Wi-5

What to do With the Wi-Fi Wild West

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Abstract

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

This deliverable presents the specification of the second version of the Cooperative AP Functionalities that are being designed in the context of Work Package (WP) 4 of the Wi-5 project. Specifically, we present a general cooperative framework that includes functionalities for a Radio Resource Management (RRM) algorithm, which provides channel assignment and transmit power adjustment strategies, an AP selection policy, and a solution for vertical handover. The RRM achieves an important improvement for network performance in terms of several parameters through the channel assignment approach, that can be further improved by including the transmit power adjustment. The AP selection solution extends the approach presented in deliverable D4.1 based on the Fittingness Factor (FF) concept, which is a parameter for efficiently matching the suitability of the available spectrum resource to the application requirements. Moreover, the preliminary details, which will allow us to extend AP selection towards vertical handover functionality including 3G/4G networks, are also presented. The assessment of the algorithms proposed in this deliverable is illustrated through the analysis of several performance results in a simulated environment against other strategies found in the literature. Finally, a set of monitoring capabilities implemented on the Wi-5 APs and on the Wi-5 controller are illustrated. These capabilities will enable the correct deployment of the cooperative APs functionalities proposed in this deliverable in realistic scenarios.

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Executive Summary

This deliverable presents the specification of the second version of the Cooperative Access Point (AP) Functionalities, which extends the first version proposed in the Deliverable D4.1 [1]. All the solutions presented in this deliverable are being defined in the context of the Work Package (WP) 4 of the Horizon 2020 Wi-5 (What to do With the Wi-Fi Wild West) project. One of the most significant features of the Wi-5 project is the cooperative approach among APs to address the lack of flexibility in current Wi-Fi networks. In this context, Wi-5 introduces a number of cooperative functionalities that have been implemented in a centralised framework, which aim to address the following challenges:

- To define a Radio Resource Management (RRM) strategy, which jointly provides a channel assignment solution finding an optimal radio configuration to minimise the level of interference, and transmit power adjustment level that addresses the Quality of Service (QoS) requirements of the applications running on the end-user's device.

- To allow the end-user's device to select the most suitable AP that satisfies the QoS requirements, and enable a horizontal handover among APs when a wireless user connected to the network changes his/her connection to another AP, if the current one can no longer provide the QoS requirements for a certain application.

- To allow vertical handovers between Wi-Fi and 3G/4G mobile networks to improve the users experience.

These functionalities have been developed in a framework to be included in the Wi-5 architecture already described in deliverable D2.4. The framework implements a set of algorithms, which cooperate to efficiently exploit the use of the radio resource, reducing interference between neighbouring APs and giving optimised connectivity for each user served by an AP. With respect to previous works in this area found in the literature, the main contributions of the proposed algorithms can be summarized as follows:

- A novel channel assignment strategy that relies on the network monitoring information has been designed to analyse and calculate the optimised channel assignment configuration across dense Wi-Fi networks.
- A RRM algorithm has been developed to combine the channel assignment strategy and a transmit power control, taking also QoS users demand into account, in order to mitigate the network-wide interference in dense Wi-Fi networks.
- An AP selection algorithm has been carried out based on a novel metric that jointly addresses QoS requirements of a flow joining a Wi-Fi network, bandwidth efficiency, and QoS requirements of the other flows active in the network.

The developed algorithms have been assessed in a simulated scenario demonstrating their efficiency through the analysis of several performance metrics against solutions found in the state of the art. In detail, an in-depth analysis of the performance is included in this deliverable showing the following achievements:

- The optimised channel assignment provides an improvement with respect to the state of the art in terms of caused interference, Signal to Interference plus Noise Ratio (SINR), and spectrum efficiency.

- The RRM algorithm provides a lower interference with respect to the state of the art maintaining the QoS required by the users.
- The AP selection algorithm allows to achieve significant improvements in terms of the blocking probability, assigned data rate, and user satisfaction against two strategies found in the literature.

Moreover, a set of radio configuration capabilities conducted on the Wi-5 APs and on the Wi-5 controller defined within WP3 and detailed in deliverables D3.2 and D3.3, have been also introduced in this document. These capabilities will allow the correct use of the algorithms to be implemented in the cooperative framework in a real-time environment.

1 Introduction

1.1 Wi-5 background

The last few years have witnessed a considerable 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 where possible, in addition to 3G/4G, to connect to the Internet due to its speed, maturity and efficiency.

Hence, Wi-Fi is facing mounting issues of spectrum efficiency due to its heavy utilisation of non-licensed frequency bands, so improvements are continuously included to standards in order to guarantee better performance and adapt it to new demands. For instance, as Wi-Fi saturation increases in areas, such as business centres, malls, campuses or even whole European cities, interference between these competing APs can begin to negatively impact users' experience. At the same time, real-time interactive services have grown in popularity and are now used across a range of mobile devices. Such devices 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 (QoE) demands.

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

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

1.2 Scope of the deliverable

This deliverable presents the second version of the cooperative APs functionalities that cover cooperative RRM solutions, wireless handover, and smart connectivity in the so-called "Wi-Fi jungle". These functionalities are exploited in scenarios where a large number of uncoordinated APs run simultaneously in both indoor public areas, such as in a shopping mall, large apartment building or an airport, and outdoor areas such as Pico-cell street deployment, ensuring more efficient frequency reuse for the communication between APs and terminals. In urban scenarios, co-channel interference between neighbouring Wi-Fi APs with an Internet connection from different service providers may occur. The Wi-5 architecture will provide an over-the-top implementation to interact with neighbouring APs to achieve the best overall configuration, minimising interference in a heterogeneous environment. This solution can also take into consideration legacy Wi-Fi APs, which are already operable with operators' remote management systems, including their channel allocation. Recent works on cooperative communications have shown that considerable network capacity and spectrum efficiency enhancements can be achieved through cooperative mechanisms such as network coding, relaying and forwarding, etc. [2]. Moreover, past and ongoing FP7 projects such as CODIV [3], iJOIN [4] and METIS [5] address the challenges of improving cellular network performance by also using cooperation mechanisms.

1.3 Document structure

This deliverable presents the second version of the specification for cooperative AP functionalities proposed in Wi-5. In detail, in section 2 we describe the state-of-the-art found in the literature related to RRM, AP selection and vertical handover strategies. In section 3 we discuss the cooperative functionalities framework, providing a set of algorithms for all the proposed solutions in Wi-Fi jungle scenarios. Section 4 presents a comprehensive assessment of the algorithms proposed in this deliverable through the analysis of several performance results in simulated environments and against other solutions found in the literature. Section 5 illustrates the set of radio configuration capabilities developed and provided in the Wi-5 APs and in the Wi-5 controller, which will enable the correct use of the algorithms presented in this deliverable in real-time scenarios. Finally, conclusions and future work are provided in Section 6.

1.4 Relationship with other deliverables

This deliverable is an in-depth extension of deliverable D4.1 “Specification of Cooperative Access Points Functionalities version 1”. All the solutions developed in this deliverable conform to the functionalities and the performance requirements defined in deliverable D2.3 “Wi-5 use cases and requirements”. Moreover, this deliverable describes the algorithms that will support the cooperative APs functionalities proposed in Wi-5 and implemented in the first and second versions of the functional architecture described in deliverables D2.4 “Wi-5 initial architecture” and D2.5i “Wi-5 interim architecture”, respectively. Furthermore, this deliverable will rely on the radio configuration functionalities and on a set of monitoring procedures designed and developed in deliverables D3.1 “Definition of the performance monitoring mechanism”, D3.2 “Specification of Smart AP solutions version 1” and D3.3 “Specification of Smart AP solutions version 2” for a proper deployment of the proposed algorithms.

1.5 Glossary

AP	Access Point
BS	Base Station
CCI	Co-Channel Interference
CDF	Cumulative Distribution Function
CQI	Channel Quality Indicator
CSA	Channel Switch Announcement
D2D	Device-to-Device
DM	Decision Making
eNodeBs	LTE base stations
FF	Fittingness Factor
GRA	Grey Relational Analysis

HeNBs	LTE base stations
IEEE	Institute of Electrical and Electronics Engineers
ILP	Integer Linear Programing
KD	Knowledge Database
LCC	Least Congested Channel
LTE	Long Term Evolution
LVAP	Light Vırtual Access Point
MAC	Media Access Control
MAS	Multi-Agent Systems
ML	Machine Learning
MCS	Modulation/demodulation and Coding Scheme
OFDM	Orthogonal Frequency-Division Multiplexing
PQA	Provided Quality Assessment
QoE	Quality of Experience
QoS	Quality of Service
RAT	Radio Access Technology
RB	Resource Block
RF	Radio Frequency
RQA	Required Quality Assessment
RRM	Radio Resource Management
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SDN	Software Defined Networking
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
STA	Wi-Fi Station
SSID	Service Set IDentifier
WLAN	Wireless Local Area Network

2 Wireless Network Resource Management in the Literature

This section reviews relevant state-of-the-art developments in terms of wireless network resources management solutions including strategies for RRM [6]-[21], AP selection [22]-[32] and vertical handover [33]-[38]. In detail, this section updates the literature review provided in the Deliverable D4.1 including new contributions found in the state of the art that address wireless network resource management.

2.1 Radio Resource Management Strategies

Many approaches to Wi-Fi RRM exist in the literature. We provide a brief summary here. In [6], the authors proposed an approach whereby an AP can select a suitable channel based on the neighboring APs it detects and its local evaluation of the least congested scanned channels. In [7], the authors proposed a heuristic algorithm that assigns a channel to an AP by analyzing the effect of partially overlapping channels on the Wi-Fi network throughput. In [8], the authors formulated the optimisation of channel assignment as a graph colouring problem. While, the authors in [9] proposed an approximation mechanism to parametrize the balance between computational complexity in a graph-based approach and desired accuracy in the channel assignment for dense Wi-Fi Networks. They have then used this approximation technique to assess the performance of a typical centralized channel assignment algorithm in a network including a varying number of residential APs.

In [10] the authors proposed a Channel Selection and User Association (CSUA) solution based on the Adversarial Multi-armed Bandit (AMAB) framework. This strategy is adopted to capture the channel states, which are unknown *a priori* due to the dynamics of wireless channels such as fast-fading and co-channel interference. In [11] the authors presented a cloud-based centralized framework called Coordination framework for Open APs (COAP) to assign radio frequency channels to individual home APs. The framework uses information about airtime utilization to strengthen the AP channel assignment. Finally, in [12] we have proposed a novel centralized AP channel assignment algorithm based on Software Defined Networking (SDN) that relies on the network monitoring information the SDN controller obtains in order to analyze and calculate the optimal channel assignment configuration across all the Wi-Fi networks. The performance analysis shows that our algorithm provides lower interference, better Signal to Interference plus Noise Ratio (SINR) and a higher spectral efficiency within the network compared to the state of the art.

A power control mechanism has been addressed in [13] to mitigate the interference in high density wireless networks. In detail, the authors proposed a distributed power control algorithm, which efficiently assigns higher transmit power to the heavily loaded cells, i.e., the cells with a higher number of users, or those which have clients with a poor channel condition. Also a dynamic transmit power control mechanism is proposed in [14]. This method is based on real time measurements of wireless link status and Wireless Local Area Network (WLAN) data usage and allows reduction of the transmit power and, hence, the interference guaranteeing at the same time the communicated data-rate. In [15] the authors proposed a simple transmit power control algorithm based on the Received Signal Strength Indicator (RSSI). Specifically, they demonstrate that the RSSI provides a sufficient metric to decide the AP transmit power, reducing interference without affecting the aggregated throughput of the network. In [16] the authors considered wireless networks including APs capable of full-duplex communication and in which the clients can only use half-duplex transmissions. In order to mitigate inter-client interference they propose the following approaches: (i) a distributed interference measurement with the aim to modulate access probabilities, and (ii) distributed power control to maximize the resulting throughput. Through this mechanism, the client with the lowest inter-client interference obtains the smallest contention window size and is selected to receive a downlink transmission from the AP.

A framework that includes channel allocation strategy for APs with power control capabilities is proposed in [17]. Specifically, the authors first formulated the channel allocation as a min-max optimization problem regarding channel utilization with constraints of data rate, channel quality, and transmission power. Second, they computed an expression to evaluate the channel utilization, which incorporates the condition of wireless channels, such as the Signal to Noise Ratio (SNR) ratio and transmission power. Finally, they proposed a new channel allocation algorithm that includes both link adaptation and power control mechanisms, in addition to the impact of Co-Channel Interference (CCI) and multiple data rates. In [18], the authors presented a detailed analysis on the benefits that can be achieved by considering a joint optimization problem that includes dynamic channel assignment and transmit power control. They then proposed a distributed algorithm that efficiently performs dynamic channel assignment and transmit power control in real time and with the ability to adjust power values and channels according to network dynamics.

Also, in [19] the authors presented a real time distributed algorithm which jointly addresses dynamic channel allocation and distributed power control. In this algorithm all the APs are able to choose any channel that reflects the current radio propagation environment and can also adjust their transmission powers to explicitly guarantee users' SINR requirements. In [20] the authors presented a novel and efficient joint radio channel allocation and power control strategy for wireless mesh networks that can be considered also in WLANs. This approach is defined as a multiple objective optimization problem, with the constraints of transmission power and traffic data rates, and with effective channel utilization as the target metric for the optimization. In [21] the authors considered a combination of power level control and rate adjusting for meeting the link quality requirements. Rate selection is determined by an estimation of the channel conditions including packet loss, delivery ratio, throughput, or SINR computation.

2.2 AP Selection Strategies

The problem of AP selection has also been addressed extensively in the literature, with many contributions focusing on wireless user devices to initiate the selection process [22]-[28]. With distributed approaches, such as game theory solutions [23]-[25], or cross-layer strategies [27], [28], the wireless device usually gathers performance related measurements from the network before selecting the most suitable AP according to a specific metric. Other more centralised approaches rely on the global view obtained from the network controller to decide the most suitable AP [29]-[33]. Although incurring more overhead, these approaches tend to be more efficient, especially in large Wi-Fi networks, since the central controller is not only able to obtain a more accurate view of the state of the whole network, but also apply load balancing to avoid congesting certain APs.

AP selection metrics have also been extensively studied in the literature with the focus on finding an AP that maximises the user's throughput. In [22], the authors propose an AP association metric called Estimated aVailable bAnd-width (EVA). This metric associates a wireless user with the AP that provides the maximum achievable throughput. In [23], the authors investigate the AP selection problem with variable channel-width WLANs using an evolutionary game theoretical approach. In this work, the authors assume that all the stations adopt the most efficient Modulation/demodulation and Coding Schemes (MCSs) to achieve their highest bandwidth efficiencies under the power constraints.

In [24], the author formulates the AP selection problem as a non-cooperative game where each user tries to maximize its own utility function, defined as the throughput reward minus the fee charged by the AP. In [25], the authors also formulate the AP selection problem as a game where players are mobile wireless users who choose radio APs to connect to the network. The authors define a new metric called Access Point Selection Parameter (APSP) based on the SINR. A utility-based AP selection approach that takes into account a wide range of interests and goals is introduced in [26].

The work presented in [27] considers the benefits of adopting a cross-layer approach in AP association. In this work, the authors propose an AP selection process based on a metric that indicates the expected throughput when associated with an AP, using combined information obtained from the physical and Media Access Control (MAC) layers. PHMIPv6, a fast hand-off mechanism presented in [28], is another cross-layer approach that uses information obtained from the MAC and network layers in order to predict which AP minimises the handoff delay time and the packet loss rate.

In [29] the authors demonstrate that in small-scale networks, the performance of centralised approaches can often outperform RSSI-based and decentralised solutions. In [30], the authors present a centralized AP selection algorithm based on a local search method. This approach aims to achieve optimal average and minimum throughputs used as base measures for decentralized algorithms.

In [31] the authors propose the use of a dynamic AP selection algorithm implemented in a SDN-based framework. In this work, the devices receive network resource-related statistics from the SDN Controller, which guide the client device to associate itself with the best available AP. Decisions are deployed in the network by the client based on the received statistics that jointly consider the network load in terms of AP bandwidth and the RSSI value. In [32] we present a novel AP selection approach based on SDN, where the controller associates the best AP to a device using an AP selection algorithm based on the Fittingness Factor (FF) concept.

