What to do With the Wi-Fi Wild West

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Abstract

This deliverable presents the specification of the final version of the Cooperative AP Functionalities that have been designed in the context of Work Package (WP) 4 of the Wi-5 project. In detail, 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, which also provides horizontal handover, and a Radio Access Technology (RAT) selection solution for vertical handover. The RRM algorithm achieves an important improvement for network performance in terms of several parameters through the channel assignment approach and the transmit power adjustment. The AP selection solution extends the approach presented in deliverables D4.1 and D4.2 and is based on a centralised potential game, which optimises the distribution of the so-called Fittingness Factor (FF) parameter among the Wi-Fi users. Such a parameter efficiently matches the suitability of the available spectrum resource to the users' application requirements. Moreover, the RAT selection solution extends the AP selection algorithm towards vertical handover functionality including 3G/4G networks. The assessment of the newest algorithms developed in the context of WP4 is illustrated in this deliverable through the analysis of several performance results in a simulated environment against other strategies found in the literature. Finally, the set of smart AP functionalities developed in the context of WP3, implemented on the Wi-5 APs and on the Wi-5 controller, and their use in the proposed algorithms are illustrated. Specifically, this deliverable describes how these functionalities can enable the correct deployment of the proposed cooperative AP solutions in realistic scenarios. Therefore, the main novel contributions of this deliverable are i) the strengthening of the AP selection algorithm, ii) the design and assessment of a new algorithm for vertical handover and iii) the presentation of the finalised integration of the cooperative AP functionalities of the Wi-5 system.

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Executive Summary

This deliverable presents the specification of the final version of the Cooperative Access Point (AP) Functionalities, which extends the versions proposed in the previous deliverables D4.1 [1] and D4.2 [2]. All the solutions presented in this deliverable are defined in the context of 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 connect to 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 user's experience.

These functionalities have been developed in a framework described in the Wi-5 architecture in deliverables D2.4 [3] and D2.5. This 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 new contributions of the proposed algorithms can be summarized as follows:

- A novel RRM algorithm has been developed to combine AP channel assignment and transmit power control. Specifically, the channel assignment relies on network monitoring information collected to analyse and calculate the optimised channel configuration across a dense Wi-Fi network. The proposed transmit power control approach takes users' QoS demands into account, in order to mitigate the network-wide interference in dense Wi-Fi networks.
- An AP selection algorithm has been developed based on a 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.

- A Radio Access Technology (RAT) selection algorithm has been designed to provide efficient connection to dual-interface devices, such as smartphones and tablets, to support vertical handovers among Wi-Fi APs and Long Term Evolution (LTE) Base Stations (BSs).

The developed algorithms have been assessed in a simulated scenario demonstrating their efficiency through the analysis of several performance metrics. In detail, the proposed cooperative AP functionalities have reached the following achievements:

- The RRM algorithm provides significant improvements with respect to the state of the art in terms of reducing the overall interference in the network, while maintaining the QoS required

by each station. An in-depth analysis of the efficient performance of the proposed algorithm can be found in D4.2 [2].

- The first version of our AP selection algorithm based on the FF has been assessed in D4.1 [1] and D4.2 [2]. In this deliverable we present an enhanced version of the algorithm, which allows us to improve its performance achieved in terms of the assigned data rate and user satisfaction.

- The algorithm designed for RAT selection and vertical handover presented in this deliverable achieves significant improvements over other strategies considered in the literature in terms of the distribution of the data rate among the users, user satisfaction and Quality of Experience (QoE).

Moreover, a set of smart AP functionalities implemented on the Wi-5 APs and Wi-5 controller and defined within WP3 deliverables D3.1 [4], D3.2 [5], D3.3 [6] and D3.4, have also been introduced in this document. These functionalities will allow the correct use of the algorithms implemented in a cooperative 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 added 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 being 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 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 final version of the AP functionalities that cover cooperative RRM solutions, smart connectivity, and wireless horizontal/vertical handovers in the so-called "Wi-Fi jungle". These functionalities are exploited in scenarios where a large number of uncoordinated APs can 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 obtain the best overall configuration, minimising interference in a heterogeneous environment. 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. [7]. Furthermore, past and ongoing FP7 projects such as CODIV [8], iJOIN [9] and METIS [10] address the challenges of improving cellular network performance by also using cooperation mechanisms.

1.3 Document structure

This deliverable presents the final version of the specification for cooperative AP functionalities proposed in Wi-5. In detail, in Section 2 we describe the updated state-of-the-art found in the literature related to RRM, AP selection, horizontal and vertical handover strategies. In Section 3 we discuss the cooperative functionalities framework, providing the set of designed algorithms for all the proposed solutions in Wi-Fi jungle scenarios. Specifically, we summarize the main aspects of our RRM approach, the enhanced version of our AP selection policy and a novel RAT selection algorithm. Section 4 presents the assessment of the newest versions of the algorithms designed in the context of WP4 through the analysis of a range of performance results in simulated environments, and against other solutions found in the literature. Section 5 illustrates the integration of the proposed algorithms with the set of smart AP functionalities developed and provided in the Wi-5 APs and in the Wi-5 controller, which are able to allow the correct use of the algorithms in real-time scenarios. Finally, conclusions are provided in Section 6.

1.4 Relationship with other deliverables

This deliverable is an in-depth extension of deliverables D4.1 “Specification of Cooperative Access Points Functionalities version 1” and D4.2 “Specification of Cooperative Access Points Functionalities version 2”. 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 functional architecture described in deliverables D2.4 “Wi-5 initial architecture” and D2.5 “Final Wi-5 architecture”. Furthermore, this deliverable will rely on the smart AP functionalities designed and developed in deliverables D3.1 “Definition of the performance monitoring mechanism”, D3.2 “Specification of Smart AP solutions version 1”, D3.3 “Specification of Smart AP solutions version 2” and D3.4 “Final specification of the Smart AP solutions” for a proper deployment of the proposed algorithms.

1.5 Glossary

3G	Third Generation broadband cellular network technology
4G	Fifth Generation broadband cellular network technology
5G	Fourth Generation broadband cellular network technology
AP	Access Point
BS	Base Station
CDF	Cumulative Distribution Function
CQI	Channel Quality Indicator
DCA	Dynamic Channel Assignment
DM	Decision Making
eNodeBs	LTE base stations

FF	Fittingness Factor
HeNBs	LTE base stations
HD	High Definition
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific and Medical
KD	Knowledge Database
LTE	Long Term Evolution
LVAP	Light Vırtual Access Point
MAC	Media Access Control
ML	Machine Learning
MCS	Modulation/demodulation and Coding Scheme
MOS	Mean Opinion Score
MRF	Multi-RAT Flows
NE	Nash Equilibrium
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
SRF	Single-RAT Flows
SINR	Signal to Interference plus Noise Ratio

SNR	Signal to Noise Ratio
STA	Wireless Station
SSID	Service Set IDentifier
TPC	Transmit Power Control
VoIP	Voice over IP
WLAN	Wireless Local Area Network
WP	Work Package

2 Wireless Network Resource Management in the Literature

This section reviews relevant state-of-the-art developments in terms of wireless network resource management solutions including strategies for RRM [11]-[30], AP selection and horizontal handover, [31]-[44], RAT selection and vertical handover [45]-[60]. Specifically, this section updates the literature review provided in the deliverables D4.1 and D4.2, including the latest progress found in the state of the art that addresses wireless network resource management.

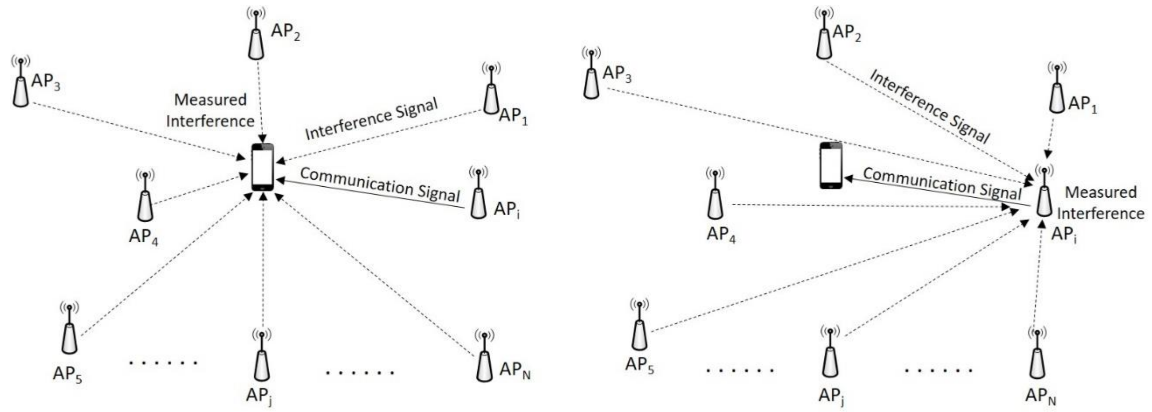
2.1 Radio Resource Management Strategies

RRM plays a central role in optimising the wireless spectrum, especially in congested Wireless Local Area Network (WLAN) environments. Solutions found in the literature have tried to address this problem by using dynamic channel assignment and transmit power control resembling the approach proposed in the Institute of Electrical and Electronics Engineers (IEEE) 802.11h amendment [61]. These primitives allow management of the channel where the transmission takes place, and control of the transmission power.

Early efforts in this field explored the possibility of adapting the radio resources of an AP to alleviate interference by estimating the quality of the channel with the wireless station (STA) it serves. Such solutions, however, required the ability to access the STA in order to obtain the necessary information to estimate the channel's quality, as illustrated in Figure 1(a). However, this is not always possible, as Wi-Fi network operators cannot always access the devices they are serving. Later contributions tried to address the problem by relying on the AP's measurements only to adjust its radio parameters. Some of these solutions focused on a per-cell approach with the aim to optimise spectrum usage within the AP's cell [11]-[26], while others were based on a per-link approach where the main focus was to optimise the quality of communication with the STA using power adjustment [27] and [28]. The per-cell solutions relied on transmit power control to adjust the size of the cell [11]-[14], dynamic channel assignment to move the AP to another less-congested channel [15]-[21], or a combination of both [22]-[26].

It is also important to note that in some of these contributions, such as in [14], the AP is responsible for the configuration of the radio resource in order to mitigate the interference. The main limitation of these localised per-cell solutions is the lack of coordination among APs, which limits the overall efficiency of the solution in dense environments. Other centralised or coordination based solutions such as [26] and [27] provided a framework for inter-AP cooperation that helped to achieve better spectrum allocation between interfering WLANs. Despite this advantage, these solutions still share a similar drawback with distributed per-cell solutions since both rely on the assessment of the cumulative interference of all neighbouring APs, as illustrated in Figure 1(b). Despite the fact that a central controller in these solutions is able to manage all interfering APs and apply a suitable radio configuration, the cumulative interference assessment does not provide the necessary information that helps in identifying the best configuration for each affected AP in order to establish an optimal configuration for the whole network.

