by the Wi-5 functionalities. In order to achieve this, an extension of the OpenFlow protocol, which is called the Wi-5 master, is deployed to communicate with 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, seamless handover 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 management, processing and storage of the monitoring information that are necessary for the implementation of the Wi-5 functionalities. A more detailed description of the overall architecture is presented in deliverable D2.5.

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

- Smart Functionalities that aim to improve the performance of Wi-Fi networks by means of radio configuration capabilities, including dynamic channel assignment, seamless handover, 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 APs under different management algorithms, 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 realization of horizontal and vertical handovers.

Both the 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 will allow them to better manage the wireless spectrum and adapt to changing conditions. Fine-grained 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 based on their transmit power, change their transmission frequency, or both, according to the observed spectrum utilization and the bandwidth requirements. Another contribution of these functionalities is to optimize the utilization of the spectrum through packet grouping. These smart functionalities can be summarized 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.

- **Seamless Handover**: This functionality allows APs to seamlessly move STAs between different APs, even if they operate in different channels.

- **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 maximizing the aggregate data rate of these networks and to distribute the load evenly between APs.

- **Packet Grouping**: This functionality will enable packet grouping between a 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] and D3.4 [19].

2.2 Cooperative Functionalities

Enabling cooperation between Wi-Fi APs or 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 solution that can provide benefits through cooperation between wireless networks. An optimal radio configuration that can minimize the effects of interference while maximizing the network capacity can only be achieved if the operators of different 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 summarized as follows:

- **Radio Resource Management**: In this functionality, APs will cooperate to find an optimal radio configuration that reduces the effect of interference on the QoS of connected devices.

- **Smart AP Connectivity (Horizontal Handover)**: This functionality will assist wireless devices in choosing the most suitable AP according to the application running on the device. It takes into account the quality of the link, the network capacity and the bit rate requirements.
- **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.

A detailed description of the Wi-5 cooperative functionalities is provided in deliverables D4.2 [3] and D4.3 [20].

3 Integration Approach of Wi-5

As described in D5.1, 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.

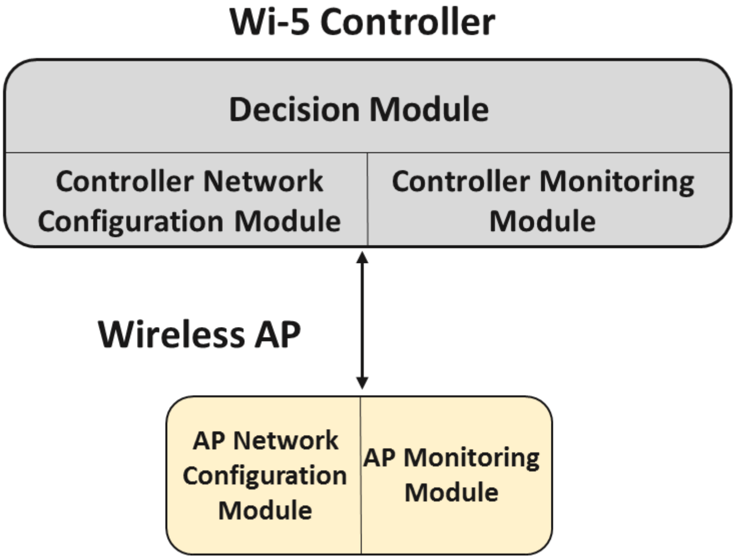


Figure 2: Diagram describing the modular implementation approach in Wi-5

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

The decision module is located in the Wi-5 controller and is responsible for processing the input provided by the monitoring module. This will be done by the Wi-5 smart and cooperative functionalities, such as the RRM algorithm, smart AP selection, load balancing, seamless handover and packet grouping. It then provides output to the network configuration module.

The network configuration module will be responsible for the implementation of the configuration obtained through execution of the algorithms in the decision module and related to the smart functionalities such as switching the channel of an AP, moving a wireless client from one AP to another, and enabling packet grouping where appropriate. This module will be located on both the Wi-5 controller and the Wi-5 APs.

Before providing a description of these modules, we can summarize our strategy to implement the smart and cooperative functionalities within the designed modules, as shown in Figure 3.

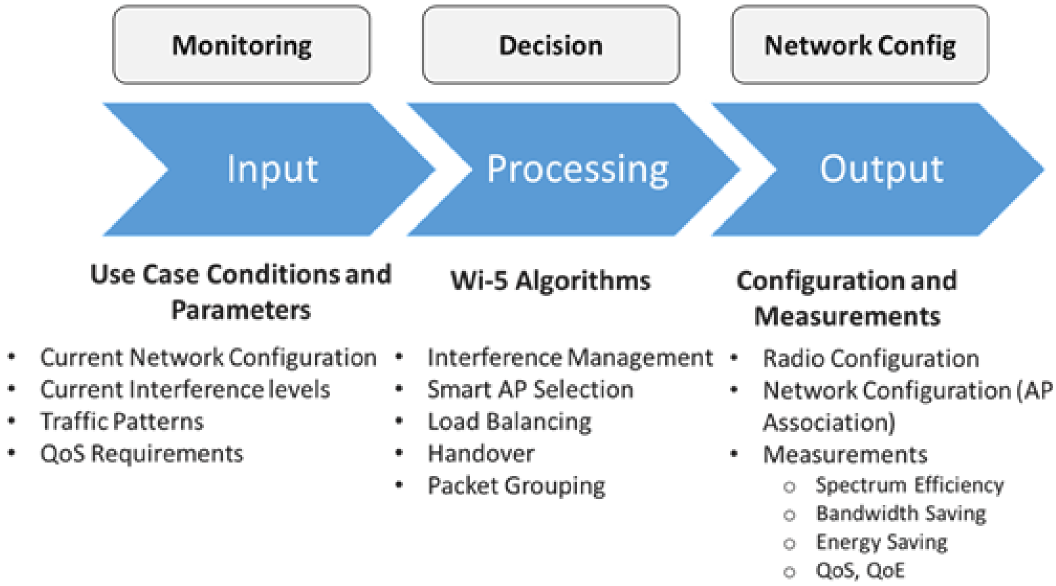


Figure 3: Wi-5 Implementation Strategy

The roles of the modules will be based on 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, QoS requirements in terms of the bit rate and latency requirements of user services will be provided by the monitoring module to the decision module as an input. Moreover, in the monitoring module, Wi-5 agents will track the interference levels sensed at each AP from the other APs 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 based on the statistics, use case conditions and parameters provided by the monitoring module. These Wi-5 algorithms were developed to implement the cooperative functionalities such as smart AP selection, horizontal handover and radio resource management, relying on the smart functionalities such as dynamic channel selection, monitoring procedures and seamless handover.
- The output of the Wi-5 algorithms will be applied in terms of network configuration of the Wi-5 APs and their assignment to the users. These configurations will be evaluated and validated by measuring performance parameters such as the throughput and delay.

We have implemented and integrated the RRM and AP selection algorithms, Load Balancing and Seamless handover functionalities utilizing the SDN based Wi-5 platform. However, the packet grouping functionality has not been integrated since the approach is designed for running in simulation environments and research implementations do not exist.

An integration strategy of the modules was introduced in the section 4 of D5.1. The proposed strategy includes a phase-wise approach which forms versions of the controller by integrating a combination of two of the three modules in a queue for any functionality. The aim of doing this was to alleviate the difficulties of the integration process for the testing and development process. Furthermore, the integration strategy proposed for this was implemented in three phases. In the first phase, the control module version-1 was obtained with the assembly of the monitoring and the decision modules. For the second phase, the strategy was to assemble the decision and the network configuration modules in parallel with the phase-1. And lastly, in the third phase, the situation of phase-2 not being carried out in parallel with the first phase was considered. This phase assembles the version-1 of the controller and the network-configuration modules to complete the Wi-5 controller, which was named as version-3. Moreover, a trial example of this phase-wise strategy was demonstrated for the Channel assignment application in the remainder of section 4 of D5.1.

However, after reflecting on our experiences with this practical integration, we decided to follow a slightly different strategy from the previously proposed phase-wise process identified in D5.1. For the rest of the integration process, our methodology was to integrate all modules of the functionalities in a single phase each time. The aim of doing this was to reduce the time overhead of testing phases separately and to give a clear demonstration of structures of the modules.

The integration of the RRM algorithms includes the utilization of MATLAB as a part of the decision module. The details of this integration process will be explained in the next sections. Further details related to the status of the implementation of the smart and cooperative functionalities and the individual performance evaluation results are provided in deliverables D3.3, D4.2 and D4.3, respectively.

3.1 Monitoring Module

In order to implement the smart and cooperative functionalities defined in Section 2, the monitoring module is in charge of providing 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 at each AP from the other APs at the available channels in the considered frequency bands.
- The number of users/flows associated with each AP.
- The quality of the link, therefore, the bit rates available for users/flows.
- Bit rate and latency requirements of user services.

As we have illustrated in Figure 2 and explained in Section 2, the monitoring module consists of two parts: one part resides in the Wi-5 controller and the other resides in the Wi-5 APs.

3.1.1 AP Monitoring Module

The Wi-5 agents running on the Wi-5 APs are in charge of collecting the monitoring information. 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*. The *radiotap* header format is a mechanism to supply additional information about frames from the driver to user space 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 includes the signal strength of the reception, the bit rate or the Modulation and Coding Scheme (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 is in charge of gathering the collected data by the Wi-5 APs and storing them. The monitoring module will be able to access the information through the SDN southbound API.

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

- Received power at each AP from the other APs.
- 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.
- 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 is responsible for triggering decisions using the Wi-5 algorithms based on the statistics provided by the monitoring module. These Wi-5 solutions are designed in order to implement the Wi-5 functionalities such as smart AP selection, horizontal handover and RRM management developed in the context of WP4, as well as load balancing, seamless handover and packet grouping developed in the context of WP3. The processing mechanisms of these functionalities are briefly summarized in the following subsections, while more detailed information can be found in D3.3 [2], D4.2 [3], D4.3 [20] and D3.4 [19].

3.2.1 Seamless Handover

Seamless handover considers the case where the STA is steered from one AP to another due to mobility of the STA throughout the network. In the Wi-5 framework, the Light Virtual Access Point (LVAP) concept 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. In the seamless handover functionality, both reactive and proactive handover approaches are proposed with the aim of utilizing the best AP during the mobility.

For the reactive handover, the decision module triggers the seamless handover decision 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. We consider the case where two Wi-5 APs operating on different or the same 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.

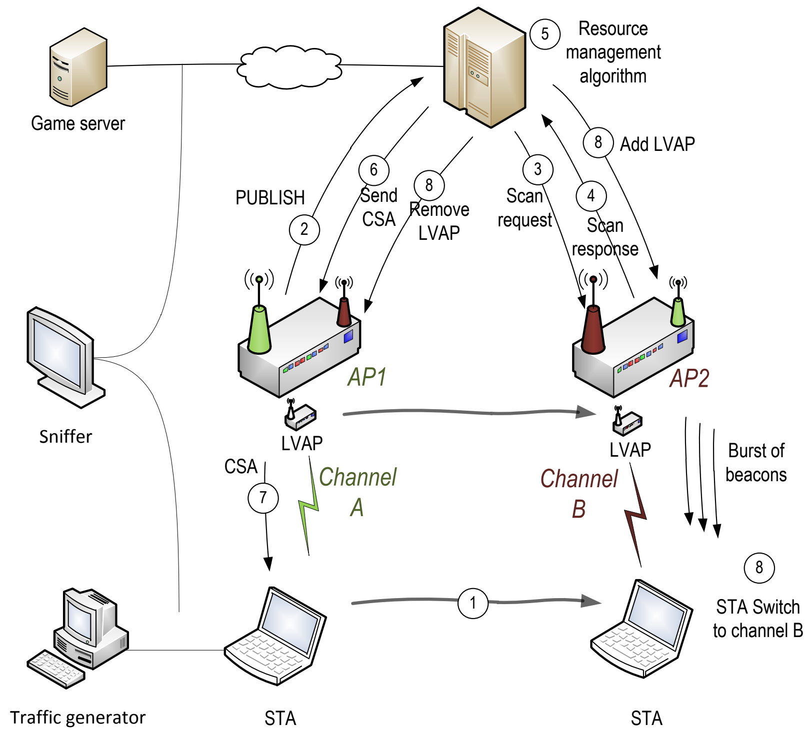


Figure 4: Description of the handover testbed used in Wi-5 integration and testing

In the Proactive handover, the triggering mechanism in the decision module is different from the reactive handover approach. Instead of triggering the decision module upon the RSSI criteria provided, the decision algorithm is now executed periodically to identify the best-placed APs while the STAs are moving. By doing this, the old values of measurements are evaluated within a weighted factor with the new measurements. The main objective of doing this is to increase the stability and accuracy of the decisions. The remaining parts of the proactive handover process is same as in the reactive handover application.

3.2.2 Load Balancing

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

The decision module triggers this functionality 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. As above, 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 APs. 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 load balancer in coordination with the proactive seamless handover functionality is run by the decision module to assign a Wi-5 AP to the STA. The Load balancing functionality should work together with the seamless handover functionality since any independent decision of load balancing has the risk of ping-pong effect in the case of activated seamless handover.

3.2.3 Smart AP Selection and Horizontal Handover

The smart AP selection algorithm is based on the Fittingness Factor (FF) concept introduced here [10], which is in charge of associating a Wi-5 AP to each new STA/flow considering its bit rate requirements. The first version of the algorithm presented in deliverable D4.1 is based on the Network Fittingness Factor metric, which efficiently addresses the QoS requirements of both a flow joining the network and other flows active in the network. A more detailed description of the algorithm is provided in deliverable D4.2 [3]. This algorithm has been then extended and presented in deliverable D4.3. In detail, the extended version is based on a centralized potential game, which still relies on the FF concept, and that allows an optimized distribution of the Wi-5 STAs among the Wi-5 APs. Note that both versions of the algorithm allow horizontal handover of the STAs towards new APs when needed, for instance when a user connected to the network needs to change his/her connection to another AP if the current one can no longer provide the QoS requirements for a certain application.

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 which includes the bit rate provided by each Wi-5 AP connected to the network depending on the radio environment and required bit rate of the connection requesting STA. Details on the computation of this information can also be found in deliverables D3.4 and D4.3. 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.

3.2.4 Radio Resource Management

The RRM algorithm addresses interference in Wi-5 networks by combining both channel assignment and transmit power adjustment techniques.

The channel assignment process is based on an objective function which reduces the magnitude of the interference in the whole Wi-5 network that is called *interference impact*. This strategy allows the Wi-5 controller to select the optimized 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 in a reactive manner due to a change of status in the network, e.g., when one or more APs change their channel.

If the channel assignment is triggered proactively by the decision module, the monitoring module in the controller provides the power levels measured at each Wi-5 AP in the network from the other Wi-5 APs, which are used to compute the path loss values between each pair of APs. This measured information is obtained from the RSSI measurements gathered from the monitoring module in each AP through the southbound API and sent to the Wi-5 controller. Then, the decision module determines the best channel configuration for each of the APs in the network utilizing the path loss values provided by the monitoring module in the controller as one of the input of the channel assignment algorithm. A detailed description of this algorithm and the use of the path loss as an input can be found in deliverables D4.2 [3], D4.3 [20], and D3.4 [19].

Channel assignment could also be triggered reactively 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 if the deviation of the accumulated interference impact level throughout the network provided by the monitoring module is above a configurable threshold as explained in detail in deliverable D4.2 [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. Moreover, the integration of this application could be in done in two ways, per AP level and per packet level. In the AP level power adjustment case, the system adjusts the transmit power of the APs for all of their transmitted packets. However, in the per packet power adjustment case, the system adjusts the transmission power of APs for each packet to be transmitted, separately. The details of the process and configurations are given in the next sections. In addition, an explicit explanation can be found in the D3.3 [2].

The monitoring module in the Wi-5 controller is in charge of collecting the required bit rate of the connection requesting STA 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 consists 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 information to the AP, and another residing in the Wi-5 AP to enforce it. Below, we will provide brief descriptions of the functionalities of the network configuration modules in the Wi-5 controller and the Wi-5 AP. Then, we will discuss how the radio and network configuration will be implemented on a per-AP and per-packet basis respectively.

3.3.1 Controller and AP Network Configuration Modules

The controller network configuration module programs 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.

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. The implementation of the network configuration functionality includes management of channel switching, transmit power setting and transmission rate settings of the Wi-5 AP. Besides the configuration of these 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.

3.3.2 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 Wi-5 APs running OpenWRT utilize *hostapd* as the 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

The *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 the Wi-5 APs running OpenWRT. 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 also 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>

3.3.3 Configuration of the per-Packet Network Parameters

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, Transmit Power Control (TPC) can be combined with routing and the MAC layer to minimize the interference.

The Click modular router provides 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 with the provided annotations. 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 will then 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 file system of the *ath9k* driver can 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 Integrating and Testing of Wi-5

4.1 Overview

The Wi-5 project aims to satisfy high user demands in terms of the data rate, connectivity and delay through the proposed functionalities. In this section, we present the details of the integration and the performance evaluations of these functionalities through a real-time testbed. The integration structure is composed of the Monitoring, Decision and Network Configuration modules, which depend on each other to form a consistent system as we have explained in Section 3. The key factors for the implementation and integration process of the proposed functionalities are the limitations and requirements of the modules. Each module requires some set of information, application and hardware suitability to implement.

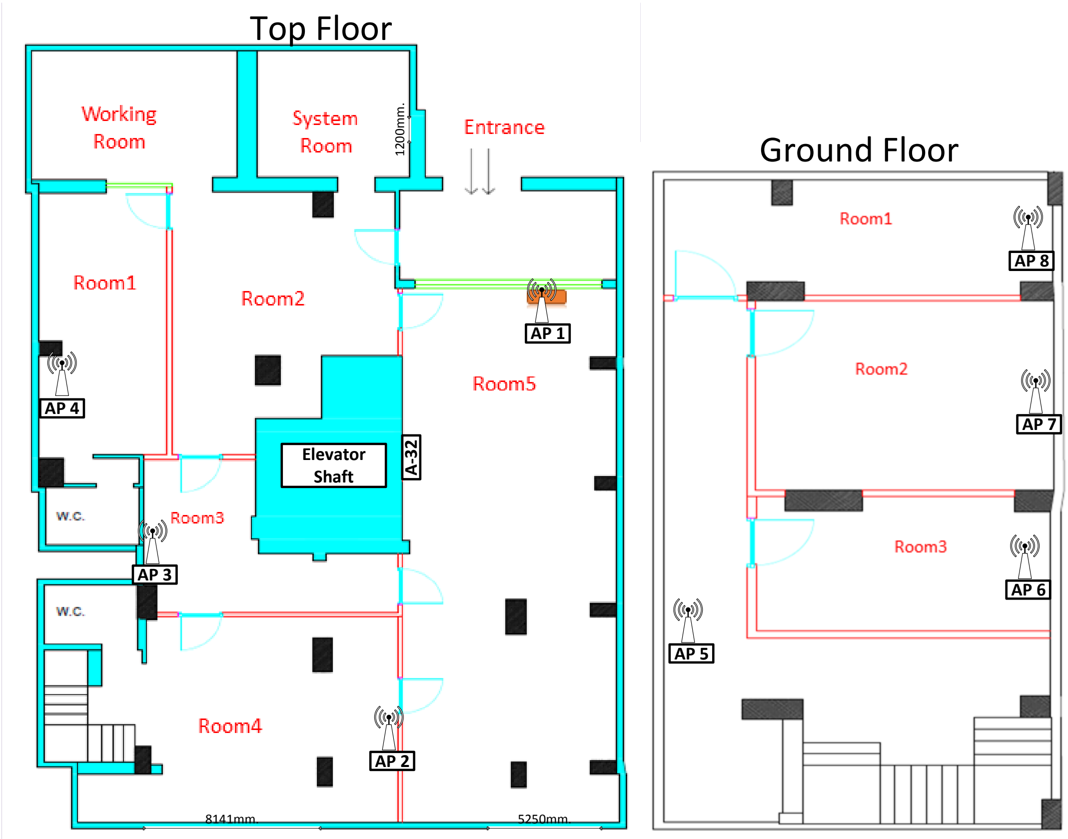
The possible use cases of the Wi-5 project were introduced in D5.1 as Large Home/SOHO, Airport, Pico-cell street deployment, Dense Apartment building and Community WiFi Networks. However, in practice we could only test the project in the SOHO and Community Wi-Fi Networks due to a late partner change during the project, resulting in the non-availability of the other environments. In this document, we will give the evaluation results of the Wi-5 functionalities for the SOHO use case. Moreover, Primetel has conducted field trial tests in a Community Wi-Fi Network use case and the results of that work are represented in D5.3 [22]. We have also extensively modelled and simulated the effectiveness of our solutions in the Dense Apartment building use case, which was first presented in D2.2 [18], and in a large shopping mall which approximates the Airport use case in D4.3.