2.3 Vertical Handover Strategies

The continuous evolution of multi-interface mobile devices as smartphones and tablets has recently driven the necessity of deploying various access networks. Therefore, nowadays devices with more than one radio interface can simultaneously access different wireless networks such as WLAN and 4G cellular networks and benefit from different ways of obtaining data connections. This new method of connecting devices has been introduced and made possible through the development of heterogeneous wireless networks. In this context, vertical handover procedures among heterogeneous networks is becoming a hot topic of research, in particular in the case of real-time applications requiring large amounts of data such as live video streaming.

In a vertical handover, the client with a multi-interface terminal will be able to switch its connection between different Radio Access Technologies (RATs) characterised by several capabilities and characteristics in order to satisfy the requirements of their applications [33]. In [34] and [35] the authors provide a comprehensive analysis of the currently developed vertical handover strategies considering various parameters, and their effect on the decision-making processes. Specifically, in [34] the authors conclude that efficient decisions can be obtained by employing as many measurable decision parameters as possible, such as RSS, bandwidth and power consumption of the terminal. While the authors in [35] conclude that although appropriate decision processes to determine the wireless access network are crucial for vertical handover, the complexity and signalling overhead behind the monitoring of the parameters needed at the decision-making time, is another challenging aspect to be considered.

In [36], the authors present another detailed state-of-the-art in the field of vertical handovers. Specifically, they firstly compare several strategies in terms of reliability, input parameters, their complexity and network selection methodology. They then highlight how particular parameters needed during decision-making should be obtained before the vertical handover decision with the corresponding network selection. On the other hand, this assumption might not be feasible in real world scenarios due to the complexity of the decision parameters which cannot be estimated in real-time, such as available bandwidth and handover delay. Finally, the authors conclude that cooperative handover management schemes along with cognitive radio might facilitate vertical handovers strategies.

In [37] the authors propose a novel agent-based cooperative approach for vertical handover in heterogeneous wireless networks. In detail, they presented Multi-Agent Systems (MAS) as a tool for handover procedures based on an intelligent decision-making mechanism, which is controlled by the cooperative agents. The defined MAS is able to predict the handover in a timely manner and also select the best available network by using Grey Relational Analysis (GRA) [38].

3 Cooperative Access Point Solutions

The cooperative AP functionalities proposed in Wi-5 aim to address the lack of flexibility in the management and utilisation of Institute of Electrical and Electronics Engineers (IEEE) 802.11 WLANs, which are inherently cooperative in nature. These functionalities aim to address the following challenges:

- **Radio Resource Management in the Wi-Fi Jungle**: When Wi-Fi APs are densely deployed in a small area, their radio signals start interfering with each other. This interference will affect the quality of communication between the AP and the end-user's device. While this interference can be acceptable for certain applications, other applications with strict QoS requirements will not be able to work properly. Wi-5 addresses this issue by enabling cooperation between APs through RRM algorithms to find an optimal radio configuration, which minimises the level of interference and considers the demands of the applications running at the end-user's device.

- **AP Selection**: In Wi-5, Wi-Fi APs assist the user to obtain the wireless network connection able to provide the best QoS required by his/her application. AP selection is developed by relying on cooperation between APs to find and select the most suitable AP which satisfies the QoS level required by the user. This functionality allows horizontal handover among APs to address changes in the QoS requirements of applications running at the users' devices.

- **Vertical Handover**: The Wi-5 architecture will assist the user also to find the most suitable network in terms of QoS between Wi-Fi and 3G/4G through seamless vertical handover.

3.1 Cooperative Functionalities in the Wi-5 Architecture

This subsection will address the cooperative functionalities in the Wi-5 architecture, which is presented in detail in Deliverables D2.4 and D2.5i. The initial design of the Wi-5 architecture relies on the separation of control and data planes in the Wi-Fi APs as part of SDN. This strategy allows having a single point where all the control operations can be integrated. The most important functionality of the architecture is the Wi-5 controller that has a global view of the network under its control, and is capable of running different algorithms for optimising the performance of the network. Hence, all the functionalities included in WP3 and WP4 can run as applications on top of the controller as illustrated in Figure 1. Furthermore, the cooperative functionalities designed and implemented in the context of WP4 will consider the functionalities developed in WP3 in order to handle the radio resources at the APs. These functionalities will be implemented through the northbound API of the Wi-5 controller, as proposed in D2.4. The configuration decided by the different cooperative functionalities will be sent to the APs through the Wi-5 controller southbound API, as depicted in Figure 1.

The use of the spectrum usage broker is not discussed in this document. However, deliverables D2.5i and D2.6 describe in detail how this business role helps to use the Wi-5 cooperative functionalities to implement inter-operators cooperation agreements.

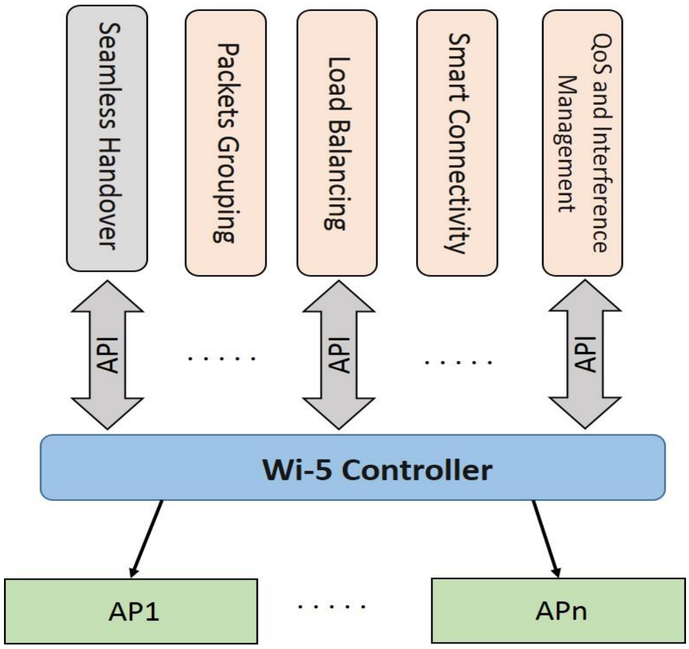


Figure 1: Diagram describing the Wi-5 architecture including the Cooperative Functionalities

3.2 Cooperative Functionalities Framework

This section describes a framework which has been included in the Wi-5 controller to provide the second version of the Wi-5 cooperative APs algorithms. In detail, it represents an enhanced version of the framework presented in Deliverable D4.1 and designed based on SDN to efficiently exploit the use of the radio resource, reducing interference between neighbouring APs and providing optimised connectivity for each user/flow that is served by an AP. Note that the enhanced version of the framework will exploit the radio configuration capabilities presented in D3.2 and D3.3 dealing with dynamic AP channel selection and transmit power control, in order to extend the assessment of the framework in real-time environments. The enhanced framework presented in this section and illustrated in Figure 2 implements a set of processes that cooperate to achieve the following objectives:

- Defining a RRM algorithm to address interference in Wi-Fi networks by combining both channel assignment and transmit power adjustment techniques. The proposed approach aims to improve the application flow QoS, while at the same time considering the effect of the configuration on the rest of the network.

- Defining an enhanced AP allocation algorithm that will assist users/flows in selecting the most suitable AP according to the application running on the station in terms of QoS requirements.

- Defining a preliminary version of the strategy that extends the AP selection towards the vertical handover between Wi-Fi and 3G/4G mobile networks.

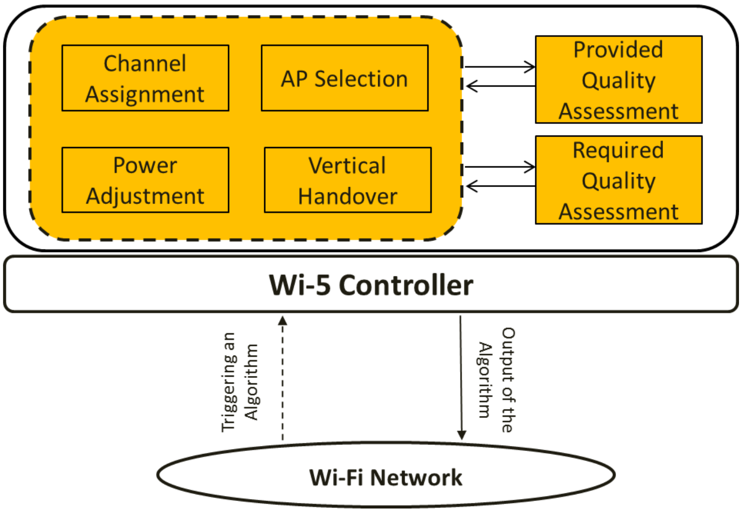


Figure 2: Extended version of the Cooperative Functionalities Framework

The *Channel assignment* process in Figure 2 considered in our RRM algorithm is based on an objective function which reduces the magnitude of the interference in the whole system. In detail, this strategy allows the Wi-5 controller to select the optimised channels 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 *Power adjustment* process considered in our RRM algorithm provides the capability of setting the transmission power of the APs such that the QoS requirements of the flows are satisfied and the level of interference in the network is maintained close to its optimal value defined through the *Channel assignment* process.

The *AP Selection* process implements a smart connectivity algorithm based on the Fittingness Factor (FF) in charge of associating an AP to each new user/flow taking into consideration the bit rate requirements. This algorithm extends the Network Fittingness Factor metric introduced in [1] and [32], which efficiently addresses the QoS requirements of both a flow joining the network and other flows active in the network.

The *Vertical Handover* process includes strategies that will allow the most suitable connection for each new user/flow between Wi-Fi APs and 3G/4G mobile stations.

The *Provided Quality Assessment* (PQA) functionality will exploit the monitoring tools detailed in deliverables D3.1 and D3.3 to detect the interference levels and compute the achievable QoS requirements for the stations in each AP. The *Required Quality Assessment* (RQA) functionality will use the monitoring tools presented in deliverables D3.1 and D3.3 to compute the application type corresponding to a certain flow and then, its required QoS. Note that these QoS requirements can easily be either proactively programmed into the Wi-5 controller [39], or reactively inferred through QoS detection techniques such as Machine Learning (ML) strategies [40]. Therefore, we assume that the information used by this process to compute the QoS requirements is available. PQA and RQA functionalities will support all the processes developed in the context of this deliverable as will be explained in the rest of the document.

The next subsections will provide a detailed explanation of the algorithms proposed in this deliverable.

3.2.1 Channel Assignment Strategy

In this subsection we first revisit our channel assignment solution, which has been introduced in [1] and [12]. We then extend the analysis of its interference-related quantity, called here *interference impact*, as a basis for providing a network-wide quality indicator from the perspective of interference. This will later be merged with a quality-oriented power adjustment mechanism to establish our proposed RRM algorithm.

For the rest of this subsection, the following network arrangement is assumed:

- We consider N Wi-Fi APs, based on the IEEE 802.11 standard, that operate on F RF channels including F_{non} of them not-overlapping each other.
- We assume $N > F_{non}$, i.e. there is channel overlapping and therefore an interference problem in the network. An example is $F = 11$ and $F_{non} = 3$ in the IEEE 802.11 2.4 GHz band where $N \geq 4$ is the starting point of channel overlapping and the densification problem.
- We assume that APs are the only elements transacting with the information required at the central controller. APs are the sensing points and measurement agents for the central controller throughout the network and the ultimate configuration is applied to APs' via the downlink.

The channel assignment optimisation problem is defined as follows:

$$A^* = \min_{A} \sum_{i \leq N} \sum_{f \leq F} G \times A^T . I \qquad (1)$$

Here $G^{N\times N}$ is defined as the network topology matrix $G \in \{0,1\}^{N\times N}$, where:

$$g_{ij} = \begin{cases} 1, & average\ power\ strenght\ of\ AP_i\ around\ AP_j\ exceeds\ a\ threshold \\ 0, & otherwise \end{cases} \qquad (2)$$

And $A^{F\times N}$ as the channel assignment matrix $A \in \{0,1\}^{F\times N}$, where:

$$a_{ij} = \begin{cases} 1, & if\ channel\ i\ is\ assigned\ to\ AP_j \\ 0, & otherwise \end{cases} \qquad (3)$$

$I \in \mathbb{R}^{N\times F}$ is defined as the matrix of the *interference impacts* for N APs and F available channels, where each $I_{i,f}$ element as an *interference impact* is the summation of the signals corresponding to channel f when it is assigned to AP_i and detected at other APs' locations. The *interference impact* for AP_i and its corresponding channel f can be expressed as follows:

$$I_{i,f} = \sum_{k \leq N, k \neq i} P_{i,k}(f) = \sum_{k \leq N, k \neq i} P_i^t \gamma_{i,k}(f) \theta_{i,k}(f) = P_i^t \sum_{k \leq N, k \neq i} \gamma_{i,k}(f) \theta_{i,k}(f) \qquad (4)$$

Here, $1 \leq f \leq F$, $1 \leq i$, $k \leq N$, $P_{i,k}$ is the average power strength of the RF channel assigned to AP_i and sensed at the close proximity of AP_k. P_i^t is the transmission power level at AP_i, $\gamma_{i,k}$ is the channel gain between AP_i and AP_k, and $\theta_{i,k}$ are coefficients varying from 0 to 1 representing the overlap between the channels assigned to AP_i and AP_k. This coefficient will be zero for non-overlapping channels. An example of such overlap is provided in [7]. Both $\gamma_{i,k}$ and $\theta_{i,k}$ are, obviously, dependent on *f*. All values are estimated and updated in real-time and are dependent on the actual characteristics of the employed RF channels as well as the arrangement of the network.

The matrix *I* reflects the interference impacts of APs' transmission powers in the objective function of (1) considering the overlap and orthogonality of the RF channels. The resulting optimised channel assignment, A^*, is supposed to minimise the summation of these impacts throughout the network. More details about the employed binary Integer Linear Programing (ILP) approach to solve (1) and the exact ILP coefficients can be found in [1] and [12].

To examine the optimality of the solution provided in (1), we need to show that the experienced interference in the network with the channel assignment based on A^* is lower than the interference by any other channel assignment combination. Let I_{acc} be the accumulation of the interferences which can be experienced at the APs' locations. We aim to use this later in the proposed algorithm to represent the network-wide quality. This, by definition, is actually the summation of the signals detectable at an AP's location and originated from all other APs:

$$I_{acc} = \sum_{i=1}^{N} \sum_{k \leq N, k \neq i}^{N} P_k^t \gamma_{k,i} \theta_{k,i} \qquad (5)$$

P_i^t, $\gamma_{i,k}$ and $\theta_{i,k}$ are the same as in (4) and we drop symbol f to avoid notation clutter. Given the resemblance between *i* and *k*'s range of values in (5) and comparing with the indexes in (4), their recast yields:

$$I_{acc} = \sum_{i=1}^{N} \sum_{k \leq N, k \neq i}^{N} P_k^t \gamma_{k,i} \theta_{k,i} = \sum_{i=1}^{N} \sum_{k \leq N, k \neq i}^{N} P_i^t \gamma_{i,k} \theta_{i,k} = \sum_{i=1}^{N} I_{i,f_i} \qquad (6)$$

where f_i denotes the instance of *f* which corresponds to AP_i. Since the linear summation with positive integer coefficients of all $I_{i,f}$ in (1) has already been shown to be optimal for A^*, for any linear summation with unit coefficients we have:

$$\forall\, i, 1 \leq i \leq N: \; \sum_{i=1}^{N} I_{i,f_i} \bigg|_{A=A^*} \leq \sum_{i=1}^{N} I_{i,f_i} \bigg|_{A=A'} \qquad (7)$$

where A' refers to any channel assignment with at least one allocated channel different from A^* and all $I_{i,f}$ are positive and greater than the threshold in (2). Applying (7) to (6) means that:

$$I_{acc}|_{A=A^*} \leq I_{acc}|_{A=A'} \qquad (8)$$

This shows that the status of the interference throughout the network and measured from APs point of view will be in its optimal situation immediately after applying the channel assignment A^*. We take this as a reference point for our RRM algorithm, which also includes the transmit power adjustment explained in section 3.2.3. Figure 3: Deviation of the accumulated interference when the optimised channels are changing depicts an example of the deviation from optimal I_{acc} for a wide range of possible changes in the optimal assigned channels. The illustrated result shows a positive and increasing trend of deviation from the optimal interference value for more changes in the APs optimal channel assignment, which is the validation of the optimality of A^*. In the RRM algorithm a threshold, denoted as δ, for acceptable deviation from the optimal interference value will be used, beyond which the channel assignment process will be triggered or the intended change will be denied.