Although per-link solutions aim to optimise the transmission power between an AP and the STAs it is serving, they suffer from a similar problem where the power adjustment relies on the cumulative interference the serving AP measures locally [27]-[30]. Moreover, since the AP cannot cooperate with adjacent-channel APs, an increase of its transmission power might harm their channels' quality, triggering these APs to try to adjust their transmission power as well. Such a lack of cooperation may have severe consequences on the performance of all the WLANs involved.



(a) (b)

Figure 1: Measuring interference at an STA (a) and cumulative interference at an AP (b)

2.2 AP Selection Strategies

The problem of AP selection has been addressed extensively in the literature, with many contributions focusing on wireless user devices to initiate the selection process. AP selection strategies can be mainly classified as distributed [31]-[41] or centralised [42]-[44] solutions. In the case of distributed strategies, a wireless device usually gathers performance related measurements from the network before selecting the best AP based on a specific metric, whereas centralised solutions rely on a global view obtained from the network controller to decide the most suitable AP.

Examples of distributed solutions found in the literature are based on game theory [31]-[35], neural networks [36], cross-layer approaches [37]-[39], and Clear Channel Assessment Threshold (CCAT) adjustment, which takes into account co-channel interference [40]. Moreover, the authors in [41], presented a classification of works dealing with AP selection for IEEE 802.11 Wi-Fi networks and then they proposed a distributed approach which addresses QoE enhancement.

In [42], the authors first presented a classification of fairness criteria that are widely adopted in centralised network resource assignment. They also proposed a centralised AP association algorithm to achieve proportional fairness based on a performance revenue function obtained when new users join the network. In [43], the authors presented a detailed survey of load balancing strategies based on different metrics and approaches. Finally, the work proposed in [44] considered Software Defined Networking (SDN)-based platforms to implement centralised approaches addressing AP selection for Wi-Fi users.

A significant shortcoming in the approaches proposed in [31]-[44] is that they consider all users to be the same whereas, in reality, each user connected to the Wi-Fi network is running an online application or accessing a service with specific and often different QoS requirements. Our solutions presented in deliverables D4.1 [1] and D4.2 [2] overcome this shortcoming by proposing an association strategy that assesses the suitability of each traffic with a specific AP in terms of its QoS requirements. On the other hand, these solutions do not address a reallocation of APs to flows connected to the network, which might improve the performance experienced by the Wi-Fi users.

2.3 Vertical Handover Strategies

In a vertical handover, the client with a multi-interface terminal will switch its connection between different RATs in Heterogeneous Networks (HetNets) characterised by several capabilities and characteristics in order to satisfy the requirements of their applications [45]. In [46] and [47], 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 [46] the authors conclude that efficient decisions can be obtained by employing as many measurable decision parameters as possible, such as Received Signal Strength (RSS), bandwidth and power consumption of the terminal. While the authors in [47] 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.

RAT selection solutions in HetNets can also be classified as either distributed [48]-[52], or centralised [53]-[60] solutions. On the other hand, there are many different ways to classify the works in this area, for example through their utilisation of the different RATs begin considered. For instance, papers [49], [50], [55] and [60] focus only on offloading the traffic from LTE to Wi-Fi networks. Other studies focus on RAT selection solutions for HetNets involving only LTE cells such as macro, femto and pico-cells [54], [57] and [58]. Finally, the works in [48], [51], [52], [53], [56] and [59] propose a complete integration between LTE and Wi-Fi going beyond the mere offloading from one network to another.

Moreover, in the domain of RRM in HetNets based on SDN technology, several innovative solutions have recently been proposed in the literature. For instance, the authors in [58] propose the use of SDN to handle all the control information among the network elements to address unexpected back-haul failures in 4G/5G HetNets, but without the inclusion of Wi-Fi technology. In [59], the authors propose a RAT scheme based on SDN where the users connect to the access nodes with the channel capacity that meets the bandwidth requirements of their applications. In [60], an SDN-based offloading control mechanism is proposed to orchestrate the offloading from LTE femto-cells to Wi-Fi nodes according to a user’s dissatisfaction parameter.

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 as reviewed in the previous section. 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.

- **Horizontal Handover**: This functionality allows seamless horizontal handover among APs which is due to the user's nomadic mobility.

- **Vertical Handover**: The Wi-5 functionalities will also assist the user to find the most suitable network in terms of QoS between Wi-Fi and 3G/4G through RAT selection that allows 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 [3] and D2.5. 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 a single point to be defined 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 WP4 can run as applications on top of the controller as illustrated in Figure 2. Furthermore, the cooperative functionalities designed and implemented in the context of WP4 consider the functionalities developed in WP3 in order to handle the radio resources at the APs. These functionalities are implemented through the northbound API of the Wi-5 controller, as presented in D2.5. The configurations decided by the different cooperative functionalities are sent to the APs through the Wi-5 controller southbound API, as depicted in Figure 2.

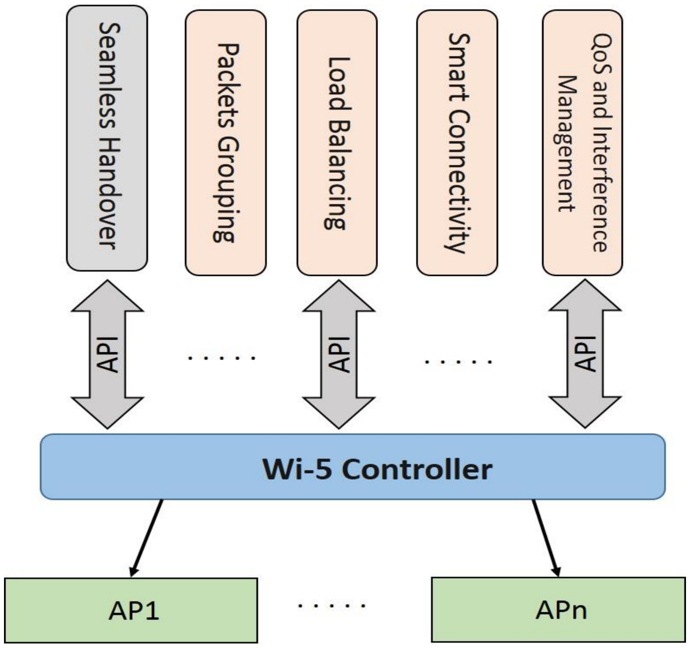


Figure 2: Diagram describing the Wi-5 architecture including the Cooperative Functionalities

3.2 Cooperative Functionalities Framework

This section describes a framework which has been included in the Wi-5 controller to provide the final version of the Wi-5 cooperative APs algorithms. In detail, it represents an extended version of the framework presented in deliverables D4.1 [1] and D4.2 [2] 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 extended version of the framework will exploit the smart AP functionalities presented in D3.2 [5], D3.3 [6] and D3.4 dealing with dynamic channel selection and AP selection, in order to extend the assessment of the framework in real-time environments. The enhanced framework presented in this section implements a set of processes that cooperate to address the above-mentioned challenges through the achievement of 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 a Smart AP selection algorithm that will allocate users/flows to the most suitable AP according to the application running on the STA in terms of QoS requirements. This algorithm could also be extended to achieve Horizontal Handover by using QoS metrics, such as the Received Signal Strength Indicator (RSSI) and the Fittingness Factor (FF) explained in detail throughout the deliverable, to reflect the wireless user's mobility.

- Defining a RAT selection strategy in the vertical handover algorithm that extends the AP selection algorithm towards the vertical handover between Wi-Fi and 3G/4G mobile networks.

This framework is presented in Figure 3 and will be explained further below.

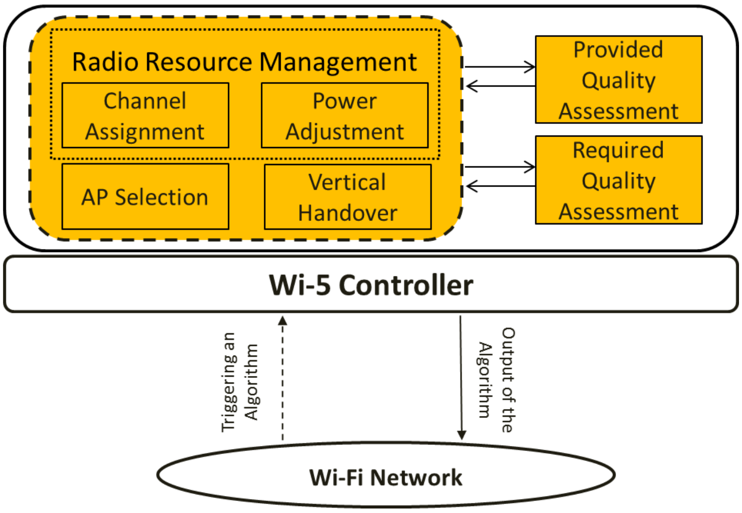


Figure 3: Extended version of the Cooperative Functionalities Framework

The *Channel Assignment* process in Figure 3, which is part of our RRM algorithm, is based on an objective function which reduces the magnitude of the interference impact in the whole system. 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 a potential gain and the Fittingness Factor (FF) concept to associate an AP to each new user/flow while taking into consideration the bit rate requirements. This algorithm extends the previous version presented in deliverables D4.1 [1] and D4.2 [2], which efficiently addresses the QoS requirements of both a flow joining the network and other flows active in the network and also enables the reallocation of the APs to the flows connected to the network when needed.

The *Vertical Handover* process implements a strategy that extends our AP Selection algorithm, to select the most suitable connection between Wi-Fi APs and 3G/4G BSs for each new user/flow running in a dual-interface device, such as a smartphone or a tablet.

The *Provided Quality Assessment* (PQA) functionality will exploit the monitoring tools detailed in deliverables D3.2 [5], D3.3 [6] and D3.4 to detect the interference levels and compute the achievable QoS requirements for the stations in each AP.

The *Required Quality Assessment* (RQA) functionality will allow us to compute the application type corresponding to a certain flow and its required QoS. Note that these QoS requirements can be either proactively programmed into the SDN controller [62], or reactively inferred through QoS detection techniques such as Machine Learning (ML) strategies. In particular, the application of ML strategies to detect traffic in real-time has attracted significant attention in past works [63], [64]. For example, the ML-based classification approach presented in [64] achieves 99% classification accuracy for Voice over IP (VoIP) traffic across the APs of their network. The source code designed for detecting traffic and, consequently, QoS requirements in [64] is available in a public repository[1]. Therefore, this capability can be easily implemented to work in our framework but the details of such an

[1] DIFFUSE: http://caia.swin.edu.au/urp/diffuse/downloads.html (accessed March 2018).

implementation are outside the scope of this deliverable. Hence, we assume that the information used by this process to compute the QoS requirements is available.