In D5.1, the testing strategy was outlined as testing the monitoring, decision and network configuration modules separately in addition to the system performance evaluations. However, after gaining some experience through practice, we decided to skip the module testing of some of the functionalities in order to save time and make a contribution by evaluating the system performance of the functionalities more extensively. For instance, we will evaluate the channel assignment algorithm of the decision module via MATLAB to validate the performance of the algorithm in a real testbed. Furthermore, many further algorithm evaluations of the functionalities via simulation can be found in D4.2 and D4.3.

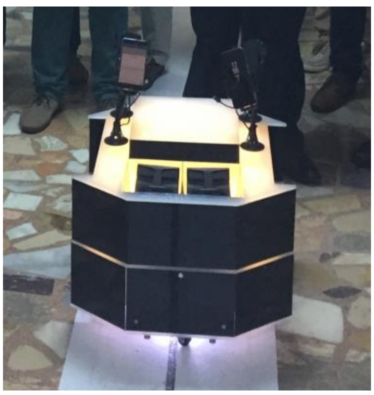
The evaluation process of these integrated system functionalities covers performance evaluations both via simulation and in a controlled testbed as planned in D5.1. For the evaluation of the functionalities, although several metrics were previously proposed and tabulated in Deliverable D5.1 [1], as illustrated also in Figure 3, some aspects to be measured during the integration of the smart and cooperative functionality tests have not been considered in our real devices. For instance, in order to assess the integration of the works carried out in the context of WP3 and WP4, we can provide QoS in terms of throughput, delay and RSSI measurements. Moreover, we introduce some functionality-specific evaluation metrics which have been useful in the evaluation process such as handover delay and average number of handovers for the seamless handover functionality. Nevertheless, some previously proposed metrics such as SINR, bandwidth saving and energy saving cannot be measured in practice due to both hardware and software limitations that we have identified in the proof of concept implementation. Other metrics such as spectrum efficiency and QoE have been addressed during the field trials and are illustrated in deliverable D5.3 [22].

Most of the tests for the SOHO use case, i.e. RRM, Seamless Handover, Load Balancing and Packet Grouping, are conducted in Airties's Mecidiyeköy Test House, which is a two floor flat including many rooms and its layout is depicted in Figure 5a. The test house has sufficient infrastructure to control the Wi-5 system via the central controller and provides us a SOHO use case environment. In addition, during the proactive handover application tests, a line-tracking robot of Airties has been used, which is represented by Figure 5b. The path of the robot can be changed easily when any different routine is required for the experiments. Moreover, note that tests assessing Vertical Handover and Smart AP Selection have been carried out in collaboration with Airties by TNO and UNIZAR facilities, respectively.

In the following sections we will explain the integration process and testing of the functionalities and algorithms, which cover logics, modules, the integration process, and performance evaluations of the functionalities.



(a)



(b)

Figure 5: a) Airties test house layout b) Airties test robot

4.2 Integration and Testing of the Radio Resource Management

The Wi-5 Radio Resource Management (RRM) algorithm has been designed to focus on two main solutions to allow efficient use of the limited radio resources of Wi-Fi networks. These solutions are "Channel Assignment" and "per-flow Transmit Power Control (TPC)". The details of these solutions can be found in deliverables D4.2 and D4.3. During the implementation and integration of these solutions we have found that, due to some unexpected fundamental limitations, the per-flow TPC included in the RRM algorithm and successfully assessed in the MATLAB based simulator cannot be integrated and tested. The details of these limitations are explained in subsection 4.2.1.

Therefore, we have focused on testing the channel assignment algorithm which is based on an objective function that reduces the magnitude of the interferences between Wi-5 APs. The input of the algorithm is the power levels sensed by each of the Wi-5 APs from the other Wi-5 APs. The integration process of these solutions involves the monitoring, decision and network configuration modules as explained in the next subsections.

4.2.1 Monitoring Module

Each proposed algorithm described throughout this deliverable requires some monitoring information as input. For instance, the channel assignment functionality requires a matrix with path losses between each pair of Wi-5 APs as input to the algorithm. In order to compute such path losses, the monitoring module in each AP measures the RSSI level of the other Wi-5 APs by an auxiliary interface and shares them with the controller. The monitoring module included in the controller then stores this RSSI information and builds the aforementioned matrix with the path losses. Note that a detailed explanation of the computation of the matrix with the path losses can be found in deliverables D3.4 and D4.3.

The TPC functionality was initially designed taking into account the use of TPC request / report elements, defined in the IEEE 802.11h standards. The usage of this TPC signaling mechanism would provide per packet power control since the transmission power of each packet is embedded into it during the transmission. However, since the Wi-5 system is only capable of operating on the 2.4 GHz because of the implementation of the Click module router, the use of TPC request / report signaling, which only operates on 5 GHz band, could not be applied in the Wi-5 implementation. Therefore, the design perspective of the monitoring module was modified so that all the measurements are done by the AP itself, instead of gathering the data from TPC request/report signals. The transmit power information and RSSI measurements of the devices are gathered by the controller in the monitoring module. Guided by this, during the integration process we have considered the assessment of the RRM algorithm including our channel assignment solution and per-AP TPC, as explained in the rest of this section.

4.2.2 Decision Module

The role of the decision module in the channel assignment application is to assign channels to Wi-5 APs according to the algorithm developed in the context of WP4, which takes the path losses matrix retrieved from the monitoring module, together with the Wi-5 APs transmit powers. The inputs are provided to the channel assignment algorithm implemented in MATLAB, which gives the final channel assignments results to the system. In the previous deliverable D5.1 [1], an offline integration approach between the MATLAB code and Wi-5 controller has been proposed. In that strategy, the monitoring module measurements are manually transferred within text files to the MATLAB code.

As a new contribution for the integration of the channel assignment provided in this deliverable, an online integration approach has been proposed and integrated with the help of smart java libraries and MATLAB. Specifically, in the online integration, the MATLAB optimization code is converted into a java jar library that is called from the controller directly. Hence, the controller gets the output of the channel assignment algorithm without requiring any external intervention/manual work.

4.2.3 Network Configuration Module

Using the network configuration module, the system then applies the new channel assignment results provided by the decision module. For the channel assignment application, this module is only responsible for the automatic channel switching of the Wi-5 APs according to the channel assignments results based on the dynamic channel assignment functionality.

The network configuration module for the TPC application can adjust the transmit powers of the Wi-5 APs, which are also decided by the decision module. As we have previously explained, there is a limitation on the modification of the power at flow-level. Hence, although it is only possible to modify the power of AP in monitor mode, the implementation of the flow based power adjustment cannot be handled with the current state of the art system. Furthermore, we found that Click Modular Router provides the information to the driver of the wireless card, but the value of the transmit power is not supported by this driver. The problem is that the part of the driver that is parsing the *radiotap* header cannot read the transmit power field. Moreover, the Linux kernel used by OpenWrt 15.05 does not parse this either. A detailed explanation of this limitation and the implementation approaches for TPC have been explained in section 4.2.3 of Deliverable D3.3, *Adjustment of transmission power*.

4.2.4 Integration and Testing

4.2.4.1 Integration of the Radio Resource Management

Our proposed analytical model for the channel assignment relies on the interference impact, which embodies the contribution of a source signal in the experienced interference throughout the network. Below, we will clarify this quantity and explain the way it indicates the network-wide interference status.

We first need the monitoring module to provide the signal strength from each AP measured by the other APs of the system to compute the path losses matrix. Once we obtain the path losses matrix, we can consider online integration for assembling the modules. Figure 6 gives the scheme of the online integration which increases the usability and speed of the Wi-5 channel assignment within real environments. The integration scheme of all modules for the channel assignment is represented in Figure 7.

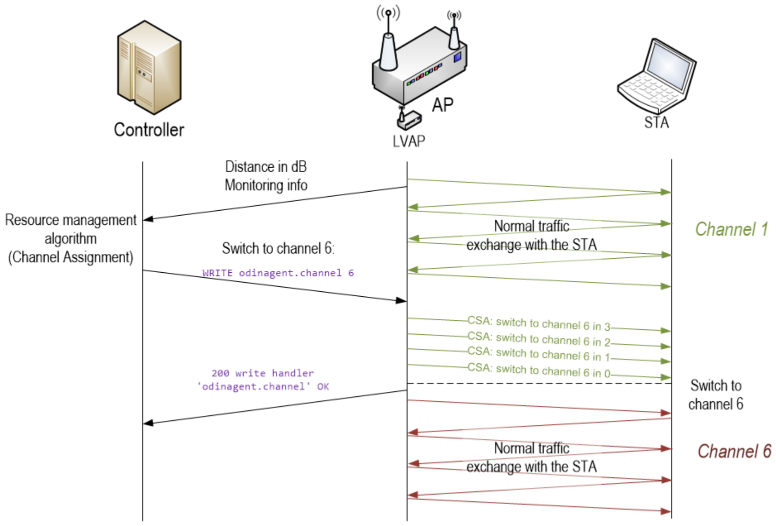


Figure 6: The scheme of the Wi-5 Channel Assignment

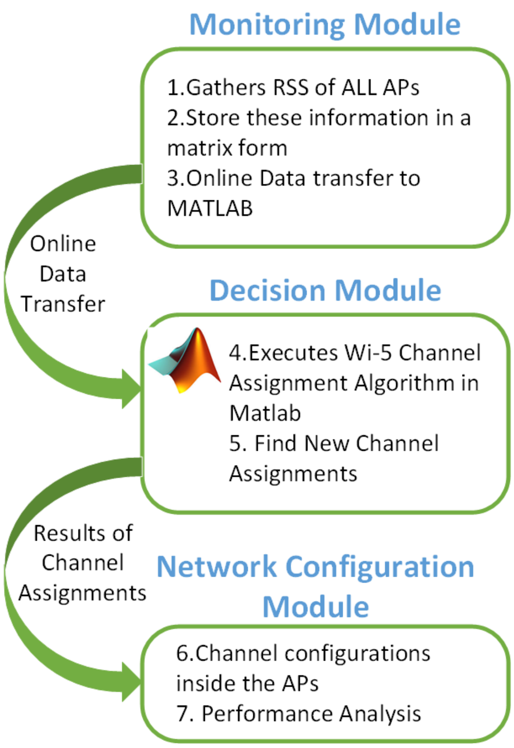


Figure 7: Integration of Modules for Channel Assignment

The steps of the online integration are provided below:

1. Wi-5 agents in each AP measures 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 are obtained, the monitoring module in the Wi-5 APs delivers this information to the monitoring module in the Wi-5 controller through the southbound API.
3. The monitoring module in the Wi-5 controller calculates the path loss values corresponding to each link and stores these values in a matrix.

4. The monitoring module inside the controller then sends the data to the decision module which includes the MATLAB code that executes the channel assignment algorithm.
5. Using online integration, the data flows between MATLAB and the controller are applied automatically. In the implementation of the online version, MATLAB optimization code is converted into a java jar library, which makes the connection between MATLAB and the controller.
6. Channels are assigned to each AP, by triggering the Wi-5 channel assignment algorithm and the Least Congested Channel (LCC) algorithm [11] (considered for comparison purposes) seperately, and applied to the APs connected to the Wi-5 network as an output of the decision module using the "*chan_switch*" function of "*hostapd_cli*", and through the southbound API utilizing the OpenFlow protocol.
7. After applying the assigned channels in the network via the network configuration module, the performance analysis of the channel assignment algorithms is performed.

4.2.4.2 Testing of the Radio Resource Management channel assignment algorithm

In order to evaluate the performance of the proposed channel assignment included in the RRM algorithm, several tests have been conducted considering different cases. These tests have been developed in scenarios with different coverings of interference ranges among the APs. The performance evaluation metric for this algorithm is based on throughput measurements. The tests were carried out in AirTies's Mecidiyekoy Test House. The test house is a two floor apartment with its layout given in Figure 5a and APs can be placed in 8 different locations as shown in the figure. In the following, we will give the details of the test cases and performance evaluations of the channel assignment functionality.

The channel assignment algorithm is evaluated in many different coverage cases through the MATLAB code implemented in the decision module.

Furthermore, some validation and verification tests are also performed by using MATLAB together with artificially generated path loss matrices, without a real testbed. In the following we first provide the results of the validation and verification tests, after which the results for performance tests at AirTies' test house are given.

In the first case, three APs are deployed considering the overlapping coverage depicted in Figure 8 where the dashed lines represent connectivity. The MATLAB script to perform this experiment is given in Script 1. The script generates 100 path losses matrices. Each entry in the matrix is randomly generated according to normal distribution with mean 50 and standard deviation 10, except for the diagonal entries that are zero. Then, the Wi-5 channel assignment algorithm is executed with this path loss matrix and the results are explained in the rest of this subsection.

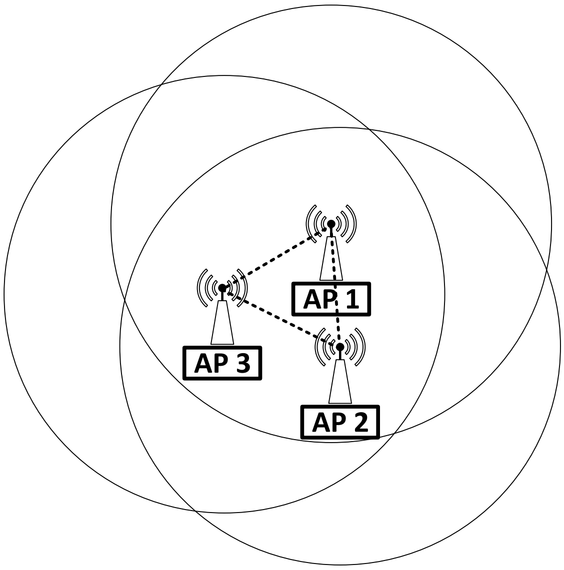


Figure 8: Channel Assignment Test Case with 3 APs within each other's range, Case 1

```
n=3;
mean_pathloss=50;
sigma_pathloss=10;
for i=1:100
      A=(randn(n,n)*sigma_ pathloss +mean_ pathloss) .* (ones(n,n) -
      diag(ones(1,n),0));
      res=getChannelAssignments(A,1);
      res
end
```

Script 1: Three overlapping AP – Case 1

For the 100 times of evaluation, the Wi-5 algorithm provides the following channel assignment:

AP1	**AP2**	**AP3**
1	6	11

The results were as expected since with this simple scenario, we would have expected to see some permutations of the {1, 6, 11} channel assignment, e.g. {6, 11, 1}.We have also used the symmetric versions of the path loss matrix, and always obtained the same result with the asymmetric version. Furthermore, there is no randomness within the output of the algorithm.

In the second case, four APs are deployed as illustrated in Figure 9. Note that the scenario has been developed in order to reduce the overlap between areas covered by AP1 and AP4. The MATLAB script for this experiment is given by Script 2. The only difference between Script1 and Script2 is the addition of the high path losses between the edge APs (i.e., AP1 and AP4).

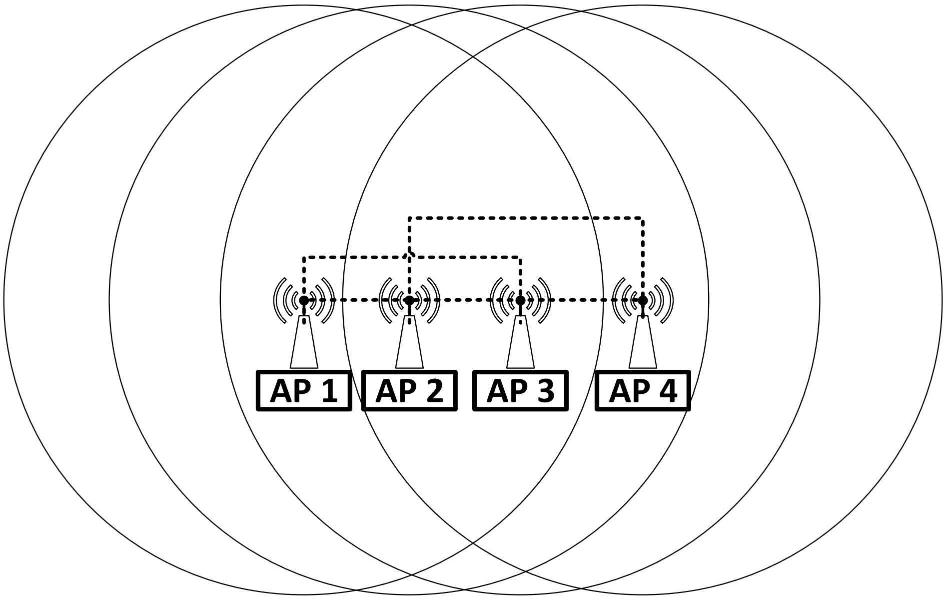


Figure 9: Channel assignment test case with 4 APs, Case 2

```
n=4;
mean_pathloss=50;
sigma_pathloss=10;
for i=1:100
      A=(randn(n,n)*sigma_pathloss+mean_pathloss) .* (ones(n,n) -
      diag(ones(1,n),0));
      A(1,4)=150; A(4,1)=150;
      res=getChannelAssignments(A,1);
      res
end
```

Script 2: Fours APs with non-overlapping coverage – Case 2

For this non-overlapping deployment case, we expect to have an assignment of different non-overlapping channels for AP1, AP2 and AP3 in order to obtain a minimum adjacent channel interference among the APs. Similarly, we expect the assignment of non-overlapping channels across AP2, AP3 and AP4. For instance, a possible expected channel assignment could be {1, 6, 11, 1}.

On the other hand, the Wi-5 channel assignment algorithm provides the following assignment:

AP1	**AP2**	**AP3**	**AP4**
1	6	1	11

We have also used the symmetric versions of the path loss matrix, and always obtained the same result. As can be found in the deliverable D4.2 [3], in order to address the interference problem in dense IEEE 802.11 WLANs, we have defined the network-wide interference quantities included in the so-called *interference impact*, which is minimized through an optimized channel assignment. Such quantities are adjacent channel interference and co-channel interference, which is represented in our work by the contention impact of the co-channel reuse given an estimation of the APs' number of active flows. Therefore, the result of the channel assignment designed in the context of WP4 is an optimized trade-off between reductions of adjacent channel and estimated co-channel interferences, respectively. Hence, in order to assess this unexpected channel assignment, which selects the same channel for AP1 and AP3, we will discuss the results in terms of the throughput provided at the end of this subsection.