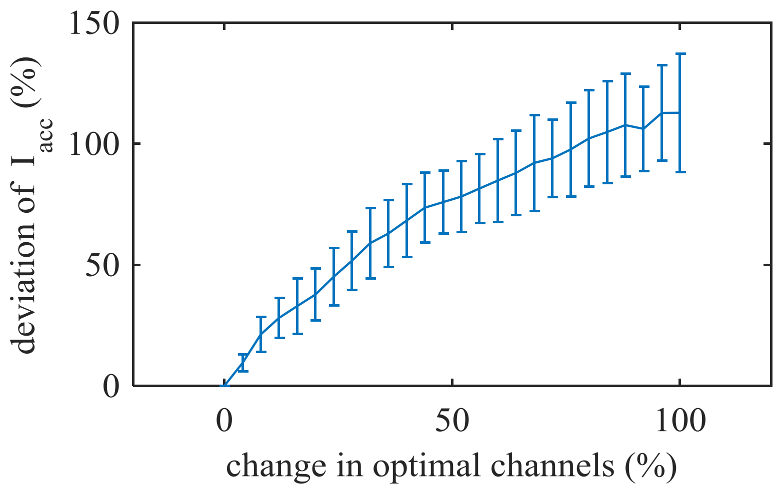


Figure 3: Deviation of the accumulated interference when the optimised channels are changing

3.2.2 Application of the Channel Assignment Strategy for Device-to-Device Communications

In this subsection we present a use case where the proposed channel assignment solution has been exploited to proactively establish and manage Device-to-Device (D2D) connections in a Wi-Fi network, considering the available radio resources and reducing the subsequent effect in terms of interference. Recently, the concept of D2D communications has become an attractive solution to the spectrum efficiency problem in wireless networks [41]-[43]. In this concept, two nearby devices can communicate directly with each other without relying on network infrastructure entities such as the Wi-Fi AP or the Base Station (BS) [44], [45].

In Wi-Fi networks, where certain devices are in close proximity and can support applications without a direct connection to an AP, D2D can improve the spectral efficiency and decrease the load on the AP, especially when the data rate requirements are high (e.g., a mobile device that is streaming video contents to a smart TV). However, despite its promising features, D2D communications require coordinated management of radio resources in order to guarantee an acceptable link quality for each D2D connection. The management of radio resources for D2D communications is particularly important in dense Wi-Fi networks where wireless devices operate over unlicensed bands with a high probability of interference. Thus, the orchestration of establishing D2D connections should be the responsibility of the network operator rather than the communicating devices themselves.

Guided by this motivation, we explore the use of our channel assignment approach implemented in the centralised Wi-5 controller for handling D2D communications. Specifically, our channel assignment scheme allow us to find an optimal channel configuration that allocates a channel for the D2D connection and, at the same, it aims to minimise the effect of this new connection on the interference levels within a dense Wi-Fi network. Figure 4 provides an overall description of the channel assignment application exploited to handle D2D connections.

In detail, each time when a new flow running in an end-user device tries to connect to the Wi-Fi network managed by the Wi-5 controller, the RQA module detects the application type corresponding to the new flow.

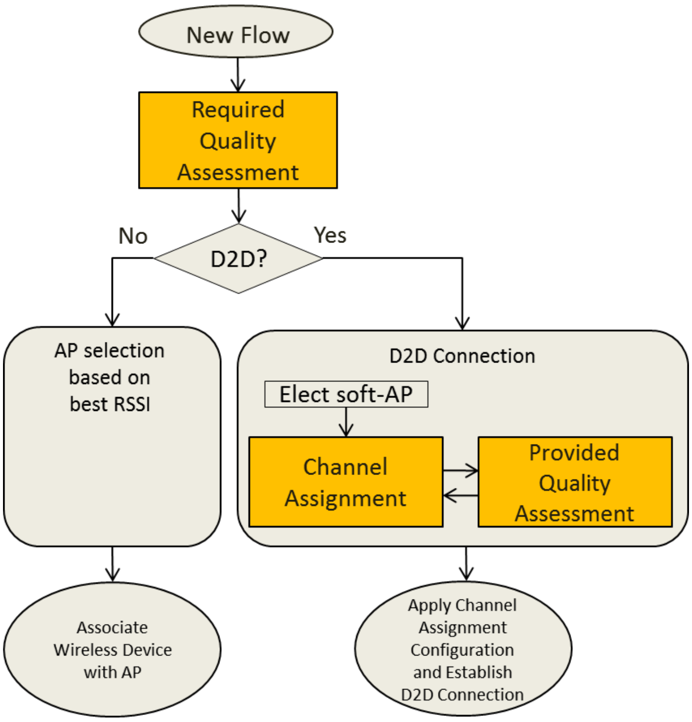


Figure 4: Application of the Channel Assignment for D2D Connections

If the detected application corresponds to a D2D flow (e.g., a user needs to print a file on a Wi-Fi connected printer or stream video contents to a smart TV), the Wi-5 controller triggers the establishment of a D2D connection. Examples of practical scenarios that involve D2D communications and can benefit from the proposed framework are: 1) a home networking scenario in which the station pairs correspond to a smart TV and a user; and 2) a home or an office networking scenario where the station pairs are, respectively, a wireless printer and a user. Many other examples can be envisioned.

Following the diagram illustrated in Figure 4, first the controller elects one of the D2D nodes as a Wi-Fi AP, which we refer to as a *soft-AP*. Once a soft-AP is elected, the channel assignment process is triggered to calculate the best channel configuration with the help of the PQA module to establish the D2D communication between the two devices, while minimising the effect of this connection on the overall performance of the network. In detail, the PQA module provides the interference levels used in the channel assignment functionality to find, through equation (1), a channel for the D2D connection with minimal impact on the overall interference levels within the Wi-Fi network. Further details on this approach can be found in [46].

On the other hand, if the detected application does not need a D2D configuration (e.g., a user watches a video on YouTube), the Wi-5 controller triggers a typical AP connection. In this case, the source and the destination are, respectively, the selected AP and the user who is watching the video. Note that since the main focus of this framework is the application of the channel assignment strategy to minimise the effect of D2D communications in terms of interference, the approach implemented in the AP selection process in this case is based only on the RSSI as recommended by the IEEE 802.11 standard.

Figure 5 describes an example where the channel assignment process is triggered to find an optimal channel configuration when a soft-AP is elected by the D2D connection framework. The left side of the figure represents the optimal channel assignment configuration across the Wi-Fi network that consists of 4 APs (the big circles) using 3 RF channels denoted by different colours (red, blue and yellow), and different STAs (the small circles), before D2D traffic is detected. Once D2D traffic is detected, the channel assignment process is triggered to find a new optimal channel assignment configuration based on equation (1) for the Wi-Fi network that consists of 5 APs (4 fixed APs and 1 soft-AP) after establishing the D2D connection. The new channel configuration is illustrated on the right side of the figure where new channels are assigned to the APs. Note that this also forces their connected devices to change channels in order to continue their services.

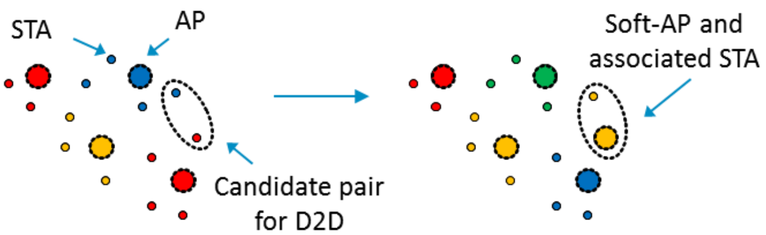


Figure 5: Channel assignment configuration including a soft-AP

3.2.3 Inclusion of the Transmit Power Adjustment and Radio Resource Management Algorithm

This subsection focuses on the inclusion of transmit power adjustment in the channel assignment strategy that allows our RRM algorithm to address both minimisation of interference in the Wi-Fi network and the QoS requirements of the users. Specifically, the network-wide interference quantity which we have defined in equation (6) above represents a direct relationship between the accumulated interference, I_{acc}, as discussed in subsection 3.2.1 and the transmission power levels of the APs. Figure 6 shows an example of this correlation between the AP transmission power levels and I_{acc} in an area of 600m×600m. Color-coded values are depicted at the locations of the APs with each colour representing the RF channel assigned to that AP. The value represents the correlation between the transmission power level of that AP and I_{acc}. The correlation values are all positive and close to +1 which highlight a strong direct relationship. However, the impacts of the APs vary based on their location and/or their assigned channels. For instance, channel 1 assigned to the central location denoted as 0.98/1-red has a correlation value of +0.98. This is higher than the correlation shown for its neighbouring AP (denoted as 0.72/4 green) because of their different channels. The same central AP has a higher correlation compared to its co-channel AP at the upper left-side of the network (denoted as 0.79/1 red) because of their different location. These variations highlight the importance of capturing the mutual relationship between radio resource parameters and the AP distribution throughout the network in our proposed approach.

The transmission power level of APs are also positively affecting the transmission rate of their corresponding downlink flows, which in turn affects the provided QoS. This opposing impact of the transmission power level over the flow-based served quality, compared to their impact over the network-wide interference, needs to be addressed in a joint quality-oriented and flow-based power adjustment scheme alongside a network-wide interference control. Assuming that the QoS requirements of the flows are known, the controller needs to adjust the transmission power of the APs such that the QoS requirements are satisfied and the level of interference in the network is maintained close to its optimal value.

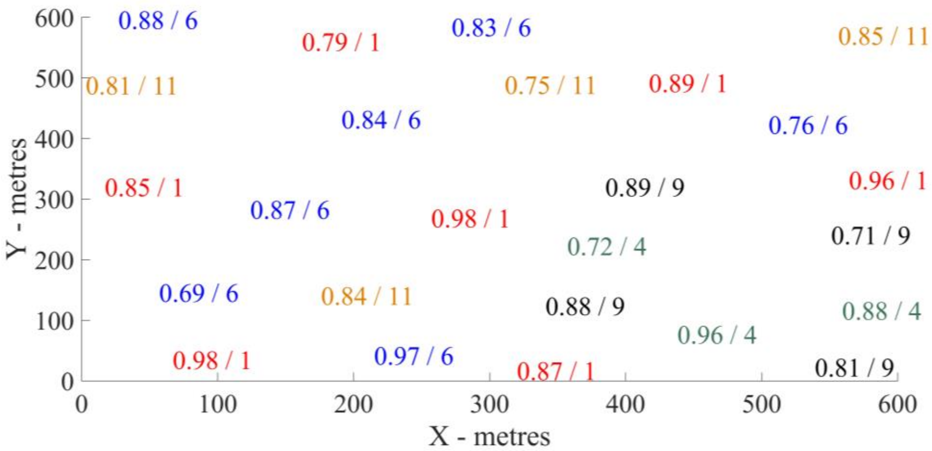


Figure 6: Correlation between the power level and accumulated interference and the impact of location and assigned channel

Figure 7 depicts the block diagram of the RRM strategy implemented on top of our Wi-5 Controller, which can maintain the trade-off between the interference status in a dense Wi-Fi network and the satisfactory power levels for all of the flows joining the APs. The main jobs designed for the proposed algorithm are as follows:

J0: optimising the AP's assigned channel given the latest status of the network and setting a reference value for the optimal network-wide interference status (i.e., the threshold δ introduced in section 3.2.1).
J1: estimating the flow's achievable rates in all available APs for a desired range of transmission power levels, and the flow's required quality. This is conducted through the PQA module, which provides the status of the flow's channel, the corresponding available rates based on the employed Orthogonal Frequency-Division Multiplexing (OFDM) scheme and the provided service for other flows already associated with the APs, and through the RQA, respectively.
J2: taking the flow's required quality into account to assess the sufficiency of the power level.
J3: assessing the impact of setting a new flow over currently active flows in the network and selecting the most suitable AP for the service.

Algorithm 1 depicts the running sequence of these jobs in the implemented algorithm for the Wi-5 controller. In detail, first the controller acquires all the measurements from the APs (line 1 in Algorithm 1) and then executes step J0 making use of (1) (line 2 in Algorithm 1). For each new flow connecting to the network, the controller assesses all the available APs that can be associated to the flow based on their RSSI (lines 3 and 4 in Algorithm 1). It then executes steps J1 and J2 for each AP (lines 5-11 in Algorithm 1). The controller then executes step J3 to select an AP for association (lines 12-13 in Algorithm 1) and finally runs J0 if flagged for the selected AP (lines 14 in Algorithm 1).

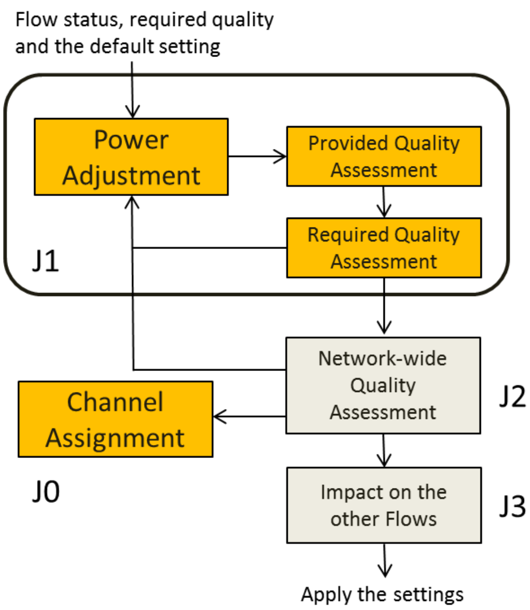


Figure 7: Joint power adjustment and channel assignment

Algorithm 1 – Power level adjustment joint with the channel assignment process

1: get network status
2: run J0: optimize the channels for all involved APs and set a threshold (i.e. δ) for acceptable deviation from optimal accumulated interference, I_{acc}
3: get new flow
4: **find** all APs available for association
5: for all involved APs
6: **run J1:** estimate the achievable rate for a set of power levels
7: **run J2:** evaluate the achievable quality of the flow and the impact on the network-wide interference
8: **if** deviation of I_{acc} is more than δ
9: **flag J0** to be run later if AP is selected
10: **end if**
11: end for
12: run J3: evaluate the impact of the rate for other flows in the APs passed through J1 and J2
13: associate the flow to the AP with the minimum impact
14: run J0: if it is flagged for the selected AP

3.2.4 AP Selection Algorithm

This subsection provides a comprehensive description of our AP selection approach in which we will also elaborate the FF and *Network Fittingness Factor* concepts and their use in the algorithm. This solution extends our previous work presented in [1] and [32] in several facets. Specifically, with respect to previous works in this area found in the literature and our previous works, the AP selection algorithm now relies on an extended version of the so-called *Network Fittingness Factor* metric. In this deliverable, such a metric jointly addresses: (i) the QoS requirements of a flow joining the network; (ii) the bandwidth efficiency; and (iii) the QoS requirements of the other flows active in the network. Moreover, with respect to [1] and [32] we also provide the following new contributions:

(i) A knowledge database is introduced in the Wi-5 controller in order to keep track of all the flows that are connected to the network. As we will explain, the information stored in the knowledge database will be crucial for the AP selection algorithm to safeguard the QoS requirements of all the flows active in the network each time when a new flow needs an AP association.

(ii) We widely strengthen the performance analysis campaign including flows requiring different bit rates, new performance metrics and experiments to assess the effectiveness of our algorithm.

(iii) We include a further reference algorithm recently developed and based on the same centralized approach, which relies on SDN [31].

Note that the AP selection algorithm can adapt to changes in the QoS requirement to allow a horizontal handover, i.e. another AP is selected for the wireless user if the current AP can no longer provide the QoS requirements for a certain application. Hence, the AP selection algorithm is triggered when either a new user joins the network, or an existing user switches to another application implying a new flow with different QoS requirements. We, therefore, consider the following processes depicted in Figure 8 upon which the algorithm relies to achieve this dynamic AP selection strategy: the already mentioned PQA and RQA, a Knowledge Database (KD) and a Decision Making (DM) module. The description of these modules in the context of AP selection is provided below.