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

3.2.1 Radio Resource Management Algorithm

The RRM algorithm aims to address the limitations found in the state of the art and illustrated in Section 2.1 through the following new contributions:

- Centralise the management of spectrum allocation in WLANs by controlling all interfering WLANs through IEEE 802.11 Transmit Power Control (TPC) and Dynamic Channel Assignment (DCA) functions. This centralised management can provide a globally coordinated spectrum allocation process and mitigate interference more efficiently. This control does not necessitate the involvement of STAs, but relies on the APs only.
- Our algorithm allocates spectrum to an STA such that it can satisfy the user's requirement while at the same time minimising the impact of any change on the rest of the network. Specifically, the algorithm starts by adjusting the transmission power between an AP and the STA it is serving through TPC functionality, taking into account the airtime occupancy of the AP. If the power adjustment results in interference that exceeds an acceptable level defined in the algorithm, the DCA functionality is triggered to assign newly optimised channels to the APs in order to minimise the interference.
- Our algorithm will estimate the interference impact of each AP's configuration on its adjacent-channel APs separately, instead of cumulatively. Accordingly, the algorithm is able to find an optimal configuration that could achieve the dual objectives of both satisfying the user requirements and minimising the interference impact on each adjacent-channel AP.
- To optimise the utilisation of the spectrum and provide fine-grained RRM, the algorithm processes the transmission power adjustment according to the demands of the STA it is serving at a specific time, i.e. the rate required by the active downlink flow that the AP is exchanging with the STA, in addition to the estimated channel quality at the AP as well as the airtime share of the STA. This is different from other TPC approaches that rely on channel quality to determine the power level when communicating with the STA.

Therefore, our approach addresses the limitations found in the state of the art as follows: 1) it allows a per-flow power adjustment to address the user's requirements, while optimising its network-wide impact in terms of interference, and 2) it offers an innovative coordination mechanism for APs through the centralised spectrum management control and novel quantification metric, so-called *interference impact*, to represent the network-wide impact of each AP.

More specifically, the approach relies on the following processes included in our Cooperative Functionalities Framework and introduced in Section 3.2:

- **Required Quality Assessment (RQA)**: For each downlink flow the AP is serving, this process identifies the rate necessary for this flow to achieve its required QoS. This process is per-flow and quality-oriented, i.e. it is triggered each time the associated STA changes to a new flow with new QoS requirements.

- **Power Adjustment**: For each downlink flow the AP is serving to its associated STAs, this process uses the required rate to identify the transmission power level required to achieve it. Moreover, the process takes into account other associated flow requirements in the same AP and all other co-channel APs which are contending for airtime. This process is triggered by the RQA process.

- **Provided Quality Assessment (PQA)**: It assesses the interference impact of transmission power adjustments on each of the adjacent-channel APs. It quantifies the interference impact of this power adjustment on each of these APs.

- **Channel Assignment**: It is triggered by the PQA process if the power adjustment results in an interference on one of adjacent-channel APs, which exceeds a specific threshold. It will determine a new optimal configuration for the channel assignment. Specifically, this process 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 Channel Assignment strategy and its joined use with the Transmit Power Adjustment process in our Per-Flow RRM algorithm has been presented in D4.2 [2].

Figure 4 illustrates the interactions between these processes in our Per-Flow RRM algorithm.

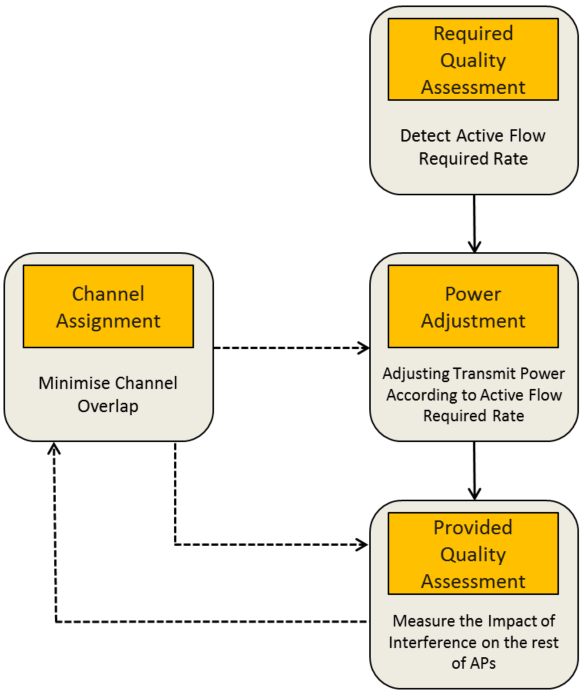


Figure 4: Diagram of the Per-Flow RRM algorithm

Figure 5 depicts the approach used in our work, where the SDN controller collects information about the signal quality and strength at each interfering AP. The controller evaluates the interference impact of each AP based on the strength of its signal received at all other AP locations. Therefore, the greater the number of accessible APs and the density of the network, the greater the accuracy of the evaluation, which is helpful in terms of the scalability of the proposed approach. Conversely, the evaluation will be less accurate in sparse networks.

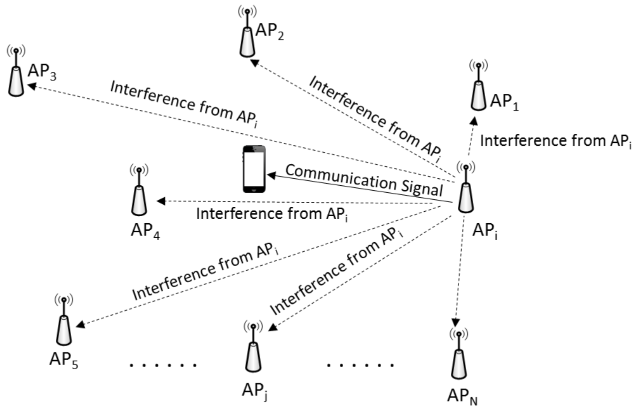


Figure 5: Quantifying interference impact used in our approach

Using this approach, given N APs and F Radio Frequency (RF) channels, we can quantify the network-wide quality by measuring the interference impact of each AP at each point in the network. The *interference impact* for AP_i and its corresponding channel f can be expressed as follows:

$$I_{i,f} = \sum_{k \le N, k \ne i} P_{i,k}(f) = \sum_{k \le N, k \ne i} P_i^t \gamma_{i,k}(f) \theta_{i,k}(f) = P_i^t \sum_{k \le N, k \ne i} \gamma_{i,k}(f) \theta_{i,k}(f) \quad (1)$$

where $1 \leqslant f \leqslant F$, $1 \leqslant i, k \leqslant N$, $P_{i,k}$ 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 $\theta_{i,k}$ is the coefficient 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 [17]. 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.

A detailed explanation of the DCA, the TPA and their interaction in our fine-grain RRM algorithm to minimize the interference impact throughout the network, together with an exhaustive performance analysis campaign, can be found in deliverable D4.2 "*Specification of Cooperative Access Points Functionalities version 2*" [2]. This deliverable will focus on the integration of the Channel Assignment and PQA with the monitoring functionalities developed in the contest of WP3, and implemented in the Wi-5 controller. Specifically, in Section 5 we will provide the details of the implementation of the channel assignment algorithm in the Wi-5 controller.

3.2.2 Smart AP Selection Algorithm

In this subsection we present our AP selection algorithm based on a potential game, which allows an efficient distribution of Wi-Fi users among the APs in a network. Potential games [65] are a tool that allows us to perform a distributed optimisation of resource allocation through the convergence to a pure Nash Equilibrium (NE), which is always guaranteed [72]. The main drawback of this tool is the complexity resulting from its implementation on large distributed scenarios such as Wi-Fi networks; in fact, players usually require overall information about the remaining players of the network, making the solution not scalable. Our choice of SDN as a management platform for these large Wi-Fi networks is justified by its centralised nature which allows us to store all the required information on the SDN controller, so such a game can be played at this central control entity. The controller selects the best AP for each application flow required by a Wi-Fi user through a potential game based on the FF concept, which represents the suitability for an AP to manage a certain flow in terms of available QoS. The inclusion of a potential game in the SDN-based controller together with the proposed suitability concept allows us to achieve improved performance in terms of users' satisfaction compared to the state of the art.

The novel contributions of this AP selection approach with respect to the state of the art illustrated in Section 2.2 can be summarized as follows:

- With respect to previous works [31]-[44], we propose a new concept for the suitability of the connection between an AP and a certain flow. We have already demonstrated the benefits of the suitability concept in deliverables D4.1 [1] and D4.2 [2], which allows us to achieve significant improvements in terms of a user's satisfaction compared to other solutions.

- With respect to our previous works presented in the previous deliverables D4.1 [1] and D4.2 [2], we strengthen our achievements through the introduction of an innovative potential game to exploit its efficiency in the performance results. Specifically, the algorithm presented in this deliverable: 1) guarantees a novel and efficient reallocation of the APs to the flows connected to the network when needed; and 2) overcomes the drawbacks in terms of the scalability of a potential game through the use of the Wi-5 SDN-based centralised controller. In fact, our previous version of the AP selection allows a reallocation of the APs only for STAs requiring a new flow connection with new QoS requirements.

In our approach, we consider a dense Wi-Fi environment as illustrated in Figure 6, which is based on our cooperative functionalities framework described in Figure 3, where the controller is capable of running an efficient AP selection for all the flows connected to the Wi-Fi network. Specifically, for each new flow trying to connect to the network, the controller plays a potential game for all the flows active in the network, to find the optimised AP allocation for all of them.

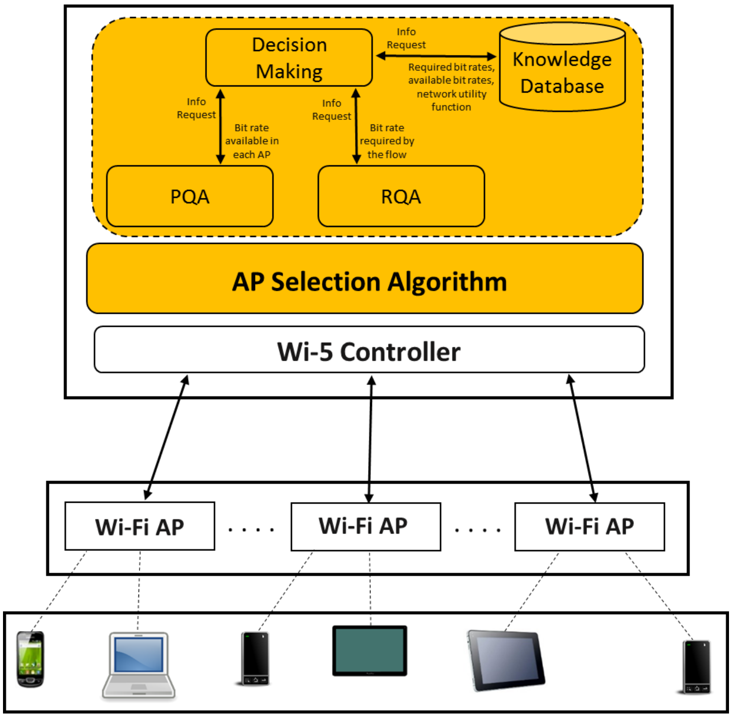


Figure 6: AP Selection Approach Using SDN Concept

From Figure 6, we can observe that the *AP Selection* process introduced in Section 3.1 and illustrated in Figure 3, includes a Knowledge Database module and a Decision Making module. Moreover, the proposed SDN-Based framework relies also on the PQA and RQA processes introduced in Section 3.1, which reside inside the Wi-5 Controller. Specifically, all the modules considered in our AP selection and their roles in the execution of the algorithm are defined as follows:

- **PQA**: This module provides the bit rate that each AP in the network can achieve for a new flow connection, measured at the physical layer, which depends on the channel bandwidth assigned to each AP, the measured inter-AP interference within the network, and the position of the station requiring the connection. Moreover, this bit rate is mapped to the most efficient Modulation/demodulation and Coding Scheme (MCS) to achieve the highest available bit rate computed by using the Orthogonal Frequency Division Multiple Access (OFDMA) approach, which has been adopted in most 802.11 protocols (e.g., 802.11 g/a/n).
- **RQA**: This module provides the QoS requirements of the flow requesting the connection as described above.
- **Knowledge Database**: This module stores the following information: 1) the QoS requirements corresponding to each active flow computed by the RQA module; 2) the link capacity in terms of the bit rate available for each active flow in the network and computed by the PQA module; and 3) the most recent computed network utility function *U*, which is a parameter needed for the AP selection algorithm and will be explained in detail in the rest of this subsection. The data stored in the *Knowledge Database* are updated, either when a new flow connects to the network or an active flow disconnects.
- **Decision Making**: This module is triggered every time a new flow needs to be associated to an AP. It first collects the available information from the RQA, PQA and *Knowledge Database* modules. Then, it uses this information to play the potential game and assign to each flow active in the network the most suitable AP based on our algorithm.