In the next case, four APs are located such that AP1 is within the wireless coverage of all other APs. Moreover, AP2, AP3 and AP4 cannot hear each other. This case is shown in Figure 10. The MATLAB script for this experiment is given in **Script 3**. The script generates 100 path losses matrices. Each entry in the matrix is randomly generated according to normal distribution with mean 50 and standard deviation 10, except the diagonal entries that are zero. Then, the path loss between AP2, AP3 and AP4 are set to a large value. Finally, the Wi-5 channel assignment algorithm is executed with this path loss matrix.

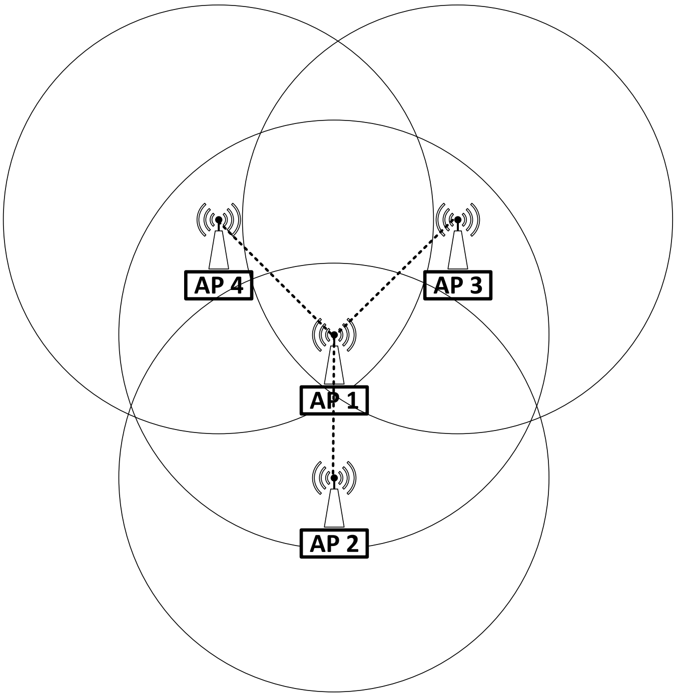


Figure 10: Channel assignment test case with 4 APs, Case 3

```
n=4;
mean_pathloss=50;
sigma_pathloss=10;
for i=1:100
      A=(randn(n,n)*sigma_pathloss+mean_pathloss) .* (ones(n,n) -
      diag(ones(1,n),0));
      A(2,3)=150; A(2,4)=150; A(3,2)=150; A(3,4)=150; A(4,2)=150;
      A(4,3)=150;
      res=getChannelAssignments(A,1);
      res
end
```

Script 3: Fours APs with non-overlapping coverage – Case 3

In this case we expect a different channel assigned to AP1 from the other APs. The expected channels assigned to AP2, AP3 and AP4 are arbitrary as long as none of them overlaps with AP1. For the 100 experiments, Wi-5 algorithm provided the following assignment 51 times:

AP1	**AP2**	**AP3**	**AP4**
1	6	9	11

and provided the very similar assignment for 49 times

AP1	**AP2**	**AP3**	**AP4**
1	6	8	11

We have also used the symmetric versions of the path loss matrix, and always obtained the same result with the asymmetric version. Both results meet the expectations since channels assigned to AP2, AP3 and AP4 do not overlap with the channel assigned to AP1. On the other hand, in order to assess the proposed channel assignment, which also estimates possible co-channel interference, we will discuss the results in terms of the throughput provided at the end of this subsection.

In the fourth case, we generate a random path loss matrix for five APs, which are located as follows:

a. AP1 is within the wireless coverage of AP2 and AP3.
b. AP2 is within the wireless coverage of AP1, AP3 and AP4.
c. AP3 is within the wireless coverage of all other APs.
d. AP4 is within the wireless coverage of AP2, AP3 and AP5.
e. AP5 is within the wireless coverage of AP3 and AP4.

This case is shown in Figure 11 where the channel assignment algorithm has been executed. The MATLAB script for this experiment is given in **Script 4**. The script generates 100 path losses matrices. Each entry in the matrix is randomly generated according to normal distribution with mean 50 and standard deviation 10, except the diagonal entries that are zero. Then, the path loss between AP1-AP4, AP1-AP5, and AP2-AP5 are set to a high value.

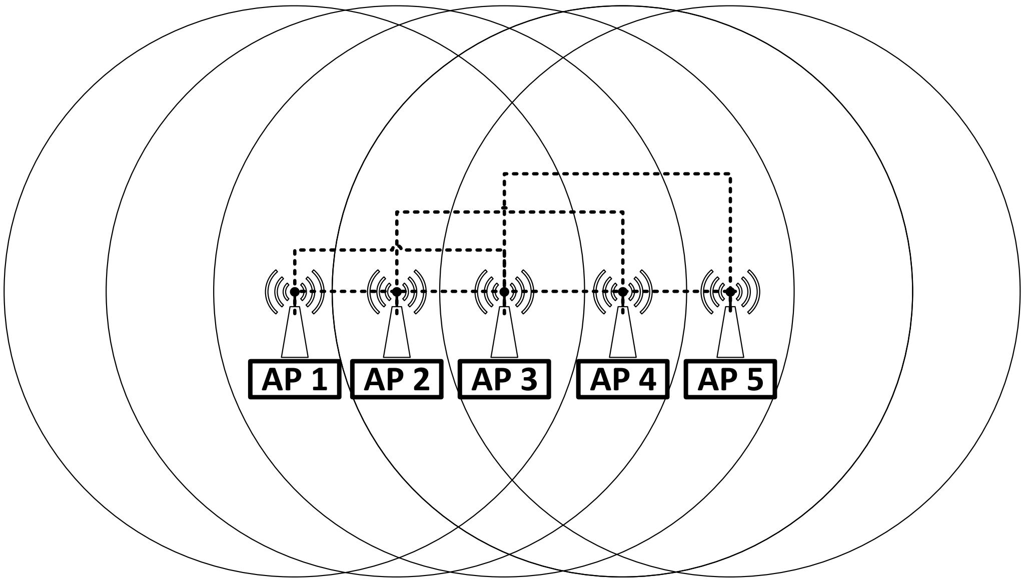


Figure 11: Channel assignment test case with 5 APs, Case 4

```
n=5;
mean_pathloss=50;
sigma_pathloss=10;
for i=1:100
      A=(randn(n,n)*sigma_pathloss+mean_pathloss) .* (ones(n,n) -
      diag(ones(1,n),0));
      A(1,4)=150; A(4,1)=150; A(1,5)=150; A(5,1)=150; A(2,5)=150;
      A(5,2)=150;
      res=getChannelAssignments(A,1);
      res
end
```

Script 4: Five APs with non-overlapping coverage – Case 4

In this experiment we expect to have different non-overlapping channel assignments for {AP1, AP2, AP3}, {AP2, AP3, AP4}, and {AP3, AP4, AP5} in order to minimize the adjacent channel interference. For instance, a valid channel assignment could be {1, 6, 11, 1, 6}. For the 100 experiments, Wi-5 algorithm always provided the following assignment:

AP1	AP2	AP3	AP4	AP5
1	6	6	11	1

We have also used the symmetric versions of the path loss matrix, and always obtained the same result with the asymmetric version. The results obtained by the channel assignment algorithm do not meet the expected results. In fact, the algorithm assigned the same channel to two nearby APs. Hence, also in this case, in order to assess this channel assignment, which selects the same channel for AP2 and AP3, due to the best trade-off between adjacent channel interference and estimated co-channel interference, we need to discuss the results in terms of the throughput provided at the end of this subsection.

The performance of the Channel Assignment is also evaluated with eight APs in the real-time testbed introduced in Section 4.1. Figure 12 illustrates the deployment plan of the Wi-5 APs. For each of the eight APs, a single STA is associated and located near the AP.

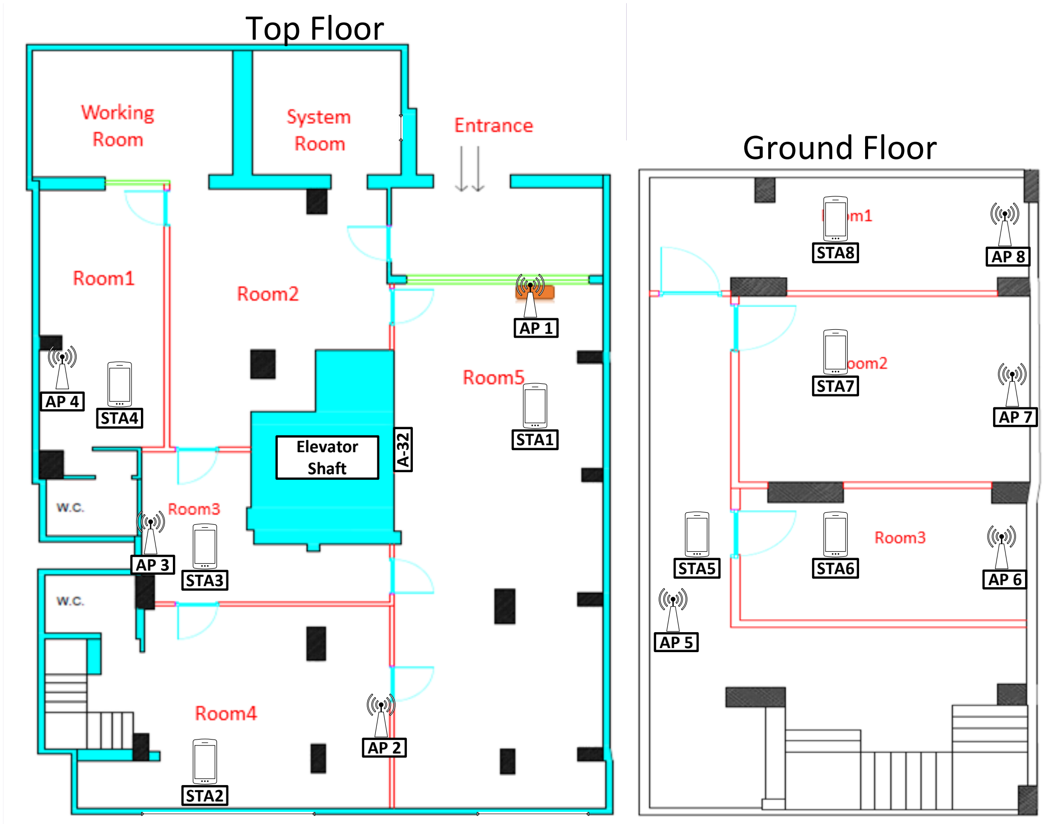


Figure 12: Test house configuration for performance evaluation tests

The path loss matrix for the given deployment is obtained at the beginning of the experiment. To achieve this, we took 10 measurements. Once we observed consistency in the measurements, we utilized one of these measurements to obtain the channel assignments for Wi-5 and LCC algorithms. Note that the Wi-5 algorithm always resulted in the same assignment, while, in the case of LCC, the channel assignment differs slightly due to the stochastic nature of the algorithm. The path loss matrix we obtained is given in Table 1.

Table 1 Path loss matrix

	AP1	AP2	AP3	AP4	AP5	AP6	AP7	AP8
AP1	0	76.366 dB	81.575 dB	75.0 dB	97.365 dB	104.99 dB	93.860 dB	82.358 dB
AP2	85.0 dB	0	65.0 dB	75.0 dB	85.0 dB	85.0 dB	85.0 dB	85.0 dB
AP3	85.0 dB	65.0 dB	0	75.0 dB	75.0 dB	76.549 dB	85.0 dB	95.409 dB
AP4	75.127 dB	75.127 dB	71.105 dB	0	85.296 dB	104.99 dB	101.02 dB	105.49 dB
AP5	102.90 dB	85.132 dB	75.0 dB	95.584 dB	0	75.0 dB	75.0 dB	75.705 dB
AP6	104.99 dB	85.0 dB	75.259 dB	104.99 dB	75.0 dB	0	75.0 dB	83.893 dB
AP7	95.268 dB	76.549 dB	85.0 dB	104.99 dB	75.0 dB	75.0 dB	0	68.665 dB
AP8	95.440 dB	85.409 dB	104.99 dB	107.59 dB	85.0 dB	85.0 dB	75.0 dB	0

The different channel assignments results in the case of the different solutions that we have considered are given in Table 2. The first three methods are the worst cases in terms of interference because all the APs are set to operate on the same channel. Wi-5 in Table 2 represents our channel assignment algorithm and LCC is the mentioned Least Congested Channel. The remaining solutions in Table 2 called Naïve-1, Naïve-2 and Naïve-3, respectively, try to optimize the network by changing the channel manually. Specifically, these naïve channel assignments are created with the aim of assigning a combination of non-overlapping channels to the adjacent APs and comparing with the performance of the Wi-5channel assignment algorithm.

Table 2 Different channel assignments used

Method	AP1	AP2	AP3	AP4	AP5	AP6	AP7	AP8
Channel 11	11	11	11	11	11	11	11	11
Channel 6	6	6	6	6	6	6	6	6
Channel 1	1	1	1	1	1	1	1	1
Wi-5	1	6	1	11	11	1	3	6
LCC	11	6	1	4	3	8	9	2
Naïve-1	1	6	11	6	1	11	6	1
Naïve-2	1	6	11	6	1	11	6	11
Naïve-3	11	6	1	6	11	1	11	6

For each channel assignment, we have performed 5 UDP downlink throughput tests, and the average downlink throughput obtained at each STA together with the total throughput are provided in Table 3.

Table 3 Throughput values for different channel assignments

Throughput (Mbps)	AP1	AP2	AP3	AP4	AP5	AP6	AP7	AP8	TOTAL
Channel 11	2.6	2.96	3.27	7.56	2.18	2.52	2.46	6.81	30.36
Channel 6	3.81	1.13	3.73	8.69	1.32	3.04	3.13	6.64	31.49
Channel 1	7.19	1.35	3.79	8.94	1.68	2.65	3.94	6.64	36.18
Wi-5	15.3	6.33	3.58	14.3	8.1	14.2	2.25	13	77.06
LCC	12.5	1.92	9.99	12.5	0.6	8.54	7.69	18.5	72.24
Naïve-1	9.53	5.24	9.13	10.6	8.43	10.9	9.41	6.49	69.73
Naïve-2	11.1	4.93	10.2	10	11.1	5.79	10.3	11	74.42
Naïve-3	9.22	2.43	9.26	16	10.2	13.5	6.22	15.9	82.73

From this table we observe that the Wi-5 channel assignment algorithm achieves more than 100% improvement over the worst case approaches where all APs are set to operate on the same channel. Moreover, the Wi-5 channel assignment algorithm improves the LCC solution by a 6% gain. We can also observe that the Wi-5 channel assignment algorithm improves the Naïve approach in two cases. However, the Naïve-3 solution achieves the best result in terms of throughput even compared to the Wi-5 algorithm.

Note that the Wi-5 controller collects information about the signal strength at each interfering AP and then, evaluates the *interference impact* of each AP based on the strength of its signal received at all other APs locations. Therefore, as we have illustrated in deliverable D4.3, the greater the number of accessible APs and the density of the network, the greater the accuracy of the evaluation. Conversely, the evaluation will be less accurate in sparse networks. Hence, this result confirms a low gain achieved by our proposed Wi-5 channel assignment algorithm with respect to other common solutions found in the state of the art, in a sparse network like the one considered in the experiment presented in this subsection. In a nutshell, this experiment validates the claims illustrated in deliverable D4.3. Further results achieved during the field trials are discussed in deliverable D5.3 [22].

4.3 Integration and Testing of the Seamless Handover

In the seamless handover functionality, the associated STAs are steered from their associated APs to other APs when the STAs move throughout the network. Light Virtual Access Point (LVAP) signaling is utilized for mobility management, and constitutes one of the most important parts of the implementation of the seamless handover: thanks to the help of the LVAP signaling, the steering process can be performed without requiring any of the STAs to go through a re-association process.

Two approaches for mobility management using handovers have been proposed and integrated upon the time, namely *reactive* and *proactive* handovers, which can be separated by the periodicity and response times for a handover decision. The details of these solutions are given in the integration and testing parts. In the following subsections, we will discuss the role of each module for the integration process and will give the performance evaluation results of the given approaches.

4.3.1 Monitoring Module

The role of this module here is to provide the controller with the RSSI information on the related AP-STA pairs. In the seamless handover, the system requires the current RSSI information of all devices to make a comparison before making a handover decision. The monitoring module also provides information of the timestamps of the received packets, which will be used during the calculation of the hysteresis time.

4.3.2 Decision Module

The decisions of handover operations are performed by this module. The role of the module is to gather the monitoring information and process it within the controller. According to both reactive and proactive handover applications, the controller decides the handover operation when it is triggered after detecting an AP able to guarantee a sufficiently higher RSSI level than the current AP.

The key criteria for handover operations are the periodicity and the timing. In the reactive handover, when the RSSI level of the connected STA falls below the defined RSSI threshold, the controller is triggered to explore any sufficiently powerful AP for the STA. On the other hand, for the proactive handover application, the system periodically updates RSSI level information of all STAs and decides the handover operation if the conditions are met.

The hysteresis threshold therefore has critical importance for this functionality since, with proper adjustment, it will help the system to avoid the ping-pong effect during handover operations.

4.3.3 Network Configuration Module

After a handover decision has been taken by the controller, this module disseminates the LVAP signals throughout the APs which are based on the specific MAC address of the intended APs and the LVAP handover signals that are sent to the STA. Layer 3 and upwards of the STAs are not aware of the handover, so the STA cannot recognize the steering operation and therefore should continue to work with negligible delays, a *Seamless Handover*. The detailed information of the process is given in the integration section.

4.3.4 Integration and Testing

The main aim of this functionality is to keep the connectivity and data rates of the moving STAs by performing handover operations. The controller module includes the monitoring and decision modules. The monitoring module gathers the information of RSSI of all STAs by the usage of auxiliary interfaces mounted on APs, and passes it to the decision module. After the controller gets the RSSI information, the decision module decides whether to handover or not. As explained before, two different approaches for handover operations have been implemented and tested, namely reactive and proactive handovers.

4.3.4.1 Integration of the Seamless Handover

In the previous deliverables D3.3 and D5.1, the reactive handover approach was proposed and implemented. However, according to our observations, since the logic behind the reactive handover relies on a trigger raised by an AP that makes the controller instruct other APs to scan the environment, the approach remains inadequate in some cases. Furthermore, in some special cases, even if a powerful AP exists near the moving STAs, the mechanism prevents a handover operation because the RSSI level of the associated STA is not below the defined threshold (e.g. -56 dBm), which eventually degrades the performance of the functionality.

At this point AirTies, the Wi-5 partner with a wider experience on the field, suggested to follow a new proactive handover approach to reduce the sufferings of the mobile STAs and performance degradations as mentioned above. In the proactive handover approach, instead of an AP triggering the handover process, the controller is continuously scanning through the APs, and periodically gathering RSSI information of the moving STAs from all the Wi-5 APs. Following this approach, the controller can pre-emptively activate the decision mechanism if any powerful AP is detected among the non-associated APs. The remainder of the section will give further details of the integration process of the approaches.