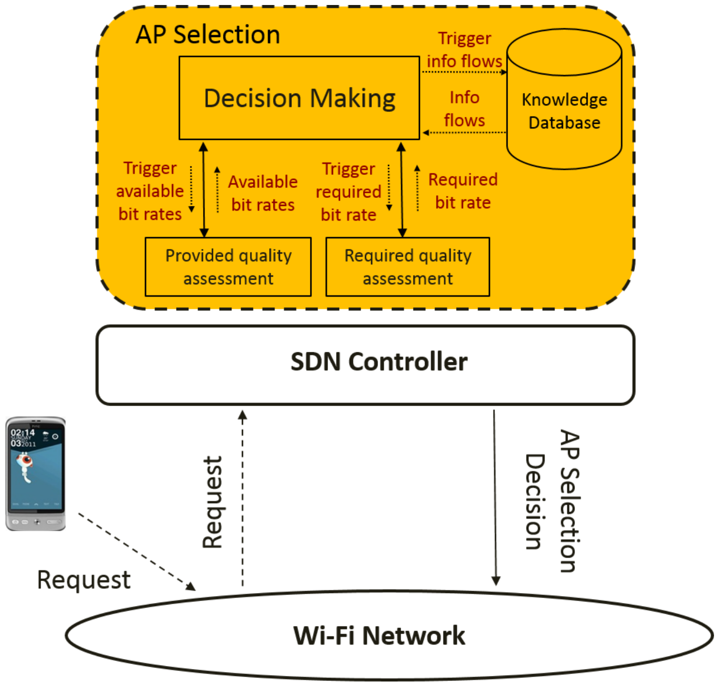


Figure 8: AP Selection Approach Using SDN Concept

The PQA module gives information on the bit rate that each AP in the network can achieve to serve the terminal request, measured at the physical layer connection. The assessment is obtained by computing the link capacity available for a certain flow in terms of the bit rate, which in turns depends on the channel bandwidth assigned to each AP, the measured inter-AP interference within the network, and the position of the terminal requiring the connection. The link capacity of an AP corresponds to the most efficient MCS to achieve the highest available bit rate under the interference level constraints. Moreover, we consider the MCSs computed by using the OFDMA approach, which has been adopted in most 802.11 protocols (e.g., 802.11 g/a/n). The RQA module translates the QoS requirements of a connection-requesting terminal into a bit-rate metric. The ML-based classification approach presented in [40] for detecting the traffic and QoS requirements can be easily implemented to work in our framework but the details of such an implementation are outside the scope of this deliverable.

The KD keeps track of all the flows connected to the network and defined as *active flows* from now on. Specifically, it stores the QoS requirements corresponding to each *active flow* and the link capacity in terms of the bit rate available for each active flow in the network. Such information will be used by the following DM process during the execution of the AP selection algorithm.

The DM module is triggered every time a new flow needs to be associated to an AP. It first collects the available information from the PQA and RQA modules, which depend on the radio environment. Then, it uses this information to calculate a FF metric for each AP according to the service it can provide for the new flow. Moreover, this process analyses the information retained in the KD to compute in each AP the change in the bit rates provided to the active flows that might be caused by the new flow. Based on this information, the DM module determines the most suitable AP for each new flow characterized by the *Network Fittingness Factor*. Finally, it updates the KD with the link capacity for each new active flow in the assigned AP. The details on the computation of the FF and on the *Network Fittingness Factor* will be provided below.

From a general perspective, we formulate the FF by extending a sigmoid function $U_{i,j}$, which denotes the bit rate achievable by the user i from the AP j for the requested bit rate. Note that with the sigmoid-based utility function, the value of $U_{i,j}$ increases as the bit rate for serving flow i by AP j increases with respect to the bit rate required for flow i. Our aim is to target a more efficient flow association to an AP through the FF concept by penalising this value if the bit rate for serving flow i by AP j is much larger than the bit rate required for flow i. The FF metric computation is based on the formulation defined in [47]-[49], while the utility function $U_{i,j}$ used to depict the QoS perceived by user i on AP j is based on the formulation proposed in [50]. Specifically, for each flow i and each AP j, a FF metric is calculated as follows:

$$f_{i,j} = \frac{1 - e^{-\frac{U_{i,j}}{\rho \cdot (R_{i,j}/R_{req,i})}}}{\lambda} \qquad (9)$$

Here $U_{i,j}$ denotes the mentioned utility function defined by the following formula:

$$U_{i,j} = \frac{\left[\rho \cdot \left(R_{i,j}/R_{req,i}\right)\right]^{\xi}}{1 + \left[\rho \cdot \left(R_{i,j}/R_{req,i}\right)\right]^{\xi}} \qquad (10)$$

The parameters ξ and ρ reflect the different degrees of elasticity between the required bit rate and the bit rate available in the APs. In particular, as we discuss in more detail below, the selection of these parameters influences the slope of the FF behaviour, which reflects the definition of the AP suitability for a certain flow with respect to the bit rate availability and the bit rate requirement. Moreover, λ in (9) is a normalization factor used to ensure that the FF metric does not exceed 1, and it is given by:

$$\lambda = 1 - e^{-\frac{1}{(\xi-1)^{1/\xi} + (\xi-1)^{(1-\xi)/\xi}}} \qquad (11)$$

$R_{req,i}$ in (9) and (10) denotes the bit rate required for flow i; $R_{i,j}$ denotes the bit rate served to flow i by AP j. Note that $R_{req,i}$ is obtained via the RQA module and $R_{i,j}$ is computed through the information obtained via the PQA. Specifically, let $\psi_{i,j}$ denote the SINR experienced by flow i when associated with AP j. $\psi_{i,j}$ can be defined as:

$$\psi_{i,j} = \frac{g_{i,j} \cdot p_j}{\sum_{k \in N'} g_{i,k} \cdot p_k + N_0} \qquad (12)$$

Here, $g_{i,j}$ is the channel gain from AP j to flow i, p_j is the transmit power of AP j, N_0 is the additive Gaussian white noise, and $N' \subseteq N$ is the set of APs interfering with AP j and therefore, affecting the SINR experienced by flow i. According to 802.11 g/a/n standards, there exists a set of defined bit rate levels between 1 Mbps and 54 Mbps that can be provided by the APs. Each of these bit rate levels represents the link capacity $b_{i,j}$ between flow i and AP j, which can be computed in the PQA module using $\psi_{i,j}$ through the Shannon–Hartley theorem. Therefore, $b_{i,j}$ can be expressed by (13):

$$b_{i,j} = f(\psi_{i,j}, BW_j) \qquad (13)$$

where BW_j is the bandwidth assigned to AP j in Hz. After the computation of $b_{i,j}$ provided by the PQA, the value of $R_{i,j}$ can be computed in the DM by considering also the number M of all the flows connected to AP j available in the controller and the maximum capacity C_j in terms of bps available in AP j. Hence, $R_{i,j}$ can be expressed as the following function g of all these parameters:

$$R_{i,j} = g(b_{i,j}, M, C_j) \qquad (14)$$

Further details of the computation of $R_{i,j}$ by making use of $b_{i,j}$ will be provided below.

Figure 9 plots the evolution of the FF values computed through (9) as a function of the ratio between the available bit rate R_b and the required bit rate R_{req} in the figure. In this example we have selected ξ = 5 because this value allows a smooth decrease of the FF when the available bit rates gradually become larger than the requirements. In fact, the greater ξ's value, the closer the FF to the sigmoid function [47]. In this figure we aim to illustrate how the selection of ρ affects the behaviour of the FF, by considering three different cases with ρ = 1, 1.3 and 1.8, respectively.

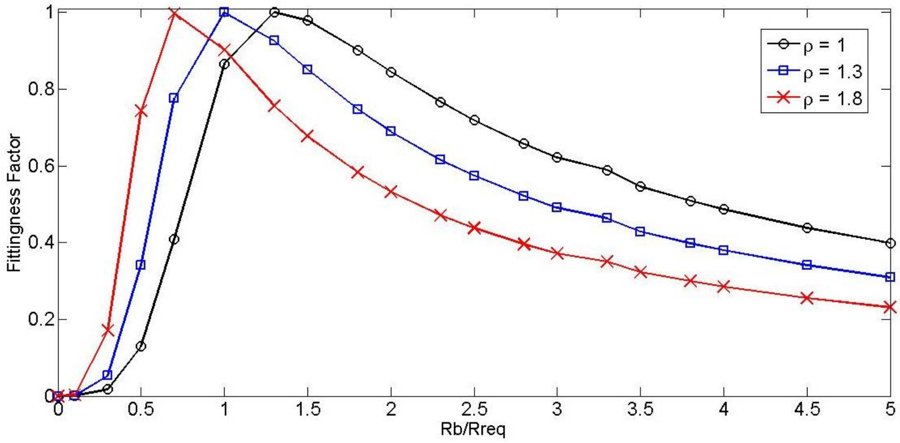


Figure 9: Fittingness factor as a function of R_b/R_{req} for different values of parameter ρ

The figure illustrates that the case $\rho = 1$ exhibits the maximum value of the FF when the available bit rate is greater than the requirement (i.e., when R_b/R_{req} is approximately 1.3). The case $\rho = 1.3$ depicts the maximum value of the FF when the assignment equals the requirement (i.e., when $R_b/R_{req} = 1$). Finally, the condition $\rho = 1.8$ exhibits the maximum FF value when the available bit rate is lower than the requirement (i.e., when R_b/R_{req} is approximately 0.7). This means that the ρ parameter defines the degree of suitability between the requirements and the APs, provided by the FF through (9). The effect of the selection of the ρ parameter in the performance results will be illustrated in Section 4.

Although the FF described previously can assist in finding a suitable AP to serve an active flow, this metric does not reflect the effect of a potential association between an AP and a flow on the rest of the network. In reality, when a wireless user is associated with an AP, the overall network capacity will decrease and serving the new flow might affect the performance of all or a part of the network. We, therefore, define another parameter called *Network Fittingness Factor* (net_f), which relies on the *Standard Deviation Function* (σ). In detail, the *Standard Deviation Function* defines the variation in terms of the average FF that might result when an AP *j* starts serving a new flow *i*.

For each AP *j*, the link capacity in terms of the available bit rate for each active flow is recomputed by considering the effect caused by the connection of flow *i*. Based on the new values of the bit rates, the FFs of the active flows are then updated through (9). Finally, the standard deviation is calculated as following:

$$\sigma_{i,j} = \sqrt{\frac{\sum_{k=1}^{K}\left(f_{k,j} - \overline{f_J}\right)^2}{K}} \qquad (15)$$

where $\overline{f_J}$ is defined as following:

$$\overline{f_J} = \frac{1}{K}\sum_{k=1}^{K} f_{k,j} \qquad (16)$$

In (15) and (16), *K* represents the number of all active flows in AP *j*, which includes the previous flows active in the AP with their FFs updated, and the new flow *i*.

Given that there are *N* APs available for selection to serve the new flow *i*, the *Network Fittingness Factor* is used to optimise the following parameters: (i) the FF metric of the AP serving the new data flow, and (ii) the standard deviation factor that maintains the performance of the overall network as much as possible, in order to determine the most suitable AP. This optimisation is formulated below:

$$\begin{aligned} net_{f_i} &= arg\,max_{j\in\{1,\dots,N\}}\left\{F_{i,j}\right\} \\ where\ F_{i,j} &= f_{i,j}\left(1 - \sigma_{i,j}\right) \end{aligned} \qquad (17)$$

Hence, net_{f_i} computed through (17) aims to optimise the individual performance of the new flow to the associated AP by maximizing its FF, while trying to safeguard the overall network performance by minimizing the impact on the other active flows through the standard deviation. Note that for an AP with no other active flows, its standard deviation value considered in (17) is 0.

The objective of this algorithm is to find a suitable AP among the N APs composing the Wi-Fi network with which the wireless user could be associated such that: (i) the AP provides the QoS performance requested by the new flow, (ii) the AP association should safeguard the overall network performance.

The KD stores for each AP j the following sets: (i) R^j_{req} that includes the QoS requirements in terms of bit rates corresponding to its active flows; and (ii) the set $B^j$with the link capacities in terms of bit rates of the active flows computed through (13).

As it is depicted in Figure Figure **8**, each time a new flow triggers the request of an AP allocation, the DM module implemented in the SDN-based controller makes use of:

- the quality information obtained from the RQA that provides the bit rate required by the new flow;
- the link capacity in terms of the bit rate for the new flow from each AP in the network obtained from the PQA;
- the QoS requirements and the available bit rates for each active flow in the network from the KD.

Algorithms 2 and 3 below depict in detail the running sequence of these interactions during the execution of the algorithm. Firstly, to find the best AP to serve a new flow i, the DM module starts by collecting the required bit rate $R_{req,i}$ from the RQA (line 1 in Algorithm 2 below). Then, for each AP j, it collects from the PQA the link capacity $b_{i,j}$ in terms of the bit rate which the AP can provide and is computed using (13) (line 4 in Algorithm 2). It then computes the set R^j of AP j, which includes the available bit rate for the new flow together with all the updated bit rates available to serve the existing active flows in AP j, where the updated bit rates take into account the effect caused by the possible connection of flow i (line 5 in Algorithm 2). Note that R^j is computed through Algorithm 3, which will be explained below.

The DM module then gets the set R^j_{req} stored in the KD, and adds $R_{req,i}$ in R^j_{req} (lines 6 and 7 in Algorithm 2). Afterwards, it computes all the FF values achieved for all the flows (including flow i) in AP j based on the bit rates in R^j and R^j_{req}, respectively, using (9) and stores these values in set FS (lines 8-12 in Algorithm 1). Hence, the DM can use (15) to compute the *Standard Deviation Function* ($\sigma_{i,j}$) for AP j based on these computed values in FS (line 13 in Algorithm 2). Afterwards, the DM module calculates value $F_{i,j}$ for AP j using (17) and stores it in set NF (lines 14 and 15 in Algorithm 2). Having completed the computation of each $F_{i,j}$ with $j \in \{1, \dots, N\}$ (between lines 3 and 16 in Algorithm 2), it determines the most suitable AP for flow i based on net_{f_i} in (17) (line 17 in Algorithm 2). Finally, the DM updates the sets R_{req} and B corresponding to the selected AP, which include the required bit rate and the link capacity for new flow i, respectively, and stores them in the KD (line 18 in Algorithm 2).

Focusing now on the computation of R^j, as defined in Algorithm 3, the DM module firstly gets the stored set B^j from the KD, which contains the link capacities (in terms of bit rates) of all the active flows in AP j, and adds $b_{i,j}$ in B^j (lines 1 and 2 in Algorithm 3). Afterwards, the DM module computes R^j by considering that all the flows associated with AP j can share the access time (lines 3-13 in Algorithm 3).

Next, let us focus on the computation of the available bit rate $R_{a,j}$ served to a flow a by AP j, as stated in lines 4-11 of Algorithm 3 and specified by (14). The upper bound of $R_{a,j}$ is defined by dividing the total capacity C_j (in bps) of AP j by the number of its active flows (note that this number indicated by M in (14), is derived in Algorithm 3 through the cardinality of set B_j). A set B'^j including the flows with their link capacities not higher than the upper bound is created in order to compute the average capacity for all the other flows. Then, the available rate served to the flow in AP j and called R' is equally shared with the other flows with their link capacities greater than the upper bound (see lines 4 and 5 of Algorithm 3). Finally, if the link capacity of a flow is lower than the upper bound, the available rate served to the flow corresponds to its link capacity (see lines 7 and 8 of Algorithm 3). Otherwise, the available rate served to the flow corresponds to R' (see lines 9 and 10 of Algorithm 3).