The large Wi-Fi network considered to assess our AP Selection algorithm consists of a set *N* of *n* APs with heavy data traffic and heterogeneous wireless user demands. Specifically, the wireless users require connections for a set *M* of *m* applications flows. Let $\psi_{i,j}$ denote the Signal to Interference plus Noise Ratio (SINR) experienced by flow *i* when allocated to AP *j*. $\psi_{i,j}$ is computed at the location of the user requiring the connection of its flow *i* to AP *j* as follows [2]:

$$\psi_{i,j} = \frac{g_{i,j} \cdot p_j}{\sum_{k \in N'} g_{i,k} \cdot p_k + N_0} \tag{2}$$

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 affecting the SINR experienced by flow *i*. The bit rate levels that APs can provide to the users range between 1 Mbps and 54 Mbps according to the 802.11 g/a/n standards, which implement OFDMA. Each of these bit rate levels represents the link capacity $b_{i,j}$ between flow i and AP j, which can be computed using $\psi_{i,j}$ through the Shannon–Hartley theorem [2] and provided by the PQA. Therefore, $b_{i,j}$ can be expressed as:

$$b_{i,j} = f(\psi_{i,j}, BW_j) \tag{3}$$

Where, BW_j is the bandwidth assigned to AP *j* in Hz. After the computation of $b_{i,j}$, $R_{i,j}$, which denotes the bit rate served to flow *i* by AP j, can be computed by considering also the number A_j of all the flows connected to AP j and the maximum capacity C_j in bps available in AP j. Hence, $R_{i,j}$ can be defined as the following function g of all these parameters:

$$R_{i,j} = g\left(b_{i,j}, A_j, C_j\right) \tag{4}$$

We now define the FF parameter, which is a performance metric with its value between 0 and 1, and originally introduced in [67]. In detail, the FF considered in this deliverable is based on the function defined in [68] and is used by the AP selection algorithm to determine the suitability of an AP j to satisfy a wireless user's QoS requirements for a certain flow *i*. Since these QoS requirements are based on the characteristics of the data flow of each wireless user, the suitability of an AP to serve them takes into account the data bit rate that the flow *i* requires, $R_{req,i}$ provided by the RQA process, and the data bit rate that an AP can deliver, $R_{i,j}$ defined through eq. (4). Hence, the FF for the flow *i* served by AP *j* can be expressed through eq. (5). All the details on the computation of $R_{i,j}$ and FF can be found in [2].

$$\phi\left(R_{i,j},\ R_{req,i}\right) = f_{i,j} \in \mathbb{R} \mid 0 \leq f_{i,j} \leq 1 \tag{5}$$

In order to optimise the distribution of the Wi-Fi flows to be served by the *n* APs of the network, we consider the network utility function *U* previously introduced and defined as the log-sum of the FFs of all the *m* flows connected to the network. In detail, we aim at optimising through U the sum of the logarithms of the FFs provided by the APs allocated to each flow *i* connected to its corresponding AP, AP_i, in order to guarantee a proportional fairness in the APs allocation. On the other hand, in the considered scenario, any flow might achieve an FF value equal to zero. Therefore, in order to avoid a possible inclusion of zero in the logarithm argument, we consider a modified version of the objective function, with the sum of the logarithms of the FFs plus one [66]. Therefore, *U* to be optimised can be defined as follows with $1 \leq AP_i \leq n$:

$$U = \sum_{i=1}^{m} \log(f_{i,AP_i} + 1) \tag{6}$$

In order to model the AP allocation problem as a potential game in the proposed algorithm, we need to firstly define all the parameters needed in any formal game: 1) the set of players, 2) the strategy space, and 3) the utility function to be optimised. These are expressed as $\Gamma = \{M,\ \{S_i\}_{i\epsilon M},\ \{u_i\}_{i\epsilon M}\ \}$ where *M* is the set of players represented by the flows active in the network, S_i is the set of strategies used by player i (flow i in our case), and $u_i\colon S \rightarrow \mathbb{R}$ is the utility function of player *i*, with $S = \times_{i\in M} S_i$ the strategy space of the game, formed by the Cartesian product of all the players' strategy sets.

Each strategy $s \in S$ is formed by the specific strategies selected by all the players of the game $s = \left(s_1, \dots, s_{i-1}, s_i, s_{i+1,} \dots s_M\right)$, and can also be expressed as $s = (s_i, s_{-i})$, where s_i is the strategy chosen by player i and $s_{-i} = \left(s_1, \dots, s_{i-1}, s_{i+1,} \dots s_M\right)$ are the strategies chosen by the rest of the players. With this, the utility function u_i is a function of s_i, the strategy selected by flow *i* (in this case, the selection of AP j, i.e., $s_i = j$), and s_{-i}, the strategy profile of the rest of the flows of the game (i.e., the profile represents the AP selections of all the other flows). One general key issue when designing a formal game is the choice of u_i in order to achieve a good overall performance considering the individual actions of all the players (i.e., in our case all the flows distributed in the Wi-Fi network). Moreover, it is also desirable for the existence of an equilibrium point to ensure the convergence of the proposed game when performing the optimisation. In this context, we include the NE in our approach, which is always guaranteed in a potential game [66].

Specifically, the NE for the game *Γ* formally represents a profile $s^* \in S$ of actions for every flow $i \in M$, which addresses the following condition [66]:

$$u_i(s_i^*, s_{-i}^*) \geq u_i(s_i, s_{-i}^*) \tag{7}$$

This condition needs to be addressed for all $s_i \in S_i$, where s_i denotes any strategy of player *i* different from s_i^*, and s_{-i}^* denotes the strategies of all the other players in the profile s^*. The convergence of the game to a NE makes it possible to reach a stable solution. Moreover, the network can react to variations in the environment because any deviation from this NE forces the system to play the game again to obtain a new NE.

Let us focus now on the definition of the potential game proposed in this section. Specifically, this is a particular game for which there exists a potential function *V*: $S \rightarrow \mathbb{R}$ to address the following condition:

$$\Delta u_i = u_i(s_i, s_{-i}) - u_i(s_i', s_{-i}) = \Delta V = V(s_i, s_{-i}) - V(s_i', s_{-i}) \; \forall i \in M, \forall \; s_i, s_i' \in S_i \tag{8}$$

This definition means that each player's individual interest is aligned with the group's interest (the potential function *V*) since every change Δu_i in the utility function of a player *i* is directly reflected in the same change ΔV for the potential function. Therefore, any player selecting a strategy that improves its utility given all other players' current strategies, will necessarily lead to an improvement in the value of the potential function. With this definition, it can be demonstrated that if only one player improves its utility given the most recent action of the other players, then the process will always converge in finite steps to a NE [66].

In our approach the flows, although representing the players of the potential game, do not take the decision on the AP selection. In fact, this decision is made by the SDN controller, which plays the game for all the active flows in the network. For the considered problem, we define the potential function *V* as the objective to be optimised, which in this case is the network utility *U* defined through eq. (6). We let the utility function u_i equal the potential function *V* for the analysed problem (identical interest games), which guarantees that eq. (8) is fulfilled and therefore the game is potential:

$$u_i(s_i, s_{-i}) = \sum_{k=1}^{m} \log(f_{k,s_k} + 1) \tag{9}$$

Where s_k represents the strategy of player *k*, i.e., its corresponding AP, AP_k. A repeated sequential game with round robin scheduling and a best response strategy (each player tries to maximize its utility) is considered for the proposed game, which is played until the pure NE is found. The objective of this algorithm is to find the most suitable AP for all the flows connected to a Wi-Fi network each time a user requires connection for a new flow. Algorithm 1 illustrates in detail the sequence of steps implemented in the controller during the execution, which is triggered each time a new flow connects to the network.

First, the *Decision Making* module collects from the *Available Bit Rates* module all the link capacities in terms of the bit rate, which each AP *j* can provide to the new flow and is computed using (3) (line 1). Then, the *Decision Making* module acquires the QoS requirements of the new flow *i* in terms of the bit rate generated in the *Required Bit Rate* and needed for the computation of the FF (line 2). Afterwards, it acquires from the *Knowledge Database* the information related to all the other flows already active in the network, i.e., the bit rate requirements and the available bit rates based on (1)-(3), and the most recent computed network utility *U* (line 3).

Then, the *Decision Making* module starts the round robin scheduling until it reaches the NE (line 6). Specifically, for each flow *i* connected to the network and for each AP covering the area in which flow *i* takes place (i.e., the APs belonging to the set named $W_i \subseteq N$ in line 9 of Algorithm 1), the *Decision Making* module computes u_i that needs to be optimised by taking into consideration the interest of all the *m* flows connected to the network (lines 8-18). Hence, the *Decision Making* module first updates all the FFs of the flows affected by the connection of flow *i* to the AP w_j belonging to the set W_i and using equations (4)-(6) (line 10) and then, it considers the updated FFs for each flow *k* connected to its own AP, i.e., AP_k, to compute u_i using equation (10) (line 11).