Reactive handover

In the reactive handover approach, the handover decisions depend on the value of two thresholds, namely RSSI threshold and hysteresis threshold. The RSSI threshold plays an important role in this functionality, since it determines the triggering event to scan the channels. If the current RSSI level of the STA is below the threshold, then the AP sends a scan request to the controller. Following the process, the controller orders the APs to get the scanning information of them. The detailed steps of the handover process are depicted in Figure 13 and explained below:

1. A STA is moving from AP1 to AP2.
2. The AP where the STA is associated launches a *publish* signal when the RSSI heard is below the RSSI threshold (-56 dBm by default).
3. After reception of the *publish* signal, the controller orders the other APs to scan the STA by *scan requests*.
4. The controller gathers the RSSI information of the STA from all the APs by *scan responses*.
5. The decision module executes the handover algorithm and decides where to handover the STA (or it may decide not to move it) according to the RSSI levels gathered.
6. After making a decision on the handover operation, the controller instructs the AP to send *Channel Switch Announcement* (CSA) signals to the moving STA. The role of the CSA signals is to force the STAs to move to the channel of the new AP.
7. AP1 sends the CSA signals to the moving STA.

8. *Remove* and *add LVAP* signals are sent by the controller to the old and new APs, respectively. Then, the new AP starts to send beacons (a burst of beacons is initially sent) to the STA, in order to make it aware of the new channel. At the end, the STA easily detects these burst beacons and switches to the new AP with minimal delay in its connection and minimum interruption of its data flow.

The figure also includes some machines on the left that were used for measuring the handover delay: a traffic generator, a server that receives the traffic, and a sniffer.

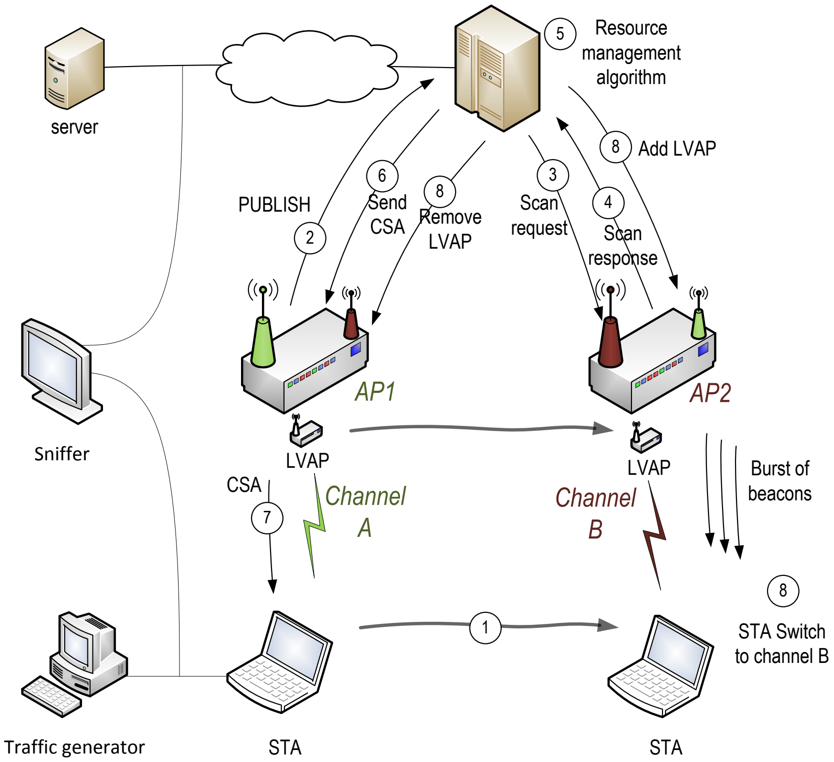


Figure 13: Description of the handover scheme and testbed

Proactive handover

In the proactive handover functionality, instead of using a trigger mechanism started by the "origin" AP as in the reactive handover, the controller now continuously evaluates the RSSI levels of a moving STA gathered from the Wi-5 APs. Each AP scans the channels and measures the RSSI of the STAs by means of their auxiliary wireless interfaces. In this functionality, to make a handover decision, three conditions must be met by the system. They can be outlined as follows:

1. An AP with better RSSI than the current AP exists.
2. The hysteresis time exceeds the threshold value.
3. The received power of the STA from the associated AP should fall below a defined power threshold.

The RSSI level of the APs are gathered and analyzed by the decision module. The RSSI information of the new RSSI levels is stored in a matrix as shown below:

	AP1	AP2	AP3	..	APn
STA₁	RSS_{11}	RSS_{12}	RSS_{13}..		RSS_{1n}
STA₂	RSS_{21}	RSS_{22}	RSS_{23}..		RSS_{2n}
….					
STAₙ	RSS_{n1}	RSS_{n2}	RSS_{n3}..		RSS_{nn}

where each element shows the corresponding RSSI level of the STA listened from the corresponding APs. For example, RSS_{11} corresponds to the RSSI level of STA-1 measured by the AP1.

A new approach for the evaluation of RSSI levels is proposed and implemented to consider the old RSSI levels and hence help to ensure the stability of the handover decisions. It is:

$$RSS_{i,j} = \alpha \, x \, new_{RSS_{i,j}} + (1-\alpha) \, x \, old_{RSS_{i,j}} \quad (1)$$

where $new_{RSS_{i,j}}$ and $old_{RSS_{i,j}}$ correspond to the new and old RSSI values of STA i listened from AP j and parameter α is a weighting factor that determines their relative impact on the handover decisions. Its value varies between 0 and 1 and in the following tests and performance evaluation section we will investigate the proper value of α through a series of different experiments.

After the decision module decides a handover operation, the remaining process to perform a seamless handover operation is the same as for the reactive handover above. In other words, CSA and LVAP signals are managed by the controller as shown in Figure 14, which depicts the signaling scheme of the proactive handover mechanism.

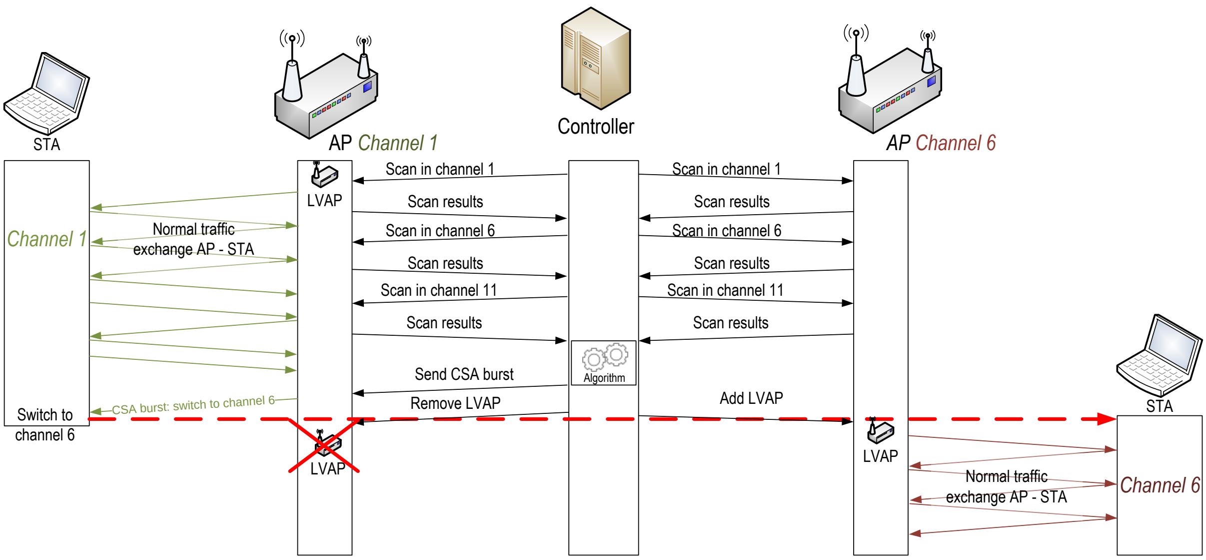


Figure 14: The Scheme of Proactive Handover and LVAP signaling

We can summarize the integration process of the proactive handover as follows:

1- The controller periodically gathers the RSSI information of all the associated STAs from all the APs.

2- After creating a database containing the RSSI values ($RSS_{i,j}$), the decision module calculates the new RSSI database matrix, according to equation 1.
3- Then, if an AP accomplishes the three conditions listed above (RSSI threshold, hysteresis threshold, power threshold), the decision module decides the handover operation to that AP.
4- The network configuration module performs the handover operation. During the handover, the CSA and remove-add LVAP signals are exchanged among the AP, the Controller and the moving a STA, i.e., the signaling procedure is performed in the same way as reactive handover.
5- At the end, the STA is steered to the new AP without interruption of its traffic flow or connection.

4.3.4.2 Testing of the Seamless Handover

Reactive handover

For the client steering tests, only the top floor of the AirTies test house has been utilized and the IP addresses that are assigned to each AP's control plane at the top floor are given in Table 4. We provide these addresses here as most of the logs report the IP addresses of the APs directly.

Table 4 IP Addresses of the APs

AP Number	Assigned IP Address
AP1	192.168.6.220
AP2	192.168.6.221
AP3	192.168.6.222
AP4	192.168.6.223

The following values are used during these experiments:

- Decision (hysteresis) interval, i.e. (the time required to wait after a handover in order to perform a new one): 15 seconds (default value)
- Signal threshold (the RSSI threshold to trigger a scan): -56 dBm (default value)
- Scanning duration: 1 second (default value)
- Number of triggers (number of observations at the serving AP before triggering a scan): 5 (default value)

The verification tests of the reactive handover application were carried out by the following experiments. First, a simple handover operation of a STA moving toward a new AP was tested.

Test handover conditions:

1. Four APs and a STA are used as shown in Figure 15.
2. STA1 is initially very close to AP1 and associated with it.
3. STA1 slowly moves towards AP2 and the RSSI values observed at all APs are continuously monitored.

It is expected from the experiment that scanning will occur at all the APs when the average RSSI of STA1 at AP1 is less than -56 dBm. Furthermore, a handover of STA1 to AP2 is expected as it is the best candidate.

Log 1 gives a sample of the logs from the controller system. First, the average RSSI of STA1 at AP1 drops to -58 dBm, which triggers a scan across other APs. AP2 has the maximum RSSI with -50 dBm. This value is higher than the RSSI of STA1 at AP1. Hence, STA1 is steered to AP2.

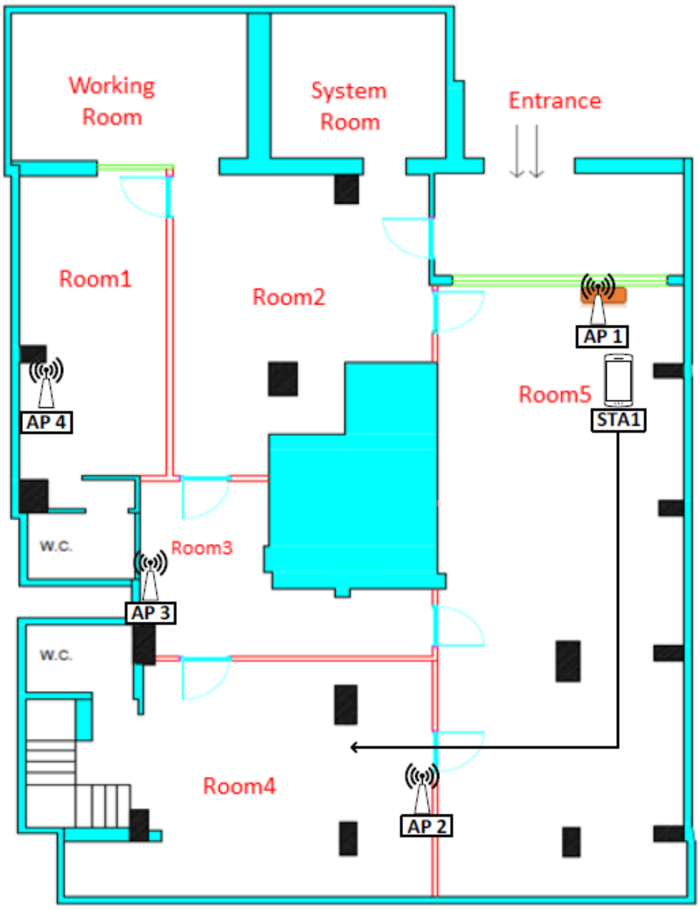


Figure 15: Hand-over Conditions Test Case

```
MobilityManager: Scanned client 38:D4:0B:F8:98:6E in agent
/192.168.6.222 and channel 1 with power -66

MobilityManager: Scanned client 38:D4:0B:F8:98:6E in agent
/192.168.6.223 and channel 1 with power -77

MobilityManager: signal strengths: new = -50 old = -58 handing off
client 38:D4:0B:F8:98:6E to agent /192.168.6.221
```

Log 1: Initial Case-1

We observe a drawback here however: the scanning decision is made based on a sample of RSSI observations at the AP that is serving the STA. However, the selection of the target AP is based on a single observation. Considering the nature of the wireless medium at the 2.4 GHz band, the RSSI measurements fluctuate a lot. Hence, a single misleading RSSI reading can lead to a suboptimal decision, resulting in unnecessary handover. For instance, the following log has also been observed during this test.

```
MobilityManager:  Scanned  client  38:D4:0B:F8:98:6E  in  agent
/192.168.6.222 and channel 1 with power -62

MobilityManager:  Scanned  client  38:D4:0B:F8:98:6E  in  agent
/192.168.6.223 and channel 1 with power -74

MobilityManager: signal strengths: new = -62 old = -66 handing off
client 38:D4:0B:F8:98:6E to agent /192.168.6.222
```

Log 2: Initial Case-2

During this run, AP3 obtains an RSSI level that is slightly better than AP2. As a result, STA1 is steered towards AP3. Once STA1 becomes immobile and stops near AP2, we have observed that it is steered again towards AP2 after the hysteresis period, as AP2 now obtains a better RSSI. Hence, the initial handover to AP3 becomes unnecessary. Based on this finding, we suggest that the decision for the target AP should be given based on multiple observations, not on a single one.

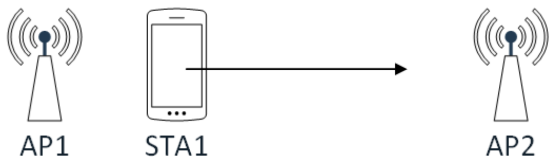


Figure 16: Possible case of suboptimal operation

We can conclude that having a fixed value of signal threshold (the threshold RSSI of STA1 at the serving AP, after which a scan and a handover decision is triggered) may cause a suboptimal operation for a STA. Consider the scenario given in Figure 16. In this scenario, STA1 is initially very close to AP1, and it is associated to AP1. Let's assume that AP1 and AP2 are not too far from each other, and STA1 starts to move towards AP2 and stops its movement very close to AP2. If the average RSSI of STA1 observed at AP1 does not go below the signal threshold, no scan will be triggered and the STA1 will remain associated to AP1. On the other hand, AP2 is clearly the best choice. In our experiments, we have observed this case, where the RSSIs of STA1 at AP1 and AP2 are around -50 dBm and -40 dBm, respectively. No scan and handover process is triggered, and STA1 stays with AP1, which suggests that the threshold value should not be fixed. This is also a drawback of the reactive mechanism where the system reacts when the RSSI level at the serving AP is below the signal threshold. Instead of a reactive system, we can follow a proactive approach where non-serving APs monitor the STA periodically, and the system steers the STA to the best possible AP without requiring a signal threshold.

To test the ping-pong effect with the two APs, the following experiments are executed with the assumptions as follows:

1. Two APs and a STA are used as shown in Figure 17. To perform this test, we moved AP3 next to AP2.
2. STA1 is approximately the same distance away from AP2 and AP3. Moreover, STA1 is static and does not move during the tests.
3. STA1 is initially connected to AP2.
4. The system is observed for a reasonable amount of time, i.e., 5 minutes. The observation time should not be too low, e.g. 30 second, since it could require some time to smooth out the effects of sudden decrements and increments in data rates due to the environmental factors by averaging the rates at the end of the experiment.

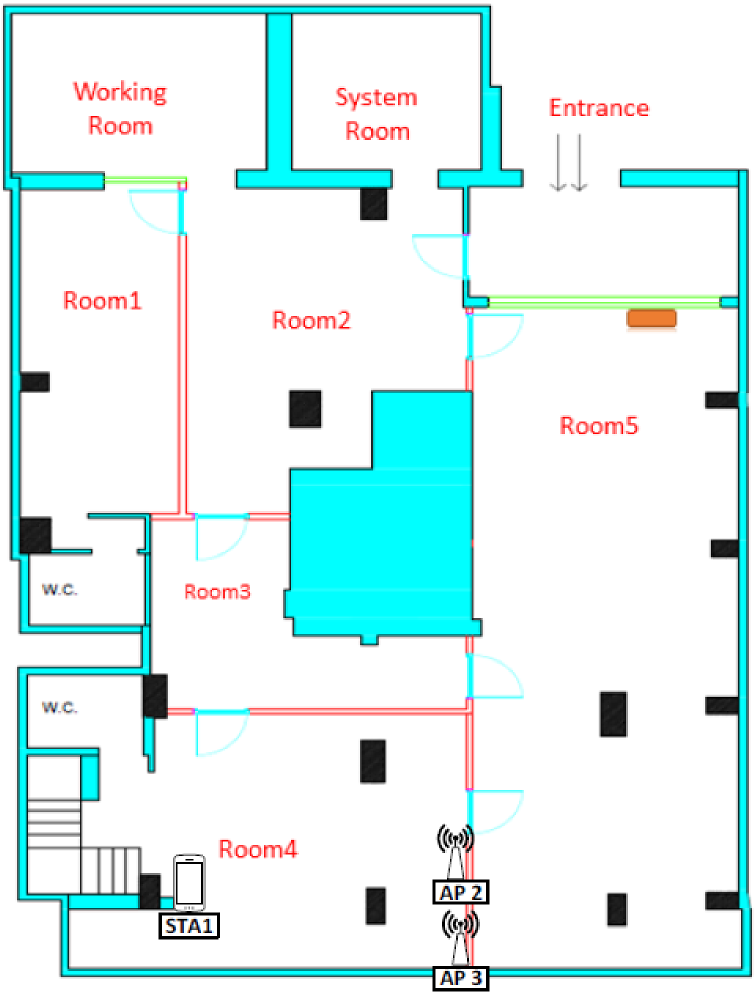


Figure 17: Deployments scheme of the Two AP for Ping-Pong Effect Test

We are expecting STA1 to stay with AP2 all the time, and to not switch across APs. Parts of the experiment logs are given below. As can be seen from the logs below, STA1 constantly switches between AP2 and AP3, causing unnecessary hand offs and disruption of the service.

```
MobilityManager: Do not Scan client 10:D3:8A:F4:CA:FB in agent (Skip same AP) /192.168.6.221 and channel 1

MobilityManager: Scanned client 10:D3:8A:F4:CA:FB in agent /192.168.6.222 and channel 1 with power -66

MobilityManager: signal strengths: new = -66 old = -71 handing off client 10:D3:8A:F4:CA:FB to agent /192.168.6.222
=================================================================

MobilityManager: Scanned client 10:D3:8A:F4:CA:FB in agent /192.168.6.221 and channel 1 with power -70

MobilityManager: Do not Scan client 10:D3:8A:F4:CA:FB in agent (Skip same AP) /192.168.6.222 and channel 1

MobilityManager: no hand off with power = -69
```

Log 3: Two AP Case-1

Obviously, a threshold value is necessary so that the STA is handed off to a new AP only when the improvement in terms of RSSI value is higher than the threshold. For instance, with a threshold value of 5 dBm, almost all of the unnecessary handovers could be avoided. We believe that this threshold may depend on the RSSI level as well. For instance, a higher threshold value (i.e. 5 dBm) could be used when the serving AP has good RSSI (greater than -65 dBm), whereas a lower threshold (i.e. 2dBm) value can be used when the serving AP has bad RSSI (less than -75 dBm). Between -65 and -75 dBm, a threshold value of 3 dBm or 4 dBm may be used.