Algorithm 2 - AP Selection

get $R_{req,i}$ from the RQA
$NF \leftarrow \emptyset$
for j=1 to N **do**
    get $b_{i,j}$ from the PQA
    compute R^j by running Algorithm 2
    get R^j_{req} from the KD
    $R^j_{req} \leftarrow R^j_{req} \cup \{R_{req,i}\}$
    $FS \leftarrow \emptyset$
    for k=1 to $|R^j|$ **do**
        compute $f_{k,j}$ based on $R_{req,k} \in R^j_{req}$ and $R_{k,j} \in R^j$
        $FS \leftarrow FS \cup \{f_{k,j}\}$
    end for
    compute $\sigma_{i,j}$ based on FS
    compute $F_{i,j}$ based on $f_{i,j} \in FS$ and $\sigma_{i,j}$
    $NF \leftarrow NF \cup \{F_{i,j}\}$
end for
decide net_{f_i} based on values stored in NF
update the selected AP's sets R_{req} and B stored in the KD

Algorithm 3 - Computation of R^j

1: **get** B^j from the KD
2: $B^j \leftarrow B^j \cup \{ b_{i,j}\}$
3: $R^j \leftarrow \emptyset$
4: $B'^j \leftarrow \{b \in B^j \wedge b \leq C_j/|B^j|\}$
5: $R' = \frac{C_j - sum(B'^j)}{|B^j| - |B'^j|}$
6: **for** a=1 to $|B_j|$ **do**
7:   **if** $b_{a,j} \leq C_j/|B_j|$ **then**
8: $R_{a,j} = b_{a,j}$
9:   **else**
10: $R_{a,j} = R'$
11:   **end if**
12: $R^j \leftarrow R^j \cup \{R_{a,j}\}$
13: **end for**
14: **return** (R^j)

We now look into the complexity of our algorithms. Let L be the number of all the active flows in the network at a certain time instant t, which are equally distributed among the N APs throughout the network. The first *for* cycle in the AP selection algorithm is called N times (line 3 in Algorithm 2). During each of the N iterations, Algorithm 2 firstly computes R^j, which calculates on average L/N bit rates served to each flow in AP j (lines 6-13 of Algorithm 3). Then, Algorithm 2 computes on average L/N FF values (lines 9-13 of Algorithm 2). Therefore, the time complexity of our AP selection algorithm is linearly related to the number of flows and we can define its approximation as:

$$O\big(N \cdot (L/N + L/N)\big) = O(L)$$

3.2.5 Vertical Handover

This subsection proposes a strategy representing a preliminary solution that will allow the most suitable connection for each new user/flow considering both Wi-Fi APs and 3G/4G mobile stations based on the FF. In detail, the Wi-5 controller will also be capable of considering 3G/4G BSs such as femtocell LTE base stations (HeNBs) and macrocell Long Term Evolution (LTE) base stations (eNodeBs) for multi-interface devices such as smartphones and tablets. Figure 10 illustrates a scenario in which our proposed framework will enable the controller to handle dual-interface devices, which can be connected to both Wi-Fi and 4G networks. For each device the bit rate levels representing the link capacity computed in the PQA module through equation (13) between a flow and an AP, will be also computed for the BSs relying on the maximum Channel Quality Indicator (CQI) experienced by a flow needed in a dual-interface device.

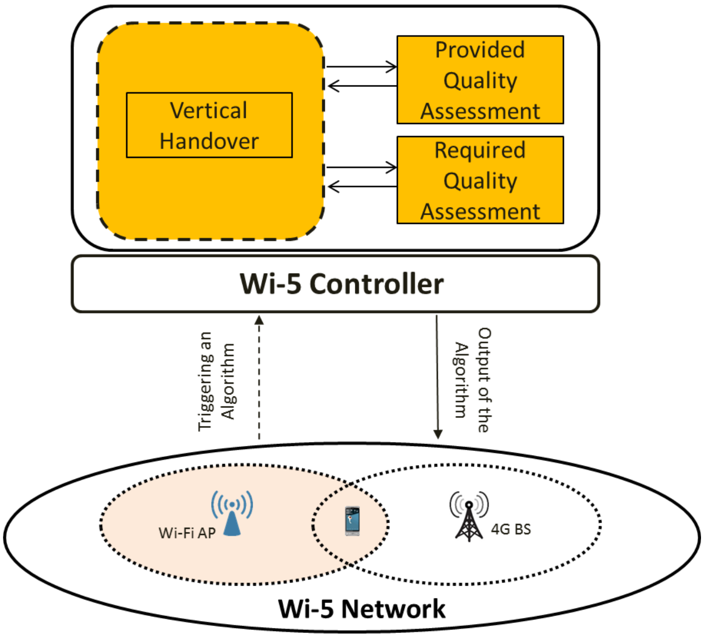


Figure 10: Proposed Vertical Handover Approach Using SDN Concept

Specifically, for a flow i and a BS j, the PQA will be able to collect from the device requiring flow i the experienced $CQI_{i,j}$ and then it will compute $b_{i,j}$ relying also on $\psi_{i,j}$, therefore, through a function defined as follows:

$$b_{i,j} = f\big(\psi_{i,j}, CQI_{i,j}\big) \qquad (18)$$

The CQI is related to the maximum MCS supported by the dual-interface device [51]. In LTE systems, 15 different CQI levels illustrated in Table 1 are foreseen. The LTE air interface uses OFDMA in the downlink direction and the available sub-carriers are grouped into Resource Blocks (RBs). In detail, each RB is a sub-channel of 180 kHz formed by 12 consecutive and equally spaced sub-carriers, each one lasting 0.5 ms. The total number of available RBs and the available data rate for a certain flow depends on the system bandwidth configuration, and is managed by the packet scheduler implemented at the BS [52]. In our framework, in order to extend the AP selection algorithm towards the inclusion of vertical handover, we will consider packet schedulers based on the FF implemented in the Wi-5 controller.

Table 1: CQI-MSC Mapping

CQI Index	Modulation Scheme	Code Rate	Spectral Efficiency (bit/s/Hz)
1	QPSK	0.076	0.1523
2	QPSK	0.120	0.2344
3	QPSK	0.190	0.3770
4	QPSK	0.300	0.6016
5	QPSK	0.440	0.8770
6	QPSK	0.590	1.1758
7	16-QAM	0.370	1.4766
8	16-QAM	0.480	1.9141
9	16-QAM	0.600	2.4063
10	64-QAM	0.450	2.7305
11	64-QAM	0.550	3.3223
12	64-QAM	0.650	3.9023
13	64-QAM	0.750	4.5234
14	64-QAM	0.850	5.1152
15	64-QAM	0.930	5.5547

4 Performance Evaluation

The aim of this section is to provide a comprehensive assessment of the developed algorithms through the analysis of several performance results in simulated environments. All the simulations developed for this purpose comprise the required network elements and functionalities including the Wi-Fi AP entities, a central controller and user stations, together with the implemented resource management functionalities. A range of different scenarios is considered to assess our algorithms.

4.1 Channel Assignment Strategy

We evaluated the performance of the channel assignment strategy introduced in section 3.2.1 in a MATLAB-based simulator that represents a dense Wi-Fi environment. This consists of 50 APs randomly deployed in an area of 1200m×1200m at a minimum distance of 100 meters from each other, with the transmit power varying from 10dBm to 25dBm. User stations are deployed randomly at a minimum distance of 1m from each other. We adopted a large-scale path loss model with the path loss exponent set to 2.5, and a fixed noise level at -95dBm.

For our evaluation, we compare the performance of our SDN-based channel assignment algorithm against two common approaches, namely: Least Congested Channel (LCC) selection mechanism and uncoordinated channel assignment. In LCC, each AP acquires a suitable channel based on the neighbouring APs' channels [6] (this can also be implemented based on the contention and retransmission statistics evaluated at the MAC layer). In the uncoordinated approach, each AP randomly acquires a channel without any prioritization, or with a prioritization over the orthogonal channels in some cases (e.g., channels 1, 6 or 11). This approach resembles a round robin assignment approach in dense Wi-Fi networks, where the number of APs is much larger than the number of available channels.

Figure 11 shows the interference levels achieved throughout the network using each of the channel assignment algorithms considered in our evaluation. The upper and lower edges of the plotted boxes are the 25th and 75th percentile of the values and the median values are indicated by the central red lines. The values which we considered as outliers are indicated by blue dots in each case. The figure shows that our SDN-based approach results in lower interference levels compared to the LCC and uncoordinated channel assignment approaches respectively. This includes a consistent reduction in the interference level for all of the monitored values, including the outliers, which results in a 3dB reduction in the average interference level in the network compared to the uncoordinated approach and a 2dB reduction compared to the LCC approach.

Figure 12 shows the Cumulative Distribution Function (CDF) of the SINR values measured at the users' stations using each of the channel assignment algorithms. This figure shows that our SDN-based solution outperforms the LCC and uncoordinated approaches by increasing the range of the achievable values of SINR and subsequently increasing the average SINR value (corresponding to CDF=0.5) by 2.5dB and 3.5dB respectively. The improvement in terms of SINR values seems slightly greater than the improvement depicted based on the interference values in Figure 11. This is due to the impact of the improvement of SINR values over the SINR-based AP association process which is employed in our simulator. A lower interference value mostly influences the AP selection process for the users at the edge of the APs' coverage area. Allowing some of these users to join an AP with a higher RSS intensifies the improvement of the performance through better AP selection.

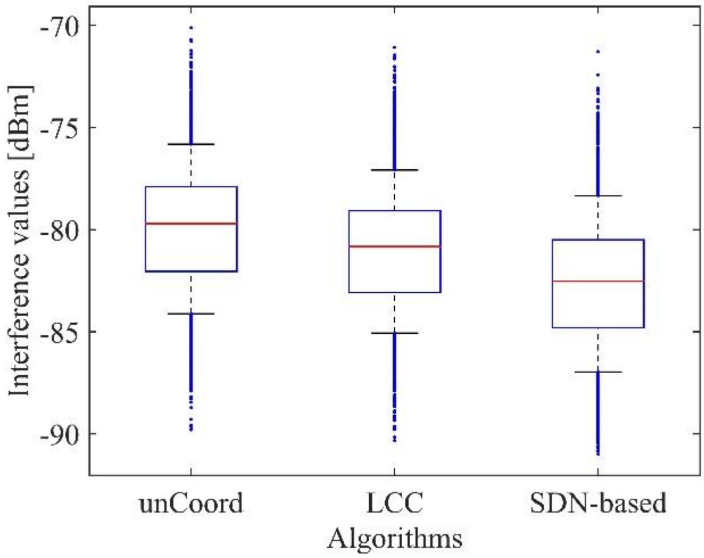


Figure 11: Average interference levels obtained using each channel assignment solution

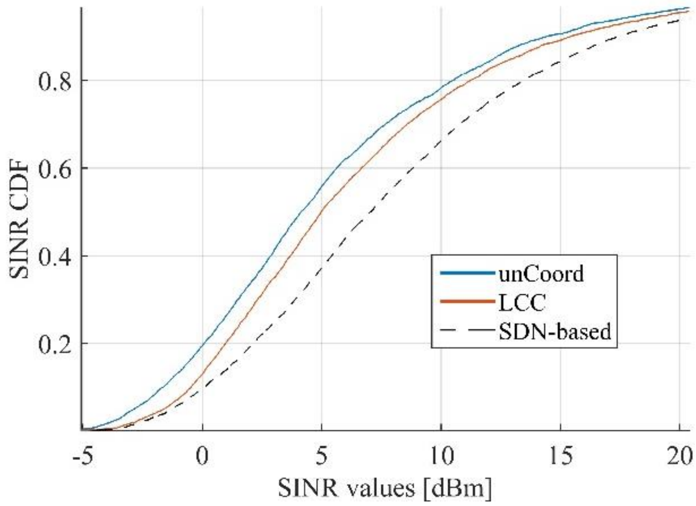


Figure 12: CDF SINR obtained using each channel assignment solution

The aim of the proposed SDN-based channel assignment algorithm is to improve spectrum efficiency by reducing the interference through optimised channel assignment to the APs. This can be evaluated through the assessment of the spectrum utilization at the physical layer in terms of the achievable rate per unit of the employed bandwidth, b/s/Hz.

Figure 13 shows the achieved spectral efficiency for the channel assignment solutions considered in our evaluation. The upper and the lower sides of the thick parts of the depicted lines represent the range of the values from 1st to the 3rd quartiles alongside the median value indicated at the middle of the lines. The outlier values are represented by the thin part of the lines. The obtained results show that our SDN-based solution outperforms LCC and uncoordinated algorithms by 0.4 b/s/Hz and 0.6 b/s/Hz on average, respectively. In terms of the channel capacity, these improvements are equal to 8Mbps and 12Mbps improvements in the achievable physical layer data rate compared to LCC and uncoordinated. This is based on a 20 MHz channel bandwidth in IEEE 802.11 2.4GHz. Furthermore, the proposed approach has expanded the range of the achievable spectral efficiency values to a higher level compared to LCC and uncoordinated algorithms.

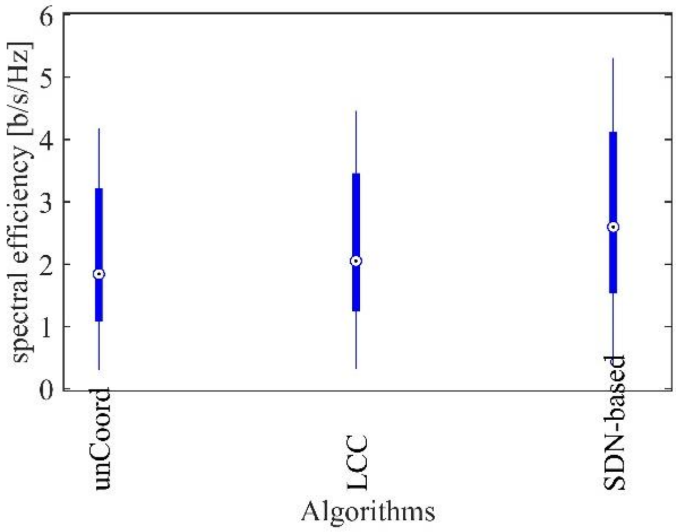


Figure 13: Spectral efficiency using each channel assignment solution

These results demonstrate that network status information such as the interference levels at each AP, the current channel assignment configuration and the network topology allows us to achieve a lower interference, better SINR and a higher spectral efficiency within the network compared to the state of the art.

4.2 Channel Assignment Strategy for Device-to-Device Communications

In this subsection, we evaluate the performance of our channel assignment strategy in a dense Wi-Fi environment that includes D2D communications alongside native Wi-Fi infrastructure. The simulations are again run using MATLAB. We investigate the performance of the network with D2D capability and compare it to the infrastructure mode of the same network (i.e., when the Wi-5 controller always triggers the AP selection process). The simulation settings and parameters are summarised in Table 2. It is worth noting that the simulated network will be further densified by the D2D connections. Once assigned, the transmit power of the AP remains unchanged during the simulation (i.e., there is no transmit power control in this evaluation). Finally, we adopted a large-scale path loss model with the exponent set to 2.5, a fixed noise level at -95dBm and the threshold in equation (2) set to -78dBm.

Table 2: Summary of the Simulation Parameters

Simulation Area	250*m* x 250*m*
Number of Wi-Fi APs	4
Minimum distance between APs	50*m*
AP Transmit Power	Assigned between10*dBm* to 25*dBm*
Users' stations deployment	Randomly at a minimum distance of 1*m* from each other and from the APs

When D2D is deployed (i.e., a new D2D connection is established), one device of each pair is transformed into a soft-AP and the other one will be associated with it. During D2D deployments, the channel assignment process is reconfigured in order to allocate new channels to the APs and soft-APs. On the other hand, in the case of the infrastructure mode, the channel assignment process is executed only at the beginning of the simulation to configure the 4 fixed APs forming the native Wi-Fi infrastructure mode. The provided rate illustrated in our performance analysis is defined as the served rate divided by the required rate demonstrated. The required rate varies from 100*kbps* to 10*Mbps* and depends on the application type. Furthermore, in this evaluation we compare the performance of our SDN-based channel assignment strategy against the LCC selection mechanism being the most common strategy spotted in the literature [6].

We firstly investigate the performance of the Wi-Fi network with D2D capability using our SDN-based framework in comparison to the infrastructure mode without D2D capability. Secondly, we study the performance of our channel assignment process in the context of D2D communications.

For the first evaluation objective, we compare the average provided rates for users in the presence of various loads in the network with and without D2D capability, which is provided by our framework. We assume a scenario where the number of users varies between 60 and 200 to create a complete range of loads compared to the capacity of the exemplified network. In order to provide a consistent comparison, we assume that there are 5 established D2D pairs in all instances of the loads. Figure 14 shows that the infrastructure mode is capable of providing the maximum efficiency for the users in an uncongested network. However, when the network becomes more congested, D2D capability provides better performance.

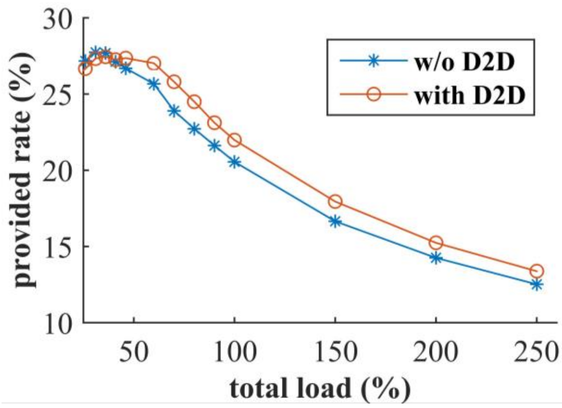


Figure 14: Provided Rate with and without D2D Capability

Figure 15 shows the rates that the network could provide to potential D2D pairs via the infrastructure mode and when D2D capability is available. It can be seen that the Wi-Fi infrastructure mode can satisfy the users with low data rates (more than 75% satisfaction for users with up to the 500*Kbps* required data rate). However, as the required data rate increases, the network performance starts to drop (just around 10% satisfaction for users with the 10*Mbps* required data rate). On the other hand, with D2D capability, the network can provide better performance for D2D pairs, especially when the data rate requirements increase (up to 55% satisfaction for a pair demanding the 10*Mbps* data rate).