The round robin scheduling is stopped when the NE is found through the condition *NE_found=1* (lines 19-21). Finally, the *Decision Making* module updates the *Knowledge Database* storing the required bit rate of flow *i* and the flows' served bit rates that have changed after the accomplishment of the NE (line 23). Note that the optimisation of *U* addresses a possible horizontal handover of the flows towards new APs when needed. However, it has been demonstrated that in SDWN-based networks, seamless inter-AP horizontal handovers can be applied without a harmful loss of connection [69]. Given *G*, the number of game cycles needed to reach the NE, *m* the number of flows active at a certain time *t* and *w*, the number of APs available on average for a certain flow, the 'while loop' is called *G* time, the outer 'for loop' is called *m* times, and the inner 'for loop' is repeated for an average of *w* times. Therefore, the time complexity of our AP selection algorithm is linearly related to the number of flows *m* and will be *O(Gwm).*

Algorithm 1 - AP Selection

1: **get** info on new flow from *Available Bit Rate*
2: **get** info on new flow from *Required Bit Rate*
3: **get** info on all active flows and last *U* from *Knowledge Database*
4: **include** info on new flow in set *M*
5: NE_found=0
6: **while** NE_found==0 **do**
7:   any_change=0
8:   **for** i=1 to *m* **do**
9:   **for** j=1 to $\#W_i$ ($W_i \subseteq N$) **do**
10:   update all FFs in the APs affected when selection s_i is the w_j-*th* AP with $w_j \in W_i$ and $1 \leq w_j \leq n$
11:   **compute** $u_i = \sum_{k=1}^{m} \log(f_{k,AP_k} + 1)$
12:   **if** $u_i > U$ **do**
13:   any_change=1
14:   assign AP w_j to flow *i*
15: $U = u_i$
16:   **end if**
17:   **end inner for**
18:   **end outer for**
19:   **if** any_change==0 **do**
20:   NE_found=1
21:   **end if**
22: **end while**
23: **update** the *Knowledge Database*

3.2.3 Vertical Handover Algorithm

This algorithm allows Wi-5 to handle vertical handovers where wireless users could be moved from a WLAN to a 4G network. With respect to the state-of-the-art illustrated in Section 2.3, the algorithm novelties can be summarised as follows:

- We propose a novel strategy that matches the most suitable RAT for a certain user based on the QoS requirements for his/her ongoing application. Such a match will enable the smart use of limited spectrum resources while guaranteeing the user's QoS demands in the most efficient way. The SDN controller provides all the monitoring information needed for our RAT selection strategy to allow a complete and efficient integration between LTE and Wi-Fi technologies.
- We propose a RAT Selection Framework based on SDN that allows the implementation of our strategy. Specifically, this framework exploits the capabilities offered by SDN including cross-layer monitoring and centralised management of different networks, which enables handover, thus allowing the implementation of an efficient RAT selection strategy.

Many research efforts, including Wi-5, are currently attempting to support the management of cellular networks in order to ease spectrum congestion. This requires extending the southbound API of the SDN controller to be able to configure the parameters of these networks and their access nodes. This is particularly helpful in the context where a single operator manages both Radio Access Networks (RANs): cellular and Wi-Fi. In such a situation, the operator can use the SDN controller to manage access to both networks and assist wireless users with their QoS demands. Such a vision is already being promoted as part of 5G, where operators are expected to manage heterogeneous networks consisting of several RATs [48], [70].

Building on these latest developments, we consider the scenario of a HetNet in which the RANs include a set N of n wireless technologies tightly merged in a unique wireless access network under the Wi-5 centralised SDN-based control. Specifically, RATs include Wi-5 APs, Femtocell LTE base stations (HeNB) and Macrocell LTE base stations (eNodeBs). The Wi-5 controller is able to handle all the access nodes of its HetNet and provide connection to a set M of m application flows required by wireless users trying to connect to the network. Note that each flow can be either a flow for applications required by a Wi-5 station (STA), or by a dual-interface device (e.g., smartphone, tablet, etc.) connected by Wi-Fi or LTE technology.

When receiving each station connection request redirected from the RAN, the SDN controller triggers the RAT selection algorithm implemented in the Vertical Handover process running on the controller as illustrated in Figure 7. Specifically, for each new flow trying to connect to the network from either a STA already connected or for a new STA, the controller finds the optimised node allocation for all the application flows active in the network.

Specifically, the PQA module gives information on the bit rate that each accessible node of the network can achieve for a new station request, measured at the physical layer connection. The assessment is obtained by the computation of the link capacity available for each new flow in terms of the bit rate, which in turns depends on the monitoring information received by the controller through the monitoring function, such as the channel bandwidth assigned to each node, the measured inter-nodes interference within the network, and the position of the station requiring the connection.

The RQA module translates the QoS requirements of a connection-requesting station achieved through the monitoring function into a bit-rate metric. The QoS requirements of the station depend on the nature of the data flow that the station is sending and receiving.

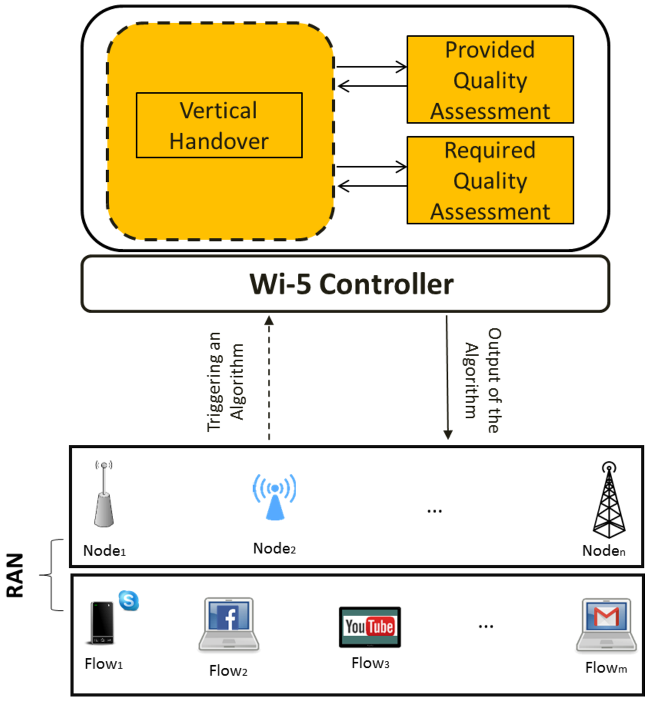


Figure 7: SDN-based Framework for RAT Selection

The Vertical Handover module is triggered every time a new flow *i* needs to be associated to a node *j*. It first collects the available information from the PQA and RQA modules, which depends on the radio environment. Then, it uses this information to efficiently match the most suitable available bit rates provided by the nodes for the required bit rates. In order to model the proposed RAT selection problem implemented in the Wi-5 controller, we again consider the FF concept also used for the AP Selection presented in Section 3.2.2.

Therefore, in our RAT selection strategy, after receiving the request from the RAN, the PQA is able to compute the available bit rate in each accessible RAT for the new flow. The available bit rate for a generic flow *i* in a generic node *j*, $b_{i,j}$, is computed depending on each specific RAT. In detail, the values of the SINR experienced by a certain flow in any accessible RAT is computed at the location of the user requiring connection for the flow using eq. (2).

In the case of Wi-Fi, the link capacity for a generic flow *i* in a generic node j, $b_{i,j}$, which is denoted in this subsection as $b_{i,j}^{WF}$, corresponds to the most efficient MCS to achieve the highest available bit rate under the interference level constraints and computed through eq. (3).

In the case of LTE, the SINR measured at the location of a user requiring connection is mapped to the corresponding Channel Quality Indicator (CQI), which represents the highest possible MCS that the user's device can process with a block error rate lower than 10% [71] and [72]. 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). Each RB is a sub-channel of capacity C_{RB} equal to 180 kHz and formed by 12 consecutive and equally spaced sub-carriers, each one lasting 0.5 ms [73]. The total number of available RBs at node j, N_{RBj}, depends on the bandwidth assigned to node j, BW_j, and allows us to compute the maximum link capacity in LTE Base Stations (BSs), $b_{i,j}^{LTE}$, for flow i experiencing CQI_i. Therefore, considering SE_i as the spectral efficiency which corresponds to CQI_i and shown in Table 1, and N_{RBj} defined through the assigned BW_j, $b_{i,j}^{LTE}$ can be expressed by equation (10) below:

$$b_{i,j}^{LTE} = SE_i \cdot C_{RB} \cdot N_{RBj} \tag{10}$$

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

After the computation of $b_{i,j}^{WF}$ and $b_{i,j}^{LTE}$ provided by the PQA, the Vertical Handover process also computes the bit rate that can be served to flow *i* by node *j* called here $R_{i,j}$, through the resource allocation algorithm defined in [2]. Note that this value also depends on the number M_j of all other flows connected to node *j*, and the maximum capacity C_j in bps available in node *j* and then, it can be expressed as a function Φ of all these parameters:

$$R_{i,j} = \begin{cases} \Phi^{WF}\left(b_{i,j}^{WF}, M_j, C_j\right) \text{ in case of } AP \\ \Phi^{LTE}\left(b_{i,j}^{LTE}, M_j, C_j\right) \text{ in case of } BS \end{cases} \tag{11}$$

The RAT selection strategy proposed in this deliverable is also based on the potential game introduced in Section 3.2.2 for our AP Selection strategy, which allows an efficient distribution of the wireless users among the nodes of the network handled by the SDN controller.

Hence, for each new flow trying to connect to the network, the controller plays a potential game for all the flows active in the network, to find an optimised node allocation for all of them. Specifically, in order to optimise the distribution of the *m* flows to be served by the *n* nodes of the network, we consider the network utility function *U* defined through eq. (6), while *U* to be optimised in the context of the potential game used in our RAT selection strategy can be defined through eq. (9).

Hence, each time a new flow needs to connect to the network, the RAN triggers the RAT selection algorithm implemented in the Vertical Handover process illustrated in Figure 7, using the following tasks:

- **Task 1**: The Vertical Handover process collects from the RQA all the bit rates required by the flows active in the network.

- **Task 2**: The Vertical Handover process collects from the PQA all the link capacities in terms of the bit rate, which each node *j* can provide to each flow *i*, $b_{i,j}^{WF}$ and $b_{i,j}^{LTE}$, using (3) in the case of Wi-Fi-based nodes and (10) in the case of LTE-based nodes.

- **Task 3**: The Vertical Handover process starts a sequential game with round robin scheduling to find the optimised value of *U* through (9) until the pure NE is found. Specifically, in each round, for each flow *i* connected to the network and for each node *j* covering the area in which flow *i* takes place, the Vertical Handover process first updates all the FFs of the flows affected by the connection of flow *i* to node *j* through (5) and then it computes *U* that needs to be optimised, including such updated FFs, $f_{i,node_i}$. Note that the optimisation of the log-sum takes into consideration the interest of all the *m* flows connected to the network. The NE is found when the controller does not further improve the utility *U*.

4 Performance Evaluation

In this section we present a comprehensive assessment of the algorithms developed in the context of WP4. More specifically, the assessment will focus on the latest progress made in this work package and the newly developed functionalities, namely, AP selection based on a potential game and RAT selection vertical handover algorithms, using MATLAB. For this purpose, we developed simulation models that include all 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 were considered to assess our algorithms.