Although the above test shows that there is a ping-pong effect without the use of a threshold, we have observed a phenomenon that prevents ping-pong to some degree during our tests, when the distance between the STA and APs is long. Generally, if the APs have the same distance and almost the same path loss towards the STA like in our case, the RSSI level of the serving AP is better than the other AP. For instance, the following log is obtained during the repetition of the same test.

```
MobilityManager: Scanned client 10:D3:8A:F4:CA:FB in agent /192.168.6.221 and channel 1 with power -80

MobilityManager: Do not Scan client 10:D3:8A:F4:CA:FB in agent (Skip same AP) /192.168.6.222 and channel 1

MobilityManager: no hand off with power = -77

MobilityManager: Scanned client 10:D3:8A:F4:CA:FB in agent /192.168.6.221 and channel 1 with power -81
```

Log 4: Two AP Case-2

Although the APs are at the same distance to the STA, the RSSI readings of the serving AP are consistently better than the other APs in the lower RSSI regime. We attribute this fact to the better antennas of the TP-Link Archer devices (used by the serving AP) compared to the antenna of the TP-Link dongle (used by the other AP). However, this phenomenon cannot be the only mechanism to prevent ping-pong as can be seen from the ping-pong logs given previously.

The next experiment was performed to evaluate the ping-pong performance in the case where three APs are used. The details of the experiment are given below:

1. Three APs and a STA have been used, as shown in Figure 18.
2. STA1 is initially very close and connected to AP1. Furthermore, STA1 is approximately the same distance away from AP2 and AP3 (AP2 and AP3 are next to each other).
3. STA1 starts to move very slowly towards AP2 and AP3.
4. The system observes it when STA1 is next to AP2 and AP3.

We expect STA1 to switch to either AP2 or AP3 and to stay with that AP until the end of the test. The logs are given below. Without using any threshold, STA1 switches between AP2 and AP3 constantly, resulting in a ping-pong effect. As can be seen from test log 5, even using a 5 dBm threshold could not prevent the unnecessary handovers that have occurred in this test. Hence, we observe the pitfalls of using a single measurement from the non-serving APs as we have previously mentioned.

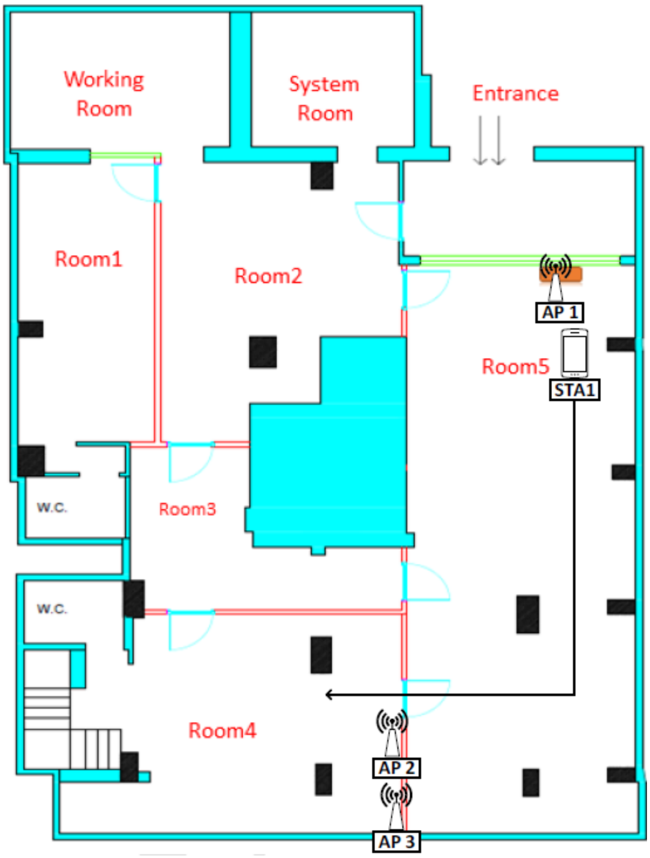


Figure 18: Ping-pong effect test with three APs and a mobile STA.

```
MobilityManager: Scanned client 10:D3:8A:F4:CA:FB in agent
/192.168.6.220 and channel 1 with power -77

MobilityManager: Do not Scan client 10:D3:8A:F4:CA:FB in agent (Skip
same AP) /192.168.6.221 and channel 1

MobilityManager: Scanned client 10:D3:8A:F4:CA:FB in agent
/192.168.6.222 and channel 1 with power -54

MobilityManager: signal strengths: new = -54 old = -62 handing off
client 10:D3:8A:F4:CA:FB to agent /192.168.6.222
```

Log 5: Three AP Case

The last test of the ping-pong effect analysis of the reactive handover algorithm was considered for the case that multiple numbers of STAs are moving among the APs. The details of the assumptions were as follows:

1. Two APs and multiple STAs, i.e., *n*, have been used. The case with 2 STAs is shown in Figure 19. The test is carried out with different *n* values, i.e. 1, 2, and 3.
2. All STAs are initially very close to and connected to AP1.
3. All STAs slowly move towards AP2 simultaneously and the corresponding RSSI values observed at both APs are continuously monitored.

The expected outcome for this experiment was to switch all the STAs to AP2. The output of the case with 2 STAs is given in Log 6 with both STAs successfully handed off to AP2.

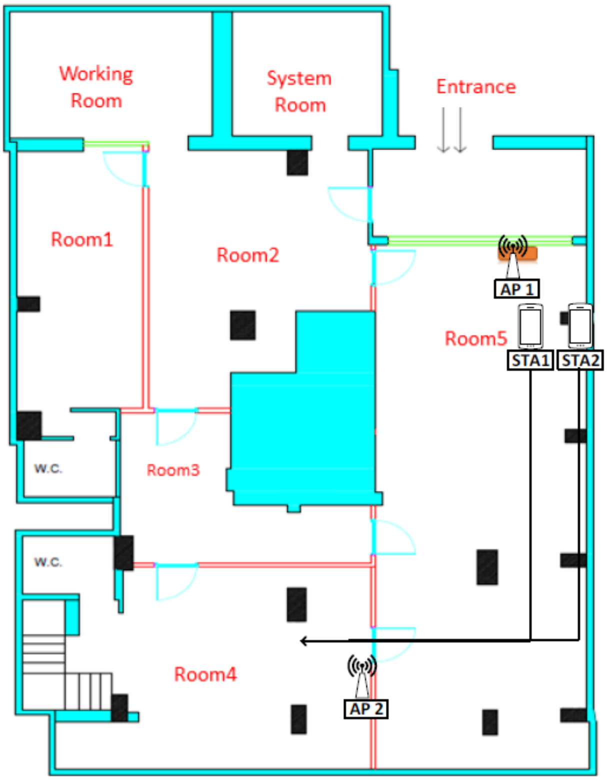


Figure 19: Multi STA handover test

```
MobilityManager: Do not Scan client F8:59:71:28:7A:71 in agent (Skip
same AP) /192.168.6.220 and channel 1

MobilityManager: Scanned client F8:59:71:28:7A:71 in agent
/192.168.6.221 and channel 1 with power -30

MobilityManager: signal strengths: new = -30 old = -61 handing off
client F8:59:71:28:7A:71 to agent /192.168.6.221
```

Log 6: Multi AP Case-1

The test output for the 3 STA case is given in Log 7. All 3 STAs are handed over successfully. However, the handover process for each STA is triggered at different times, although the STAs are co-located. Finally, there are a couple of cases where the scan process on the target AP could not detect a particular STA, indicating a RSSI level of -256 dBm. We will elaborate on this behavior in the rest of this subsection.

```
MobilityManager: Do not Scan client 38:D4:0B:F8:98:6E in agent (Skip
same AP) /192.168.6.220 and channel 1

MobilityManager:   Scanned   client   38:D4:0B:F8:98:6E   in   agent
/192.168.6.221 and channel 1 with power -60

MobilityManager: signal strengths: new = -60 old = -68 handing off
client 38:D4:0B:F8:98:6E to agent /192.168.6.221
```

Log 7: Multi-STA Case-2

As discussed above, scanning a STA when using the Wi-Fi dongle is an error-prone process. These errors increase the duration of the handover process. This observation also emphasized the need for a decision process with multiple measurements and proactive logic.

Furthermore, we believe that with multiple stations moving together, the reactive handover process is problematic due to the sequential nature of the scanning. Consider the case given in Figure 19 with multiple stations (i.e., 5) moving together. In such a case, AP2 should perform a scan for each STA sequentially, with a default scan duration of 1 sec. This scan process therefore takes 5 seconds in total. During this time, if the STAs move past AP2 and get very far from AP1, they are likely to be disconnected because a handover decision is not made for a STA until a scan is performed. Due to the sequential nature of scanning, a long delay in the scanning may cause disconnections. One possible remedy to this problem is to scan multiple STAs in a single scan. However, this option has not been tested, as the proactive approach solves this problem.

The following experiment investigates the handover delay performance of the reactive handover application in the case where two APs are deployed in the setup. The details of the experimental setup are as follows:

1. Two APs and multiple STAs, i.e., *n*, are used. The deployment scheme with 2 STAs is shown in Figure 19. The test is carried out with different *n* values, i.e. 1, 2, and 3.
2. A computer is used during the test to take sniffs of the wireless medium, control and data planes simultaneously. A detailed scheme of the setup is demonstrated by Figure 20 .
3. All STAs are initially very close and connected to AP1, and each STA sends TCP traffic (generated using *iperf*) to a computer connected to the data network.
4. All STAs slowly move towards AP2 simultaneously.

It is expected that all the STAs switch to AP2. After parsing and analysing the sniff data, we expect a reasonable handover delay for all the involved STAs. In the performance evaluations of the seamless handover functionality, one of the key performance criteria is the handover delay, which should be at a tolerable level to reduce the loss rates and maintain the connectivity.

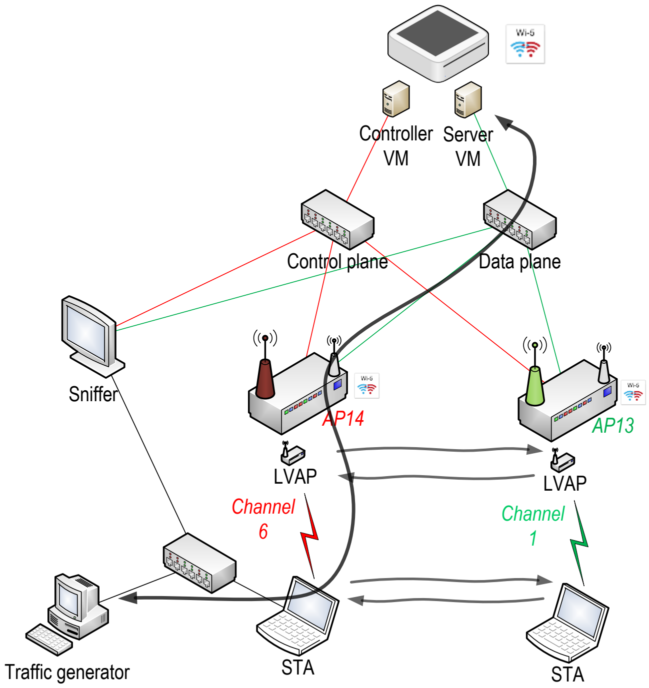


Figure 20: Test Setup for measuring the handover delay

Measuring the handover delay is a cumbersome and hard task. When a handover decision is made, the controller sends a "*remove_vap*" message to the serving AP, which responds with "*remove_vap OK*" message. Furthermore, the controller also sends "*add_lvap*" message to the target AP (that will serve the STA), and the target responds with "*add_lvap OK*" message. These message exchanges occur simultaneously between the controller and the serving AP, and between the controller and the target AP. To measure the handover delay, we mark the time of the "*remove_lvap*" message of the controller and the time of the first transmission occurring on the wired portion of the data plane (i.e. between the target AP and the destination computer) after the "*remove_lvap*" message. We use the difference between these two times as the handover delay. We wrote a Python script in order to calculate the handover delay as above after obtaining a number of handovers in the network. This script is useful for calculating the more accurate delays and saves in time.

The handover delays for individual STAs as well as the overall average (average of all involved STAs) for each case are given in Table 5. We should mention that STA2 and STA3 used in the experiments are mobile handsets, whereas STA1 is a notebook computer. When there is a single STA, the handover delays are relatively reasonable with an average value of 21.9 milliseconds (ms). On the other hand, we see a significant increase in the handover delay when the number of stations increases. The average handover delay with 2 STAs is around 1.5 seconds, whereas it is around 1.8 seconds with 3 STAs. Moreover, we observe that the handover delay is especially large for STA2 and STA3 (mobile handsets). Some possible reasons in this increased delay are:

- The drawback of using a separate scan for each STA, as mentioned before.
- Non Wi-5 related Wi-Fi issues.
- Some other issue (e.g. power saving, antenna capability, etc.) with mobile handsets.

Unfortunately, we could not identify the exact source of this problem. However, it is certain that increasing the number of STAs negatively affects the handover delay.

Table 5 Handover Delays for the Multi-STA experiment

	1 STA	2 STAs		3 STAs		
Handover Delay(ms)	**STA1**	**STA1**	**STA2**	**STA1**	**STA2**	**STA3**
Average	21.9	17.4	1645.8	112.9	721.8	3137.1
Minimum	0.3	0.1	0.4	0.3	0.1	0.472
Maximum	47.4	95.6	8305	802.8	3750	10605
Standard Deviation	16.1	27.5	3097.4	259.2	1271.5	4010.9
Overall Average	21.9	1562.5		1847.2		

One of the key parameters of the handover applications is the “hysteresis threshold” which directly affects the handover decisions along with the movement of STAs. The impact of a test decision interval (hysteresis interval) was investigated by the following experiment:

1. All 4 APs are located on the top floor, as shown in Figure 21.
2. A person with a STA tours the house using the grey path shown in the figure. To elaborate, the person starts the tour next to AP1 in Room 5, then follows the path Room4 – Room3 – Room2 – Room1 – Room2 – Room5. The experiment is performed using different moving speeds: slow walk, regular walk, fast walk, and run. Furthermore, we utilize different decision intervals (also called the hysteresis interval): 2, 5, 10 and 15 secs. We do not try values lower than 2 seconds because of the 1 second scan time.
3. For each case, we record the number of handover decisions and the total number of decisions (whether they result in a handover or not).
4. Compare the results obtained with different input parameters.

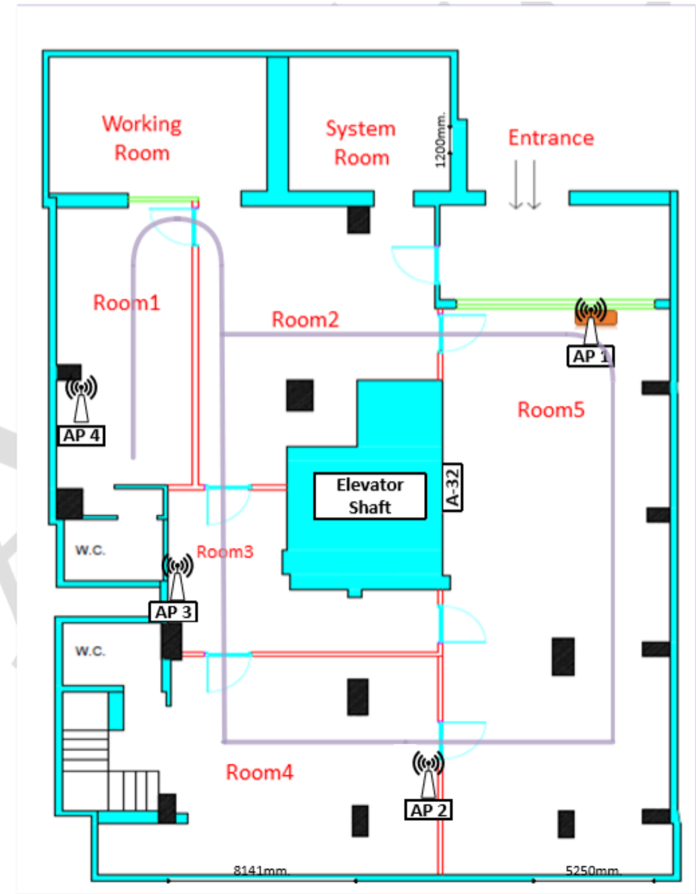


Figure 21: Setup for handover decision interval tests

It is expected that the average number of handovers will be around 4 for each case for a number of important reasons:

- The throughput obtained in the 2.4 GHz band is very limited, and it is hard to perform a detailed analysis with such limited capacity.
- The throughput varies significantly between each run depending on the wireless environment. In such a rapidly changing environment, it becomes almost impossible to perform analysis using the throughput.

Hence, we do not utilize the throughput values but the number of handovers. To be consistent across different parameters, a person carrying the STA keeps its speed constant across the same mobility experiments.

We provide the average number of handovers and average number of decisions in Table 6 and Table 7, respectively.

Table 6 Average number of handovers in a tour

Decision period(sec)/Speed	Run	Fast walk	Normal Walk	Slow Walk
2	2.25	3.75	3.75	4.5
5	2.5	3.5	4	5
10	1.25	2.75	3.25	5.25
15	1.25	1.75	3	3.75

Table 7 Average number of decisions in a tour

Decision period(sec)/Speed	Run	Fast walk	Normal Walk	Slow Walk
2	2.5	3.75	4.25	6.5
5	3	4	5.25	6.25
10	1.75	2.75	3.25	5.75
15	1.5	2	3.5	5.25

By looking at the data, we observe that even 2 seconds may not be tolerable when the mobility of the user is high, i.e. running. For other mobility patterns, we observe that having smaller values for the decision interval is beneficial. For slow mobility, normal walk and slow walk, the value of the decision period does not significantly affect the number of handovers. On the other hand, the average number of decisions is inversely proportional to the decision period, as expected.

All in all, we can conclude that performing a 1 sec scan for each handover limits the system for highly mobile users, as it limits the range of the decision interval. Hence, we suggest using a smaller value. However, this may adversely affect the performance of the system as having a smaller scan time makes it hard for other APs to detect the station. This data also favors our argument about a proactive system that we have described before. Therefore, the next tests will focus on the proactive system, which overcomes these limitations.