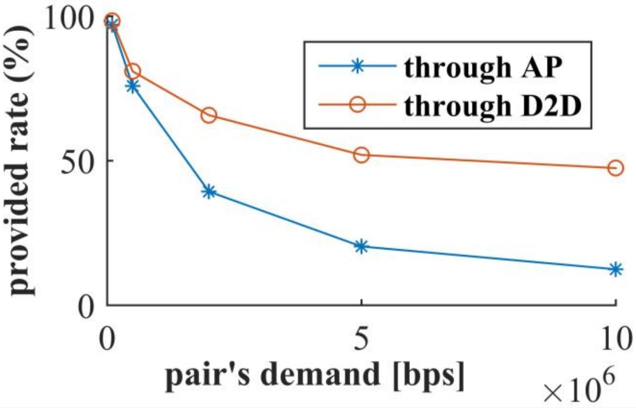


Figure 15: Provided Rate for D2D pairs with and without D2D Capability

Figure 14 and Figure 15 demonstrate that the D2D capability provided by our proposed framework helps to increase the network capacity and improve its performance especially in a spectrum congested environment. These results also show that data requirement demands, especially when high, are better served when the network offers a D2D capability. However, as shown in Figure 16, the performance of the network in this context also depends heavily on the distance between the D2D pairs. Figure 16 shows that paired users who are far from each other are better-off using the infrastructure mode (i.e., go through the AP). Thus, there is a trade-off between the impact of the path loss in a D2D connection and the restriction of the capacity of the APs in the infrastructure mode. For instance, in this scenario the maximum recommended distance between devices for taking advantage of D2D connections is approximately 45m due to the path loss.

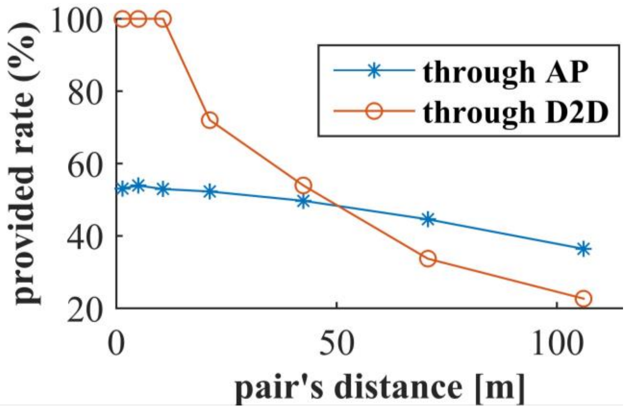


Figure 16: Provided Rate in function of Pair’s Distance

For the second evaluation objective, we compare the performance of the network in terms of SINR in the presence of D2D communications. As discussed previously, each D2D soft-AP is assigned a dedicated channel, which adds to the densification of the network and might increase the overall interference, hence affecting its performance. The increased network interference results in a degradation of the average SINR in the network for all users. Figure 17 shows the impact of the interference in the form of average SINR in the case of LCC and our proposed Channel Assignment Process. It can be seen from Figure 17 that our SDN-based approach achieves better performance than LCC’s for D2D pairs ranging between 1 and 40.

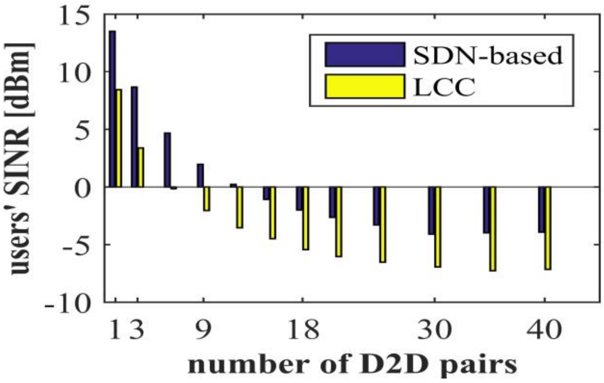


Figure 17: Reception Quality in terms of SINR – Impact of the D2D Deployment Size

Finally, Figure 18 illustrates the improvement in the achieved data rate for all users in the network with the two channel assignment approaches (LCC and SDN-based). Figure 18 clearly shows that our SDN-based framework outperforms LCC by more than 6% from approximately 30 D2D pairs allowing the network to accommodate more D2D connections. It can be seen that when the LCC approach is used, the network performance reaches its maximum when serving 20 D2D connections. As the number of D2D connections increases, the network performance degrades and the network becomes unable to cope where the number of D2D connections exceeds 40. On the other hand, for the same number of D2D users, our SDN-based framework allows the network to provide a higher data rate. This proves that our SDN-based framework manages the interference created by D2D connections much better through the channel assignment process, which provides optimal channel assignment configuration.

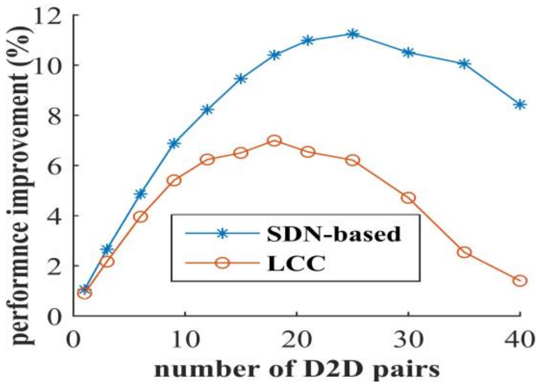


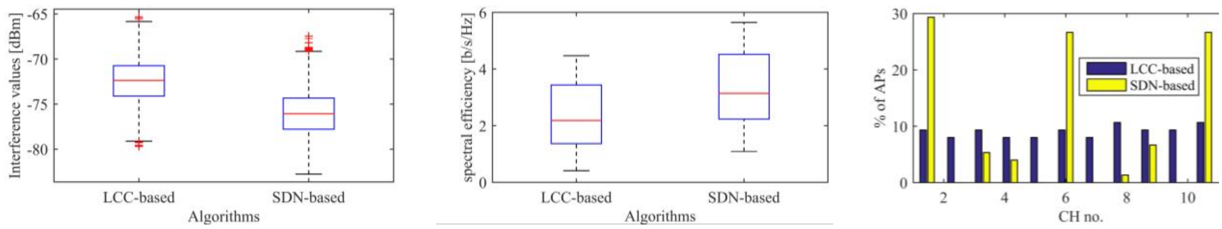
Figure 18: D2D Performance – Impact of the Interference Management Approach

Therefore, the simulation results illustrated in this subsection demonstrate that our framework significantly improves the network performance when D2D connections are deployed.

4.3 Radio Resource Management Algorithm

To evaluate the benefits of the proposed RRM algorithm, we use MATLAB to simulate a dense Wi-Fi environment that consists of 25 fixed Wi-Fi APs randomly deployed in an area of 300m×300m at a minimum distance of 50m from each other. The APs transmit power varies from 0dBm to 40dBm and can now be dynamically adjusted during the simulation process. User stations are again deployed randomly at a minimum distance of 1m from each other and from the APs. We adopted a large-scale path loss model with the path loss exponent set to 2.5, a fixed noise level at -99dBm and the threshold in equation (4) is set to -80dBm.

For the first evaluation, we compared the average interference level throughout the network based on LCC and our SDN-based approach in Figure 19(a). The upper and lower edges of the plotted boxes are the 25th and 75th percentile of the values and the median values are indicated by the central red lines. The values which we considered as outliers are indicated by red symbols in each case. The results show a more than 3 dB improvement which is reflected in the achievable SINR and subsequently the higher spectral efficiency as shown in Figure 19(b). An extra 0.8 b/s/Hz improvement with the proposed centralized channel assignment leads to 16Mb/s extra capacity achievable at the physical layer and for each employed RF channel throughout the network. This is 25% of a standard IEEE 802.11g-SISO capacity per channel. Figure 19(c) shows the combination of the channels which have been assigned through LCC and our proposed approach. The non-overlapping channels 1, 6 and 11 have been used more frequently in our centralized model alongside a limited number of overlapping channels 3, 4, 8 and 9. This combination of overlapping and non-overlapping channels provides an optimal trade-off between co-channel and adjacent-channel interference impacts, given the exemplified network status.



(a) (b) (c)

Figure 19: The proposed channel assignment process performance

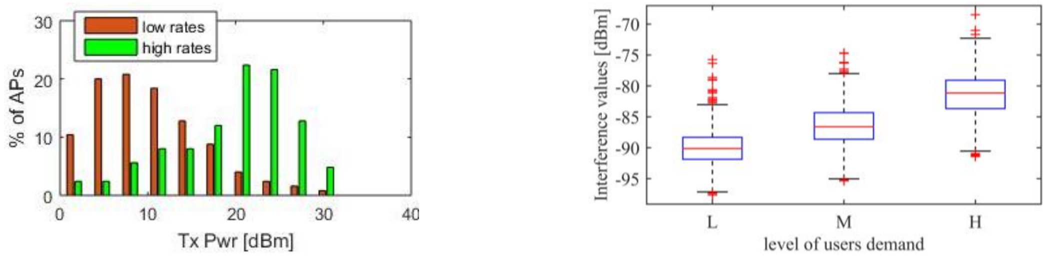
For the second evaluation, we assume two scenarios. In Scenario A, all the flows are transmitted at the default power level (i.e., 20dBm); and Scenario B includes the RRM algorithm with power control, where the adaptive power level is used according to each flow's demand (i.e. required bitrate). The power level distribution of the flows in each scenario is presented in Figure 20(a), with the transmission power level distribution of scenario A flows represented in the blue bar, and the power level distribution of scenario B flows represented in the yellow bars. Figure 20(b) shows a comparison of the interference levels measured in the network using the RRM algorithm without and with power control (i.e. channel assignment without and with power control). The results presented in this figure show that the complete RRM algorithm (Scenario B) offers a 15dB reduction in interference over the channel assignment only algorithm (Scenario A).

(a) (b)

Figure 20: Power adjustment performance and its interference control impact

A user's demand dependency of the proposed power control mechanism is expected to result in a higher power level when the average demand of the users is high. This has been shown in Figure 21(a) where the distribution of adopted power levels is compared for the flows with low and high transmission rates.

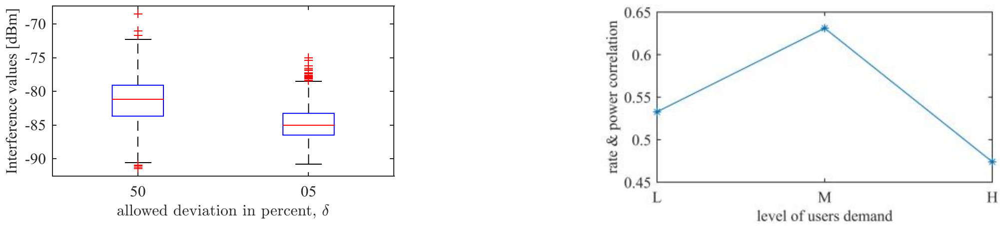
The higher the average demand, the higher the median of the adopted power levels. However, higher values of transmission power jeopardise network-wide control of the interference level achieved through the optimal channel assignment. Figure 21(b) depicts the average interference levels measured in the network after the RRM algorithm is applied for three classes of flows (high, medium, low). The results presented in this figure show that higher transmission rate flows result in higher interference. This shows that the proposed radio configuration algorithms cannot meet the demands of flows with high rates requirements, without resulting in higher interference levels throughout the network. Subsequently, although the transmit power adjustment will help to increase the transmission rate of a flow, it could result in higher interference levels that degrade the network-wide served quality.



(a) (b)

Figure 21: Interference intensification as a result of the users' demand dependency of power levels

To address this limitation, we propose to apply an upper-bound threshold for the maximum acceptable deviation of interference quantity from its optimal value (denoted as δ in Section IV). The effect of this improvement is shown in Figure 22 where the optimal value is achieved by applying the channel assignment optimisation algorithm, and deviation from this value is a result of the new flows' corresponding downlink transmission powers. The higher acceptable deviation (50% in Figure 22(a)) results in a higher network-wide interference compared to the lower acceptable deviation of 5%. Note that in both cases, eventually, the channel assignment process will be triggered to re-adjust the channels. This could be too frequent and disruptive with a very low deviation threshold. By introducing a threshold on the power level for the sake of interference control, we expect a reduction of the positive correlation between adjusted power levels and the demand of the flows, as shown in Figure 22(b). This figure shows the correlation between the transmit power and the required data rate increases with the transmission rate demands rising from low to medium rate flows. However, this correlation drops when high rate flows are used. This is due to the fact that the RRM tries to control the interference in the network by denying very high transmission power levels.



(a) (b)

Figure 22: Correlation between user's demand and power level through a network-wide interference control

The performance analysis, therefore, demonstrates that taking into consideration the network-wide status information as well as the flow-based QoS requirements, allows us to achieve a lower interference while maintaining the performance for a wide range of users' quality demands.

4.4 AP Selection Algorithm

To evaluate the AP selection approach presented in section 3.2.4, we have simulated an area of 1050×1050 m^2 with 50 APs at a minimum distance of 75 meters, with a transmit power of 25 dBm, and a free space path loss with exponent 2. The values of BW_j in equation (11) and C_j considered in Algorithm 3 are set, respectively, as 20 MHz and 54Mbps for all the APs composing the network.

In the evaluation, we simulate a dense wireless environment, in which a new downstream flow trying to connect to the network is created every 3 minutes. The new flow, representing a new wireless user, or an existing user with new QoS requirements, is created in a random position within the designated area. The evaluation is stopped when the number of flows connected to the network reaches1000 and, therefore, the total simulation time is of 50 hours. Finally, in the evaluation we simulate the Wi-5 controller that executes the AP selection algorithm every time a new flow tries to join the network. The QoS requirements of the active flows of the stations trying to connect are randomly generated from a set of bit rates that vary between 40kbps and 5Mbps. We have chosen these values in order to represent the minimum bit rates required for common applications, which are illustrated in Table 3.

Table 3: Bit Rate Requirements

Application	Minimum Bit rate
VoiP with ilbc_mode_20 codec	40 kbps
VoiP with G.726 codec	50 kbps
YouTube	500 kbps
Premium YouTube	1 Mbps

For instance, 40kbps is approximately the minimum bit rate requirement for VoIP when an *ilbc_mode_20* codec working at 15.2kbps is used; whereas, 50kbps is approximately the minimum bit rate when a *G.726* codec working at 24kbps is considered[1]. The minimum bit rate requirement for watching videos on YouTube is 500kbps, and rises to 1Mbps in the case of premium content such as movies, TV shows and live events[2]. Finally, 5Mbps is the minimum bit rate recommended for High Definition (HD) quality videos on Netflix[3]. The minimum bit rate represents the $R_{req,i}$ of an active flow i presented in (9). Moreover, for the sake of simplicity, we do not consider possible effects of the interference from wireless devices using VoIP in the uplink direction. This is a reasonable assumption, since we focus on demonstrating how the selection of the most suitable AP addresses both flows' QoS performance and spectrum efficiency.

To benchmark the performance of the proposed AP selection algorithm, two strategies presented in the literature are considered as proper candidates that address the same problem analysed. Specifically, we compare our AP selection algorithm against the following reference strategies:

1. An AP selection algorithm that associates each new flow with the least loaded AP, which provides a sufficient RSSI based on the QoS requirements as proposed in [31]. We consider this AP load-based solution because it also targets a same centralized approach relying on SDN. Moreover, by comparing our algorithm to this scheme we also demonstrate that the FF metric allows us to achieve better performance against an AP selection strategy that tries to optimize the load balance of the APs.

[1] Cisco, http://www.cisco.com/c/en/us/support/docs/voice/voice-quality/7934-bwidth-consume.html (accessed November 2016).
[2] YouTube, https://support.google.com/youtube/answer/78358?hl=en-GB (accessed November 2016).
[3] Netflix, https://help.netflix.com/en/node/306 (accessed November 2016).