4.1 Evaluation of AP Selection Algorithm

4.1.1 Simulation Scenario and Results

In our evaluation of the AP selection algorithm, we simulate the SDN-based controller presented in two scenarios representing dense Wi-Fi environments: *Scenario A* and *Scenario B*. Scenario A consists of n=5 APs randomly deployed in an area of 100×100 m^2 with a minimum distance of 7 meters between them, and a set of m=1, …, 100 flows gradually generated in the area. Scenario B includes n=15 APs randomly deployed in an area of 300×300 m^2 at a minimum distance of 20 meters, and a set of m=1, …, 400 flows gradually generated in the area.

The QoS requirements of the station flows trying to connect have been randomly generated from a set of bit rates that vary between 40 kbps and 2 Mbps in order to represent the minimum bit rates required for common online applications (e.g., VoIP, and video streaming on YouTube). The transmit power for all the APs is 25 dBm. The values of BW_j in (3) and C_j in (4) are set, respectively, at 20 MHz and 54 Mbps for all the APs composing the network.

To benchmark the performance of the AP selection algorithm, we compare it against the following reference strategies: 1) AP selection based on RSSI as considered in the 802.11 standards; and 2) AP selection proposed in [2], which assigns an AP to a flow based on the metric called *Network Fittingness Factor* (*Network FF*). The Network FF metric jointly addresses the QoS requirements of a flow joining the network, and the QoS requirements of the other active flows in the network. Moreover, we consider this strategy that we proposed in D4.2 [2] because it targets the same centralised approach relying on SDN and it out-performs other approaches found in the state of the art, such as the work proposed in [44]. Note that also the time complexity of this AP selection algorithm is linearly related to the number of flows and is *O(m)*.

The evaluation of our new approach against the above two strategies focuses on the following performance metrics:

- ***Average Data Bit Rate***: This is the statistical distribution of the data rates assigned to all the flows (e.g., minimum, maximum and median values).
- ***Satisfaction***: This is the percentage of flows connected to the network with their served data bit rates higher than or equal to their given requirements, and updated for each new connection. Consequently, a flow is considered unsatisfied when its served bit rate is lower than its requirement.
- ***Percentage of Flows with Good Mean Opinion Score (MOS)***: This metric is considered to address the QoE of an application provided to a certain flow as the perceived acceptability from the user's perspective [74]. In this paper we use the MOS as a metric that reflects the

user's view on the quality of the network. The MOS is an arithmetic mean of all the individual scores obtained by the result of subjective tests, which can range from 1 (worst) to 5 (best). The meaning of each score is shown in Table 2 in terms of quality and impairment. In the context of our analysis, we illustrate the percentage of flows that obtain at least a *Good* quality at the end of the simulation.

Note that the QoS requirements of the active flows from devices trying to connect have been randomly generated from a set of bit rates that range between 40 kbps and 2 Mbps. We have considered these values in order to represent most common online applications such as VoIP, Video Streaming, etc., which are summarised in Table 3. Specifically, for each application in this table, we illustrate: (i) the bit rate requirements, (ii) the achievable MOS when assigning these requirements, (iii) the corresponding quality perceptible by the end-user, and (iv) the impairment corresponding to the quality.

In the case of VoIP, we have considered 40 kbps and 60 kbps, which are the approximate bit rate requirements that guarantee a *Good MOS* when the *G.729* codec and *G.726* codec are used, respectively[2]. While in the case of video streaming, the minimum bit rate requirement for watching videos on YouTube is 500 kbps, and it is 1 Mbps in the case of premium content such as movies, TV shows and live events[3]; and finally, 2 Mbps is the minimum bit rate recommended for videos on Netflix[4]. A detailed analysis that explains the relation between the *Good MOS* and the guaranteed minimum bit rate requirements illustrated in Table 3 can be found in [75].

Note that, for the sake of simplicity, in the analysis of the performance we illustrate the achieved results only for downlink transmissions also in the case of VoIP. This is a reasonable assumption, since maintaining the minimum bit rates required for VoIP illustrated in Table 3 guarantees the *Good MOS* for both downlink and uplink transmissions[2].

Table 2 – Mean Opinion Score (MOS)

MOS	Quality	Impairment
5	Excellent	Imperceptible
4	Good	Perceptible but not annoying
3	Fair	Slightly annoying
2	Poor	Annoying
1	Bad	Very annoying

Table 3 – Bit Rate Requirements and MOS

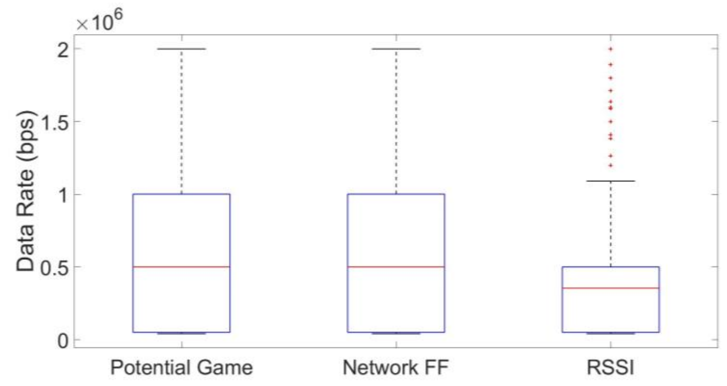
<table>
<tr><th>Application</th><th>Bit rate</th><th>MOS</th><th>Quality</th><th>Impairment</th></tr>
<tr><td>VoiP G.729</td><td>40 kbps</td><td>3.92</td><td rowspan="5">Good</td><td rowspan="5">Perceptible but not annoying</td></tr>
<tr><td>VoiP G.726</td><td>60 kbps</td><td>3.85</td></tr>
<tr><td>YouTube</td><td>500 kbps</td><td>4.5</td></tr>
<tr><td>Premium YouTube</td><td>1 Mbps</td><td>4.5</td></tr>
<tr><td>Netflix</td><td>2 Mbps</td><td>4.5</td></tr>
</table>

Figure 8(a) and Figure 8(b) illustrate the performance results of our Potential Game-based AP selection algorithm against the state of the art for Scenario A, in terms of the data rate and satisfaction,

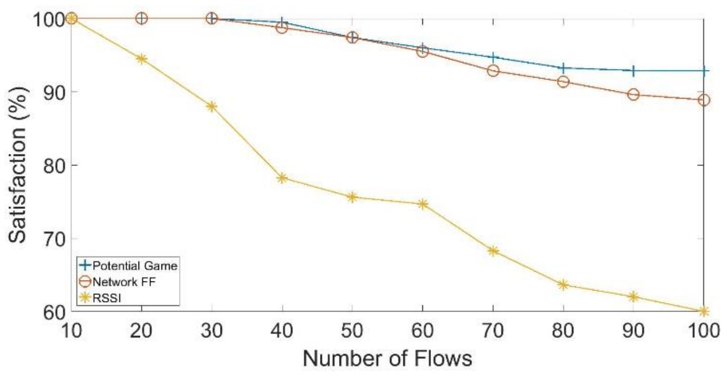
[2] http://www.cisco.com/c/en/us/support/docs/voice/voice-quality/7934-bwidth-consume.html (accessed March 2018).
[3] https://support.google.com/youtube/answer/78358?hl=en-GB (accessed March 2018).
[4] https://help.netflix.com/en/node/306 (accessed March 2018).

respectively. In Figure 8(a) the upper and lower edges of the plotted boxes representing the data rate distribution are the 25th and 75th percentile of their values for 100 connected flows, while their median values are indicated by the central red lines. The values which we considered as outliers are indicated by red symbols. This figure illustrates how the Potential Game-based approach and the Network FF-based one allow an equal distribution around the median value in terms of the data rate compared to the RSSI-based solution. Therefore, both solutions based on the FF guarantee the same fairness in the network.

Figure 8(b) shows the performance in terms of the satisfaction as a function of the number of the flows connecting to the network. This figure illustrates that the Potential Game-based algorithm offers better flow satisfaction than the Network FF-based and RSSI-based solutions. For instance, from the figure we can observe that when there are around 85 connected flows, the percentage of satisfied flows is 90% in the case of Network FF and it decreases to 89% for 100 connected flows. However, the percentage of satisfied flows for the Potential Game-based solution is 93% that is maintained even when all 100 flows are connected to the network. Furthermore, if we look at the unsatisfied flows in this case, the Potential Game based approach reduces the number of unsatisfied flows from 11% in the Network FF-based solution to 7%, which implies approximately a 36% gain in the case of 100 flows connected to the network.



(a)



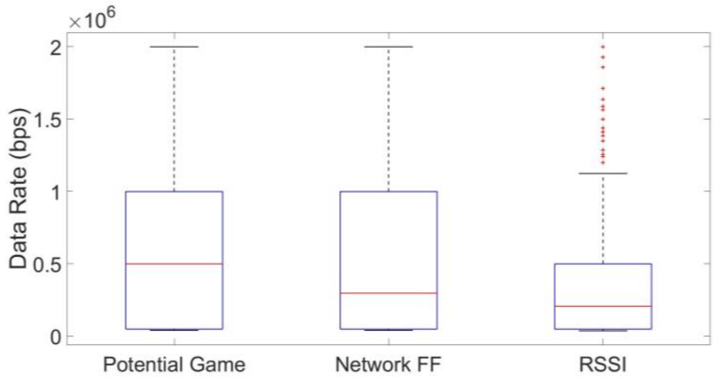
(b)

Figure 8: Distribution of the Data Rates (a) and Satisfaction (b) in Scenario A

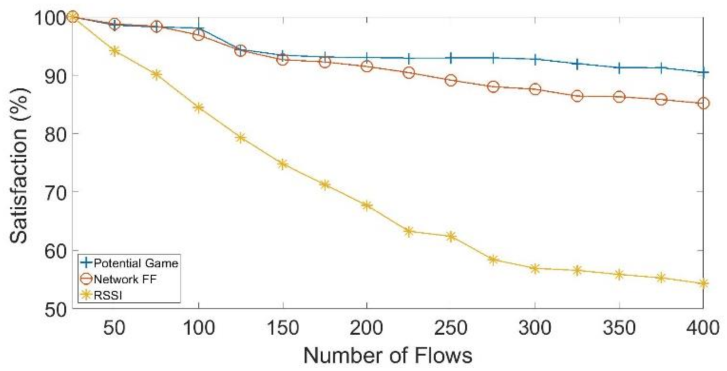
For Scenario B, Figure 9(a) illustrates that in the case of 400 active flows in the network, the Potential Game-based solution maintains an equal distribution around the median value in terms of the data rate, guaranteeing a best fairness also compared to the Network FF-based algorithm, which is characterized by a lower median data rate value.

In addition, the Potential Game-based algorithm continues to outperform the Network FF-based and RSSI-based solutions in terms of the average satisfaction as illustrated in Figure 9(b). The percentage of satisfied flows is 90% when there are around 220 connected flows in the case of Network FF, while in the case of Potential Game, the percentage of satisfied flows is 91% even when all 400 flows are connected to the network. Moreover, in this scenario the Potential Game-based approach reduces the number of unsatisfied flows by around 40% in comparison with the Network FF-based strategy when 400 flows are connected to the network.