Proactive handover

The performance of the proactive handover has also been tested in the Airties Mecidiyeköy Test House considering the following assumptions:

1. 4 APs are located as depicted in Figure 22 so that the RSSI levels of each AP from the other APs are minimized. With this deployment, we are aiming to create a suitable handover environment for a STA while moving among the Wi-5 APs.
2. A person with a STA moves from Room5 through the sequence of Room 4, Room3, Room1, and Room 2 along the path, which is illustrated by the purple line in Figure 22. For each of the evaluation set of parameters, 4 tours are completed, and the average values are reported.
3. The effect of the new parameters that are introduced in the integration part above has been examined with a series of experiments. To analyze the effect of the change of the parameters on the handover decisions, one of the parameters is kept constant while the other one is changed. We examined the *alpha* parameter for 1, 0.8 and 0.6 values, and Hysteresis Threshold for 2, 4, 10 secs.
4. The speed to steer the STA is an important factor for the evaluation of the functionality. The tests are conducted with three movement cases which are *Robot*, *Normal Walk* and *Fast Walk*. The slowest movement type is the *Robot* case represented by the test robot of AirTies. In the case of *Normal Walk* and *Fast Walk*, a person carrying a STA has walked through the path with normal and faster speeds.

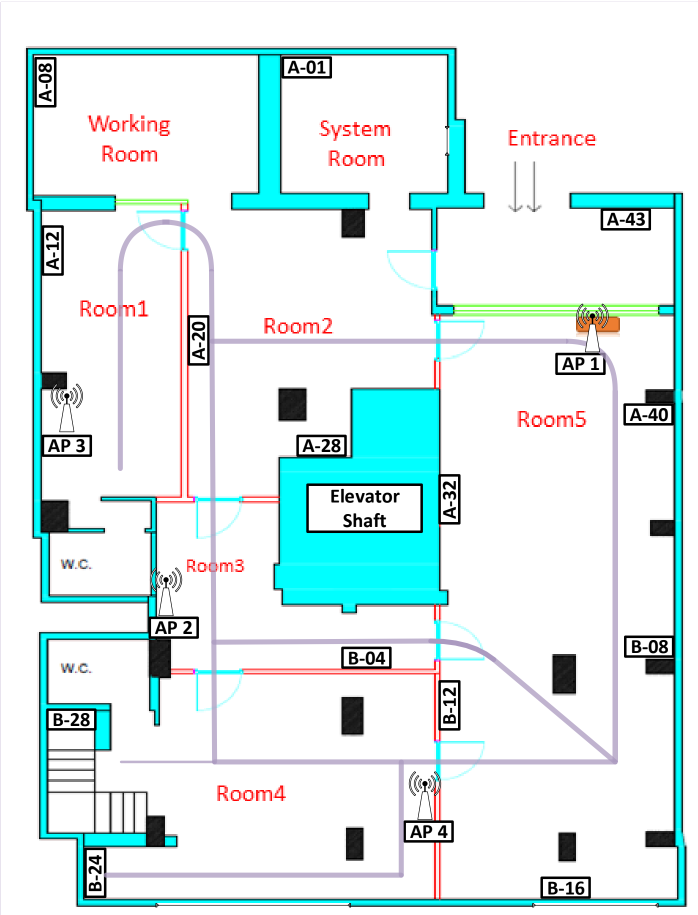


Figure 22: Setup for Proactive Handover Tests

The expected outcome for the proper parameters is to have 4 handover decisions and operations upon completing a tour (there are 4 APs). Furthermore, we expect to have an increment in the number of handovers when the value of *alpha* is higher, since the percentage of the historical RSSI values are reduced in the calculation of RSSI metric, and a decrement in the case of reducing *alpha*. For the evaluation of the hysteresis threshold, we expect to observe more handovers when the value of the parameter is reduced by keeping the alpha constant at 0.8 and fewer handovers for the reverse case.

The results of the evaluation of the alpha parameter are given in Table 8. For these experiments, the hysteresis threshold is set to 4 sec. It is obvious that at the value of 0.8 for alpha, the average number of handovers becomes around 4 which was decided as a reference handover number upon completing the tour. Furthermore, it is observed that, when the value of *alpha* is reduced, the number of handovers gets reduced as expected.

Table 8 Effect of Alpha Parameter for h:4

	α:1 #Handover	**α:0.8 #Handover**	**α:0.6 #Handover**	**Avg #Decision**
Robot	7.75	4.5	4	564
NormalWalk	5.75	3.75	2.5	184
Fast Walk	5.75	3	2	100

The hysteresis threshold can also affect the system handover decisions. The detailed impacts of this parameter on the handover decisions are given in the above integration section. While evaluating the hysteresis threshold, the value of alpha is kept constant at 0.8, which was decided in the aforementioned experiment as a reasonable value for the rest of the experiments.

Table 9 Effect of Hysteresis Threshold for α: 0.8

	h:2 #Handover	**h:4 #Handover**	**h:10 #Handover**	**Avg #Decision**
Robot	7.5	4.5	4.5	564
NormalWalk	7	3.75	3.75	184
Fast Walk	7	3	2.75	100

Table 9 gives the test results for changes to the hysteresis threshold. The results of the experiments clearly show that the value of 4 sec for the hysteresis threshold is a proper value. Since the average number of handovers for all movement types becomes close to 4 by this value. Furthermore, a decrease in this parameter results in an increase in the number of handovers which could be expected because, with this threshold, the decision module tries to ensure the RSSI levels for a period. Any decrease in this parameter will cause sudden handover decisions and may lead to a ping-pong effect.

The number of decisions for the experiments is calculated by summing all the handover and non-handover decisions due to mismatch of the conditions among the tours. The average number of decisions remains the same for the tests with robot, since the number of decisions for a tour depends mostly on the tour interval besides the parameters. Therefore, the usage of the Robot provides us with reproducible experiments.

When the results of the average decision are examined for both experiments, it is obvious that the shortest tour interval with the *Fast Walk* has the lowest number of average decisions, which meets with our expectations. This high-speed movement type also results in fewer handover decisions for both of the experiments because the speed of this movement causes the required time and RSSI conditions to jump during the movement.

In conclusion, the modules of this functionality work as expected in general. Proper values for the parameters play an important role in order to make the functionality work in a proper way.

4.4 Integration and Testing of the Vertical Handover

In the Wi-5 project, we have studied vertical handovers to another wireless network not operating in the 2.4 or 5 GHz bands as one of the mechanisms to manage Wi-Fi resources in the situation of (near) network congestion. Hypothetically, it can be expected that service degradation can be avoided if specific Wi-Fi clients can be relayed to another network, for instance to a 4G or 5G network.

From the viewpoint of a user, the vertical HO should provide a seamless handover of the client terminal to another network without loss or noticeable interruption of the connection. To do so, cooperation is needed between the Wi-Fi network and the receiving network. However, the Wi-5 project scope is limited to Wi-Fi networking technology and as such we have limited our work to the hand off part of the Wi-Fi network, i.e. we do not consider the full handover.

In this subsection we present the work and results to prove that a vertical HO can indeed be used as a mechanism to avoid network congestion. Specifically, we describe the mechanism and the results from an experiment carried out in the TNO facilities.

The networking concept that we used for the vertical HO relies on blacklisting a specific client, which subsequently is removed from the Wi-Fi network prompting a Vertical HO. Once the congestion is sufficiently relieved, the client is removed from the blacklist and can connect again.

The objective of the vertical HO test of this subsection is to demonstrate *i)* the feasibility of removing a client in the Wi-5 network based on the output of the decision module and *ii)* the ability to relieve congestion in the Wi-5 network when operating under high congestion conditions.

Clearly, removing a client from the network to conserve the performance of the remaining clients may seem a disproportionate measure: all the clients should benefit from the use of this blacklist without penalizing any of them. However, in a full solution, the Wi-Fi and mobile network would cooperate, thus offering a fair solution to all. In any case, full congestion should be avoided at all times because it would represent a waste of resources and the transfer of one or more clients to another network in this situation can be considered most appropriate.

4.4.1 Monitoring Module

The monitoring module here is required to collect the loads of all the APs in the network, the traffic demands of all clients, and the interference levels.

4.4.2 Decision Module

With the information from the monitoring module, it will be possible to calculate the demanded and available network resources, and the optimal assignment of the clients to the APs. If there is no assignment possible without incurring significant network congestion, one or possibly more specific clients should be selected and handed over to the mobile network. As said above, the networks should cooperate to avoid penalization of some clients.

Testing of the decision module is not included in this test. However, based on the available network resources and on the load of the APs, a decision-making strategy that allows us to include certain clients in the blacklist can be easily integrated in the module. For instance, the blacklist could be created from clients that do not reach a certain Fittingness Factor (FF), which represents the crucial metric in the optimization process and is included in the vertical HO algorithm presented and assessed in deliverable D4.3.

4.4.3 Network Configuration Module

To connect to the Wi-5 network, a client transmits a broadcast probe request. The controller checks whether the client is on the blacklist, and if not, the controller creates an LVAP and selects the appropriate AP which replies with a probe response that includes the LVAP's BSSID. Using this information, the client sends an association request. Subsequently, upon reception of an association response from the network, authentication request and response messages are exchanged. When honored by the network, the client is connected.

To remove a client from the Wi-Fi network, the client is first placed on the blacklist. Next the network sends a de-authentication message to inform the client that the connection is dropped. Upon loss of the connection, the client may try to reconnect, but upon the probe requests the client will not receive a probe response from its LVAP since it has been blacklisted so the client cannot reconnect. At this point we assume that a dual-interface device (e.g., smartphone, tablet, etc.) may revert back to its mobile network connection. While this approach will certainly not be seamless at this stage, it may allow applications running in the STA to satisfy their bit rate requirements better than the congested Wi-Fi network.

If later, the network demands are lowered, or if the available resources are increased, the Wi-5 network can serve new clients. In this case the clients that are blacklisted are removed from the list. Upon the next iteration of a client discovering nearby APs through sending broadcast probe requests, it can connect again following the regular procedure.

4.4.4 Testing of Feasibility of Vertical Handover

The objective is to demonstrate the feasibility of removing a client in the Wi-5 network based on the output of the decision module. Cooperation with the network receiving the removed client undoubtedly helps relieve the congestion and increase the overall experienced QoS. Therefore, we have developed an artificial sequential test scenario. We have 2 APs (Netgear R6100 for both AP1 and AP2) operating in the same frequency channel but configured as separate networks. The APs are installed in the same lab room, thus creating spectral interference. To complete the setup, we have 3 client stations (laptops, STA1, STA2 and STA3). STA1 and STA2 connect to AP1, STA3 connects to AP2 only. AP1 is an access point part of a Wi-5 network, while AP2 is a traditional independently operating AP. The *iperf* traffic generator is used to produce TCP- and UDP-based streams. AP2 is connected to the internet, and STA3 is used for a streaming video service.

In the test setup, the bit rate of the connections is limited to 10 Mbps at the physical layer due to limitations regarding the internal virtual interface of the click modular router installed on AP1.

When everything is properly connected and configured, the following test cycle is executed from period P1 to period P6:

P1. STA1 is connected to AP1 and a TCP-based stream is initiated, STA2 and STA3 are not connected. A throughput of approximately 10 Mbps including Ethernet+IP+Transport protocol headers is achieved,

P2. STA2 is connected to AP1, next to STA1. Now the 10 Mbps throughput is divided over both clients,
P3. STA3 is connected to AP2 and the streaming video service with a 4 Mbps throughput is started, which causes interference to the AP1 network, decreasing the throughput of both STA1 and STA2,
P4. STA1 is blacklisted and disconnected from AP1, the available throughput for STA2 increases,
P5. STA3 stops the streaming service, the available throughput for STA2 increases even further,
P6. STA1 is removed from the blacklist, STA1 reconnects and shares throughput with STA2.

Each period takes 30 s. The throughput is shown in Figure 23.

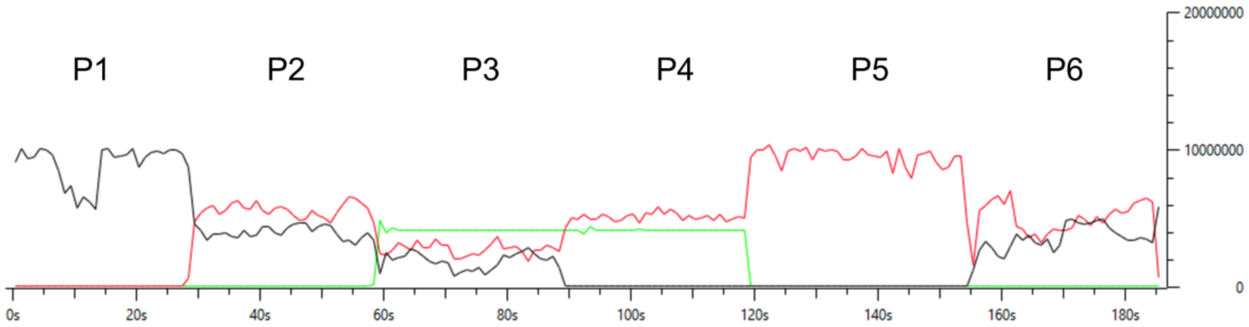


Figure 23: Throughput of STA1 (black), STA2 (red) and STA3 (green) during the test cycle.

The result of the test in Figure 23 clearly shows that in period P2, STA1 and STA2 share the available throughput (about 5 Mbps each), but that the throughput drops when the streaming service of STA3 is started. In period P4, STA1 is disconnected, which allows the restoration of the >5 Mbps service to STA2. Next (P5), the streaming service of STA3 is stopped as well, and STA2's throughput increases further up to 8 Mbps. Finally, at the beginning of P6, STA1 is removed from the blacklist and connects again where the throughput is shared between STA1 and STA2.

This simple test proves that, in the case of network congestion, a vertical handover towards a cooperating network, which receives STA1 included in the blacklist through our decision module is feasible. This approach allows us to improve the performance of the Wi-Fi network without penalizing the transferred client.

4.5 Integration and Testing of Smart AP Selection

The Smart AP Selection algorithm is based on the Fittingness-Factor (FF) and developed in the context of WP4 again exploits the seamless handover functionality which can be exploited here to assign the STAs to the APs based on the services they are running. For example, a specific AP could be devoted to STAs running a service with real-time requirements. In this section we define a general scheme of the Smart AP selection including four operational modes named RSSI mode, FF mode, Load Balancer mode and Detector mode. The roles of each mode can be explained as follows:

- RSSI Mode: In this case the Smart AP Selection is based on the decision of the best AP as in the proactive handover presented in Section 4.3. Specifically, when the scheme works in the RSSI mode, each STA is assigned to the AP with the best RSSI.
- FF Mode: In this case the Smart AP Selection is based on the decision mechanism that considers the FF value as presented in deliverables D4.1-D4.3 with the main aim to select the most suitable AP in terms of the available bit rate.

- Load Balancer Mode: In this case the Smart AP Selection is based on load balancing between all APs, executed together with the proactive handover operation. Note that the Load Balancing scheme executed is explained in Section 4.6.
- Detector Mode: In this case an AP is devoted to STAs that start running real-time services such as VoIP. A detailed explanation of this mode can be found in D3.4.

The scheme of the Smart AP selection is given in Figure 24, which depicts the roles of the module blocks. In this subsection we will focus on the FF mode of the seamless handover.

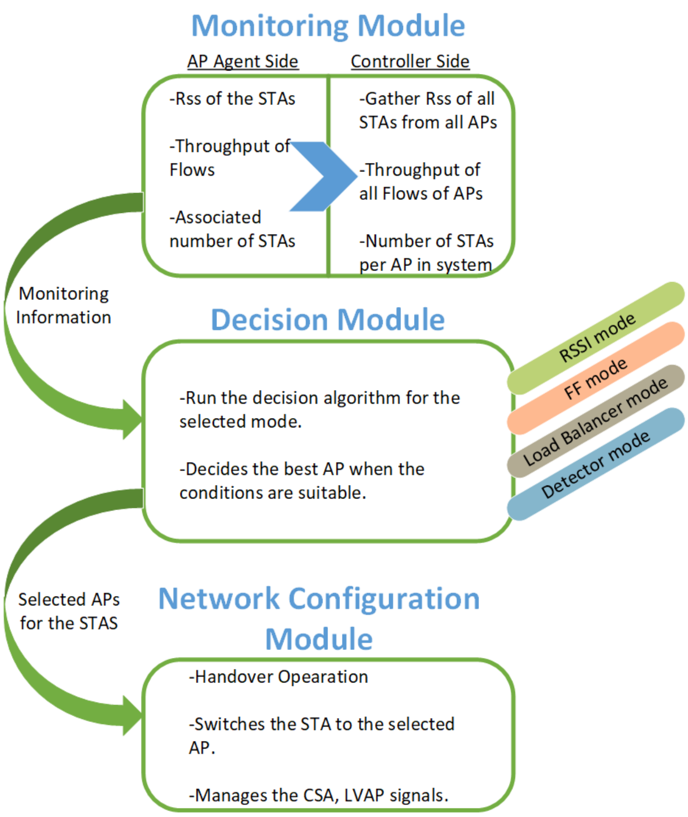


Figure 24: The scheme of the Smart AP selection

4.5.1 Monitoring Module

The Smart AP Selection algorithm based on the FF requires some monitoring information in both AP agents and the controller. Specifically, in the case of FF mode, the required information has been explained in detail in deliverables D3.4, D4.2 and D4.3 and are: (i) the number of STAs associated to each AP; (ii) the achievable physical bit rates; and (iii) the RSSI detected in each AP from each connected STA. This monitoring information is crucial in the decision-making process at the Wi-5 controller during the execution of the AP Selection algorithm.

4.5.2 Decision Module

The role of the decision module is to assign an AP for each STA that provides the maximum FF based on the information provided by the monitoring module. The FF is a metric representing the suitability in terms of available QoS between an AP and a certain STA3. The MATLAB code implemented in the context of WP4 and detailed in deliverables D4.2 and D4.3, which computes the FFs provided by all the APs for each STA based on the received information, has been implemented in the Wi-5 controller in Java and used for the execution of the algorithm.

4.5.3 Network Configuration Module

Through the network configuration module, the system allows us to connect the STA to the AP selected by the decision module. In the context of the AP selection algorithm based on the FF, this module is only responsible for the automatic assignment of the Wi-5 APs to each connected STA.

4.5.4 Integration of the Smart AP Selection based on the FF

In order to demonstrate the feasibility of the FF, which is the crucial metric included in the Smart AP Selection algorithm, a test has been conducted and explained in this subsection. This test has been carried out by UNIZAR in collaboration with AirTies that helped implement the MATLAB function which computes the FF in the Wi-5 controller.

The scenario considered in UNIZAR for this test is illustrated in Figure 25. The aim of this experiment is to demonstrate how the Wi-5 controller is able to connect each STA to the AP providing the maximum FF, while STA.215 showed in Figure 25 moves from the room it is located in to another. Therefore, in the considered scenario we included three Wi-5 APs distributed in three different rooms, i.e., AP13, AP14 and AP15, and three STAs, i.e., STA.222, STA.212 and STA.215. The decision module uses the information received from the monitoring module to compute the available bit rate for each STA in each AP illustrated in the figure. Then, it uses this information, together with the bit rate requirement of each STA, to find the AP guaranteeing the maximum FF to each of them. Finally, the controller connects each STA to the AP providing the maximum FF through the network configuration module. Note that the details on the real-time computation of the maximum FF for all the STAs in the decision module can be found in deliverable D4.3, Section 5.3.2. The required bit rates, which represent one of the input to compute the FF achievable in each AP, in this experiment are 2 Mbps for all the STAs.