2. An AP association solution where the selection criteria are based on the data rate an AP can achieve as proposed in [19]. We consider this data rate-based strategy because it is a common policy to decide whether or not to associate with an AP, assuming that each flow shares the access time equally with the others associated with the same AP.

The evaluation of our approach focuses on the following performance metrics:

- ***Average Blocking Probability***: This is the average probability to deny connection of a flow when it decreases the average satisfaction (defined below) that the selected AP guarantees to the connected flows by a certain percentage. This probability is updated each time a new flow is associated to an AP of the network.
- ***Average Data Bit Rate***: It represents the average data rate in terms of bps that the assigned APs serve to the flows connected to the network. Specifically, for each new flow *i* associated to an AP j, we firstly compute the data bit rate d_i served to the flow as follows:

$$d_i = \begin{cases} R_{req,i} & if\ R_{i,j} \geq R_{req,i} \\ R_{i,j} & otherwise \end{cases} \quad (19)$$

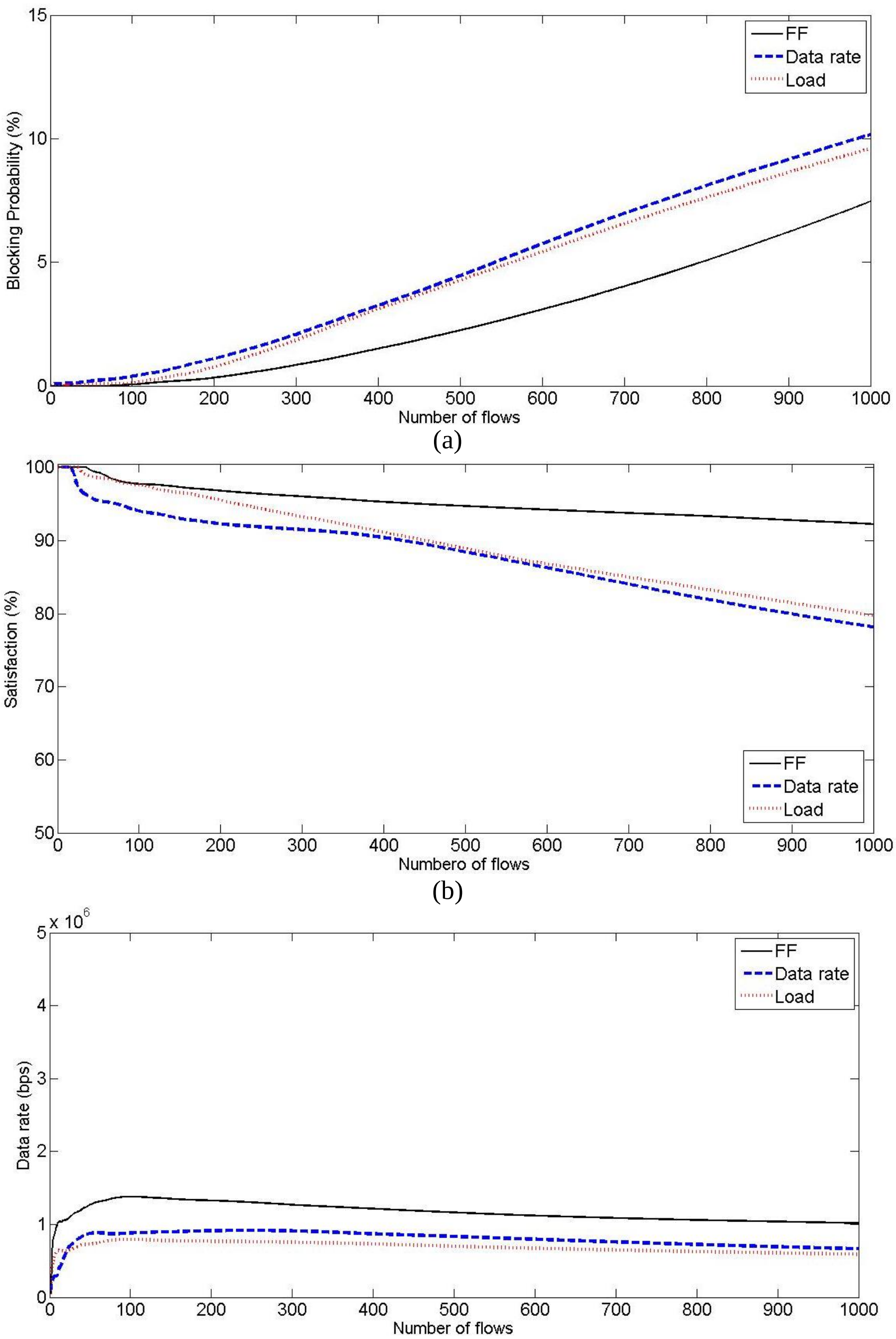
  Then, we consider as a performance metric the data rate averaged for all the flows active in the network on the simulation.
- ***Average Satisfaction***: This is the average percentage of flows connected to the network with their served data bit rates (i.e., d_i value for the generic flow *i*) higher than or equal to their given requirements $R_{req,i}$. This percentage is updated each time a new flow is associated to an AP of the network.

Moreover, we have focused on two cases illustrated in Figure 9 for two different experiments:

1. In the first experiment we have considered ξ = 5 and ρ = 1.3 in (1), which corresponds to maximizing the FF when the available bit rate equals the minimum bit rate requirements of the application (see Figure 9). Therefore, in the first experiment, net_{f_i} computed through (8) aims to optimise the individual performance of the new flow to the associated AP by maximizing its FF, which exhibits the maximum value when the assigned bit rate equals the required bit rate.
2. In the second experiment we have considered ξ = 5 and ρ = 1 in (1), which corresponds to maximizing the FF value for more efficient APs in terms of the bit rate (see Figure 9). Hence, in the second experiment, net_{f_i} aims to optimise the individual performance of the new flow to the associated AP by maximizing its FF, which exhibits the maximum value when the available bit rate is greater than the required bit rate.

Therefore, through these experiments, we also aim to analyse the trade-off between the selection of the parameters in equation (9) and the achieved performance results. Considering the configuration previously described, the FF-based algorithm and the strategies for maximizing the achievable data rate and the AP load have been executed in the controller every time when a new user tried to join the network or an active user needed a new flow with different QoS requirements.

The results achieved for the first experiment are illustrated from Figure 23 to Figure 25. In detail, Figure 23 shows the performance results in terms of the number of flows, achieved by our proposed algorithm (FF) and by the data rate-based and AP load-based strategies. The analysis considers the blocking of a new flow when it decreases the average satisfaction that the selected AP guarantees to the active flows by 10%.



(c)

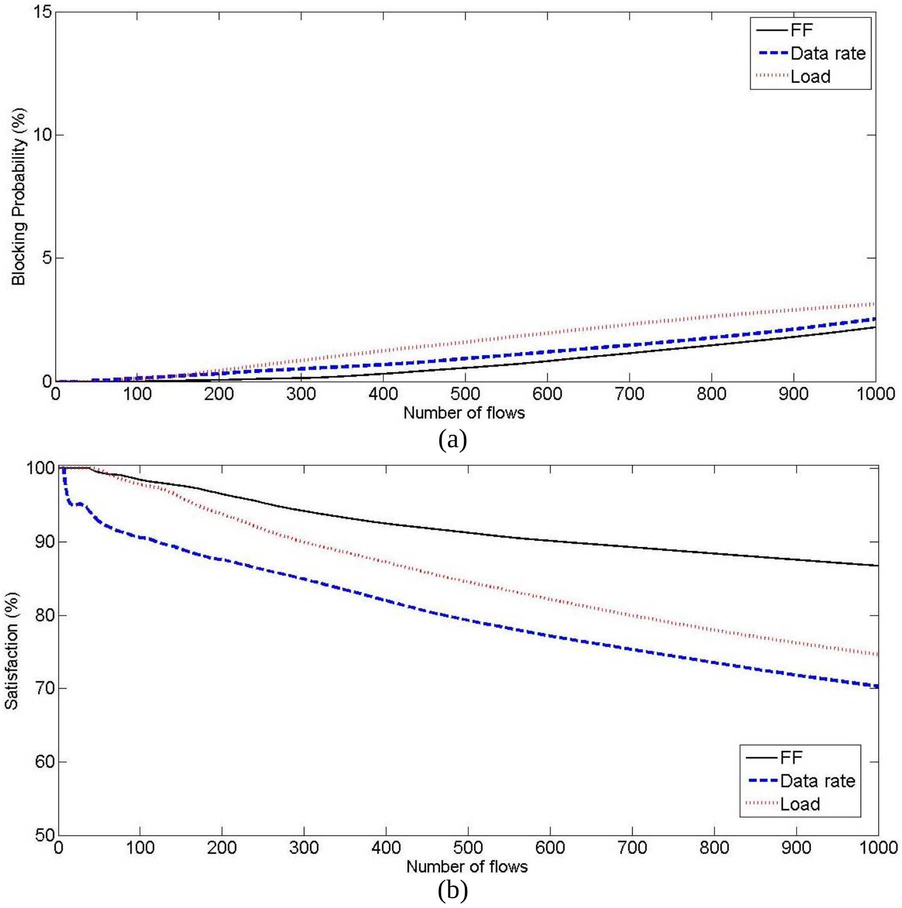
Figure 23: Performance results when the average satisfaction is decreased by 10%. (a) Blocking probability, (b) Satisfaction, (c) Data rate

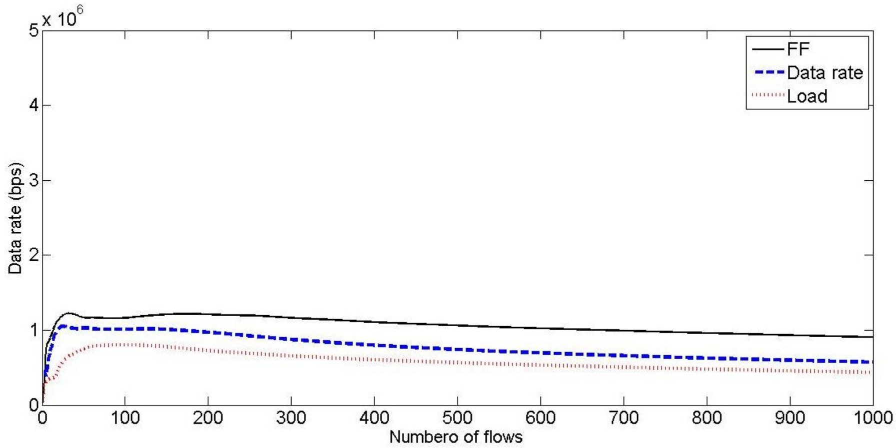
The performance in terms of the blocking probability is illustrated in Figure 23(a) where we can observe that our AP selection algorithm reduces the blocking probability compared with the data rate-based and AP load-based solutions. In particular, the figure illustrates that when the number of flows reaches 1000, AP selections based on the data rate and AP load result in around 10% of blocked flows. For the same number of flows, the AP selection based on the FF results in approximately 7% of blocked flows.

Figure 23(b) shows the performance in terms of the average satisfaction as a function of the number of the flows connecting to the network. This figure illustrates that the FF-based algorithm offers significantly better flow satisfaction than the data rate-based and load-based solutions. Specifically, when the number of flows reaches 1000 our AP selection algorithm outperforms the data rate-based strategy by around 18%, and the AP load-based solution by around 14%.

Figure 23(c) illustrates the average data rate available for each flow as a function of the number of the flows that join the network. In this case, the FF-based algorithm again outperforms the data rate-based and load-based solutions. For instance, in case of 1000 flows our FF-based AP selection algorithm outperforms the data rate-based strategy by around 35%, and the AP load-based solution by around 42% in terms of assigned data rate. The better performance results achieved by our algorithm can be attributed to the optimisation approach to finding a suitable AP while not degrading the overall performance of the network.

Figure 24 illustrates the performance achieved as a function of the number of flows considering the blocking of a new flow when it decreases the average satisfaction that the selected AP guarantees to the active flows by 20%. In this case, the condition that determines the blocking allows the algorithms to accept more flows into the network compared to the previous case.





(c)

Figure 24: Performance results when the average satisfaction is decreased by 20%. (a) Blocking probability, (b) Satisfaction, (c) Data rate

Figure 24(a) shows that although this condition enables a significant improvement in terms of the blocking probability for all the strategies, our AP selection algorithm still outperforms the data rate-based and load-based solutions.

Figure 24(b) shows that in this case the performance in terms of the average satisfaction as a function of the number of the flows connecting to the network slightly decreases for all the strategies compared to the previous case. Nevertheless, our solution still delivers the best results.

Figure 24(c) also illustrates a slight decrease of the performance results in terms of the average data rate available for the flows. This result was expected, as the condition that drives the blocking probability allows the algorithm to accept a greater number of flows, decreasing the overall performance of the network. However, our algorithm continues to outperform the data rate-based and load-based solutions.

Figure 25 summarizes the % gains achieved by the FF-based algorithm over both the data rate-based and the AP load-based algorithms in terms of the average satisfaction, as a function of the number of flows. This analysis considers the blocking of a new flow when it decreases the average satisfaction by 20%, considered as a better condition to balance the trade-off between the blocking probability and average satisfaction. In fact, as we have shown, this condition allows to decrease the blocking probability for all the strategies at the expense of slightly degrading performance in terms of the satisfaction and data rate. For instance, in the case of our FF-based algorithm for 1000 flows we can observe an improvement of around 70% in terms of blocking probability at the expense of reductions of around 6% and 11% for the satisfaction and the data rate, respectively, with respect to the results illustrated in Figure 23.

Figure 25 shows that the FF-based algorithm achieves an improvement to the data rate-based approach in terms of the satisfaction, ranging from 8% for 100 flows to 18% in the case of 1000 flows. The improvement accomplished by the FF-based algorithm over the AP load-based approach ranges from 1% for 100 flows to 14% in the case of 1000 flows.

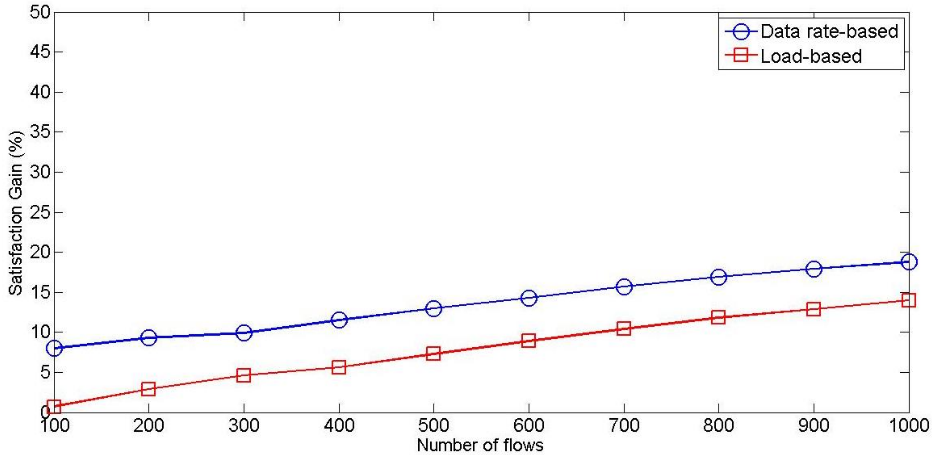


Figure 25: Gains in terms of satisfaction achieved through the FF-based algorithm as a function of the number of flows when $\rho = 1.3$

For the second experiment, we considered the setting $\rho = 1$ in (1), which corresponds to the condition of maximizing the FF value for more efficient APs in terms of the bit rate. Specifically, Figure 9 shows that the case $\rho = 1$ means that the FF reaches its maximum value when the available bit rate is approximately 1.3 greater than the requirement.

For this experiment we measured the % gains obtained from our FF-based algorithm over both the data rate-based and the AP load-based solutions in terms of the average satisfaction. The results are presented in Figure 26. These results show that the FF-based algorithm outperforms the data rate-based solution within a range between 9% and 21%. The figure also shows that the FF-based algorithm outperforms the load-based algorithm in terms of the satisfaction by a margin that varies between 2% and 16%.