Therefore, the improvement achieved by the Potential Game-based approach in terms of fairness and illustrated in Figure 9(a) provides a further improvement also in terms of satisfaction in Scenario B with respect to our previous solution, as shown in Figure 9(b). In summary, from this analysis we can observe that the greater the number of flows on average in each AP, the greater the improvement delivered by the Potential Game-based solution with respect to state of the art in terms of both fairness in the distribution of the data rate and satisfaction.



(a)



(b)

Figure 9: Distribution of the Data Rates (a) and Satisfaction (b) in Scenario B

Figure 10 illustrates the percentage of flows that achieve at least 50% and 90% of their requirements (i.e. required bit rates) in both Scenarios A and B (SA and SB in the figure, respectively). The figure shows that in both scenarios our AP selection algorithm based on the Potential Game outperforms the Network FF-based and RSSI-based solutions. For instance, in Scenario B, although not all the users are completely satisfied, 93% of the flows get 90% of their requirements in the case of Potential Game, whereas in the cases of Network FF and RSSI, 85% and 56% of the flows get the same percentage, respectively.

Finally, Figure 11 shows the percentage of flows that achieve at least a *Good MOS* in both Scenario A and B (SA and SB in the figure, respectively). These results show that in the case of Voice, all the solutions can guarantee a *Good MOS* to all the flows connected to the network in both scenarios. On the other hand, the results also show that our Potential Game-based AP selection algorithm outperforms both of the other solutions in terms of the percentage of flows requiring a connection for video streaming and reaching at least a *Good MOS*. Specifically, the Potential Game-based AP selection algorithm outperforms the Network FF-based approach by 7% and 10% in Scenario A and B respectively, and the RSSI-based solution by 64% and 70% in Scenario A and B respectively.

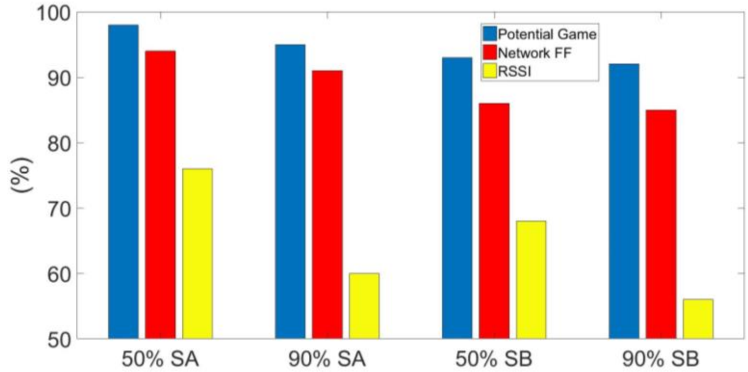


Figure 10: Percentages of flows partially satisfied

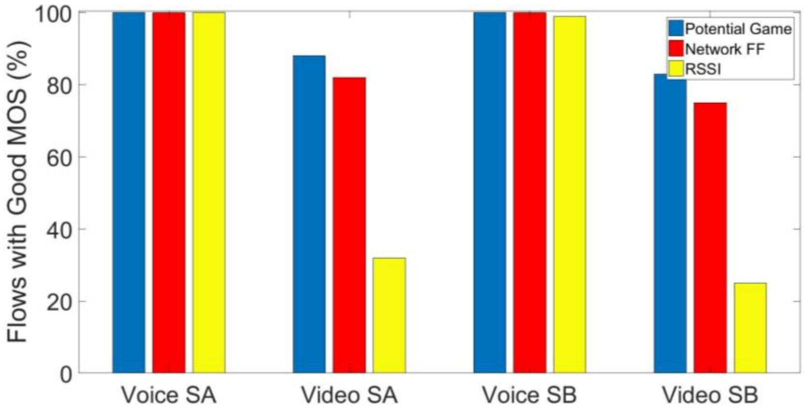


Figure 11: Percentage of flows with at least *Good MOS*

4.1.2 Results obtained from a Large WLAN Use Case

In this subsection we address the problem of AP selection in large scale WLANs through the study of the Kings Avenue mall, which is the biggest shopping mall in Cyprus and is located in the city of Paphos, Cyprus. Hence, we model a use case represented by such a mall, which consists of two floors where Wi-Fi coverage is provided by a number of APs uniformly deployed within the building.

The building covers an area of 103000 m^2 including basements and a parking area with capacity for 1250 vehicles. A large WLAN is deployed to provide Wi-Fi connectivity in an area of approximately 41000 m^2 distributed in the two floors as illustrated in Figure 12. The WLAN consists of 7 IEEE 802.11n/ac APs, deployed at a distance of approximately 33 meters from each other. The APs composing the WLAN have been designed to reach high capacities through, for instance, automatic interference mitigation and transmit beamforming, which are crucial to increase the capacity provided to the customers in high-density environments. On the other hand, the current design does not consider a smart allocation of the APs among the customers taking into account their QoS demands that might exploit better the potentiality of these APs. In this context, our study investigates the performance of the WLAN located in the shopping mall use-case through simulations to expose the limitations of the conventional AP selection approach with regards to wireless users' satisfaction and the capacity of the networks. Specifically, we propose the implementation of our AP selection algorithms that address QoS requirements using the FF concept. The first algorithm is based on the *Network Fittingness Factor* that we have proposed and assessed in D4.1 [1] and D4.2, and the second is based on the centralised *Potential Game* illustrated in Section 3.2.2.

The main objective of the study is to efficiently exploit the potentiality of the APs composing the WLAN of the shopping mall in terms of capacity. Moreover, we want to demonstrate how the flexibility of SDN allowed to implement two smart AP selection strategies in the central controller able to handle the APs located in the considered use-case, giving the service provider the possibility to select its most preferable strategy.

The APs are located on the roof of the first floor and their distribution is illustrated in Figure 12(a). These APs could provide a theoretical capacity up to 450 Mbps and 1300 Mbps, in 2.4 GHz and 5 GHz, respectively.

A key functionality of our coordinated allocation of the APs is the inclusion of realistic QoS demands of the Kings Avenue mall customers. Hence, the downlink bit rate requirements in terms of throughput were monitored using NetFlow software for a set of more than 4000 customers connecting to the WLAN during the whole month of June 2017. This analysis then provided a realistic statistical characterization of the expected throughputs required for downlink applications experienced by actual Wi-Fi customers, and used in our smart AP selection algorithms. In detail, the customers during the month used applications requiring on average approximately 111 kbps throughput with peak values of around 1.1 Mbps.

Figure 13 illustrates the Cumulative Distribution Function (CDF) of these throughput bit rates. Specifically, the horizontal axis represents the domain of the throughput values required by the customers during the analysed month, while the vertical axis is their probability to be required. The use of this CDF in the algorithm will be clarified in the rest of this subsection.

(a) First Floor

(b) Ground Floor

Figure 12: Floorplans of the Kings Avenue mall

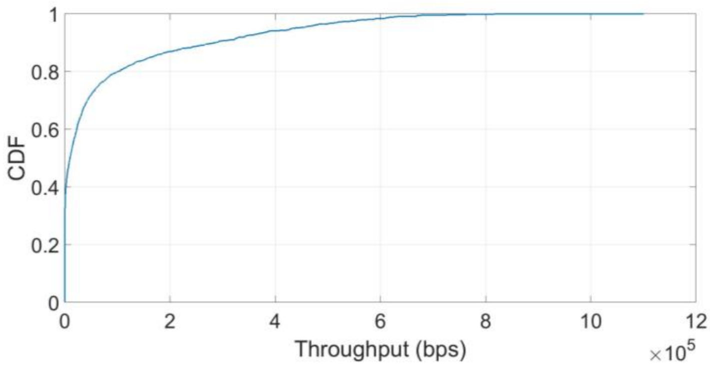


Figure 13: CDF of required bit rates

The objective of this study is to find the most suitable AP for all the flows connected to the Wi-Fi network provided in the Kings Avenue mall each time a customer requires connection for a new flow *i*. In our work, we consider that the WLAN located in the shopping mall use-case is controlled via our SDN-based framework illustrated in Figure 6. Specifically, for each new flow connection, the QoS requirement is generated within the RQA module from the CDF shown in Figure 13, through the *inverse transform sampling* method. This method represents a classical approach to generate pseudo-random samples from a probability distribution, such as a CDF [76]. In detail, let *X* be the set of throughputs with their distribution defined by the CDF here named *F*, and the *inverse transform sampling* method is applied as follows:

- For each new simulated flow *i*, the *Required Bit Rate* module generates a random number *a* from the standard uniform distribution in the interval [0, 1], which represents a pseudo-random sample transformed by the CDF *F* to a realistic throughput required by a customer.
- It then computes the value $x \in X$ such that $F(x) = a$.
- It finally sends *x* to the *Decision Making* module as the QoS requirement of flow *i* from the distribution defined by *F*.

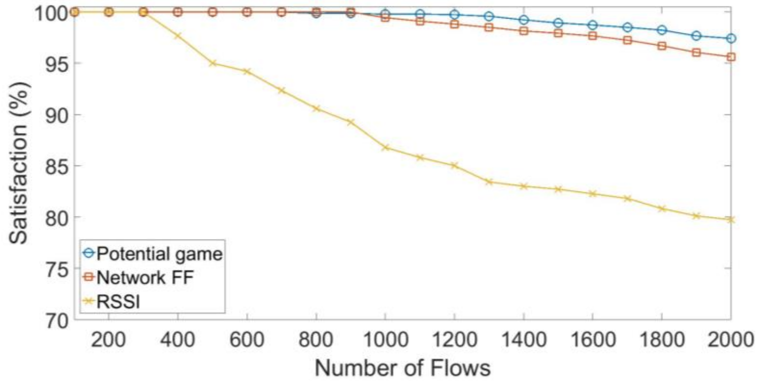
Then, the *Decision Making* module collects from the PQA module all the link capacities in terms of the bit rate, which each AP *j* can provide to the new flow *i* and is computed using (4). Hence, the *Decision Making* module gets the information stored in the *Knowledge Database* related to all the other flows already active in the network, i.e., the bit rate requirements and the available bit rates based on (3) and (4), and the most recent computed network utility *U* needed in the case of the *Potential Game*-based approach. Afterwards, the *Decision Making* module can run one of the algorithms, i.e., either based on *Network Fittingness Factor* [1], [2] or the *Potential Game* presented in detail in Section 3.2.2.

We modelled the first floor of the King Avenue mall illustrated in Figure 12(a) using MATLAB. In this model, we considered the SDN controller that manages this section of the WLAN. Specifically, we have simulated the area of 230m×90m representing the first floor and covered by 7 802.11n APs. Moreover, for this evaluation we have considered the path loss based on the ITU model for commercial areas in buildings [77]. The values of BW_i needed in eq. (3) and C_i needed in eq. (4) (i.e., the AP's bandwidth and maximum reachable capacity) as well as the AP's transmit power are set for all the APs as 20 MHz, 450 Mbps, and 20 dBm, respectively.