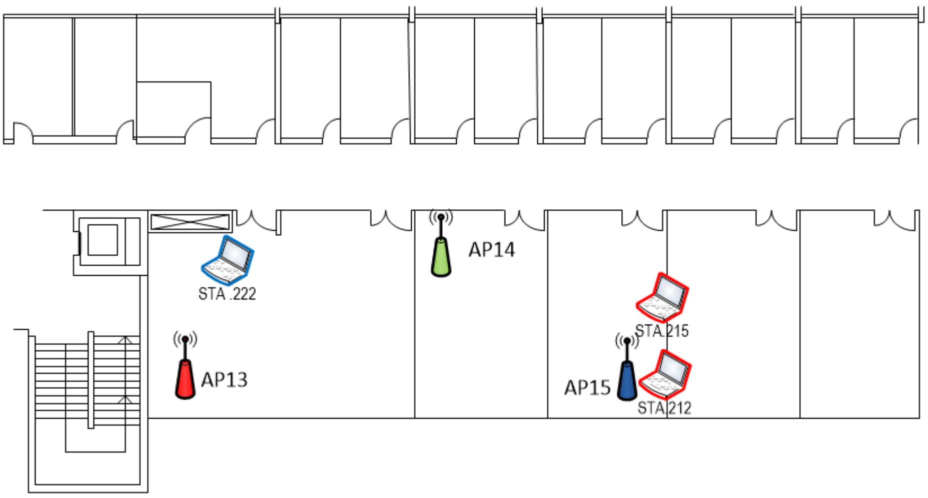


Figure 25: Scenario to test Fittingness Factor computation at UNIZAR

Each STA included in the scenario illustrated in the figure is connected to the AP providing the maximum FF. Therefore, STA.222 is connected to AP15, STA.212 and STA.215 are connected to AP13. The number corresponds to the last octet of its IP address. Figure 26 shows a screenshot of the functionality running in the controller illustrating the connection of each STA in its AP made through the network configuration module. Specifically, STA.222 achieves the maximum FF, i.e. 0.097 in AP15, based on the required bit rate and the available bit rate, which in this case are 2 Mbps and 34.02 Mbps, respectively. Moreover, from Figure 26 we can observe that also STA.212 and STA.215 are connected to the AP providing the maximum FF, i.e. AP13 where the achieved FF is 0.11 and 0.25 for STA.215 and STA.212, respectively.

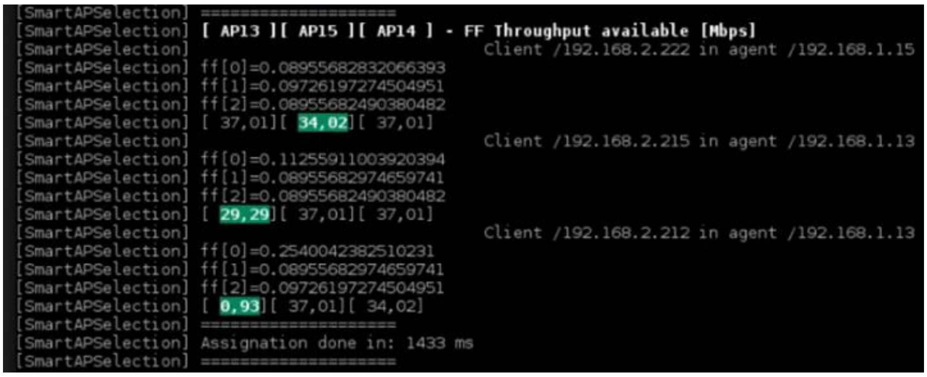


Figure 26: Screenshot illustrating initial configuration

Figure 27 illustrates how we moved STA.215 towards another room, whereas Figure 28 shows how STA.215 changed its connection from AP13 to AP15 after it reached the new room. Finally, Figure 29 shows a screenshot illustrating the connection of each STA after STA.215 changed its AP connection. In detail, from the figure we can note that STA.222 maintained its connection to AP15, which still guarantees the maximum FF, i.e. 0.29 in this case, despite the decrease of the available bit rate due to the connection of STA.215. Moreover, STA.215 changed its connection to AP15 guaranteeing the maximum FF, which is 0.29 in this case. Finally, from the figure we can observe that STA.212 maintained its connection to AP13, which guarantees the maximum FF still equal to 0.25.

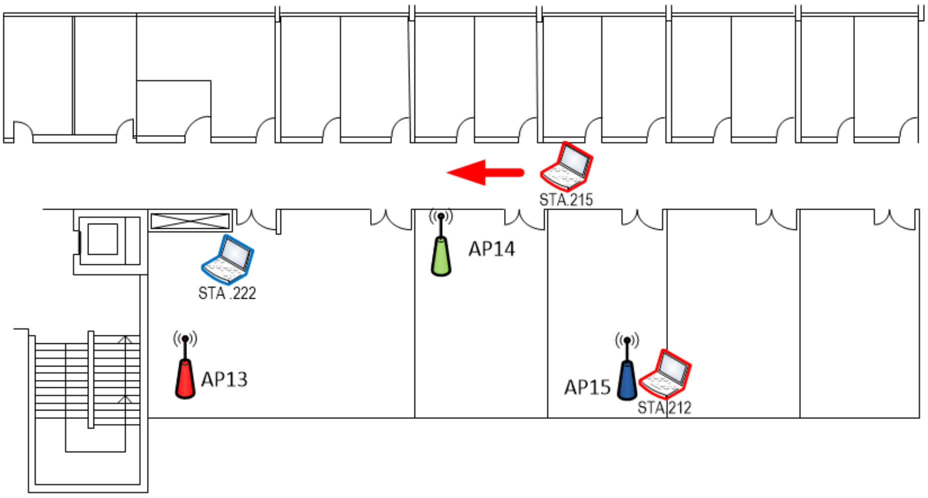


Figure 27: STA moving towards new AP

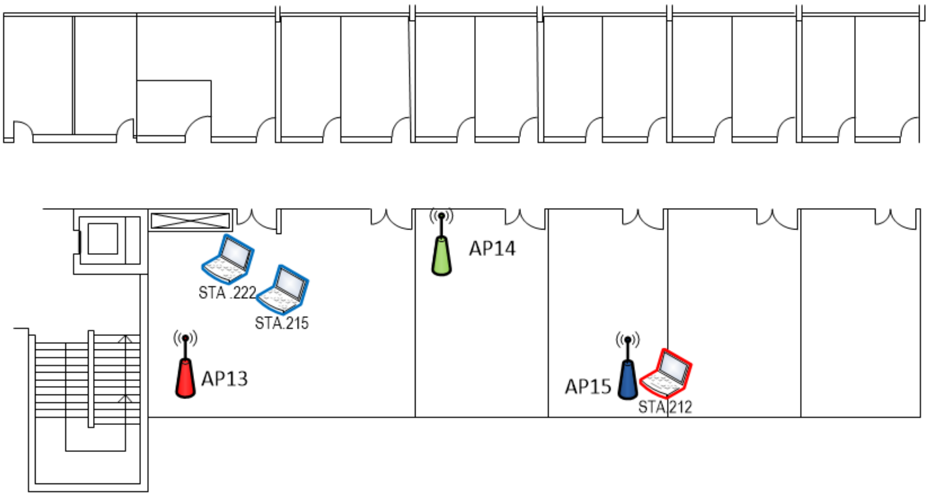
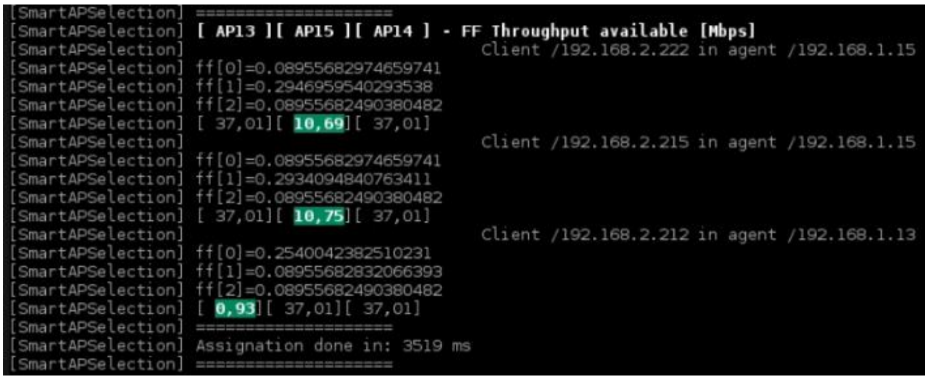


Figure 28: STA connecting to new AP



```
[SmartAPSelection] ====================
[SmartAPSelection] [ AP13 ][ AP15 ][ AP14 ] - FF Throughput available [Mbps]
[SmartAPSelection]                          Client /192.168.2.222 in agent /192.168.1.15
[SmartAPSelection] ff[0]=0.08955682974659741
[SmartAPSelection] ff[1]=0.2946959540293538
[SmartAPSelection] ff[2]=0.08955682490380482
[SmartAPSelection] [ 37,01][ 10,69][ 37,01]
[SmartAPSelection]                          Client /192.168.2.215 in agent /192.168.1.15
[SmartAPSelection] ff[0]=0.08955682974659741
[SmartAPSelection] ff[1]=0.2934094840763411
[SmartAPSelection] ff[2]=0.08955682490380482
[SmartAPSelection] [ 37,01][ 10,75][ 37,01]
[SmartAPSelection]                          Client /192.168.2.212 in agent /192.168.1.13
[SmartAPSelection] ff[0]=0.2540042382510231
[SmartAPSelection] ff[1]=0.08955682832066393
[SmartAPSelection] ff[2]=0.08955682490380482
[SmartAPSelection] [ 0,93][ 37,01][ 37,01]
[SmartAPSelection] ====================
[SmartAPSelection] Assignation done in: 3519 ms
[SmartAPSelection] ====================
```

Figure 29: Screenshot illustrating configuration after handover

Through this simple experiment we can outline the following conclusions:

- We have demonstrated that the Wi-5 controller is able to compute in real-time the available bit rate for each STA in each Wi-5 AP and use this information, together with the bit rate requirements, to compute the FFs metric needed for our smart AP selection.
- We validated our claim that the AP with the best RSSI does not always represent the best connection, which in this experiment corresponds to the best available data bit rate. For instance, from Figure 29 we can observe that STA.222 although it can obtain 37.01 Mbps in AP13 and AP14, is connected to AP15 providing 10.69 Mbps and the maximum FF to the STA. The reason of this connection is that 10.69 Mbps is closer to 2 Mbps than 37.01 Mbps and, therefore, more suitable for the STA's bit rate requirement. Therefore, this association allows us to satisfy the requirements of the STA and save bandwidth.
- We obtained interesting feedback that we did not take into account during the design of the algorithm and its assessment through simulations, which allowed us to improve our smart AP selection. Specifically, from Figure 29 we can observe that STA.212 is connected to AP13 providing 0.93 Mbps and the maximum FF to the STA. On the other hand, the assignment that tries to save bandwidth by penalizing the connection to other APs which provides higher bit rates does not satisfy the STA running an application requiring 2 Mbps. Therefore, the introduction of a threshold that will guarantee a certain minimum bit rate for the STAs in a sparse network like the one considered in this experiment, will be taken into account to improve the design of the algorithm.

4.6 Integration and Testing of the Load Balancing

The freedom to associate any STAs to any APs brings the potential risk of unevenly distributed traffic in densely deployed networks. Having such unbalanced distributions can result in inefficient use of the available resource, which results in some of the STAs with low data rates and even connection losses. The motivation of the load balancing functionality in Wi-5 was to get rid of this potential issue through the centrally controlled solution which balances the APs' loads by managing associations of all the STAs over the network. While the details of this functionality can be found in the D3.4, in this section we provide a brief explanation of the implementation of the Load Balancing in UNIZAR and the role of each module when the Smart AP selection scheme works in Load Balancer mode.

The centralized controller provides a straightforward solution for us, since all association requests have to be approved here in advance. The controller therefore has the ability to assign a STA to any Wi-5 AP and move it seamlessly from one Wi-5 AP to another. Furthermore, the functionality also enables the management of all the associated STAs even if the APs are in different channels. For the integration of this functionality the modular approach was again applied. In the following subsections, the role of each module will be briefly explained.

4.6.1 Monitoring Module

The monitoring module of the load balancing functionality requires to monitor all association requests, number of associated STAs, and the traffic loads in the APs. The central controller gathers all this information and sends them to the decision module. In addition to the association information, the controller also stores the RSSI of all the connected STAs and channel information throughout all the Wi-5 APs.

To support this functionality even when the APs are operating in the different channels, an auxiliary interface was included in the APs which performs scanning operations over other channels. This auxiliary interface was used primarily to scan and report the ordered channel information.

4.6.2 Decision Module

The decision module executes the load balancing, which takes the inputs introduced above from the monitoring module. The role of the central controller is to manage the association requests of the STAs according to the load balancing presented in deliverable D3.4. According to the result of the decision module, the controller allows a new STA to associate with the desired AP or forward it through to another AP. The result of load balancing can also re-direct previously associated STAs if an unbalanced load distribution among APs is detected.

4.6.3 Network Configuration Module

When an STA movement is ordered by the decision module, this module performs the movement operation seamlessly by transferring LVAPs between APs which, as previously described, requires no modification in the STA for the assignment and movement operations. The network configuration module orchestrates sending the CSA signals to the related STAs when the channel switch is initiated.

4.6.4 Integration of the Functionality

The load balancing follows the procedures illustrated in Figure 30 when the smart AP selection scheme works in the Load balancer mode:

1. It is run every 600ms, however, this value could be changed as explained in deliverable D3.4, and the controller requests the RSSI matrix explained in subsection 4.3.4.1, in the same way as in the case of the proactive handover.
2. Then, the load balancing algorithm is run in the decision module.
3. Any changes are implemented in the network, handing off the STAs to other APs when required.

If necessary, a burst of CSA beacons are sent to the user, when it has to be handed off to an AP in another channel as also described in section 4.3.4.1.

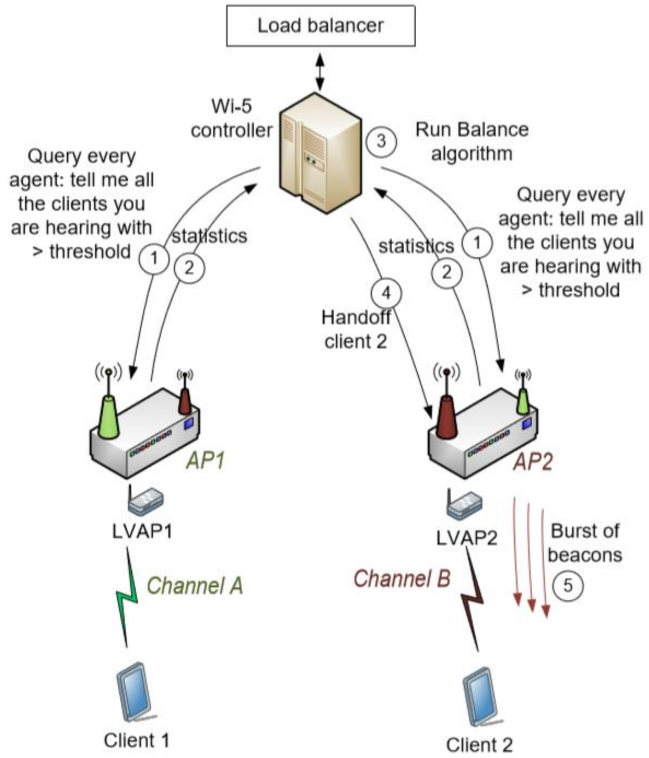


Figure 30: The signaling scheme of Load Balancing

4.6.5 Testing of the Load Balancing

The testing of this functionality was not carried out in the context of WP5 itself because it is required to work in close coordination with the handover application to avoid the ping-pong effect. Since the developed approach works as a component of the proactive handover application to integrate the load balancer mode into the Smart AP functionality, the related evaluation results of the load balancing application can be found in D3.4 and D4.3, which include extensive evaluations of the Smart AP Selection functionality.

4.7 Integration and Testing of the Packet Grouping Functionality

The objective of this functionality is to define and implement the mechanisms for packet grouping / frame aggregation between the AP and the end device, as specified in the IEEE 802.11n [18] and 802.11ac [17] standards. Two forms of frame aggregation are explored: Aggregated Mac Service Data Unit (A-MSDU), and Aggregated Mac Protocol Data Unit (A-MPDU). In addition, Layer 3 optimization [12] has also been explored by Wi-5 in certain scenarios where legacy 802.11 devices (prior to 802.11n) exist, as this optimization is not possible at Layer 2.

A detailed study of Layer 3 optimisation was included in D3.2 considering the scenarios where it can be useful, e.g. 802.11-based community networks in which the traffic goes through a number of wireless hops [13] and the delay limits that appear depending on the applications. In addition, an analytical calculation of the achievable savings was presented, considering the reduction in terms of packets per second and bandwidth. Finally, a series of tests were performed in the lab in order to measure the savings, and the modification of the traffic profiles were run and presented.

The integration of the packet aggregation functionality was limited from the beginning since the testbed runs with Click Modular Router [14], which only supports the 802.11a-b-g standards. As we could not integrate the packet grouping/frame aggregation with the Wi-5 proof of concept implementation, we have performed the following studies:

1) Doing Performance analysis of the proposed approach and algorithm within the network simulator 3 (ns3), which is a discrete-event network simulator. One of the advantages of using such a simulator environment is the ability to use huge numbers of clients and APs within the system. Different QoS analysis and traffics types are considered while packet grouping operation is executed. The details of the simulation parameters and the performance evaluation results have been given in D3.4 and published in [15]
2) Building a kind of "software for testing frame aggregation" is introduced in section 4.4.2 of D3.3. This isolated software does not work with the Wi-5 proof of concept implementation framework; it only allows testing the proposed approach between an AP and a STA without any controller structure.
3) Tests for the effect of aggregation in a subjective quality manner are detailed in section 4.4.3 of D3.3. However, these tests were not undertaken as part of our implementation and the work in these tests focused on implementing the aggregation at Layer 3 and measuring the effect of this on subjective quality [16].

4.8 The Scalability performance evaluation of the Wi-5

The motivation behind this section was to investigate whether the Wi-5 system supports multiple numbers of STAs successfully or not, considering a densely deployed network. During the experiments, multiple STAs were configured in order to saturate simultaneously uplink and downlink using either UDP or TCP traffics in a certain interval. Since the Wi-5 system generates beacon messages for each connected STA, one expected outcome would be to see more performance degradation in data rates when a large number of STAs is connected to the same network. In other words, in addition to expected degradation due to channel sharing as can be commonly observed in traditional Wi-Fi environments, an extra performance degradation due to the extra beacons for each STA could result in lower data rates.

To observe the extra performance degradation, different scenarios with the Wi-5 system activated or deactivated were conducted in experiments by using a single Wi-5 AP (TP-Link 1750 Archer with OpenWrt 15.05). During the experiments, the *Iperf* [1] network creator tool was used to generate the different type of traffics, i.e., UDP and TCP with different flow directions, i.e., Uplink and Downlink. For the performance evaluation of the system, only end-to-end throughput was used. The tests were carried out in AirTies' main office building and each STA was located close to the AP to obtain the

[1] iPerf, https://iperf.fr

best performance. The network scheme for the test is demonstrated by the Figure 31. The end-to-end throughput was measured for each flow by also using *Iperf*.

To perform the 'Wi-5 Deactivated' test case, the AP is configured such that the Control and Data Planes are bridged, just like a commercial off the shelf AP. The bridging process can be done through the network configuration file in the AP, which is the default process. Since the controller and data messages are in the same plane, there is no requirement to use an additional server PC to process the

data plane. A controller PC will be sufficient to control the AP and generate the traffic through the same AP. During the experiments, the number of STAs was increased incrementally to see the performance degradation clearly.