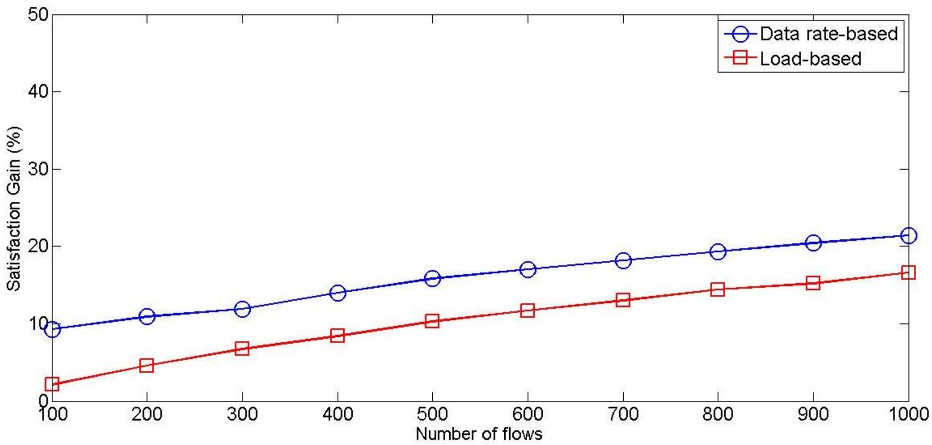


Figure 26: Gains in terms of satisfaction achieved through the FF-based algorithm as a function of the number of flows when $\rho = 1$

Note that in this case, the gains achieved by our algorithm are improved in comparison with those in Figure 25. On the other hand, this condition in (9) affects the performance result of our algorithm in terms of the blocking probability. Specifically, for instance, when $\rho = 1.3$ in (9) and the number of flows reaches 1000, the AP selection based on FF achieves a blocking probability of approximately 2% (see Figure 24(a)); whereas, this value is around 3% when $\rho = 1$ in (9).

This demonstrates that by adjusting the *Network Fittingness Factor*, through (17), a trade-off can be made for the optimisation between the blocking probability and the users' satisfaction. However, the setting $\rho = 1.3$ in (9) allows outperforming the state of the art, both in terms of blocking probability and users' satisfaction.

Hence, the performance analysis demonstrates that our algorithm achieves significant improvements over both solutions found in the literature in terms of the blocking probability, assigned data rate and user satisfaction, when selecting $\rho = 1.3$ in the FF formulation.

5 Radio Configuration Capabilities

All the algorithms proposed in this deliverable have been evaluated via MATLAB-based simulations. In order to allow the correct deployment of the algorithms in a real-time environment, the set of radio configuration capabilities conducted on the Wi-5 APs and controller as defined in deliverables D3.1, D3.2 and D3.3 will be considered. The Wi-5 capabilities needed in the context of the algorithms presented in this deliverable can be classified into monitoring procedures and seamless handover.

The role of the monitoring procedures is to provide information on: (i) the interference level sensed from each AP at the available channels in the considered frequency bands; (ii) the number of users/flows associated to each AP; and (iii) identification of users' service requirements, e.g. in terms of the demanded bit rate or run-time perceived quality by the users. These monitoring mechanisms will be helpful during the decision-making process at the Wi-5 controller and they also contribute to RRM and AP Selection algorithms to each new user/flow joining the network.

The monitoring of the interference levels will support the algorithms implemented in the *Channel assignment process* during the radio configuration optimisation in two different cases: (i) during the initialization of the Wi-Fi network considering the interference between the APs caused by the default transmit power; and (ii) during a possible reassignment of the channels to one or more APs due to a change of status in the network. The changes comprise any alterations in the APs arrangement, transmission powers and/or their served users' statistics. The result of this algorithm will provide the Wi-5 agents with the channel allocated to each AP. Moreover, the monitoring of the interference levels will allow the controller to estimate the achievable physical bit rates, computed by the PQA functionality and exploited by the algorithms proposed in this deliverable. The number of flows associated with each AP and the detected bit rate requirements computed in the RQA block will support the AP allocation process during the selection algorithm based on the FF executed when a new flow tries to join the network.

In the deliverable D4.1 [1] we illustrated the set of monitoring procedures to be conducted on the Wi-5 APs and on the Wi-5 controller, and the measurement framework considered in the context of Wi-5 defined to collect the required information. Moreover, we also discussed possible limitations of the measurement processes, including the effect of the monitoring delay and its possible inaccuracy, as well as the scalability and reachability aspects of the process.

The role of the seamless handover capability is to allow the horizontal handover between APs when a wireless user needs QoS requirements for a certain application if his/her current AP can no longer provide it. Moreover, the seamless handover capability will be extended to enable the vertical handover, which will include the management of BSs in the Wi-5 controller.

In this section we first present our latest progress on the parameters that can be gathered from the network through the measurement framework developed in the context of WP3. We then illustrate the latest progress towards the seamless handovers.

5.1 Monitoring Procedures

The solutions researched in the Wi-5 project have been integrated into an open-source implementation[4], based on the Odin framework [53]. As a result of Task 3.1 of the project, a series of parameters have

[4] This is the GitHub repository used for this aim: https://github.com/Wi5

been gathered from the network, which can be used as inputs for the algorithms implemented in the cooperative framework. More detailed information about these parameters can be found in Deliverables D3.2 and D3.3.

5.1.1 Radio parameters

Each of the APs (known as *agents* in Odin) is able to gather different statistics from the associated STAs. Specifically, the Odin agent running in each AP receives and sends frames to/from the associated STAs and stores different statistics of each of the exchanged packets. The Odin controller can then request the statistics from the agent. Every time the statistics are sent to the controller, the agent resets them and starts gathering the information again.

A series of *periodic reports* has been included in the agent, in order to let the user know the status of each AP and the associated STAs. The information achieved in the *periodic reports* includes: the MAC created by the controller for each STA (i.e. the BSSID that the AP uses for communicating with this STA); the IP address of the STA; different parameters regarding the transmitted packets between the AP and the STA such as the average rate, noise level, average length and air time usage. This is done for both the uplink (STA to AP) and the downlink (AP to STA) directions. The statistics correspond to the measurements of the link between the AP and the STA, but are always measured in the AP wireless interface. A detailed description of the periodic reports can be found in the Deliverable D3.3.

The values of these parameters are provided by Radiotap [54], which is the *de-facto* standard for injection and reception of 802.11 frames in operating systems such as Linux, FreeBSD[5], openBSD[6] and netBSD[7]. Windows also supports Radiotap with *airpcap*, which is a functionality that enables it to gather the radio parameters of the received frames from the driver to user space, and that allows user space applications to specify the transmission parameters. It is based on a number of fields specified on a bitmask *presence* field in the Radiotap header. Note that some drivers may not provide some of the parameters. For example, in our case the driver does not provide the value of the noise[8], i.e. the RF noise power at the antenna.

The user can define different timing periods in the agent:

- A time interval after which the statistics will appear on screen.
- A time interval after which the statistics of old STAs will be removed.

These statistics are sent to the Wi-5 controller under its request, and they can be used by the algorithms implemented in the cooperative framework. For instance, through the periodic report, the number of active flows in each AP can be detected and included in the AP Selection algorithm.

As a proof of concept, an application called `ShowStatistics.java` has been built in the Wi-5 controller[9], which shows the results of the statistics gathered from the APs. We next show the output of this

[5] FreeBSD project: https://www.freebsd.org/
[6] OpenBSD project: https://www.openbsd.org/
[7] NetBSD, a free, fast, secure, and highly portable Unix-like Open Source operating system: https://www.netbsd.org/
[8] For further information: http://www.radiotap.org/defined-fields/Antenna%20noise
[9] See https://github.com/Wi5/odin-wi5-controller/blob/development/src/main/java/net/floodlightcontroller/odin/applications/ShowStatistics.java

application, when statistics from two APs (`192.168.101.9` and `192.168.101.10`) are gathered. The first AP has an STA associated (`192.168.1.200`).

```
[ShowStatistics] 1/192.168.101.9
        Uplink station MAC: 40:F3:08:88:66:C0 IP: 192.168.101.200
                num packets: 14
                avg rate: 23714.2857143 kbps
                avg signal: -34.4715803134 dBm
                avg length: 49.7142857143 bytes
                air time: 1.61066666667 ms
                init time: 1472547242.307101602 sec
                end time: 1472547251.279112125 sec

        Downlink station MAC: 40:F3:08:88:66:C0 IP: 192.168.101.200
                num packets: 18
                avg rate: 12000 kbps
                avg signal: 25 dBm
                avg length: 86.8333333333 bytes
                air time: 1.042 ms
                init time: 1472547242.361167266 sec
                end time: 1472547251.709062530 sec

[ShowStatistics] Agent: /192.168.101.10
[ShowStatistics] Last ping heard from agent /192.168.101.10 1472547344335
```

As can be observed, the parameters gathered in the agent and shown in the controller are: number of packets, average rate, signal level and length, airtime usage, initiation and end of the interval. The application also shows the timestamp of the last ping heard from the agent, as every agent sends regular *keep alive* messages to the controller (every second by default).

A mechanism has also been included in the Wi-5 controller which allows us to collect the power sensed in each Wi-5 AP from the rest of Wi-5 APs. Specifically, an auxiliary wireless interface `mon1` has been added to the AP, in order to allow scanning without disrupting ongoing connections of the STAs.

During the process of detecting other Wi-5 APs, some primitives are executed by the controller, which can tell an AP to start sending beacons with a specific SSID (it can be e.g. "`init_odin`") using the auxiliary interface `mon1`. Then, the controller can tell the rest of the Wi-5 APs to scan for these specific beacons. After the scanning interval, each AP sends back a table to the controller including the BSSID, the SSID and the average power of all the beacon frames heard. One example would be:

```
BSSID                           SSID            Average power
04:20:AC:37:FA:2B               odin_init       48
60:e3:27:1d:32:b7               odin_init       36
c4:6e:1f:8c:dd:d2               odin_init       56
```

The average power is updated with the power with which each beacon has been received. It is measured in the same units given by the Radiotap. Further details on this mechanism are available in Deliverable D3.1.

5.1.2 Service detection

Another input to the algorithms implemented in the cooperative framework is the information about the flow's required quality in the network. As we have explained in section 3, this information can be translated in the cooperative framework into the QoS requirements of a connection-requesting terminal and then, into a certain bit-rate.

Different automatic tools for detecting services are available, and some of them are based on ML, thus avoiding the need for deep packet inspection such as *Diffuse* software [40]. In the context of the Wi-5 project, since these tools do not represent the main target, we have developed a special Odin agent which listens for flows already classified through other tools. This agent has a network interface where the packets of interest are received, grouped into flows and periodically sent to the Wi-5 controller and used in RQA module. More detailed information can be found in Deliverable D3.1.

5.2 Seamless Handover Capability

Fast and seamless handovers are an essential capability needed to implement our proposed AP selection and vertical handover algorithms. Therefore, in the Wi-5 controller, a radio configuration capability has been implemented to allow horizontal handover between APs when a wireless user connected to the network changes his/her connection to another AP. Figure 27 illustrates an example of horizontal handover, which includes the different steps: when the STA starts moving (1), AP1 starts receiving a lower power level, so it reports this information to the controller through the PUBLISH message (2). The controller sends a scan request message to the APs in the neighborhood (3), which, after a scanning period, return their results (4) including the power level they have heard of that STA.

The controller, using the information gathered from the different APs, can run its resource management algorithms and make a handoff decision (5). The decision is implemented in different steps: first, a number of Channel Switch Announcements (CSAs) are sent to the STA (6) and (7) telling them to switch to the channel of AP2. Finally, the Light Vırtual Access Point (LVAP) of the STA is removed from AP1 and added to AP2 (8). This has to happen just in the moment when the STA receives the last CSA and switches its channel. Very fast handovers (between 30 and 150 ms) including a channel switch have been achieved following this scheme. More details are given in Deliverable D3.3, and also in a recently published paper [55].

Moreover, this handover capability will be extended in the Wi-5 controller in order to allow vertical handover towards 4G BSs. Also all the details on seamless handover can be found in Deliverable D3.3.

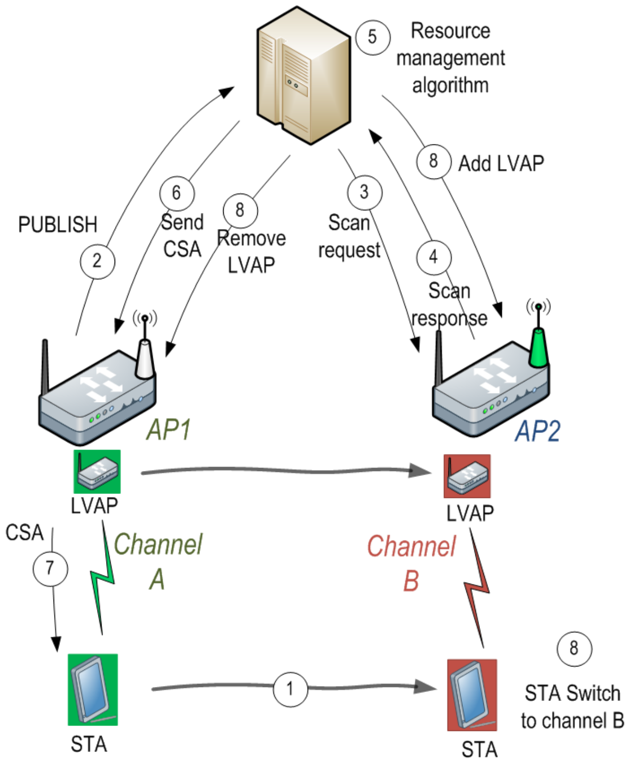


Figure 27: Example of horizontal handover

6 Conclusions and Further Work

This deliverable has presented the second version of the Cooperative APs Functionalities, which have been developed within Work Package (WP) 4 of the Wi-5 Project. A detailed literature review has been provided, including several new research works in the context of RRM strategies for channel assignment and transmit power control, AP selection solutions, and vertical handover.

Then, the cooperative functionalities have been addressed in the Wi-5 architecture, of which the first version has been presented in detail in Deliverable D2.4. After that, the second version of the cooperative framework, which includes innovative functionalities for RRM solutions, an AP allocation strategy and a preliminary proposal for vertical handover, have been presented. Specifically, this framework has been designed and developed to efficiently exploit the use of the radio resource, reduce interference between neighbouring APs and provide optimised connectivity for each user that is served by an AP.

The RRM strategy has been designed to jointly provide a channel assignment solution, which finds an optimal radio configuration minimising the level of interference, and a transmit power adjustment able to address the Quality of Service (QoS) requirements of the applications running on the end-user's device. Another algorithm has been designed to assist the user in the selection of the most suitable AP according to the application running on the station in terms of QoS requirements. Specifically, this relies on the Fittingness Factor (FF) concept, which is a parameter for efficiently matching the suitability of the available spectrum resource to the application requirements. Furthermore, the preliminary details on extending the AP selection towards a vertical handover functionality, including 3G/4G networks, are illustrated in this deliverable.

After the presentation of the developed algorithms, a set of experiments has been illustrated to assess these solutions through the analysis of performance results in MATLAB-based simulated environments. The results of the assessment of the optimized channel assignment included in the RRM algorithm have shown an improvement over the state of the art in terms of caused interference, SINR, and spectrum efficiency. The channel assignment algorithm has then been considered in a scenario including the establishment of D2D communications. Specifically, we have demonstrated that the proposed strategy allows us to reduce the effect of these communications in terms of the overall capacity of the network and the interference on other Wi-Fi users. Then, the performance of the RRM algorithm has been assessed showing that it provides a lower interference while maintaining the status for a wide range of users' quality demands. This is achieved by taking into account the correlations and mutual relationships between transmission power levels, the required quality of the users and the network-wide interference quantity in the proposed algorithm. The AP selection algorithm has been evaluated to enable its comparison against two strategies found in the literature. The evaluation results have shown that our algorithm achieves significant improvements, when selecting $\rho = 1.3$ in the FF formulation, over the solutions considered for the comparison in terms of the blocking probability, assigned data rate, and user satisfaction.

As a part of future work, the cooperation framework will be extended to also cover the vertical handover introduced in this deliverable. Moreover, further performance analysis will be carried out to assess the overall framework through new metrics representing the whole network performance such as the user's Quality of Experience.

Finally, the radio configuration parameters addressing the dynamic APs channel assignment and the transmit power control, together with the monitoring tools developed within the WP3 and illustrated in the deliverables D3.1, D3.2 and D3.3, will be considered to allow the correct deployment of the cooperative framework also in a real-time environment.

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