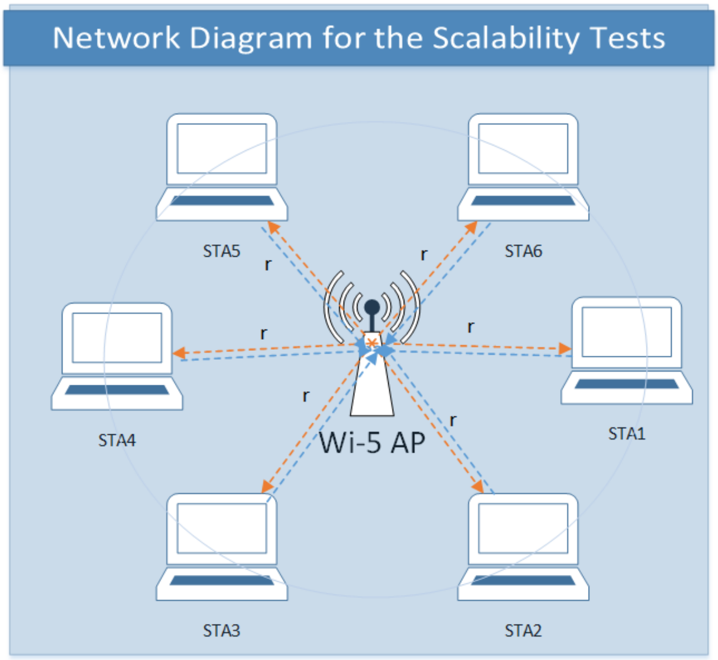


Figure 31: Network Diagram for the Scalability Tests

In the setup of the 'Wi-5 Activated' case, firstly, the Controller and Data planes should be separated by the configuration of the AP because the roles of these planes are different. After the separation process, one extra PC is configured to work as a traffic generator and Dynamic Host Configuration Protocol (DHCP) server, which assigns IP addresses to the network devices. A controller PC was also required to run as the controller of the Wi-5 system and should be connected to the AP through the controller plane port.

4.8.1 Uplink TCP Traffic Performance Tests

In this case, all the STAs generate uplink TCP traffic towards the AP simultaneously. The duration of the traffic was set to 100 seconds. We expected to see sharing the single link capacity with the number of STAs in the channel.

Table 10 and Table 11 indicate that for both the 'Wi-5 Deactivated' and 'Wi-5 Activated' cases, some of the STAs get more channel usage than the others. The overall throughput values are nearly the same when the number of STAs are increased. Furthermore, there is no connectivity problem with any of them. In conclusion, the Wi-5 system with the TCP uplink traffic provides almost the same performance for both Wi-5 activated and deactivated cases.

Table 10 Wi-5 Deactivated - TCP Uplink Test Results

	Without Wi-5, (Uplink)TCP Traffic(100sec)							
# of STAs	***STA1 THR***	***STA2 THR***	***STA3 THR***	***STA4 THR***	***STA5 THR***	***STA6 THR***	**Avg STA Thr(Mbps)**	**Overall Thr(Mbps)**
1	10,6	X	X	X	X	X	10,6	10,6
2	2,86	6,52	X	X	X	X	4,69	9,38
3	2,94	4,07	1,21	X	X	X	2,74	8,22
4	3	3	1,58	1,18	X	X	2,19	8,76
5	1,25	1,46	2,41	1,37	2,62	X	1,822	9,11
6	2,09	0,428	1,81	2,92	1,03	1,54	1,6556	9,818

Table 11 Wi-5 Activated - TCP Uplink Test Results

With Wi-5, (Uplink)TCP Traffic(100sec)								
# of STAs	***STA1 THR***	***STA2 THR***	***STA3 THR***	***STA4 THR***	***STA5 THR***	***STA6 THR***	**Avg Sta Thr(Mbps)**	**Overall Thr(Mbps)**
1	11.8	X	X	X	X	X	11.8	11.8
2	3,87	4,72	X	X	X	X	4,295	8,59
3	4,46	1,62	3,85	X	X	X	3,31	9,93
4	4,79	2,12	4,04	0,926	X	X	2,969	10,95
5	2.6	2.2	3	1	0.78		1.916	9.58
6	2	1.4	3	0.76	0.5	0.8	1.41	8.46

4.8.2 Downlink TCP Traffic Performance Tests

In this case, the AP generates the TCP traffic for each of the STAs separately. The traffic flows were generated for 100sec by *Iperf*.

One problem faced during the first trial of the Wi-5 Activated case was the fairness problem. Due to the small size of the transmission and reception queues in the MAC layers of the APs with their click configuration file of the AP (it was set to a default value 50), the traffic flows of some STAs were stopping early. This results in starvation of the STAs in terms of low data rates. In such a case, one of the STAs generally dominated the channel and the others were suffering from low throughputs and even could result in connection losses. To solve this problem, one possible approach would be to increase the queue size to have fair channel usage among traffic flows of the network. After increasing the queue size to 500, a better fairness among the STAs was observed. We expect that the Wi-5 deactivated case can have better performance in terms of scalability as the Wi-5 activated case applies the LVAPs, which brings extra overhead to the system.

The results in Table 12 and Table 13 indicate that some of the STAs gets more throughputs than the others. One reason for this unfair behavior could be due to the usage of different STAs, which have their own characteristics, protocol implementation, and rate capacities. The single link throughput performances of these cases were observed to be almost the same. As the number of STAs reaches four, fairness and connectivity problems are observed within the Wi-5 system.

Table 12 Wi-5 Deactivated Case - TCP Downlink Test Results

	Without Wi-5, (Downlink)TCP Traffic(100sec)							
# of STAs	***STA1 THR***	***STA2 THR***	***STA3 THR***	***STA4 THR***	***STA5 THR***	***STA6 THR***	**Avg Sta Thr(Mbps)**	**Overall Thr(Mbps)**
1	7,85	X	X	X	X	X	7,85	7,85
2	3,8	3,7	X	X	X	X	3,75	7,5
3	2,29	2,36	2,27	X	X	X	2,306667	6,92
4	1,7	1,73	1,74	1,86	X	X	1,7575	7,03
5	1,22	1,19	1,38	1,39	1,31	X	1,298	6,49
6	0,773	0,814	0,8	0,847	0,82	0,829	0,8108	4,883

Table 13 Wi-5 Activated Case - TCP Downlink Test Results

With Wi-5, (Downlink)TCP Traffic(100sec)(Queque_Size:500)								
# of STAs	***STA1 THR***	***STA2 THR***	***STA3 THR***	***STA4 THR***	***STA5 THR***	***STA6 THR***	**Avg Sta Thr(Mbps)**	**Overall Thr(Mbps)**
1	8.06	X	X	X	X	X	8.06	8.06
2	4,7	4	X	X	X	X	4,35	8,7
3	3	3,2	3,1	X	X	X	3,1	9,3
4	2,8	4,39	0	0	X	X	1,80	7,19
5	3.1	2.2	1.1	0	0		1.28	6.4
6	3.2	4	0.4	0	0	0	1.9	7.6

4.8.3 Downlink UDP Traffic Performance Tests

The same system setup as in the previous experiments was used for sending downlink UDP traffic from the AP to the STAs for this case. The queue size has been set to 500, and 10Mbits/sec traffic is sent to each STA. We expected to observe fairness between the multiple STAs but, since the LVAP signaling in the Wi-5 system is generated for each STA, the Wi-5 Deactivated system could have better performance comparted to the Wi-5 Activated system.

Table 14 and Table 15 demonstrate that for UDP downlink traffic, the Wi-5 Activated case has more performance degradation compared to the Wi-5 Deactivated case. When the number of the STAs is 4 or more, fairness and connectivity problems can be observed with the Wi-5 system. Thereby, the scalability of Wi-5 with UDP Downlink traffic was not sufficient.

Table 14 Wi-5 Deactivated case- UDP Downlink Test Results for 10 Mbits/sec traffic

	Without Wi-5, (Downlink)UDP Traffic, 10 Mbits/sec (100sec)							
# of STAs	***STA1 THR***	***STA2 THR***	***STA3 THR***	***STA4 THR***	***STA5 THR***	***STA6 THR***	**Avg Sta Thr(Mbps)**	**Overall Thr(Mbps)**
1	9,15	X	X	X	X	X	9,15	9,15
2	4,9	4,92	X	X	X	X	4,91	9,82
3	3,18	3,15	3,13	X	X	X	3,153	9,46
4	2,32	2,24	2,02	2,21	X	X	2,1975	8,79
5	1,71	1,69	1,49	1,68	1,49	X	1,612	8,06
6	2,7	2,01	1,83	1,16	0,717	1,1	1,6834	9,517

Table 15 Wi-5 Activated case-UDP Downlink Test Results for 10 Mbits/sec traffic

With Wi-5, (Downlink)UDP Traffic, 10 Mbits/sec (100sec)(Queque_Size:500)								
# of STAs	***STA1 THR***	***STA2 THR***	***STA3 THR***	***STA4 THR***	***STA5 THR***	***STA6 THR***	**Avg Sta Thr(Mbps)**	**Overall Thr(Mbps)**
1	3.78	X	X	X	X	X	3.78	3.78
2	1,18	1,71	X	X	X	X	1,445	2,89
3	1,07	0,965	1,09	X	X	X	1,041	3,125
4	0,872	0,957	0,979	0	X	X	0,936	2,808
5	0.8	0.6	0.9	0.4	0	0	0.56	2.6
6	1.2	0.2	0.5	0	0	0	0.32	1.9

As a conclusion, in the scalability tests conducted, the performance of the Wi-5 system has been investigated by using multiple traffic flows. Because of the additional LVAP signaling with the usage of Wi-5, less fairness in data rates was observed in comparison with the Wi-5 Deactivated case. After increasing the queue size, the performance of the Wi-5 Activated cases became better. The test results prove that the Wi-5 environment can support multiple STAs simultaneously and that they can experience fair channel usage. However, some fairness problems occur with the usage of 4 or more STAs and the reason behind that could not be clearly identified. We expect this is a result of developing the Wi-5 implementation as a proof of concept, and commercial implementations could largely mitigate these issues. As an overall result, unless only UDP downlink traffic is used, the Wi-5 system provides sufficient rates even when multiple STAs are demanding connectivity, although extra costs (i.e. LVAPs) are produced with it. As a result of these performance results and the weaknesses exposed in basing our implementation on the Click modular router, Wi-5 is also investigating ways to replace this functionality going forward.

5 Conclusions

This document has presented the integration approach and performance evaluations of the Wi-5 functionalities. The Wi-5 SDN platform has been briefly summarized with the smart and cooperative functionalities provided by the SDN based architecture. The descriptions of the Wi-5 APs and the Wi-5 controller have also been provided by considering a modular approach that has been taken to model them with 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 from the monitoring module and 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 and triggers decisions for the Wi-5 functionalities such as interference management, smart AP selection, load balancing, seamless handover, and 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 switching the channel of an AP, handing over the client from one AP to the other, or 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, the Wi-5 integration strategy has been defined and explained. The integration approach of each functionality involves a set of specific requirements which can limit the integration of some functionalities. These limitations are explicitly explained in the integration parts and module explanations. Close, collaborative integration and feedback with WP3 and WP4 provided the basis for development of the functionalities alongside the integration process. Online integration for the channel assignment application and the proactive handover application are examples of this kind of development. The motivations behind them were to provide a more real-world system to reduce the delays experienced and increase the users' satisfactions in terms of data rates.

The functionality tests have been carried out mostly in Airties' Mecidiyeköy test house which provides a centrally controlled platform for the Wi-5 project. The definitions of the tests were created and designed on a functionality-specific basis according to the design objectives of each functionality. We found that some test metrics such as SINR, QoS measurements, dropped connections and average user satisfaction were not applicable due to limitations in both software and hardware capabilities of real devices, although they were planned to be measured as reported in deliverable D5.1. Ultimately, the selected test metrics were throughput, delay and RSSI measurements. Each of the test definitions is presented, along with the deployment schemes and the expected outcomes, in order to provide a better understanding of the design objectives of the Wi-5 solutions.

The integration results demonstrate that the Wi-5 solutions provide massive performance improvements in many different conditions where a traditional Wi-Fi can suffer in terms of data rates, delays and connectivity. The integration results of the RRM functionality prove that throughput improvements as a result of a proper interference management are possible in the cases where several numbers of devices are deployed in close proximities.

On the other hand, the integration results of the seamless handover functionality validate and prove the expected performance improvements in terms of delays and data rates when handling mobile STAs in the system. In a traditional Wi-Fi environment, the movement of a STA from one AP to another involves several re-association processes, which brings significant delay and data loss costs. Moreover, in the Seamless handover section, we demonstrate that by the use of this functionality, one can get rid of these non-desired overheads and achieve a smooth handover operation among the APs. During the handover operations, Light Virtual Access Point (LVAPs) signals were used to do the steering operations without requiring any of the STAs to go through a re-association process.

The proposed functionalities have been designed as proof of concept work and evaluated by an extensive series of simulations and basic implementations. The only limitations we experienced here were in evaluating the per-flow TPC functionality (which is part of the RRM algorithm but not supported in the implementation) and the packet grouping. The TPC was tested via simulation in D4.3 and implemented on a per-AP basis here, while the packet grouping functionality was evaluated in the network simulator 3 (NS-3) and the results were provided in detail in deliverable D3.4. The details and limitations of the packet grouping functionality are given in this document, which also covers the extensive integration approaches.

The vertical handover functionality (VHO) gives a solution to support moving STAs to another wireless network not operating in the 2.4 or 5 GHz bands as an additional mechanism to manage the Wi-Fi resources in the situation of network congestion. The motivation for the VHO functionality was to avoid Wi-Fi network congestion so the design relies on blacklisting a client if it causes congestion. We do not consider the process of integrating with the mobile network here. A set of simple tests for the VHO functionality proves that, in case of network congestion, a vertical handover towards a cooperating network which receives the blacklisted STA is feasible. This approach allows us to improve the performance of the Wi-Fi network without significantly penalizing the transferred client assuming it is a dual-interface device and its traffic requirements can be met by the mobile network.

Moreover, the feasibility of the computation of the Fittingness Factor (FF) metric, relying on the monitored information available in the controller, has been also proved through a simple experiment. This metric will be crucial in the Smart AP Selection algorithm implemented in the context of WP4.

A brief explanation of the integration of the Load Balancing functionality in the Wi-5 system has also been presented in this deliverable. All the details of this implementation were provided in deliverable D3.4.

In summary then, all the proposed and integrated solutions of the Wi-5 project provide impressive performance improvements that can be put forward as an alternative way to alleviate the problems of a traditional Wi-Fi system in densely deployed networks. Moreover, by the expanded set of test cases, we prove the expected performance enhancements delivered by the Wi-5 solutions in real testbeds.

References

[1] A. Arsal, J. Saldana, A. Raschella, "Testbed Description and Definition of the Tests", Deliverable D5.1 of Wi-5 Project.

[2] J. Saldana, L. Sequeira, J. R.-Mas, J. F.-Navajas "Specification of Smart AP solutions version 2" Deliverable D3.3 of Wi-5 Project.

[3] A. Raschella, F. Bouhafs, J. Almodovar, J. Saldana, A. Arsal "Specification of Cooperative Access Points Functionalities version 2", Deliverable D4.2 of Wi-5 Project.

[4] J. Guo, T. Tsuboi, J. Zhang, "Location Aware Fast Handover Between WiMax and WiFi Networks", MITSUBISHI ELECTRIC RESEARCH LABORATORIES, 201 Broadway, Cambridge, Massachusetts 02139, 201, http://www.merl.com/publications/docs/TR2010-112.pdf, 2010.

[5] Radiotap standard for 802.11 frame injection and reception. http://www.radiotap.org.

[6] J. Saldana, L. Sequeira, J. R.-Mas, J. F.-Navajas "Definition of the performance monitoring mechanisms", Deliverable 3.1 of Wi-5 Project.

[7] J. Neyman, "Outline of a theory of statistical estimation based on the classical theory of probability." Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences 236.767 (1937): 333-380.

[8] M. Achanta, "Method and Apparatus for Least Congested Channel Scan for Wireless Access Points," US Patent No. 20060072602, Apr. 2006.

[9] I. Berberana "Wi-5 use cases and requirements", Deliverable 2.3 of Wi-5 Project.

[10] J. Pérez-Romero, O. Sallent, R. Agustí, "A Novel Metric for Context- Aware RAT Selection in Wireless Multi-Access Systems", International Conference on Communications (ICC) conference, Glasgow, UK, 24-28 Jun. 2007.

[11] M. Achanta, "Method and Apparatus for Least Congested Channel Scan for Wireless Access Points," US Patent No. 20060072602, Apr. 2006.

[12] J. Saldana, I. Forcen, J. Fernandez-Navajas, J. Ruiz-Mas, "Improving Network Efficiency with Simplemux," IEEE CIT 2015, International Conference on Computer and Information Technology, pp. 446-453, 26-28 October 2015, Liverpool, UK.

[13] Jose Saldana, Andres Arcia-Moret, Arjuna Sathiaseelan, Bart Braem, Ermanno Pietrosemoli, Marco Zennaro, Javier Simo-Reigadas, Ioannis Komnios, Carlos Rey-Moreno, "Alternative Networks: Towards a Global Access to the Internet for All", IEEE Communications Magazine, vol. 55, no. 9, pp. 187-193, 2017.

[14] Kohler, R. Morris, B. Chen, J. Jannotti, M.F. Kaashoek, "The Click modular router," ACM Transactions on Computer Systems (TOCS), 18(3), 263-297, 2000.

[15] Jose Saldana, Jose Ruiz-Mas, Jose Almodovar, "Frame Aggregation in Central Controlled 802.11 WLANs: the Latency vs. Throughput Trade-off," in IEEE Communications Letters, vol.21, no. 11, pp. 2500-2530, Nov. 2017.

[16] M. Suznjevic, J. Saldana, M. Matijasevic, and M. Vuga, "Impact of Simplemux Traffic Optimisation on MMORPG QoE," presented at the PQS 2016, 5th ISCA/DEGA Workshop on Perceptual Quality of Systems, Berlin, Germany, 2016.

[17] J. Saldana, L. Sequeira, J. Ruiz-Mas, J. Navajas, A. Raschella, J. Almodóvar, A. Arsal, "Specification of Smart AP solutions-version 2", Deliverable 3.3 of Wi-5 Project.

[18] Hartog, F. *et al*, "Wi-Fi optimisation solutions roadmap", Deliverable 2.2 of Wi-5 project.

[19] J. Saldana, R. Munilla, J. Ruiz-Mas, J. Navajas, A. Raschella, J. Almodóvar, S. Eryigit, “Final specification of the Smart AP solutions”, Deliverable 3.4 of Wi-5 Project, April 2018.

[20] A. Raschella, F. Bouhafs, J. Saldana, “Final Specification of Cooperative Functionalities”, Deliverable 4.3 of Wi-5 Project, April 2018.

[21] F. Bouhafs, M. Mackay, F. den Hartog, J. Saldana, A. Arsal, “Wi-5 Final Architecture”, Deliverable 2.5 of Wi-5 Project, April 2018.

[22] V. Pilavakis, A. Raschella, “Evaluation results”, Deliverable 5.3 of Wi-5 Project, April 2018.