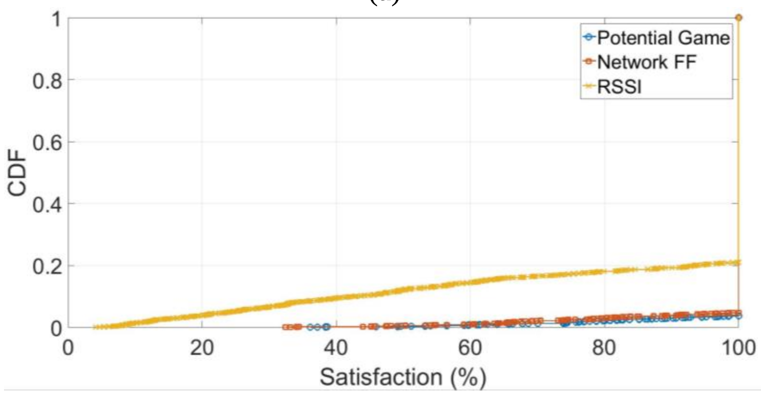
To model the data traffic of wireless users inside the shopping mall, we simulated a set of *m* active flows, where $1 \leq m \leq 2000$ in order to represent a realistic number of customers in busy hours. The QoS requirements of these flows follow the CDF presented in Figure 13, and are generated using the *inverse transform sampling* method as explained in Section 3.2.2. We compare the performance of our algorithms, i.e., based on the Network FF presented in [1], [2], and on the potential game illustrated in this deliverable, against AP selection based on the RSSI as considered in the 802.11 standards.

Figure 14(a) here shows the obtained results in terms of the satisfaction as a function of the number of active flows connecting to the network. From this figure, we can observe that the AP selection solutions based on the *Potential Game* and *Network Fittingness Factor* outperform the RSSI-based solution, with a satisfaction improvement reaching approximately 18% when the number of active flows is *m*=2000.

Figure 14(b) shows the CDF distribution of the satisfaction of the *m* active flows when *m*=2000. The obtained results show that the solutions based on the *Potential Game* and *Network Fittingness Factor* outperform the RSSI-based mechanism. For instance, the probability that the percentage of satisfied flows is less than 100% is around 3% and 5% in the cases of *Potential Game* and *Network Fittingness Factor*, respectively, while in the case of the RSSI-based strategy this probability is approximately 21%.



(a)



(b)

Figure 14: Performance results

Table 4 – Average Throughput

	Average Throughput (kbps)
Requirements	110.8
Potential Game	103.4
Network FF	96.1
RSSI	68

Finally, Table 4 shows the results in terms of the averaged throughput achieved by *m* active flows when *m*=2000 together with the average throughput required by the wireless users obtained using the CDF illustrated previously in Figure 13. From this table, we can observe that the best result is achieved when the AP selection algorithm based on the *Potential Game* is applied, which obtained the highest and closest value to the requirements compared to the *Network Fittingness Factor*-based and RSSI-based solutions.

These results prove that in a scenario such as the shopping mall use-case, our AP selection solutions yield much better performance compared to the 802.11 standards. This is mainly due to the fact that these solutions allocate WLAN resources more efficiently while considering the QoS requirements of wireless applications. Moreover, neither solution incurs high complexity, as it is linearly related to the number of flows connecting to the network. Moreover, the results achieved in this deliverable show that the *Potential Game*, also when applied to this use-case, outperforms the *Network Fittingness Factor* in terms of satisfaction and throughput by 3% and 7%, respectively, when the number of active flows is m=2000. This improvement is due to the further optimised allocation of APs achieved by the *Potential Game* when the number of active flows is at its maximum.

However, this improvement comes at a higher complexity cost when compared to the *Network Fittingness Factor* as already explained in Section 3.2.2. Therefore, a trade-off could be made by the service provider between higher efficiency for the customers of the Kings Avenue mall and lower complexity when the SDN framework is used to manage large WLANs.

4.2 Vertical Handover Algorithm

In order to evaluate our proposed RAT selection framework, we simulate a HetNet managed by an SDN controller. In addition to the controller, the HetNet consists of 20 nodes that include 15 Wi-Fi APs and 5 LTE Femtocells (HeNB). These nodes are randomly deployed in an area of 250×250 m^2 at a minimum distance of 40 meters among them. This distribution of nodes represents a realistic and typical example of a dense environment with overlapping coverage areas among the nodes [78], [79]. We also simulate a set of m downlink flows requesting connection, where m varies between 1 and 400. In order to reflect the heterogeneity of radio access in these simulated flows we assume the following:

- Single-RAT Flows (SRFs) that are related to wireless devices that can only connect to a Wi-Fi AP. These flows represent 10% of the overall flows generated in the network.

- Multi-RAT Flows (MRFs) that are related to wireless devices that can connect to either a Wi-Fi AP or an LTE HeNB in overlapped areas.

A performance analysis is provided for all the flows, i.e., SRFs and MRFs, connected to the network and managed by the SDN controller. Other simulation parameters that help to define a typical dense HetNet scenario such as the propagation and node settings are included in Table 5 [78], [79], and [80]. The QoS requirements of the active flows from devices trying to connect have been randomly generated from a set of bit rates that range between 40 kbps and 5 Mbps for these experiments.

Table 5 – Simulation Parameters

Parameter	Wi-Fi AP	LTE HeNB
Operating Frequencies	2.412-2.472 GHz	2100 MHz
Channel Bandwidth	20 MHz	
Transmit Power	20 dBm	
Maximum Capacity	54 Mbps	100 Mbps
Node Gain	2 dBi	2.2 dBi
Path Loss	Log-distance model	
Noise Power	-92dBm	

In order to benchmark the performance of the proposed RAT selection framework, we compare it against the following reference strategies:

1) The RAT selection scheme based on 3GPP and 802.11 standards. Here, in the case of SRFs, a flow is associated to the Wi-Fi AP providing the highest RSSI. While in the case of MRFs, the Wi-Fi preferred scheme, which is typical in dense urban environments, is considered. Specifically, in areas where Wi-Fi and LTE are both available, a MRF is associated to the AP providing the highest SINR if it is above a threshold equal to 3 dB, and otherwise to the HeNB [50], [53].

2) The load-aware RAT selection scheme proposed in [53], which assigns each flow to a RAT based on the best throughput estimation. We consider this load-aware scheme because it also targets a similar approach which relies on a network-based centralised scheme for the RAT assignment. By comparing our solution to this scheme, we demonstrate that the monitoring information available at the SDN-based controller allows us to compute the FF, which addresses the suitability concept for achieving better performance against such an RAT selection strategy.

The evaluation of our approach against the above two strategies focuses on the following performance metrics similar to Section 4.1.1 above:

- ***Average Data Bit Rate***: This is the statistical distribution of the data rates assigned to all the flows (e.g., minimum, maximum and median values).

- ***Satisfaction Percentage***: This is the percentage of flows connected to one of the RANs that provide served bit rates higher than or equal to their given requirements and updated for each new connection.

- ***Percentage of Flows with Good Mean Opinion Score (MOS)***: This is the percentage of flows that obtain at least a *Good* quality at the end of the simulation.

Based on the simulation configuration described above, our approach and the other existing strategies for maximizing the SINR and the throughput estimation were executed in the controller every time a new user tried to join the network, or an active user needed a new flow with different QoS requirements. The achieved results are illustrated in figures 15, 16 and 17.

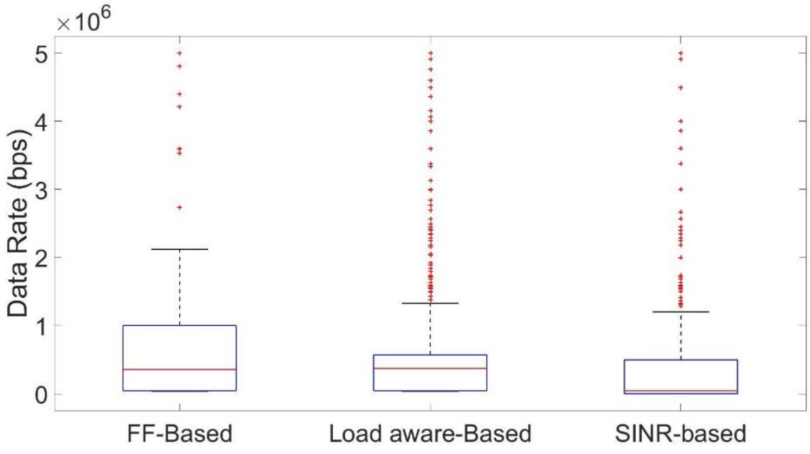


Figure 15: Distribution of the Data Rates

In detail, in Figure 15 the upper and lower edges of the plotted boxes representing the data rate distribution are the 25th and 75th percentiles of their values for 400 connected flows, while their median values are indicated by the central red lines. The values considered as outliers are indicated by red symbols. Accordingly, these results show how our FF-based approach provides a data rate assignment that depends on the data rate requirements, which varies between 40 kbps and 5 Mbps. In fact, most of the assigned data rates are concentrated within the plotted box, i.e., between approximately 40 kbps and 1 Mbps, while the distribution of data rates higher than 1 Mbps is reduced. In the cases of the Load aware-based and SINR-based solutions, the distribution of the assigned data rates higher than 1 Mbps increases considerably with respect to our FF-based approach because they address the best expected throughput and SINR, respectively, and do not take into account the data rate requirements. These results demonstrate how the proposed FF-based approach allows the best fairness in terms of the distribution of data rates because it enables us to assign the most suitable data rates to the requirements rather than the higher ones compared to the Load aware-based and SINR-based solutions.

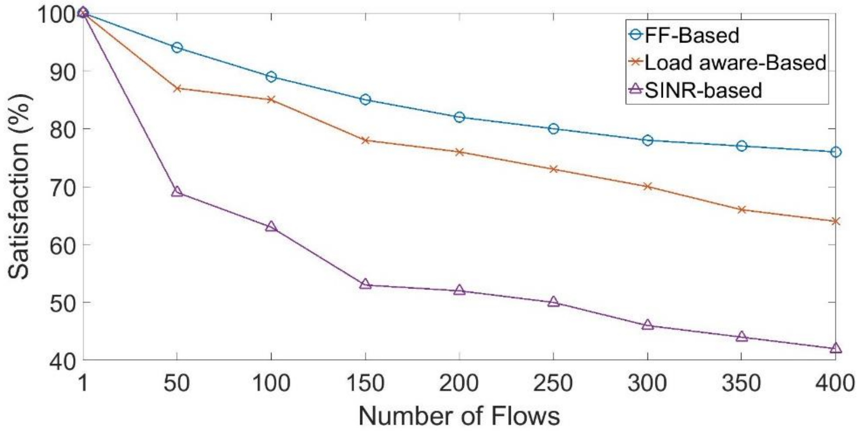


Figure 16: Satisfaction percentage

The results shown in Figure 15 also have an implication of the satisfaction of wireless users as providing the required bit rate is an objective of our approach. This can be observed in Figure 16, which illustrates the performance analysis in terms of the achieved satisfaction as a function of the number of the flows connected to the network. This figure shows that the proposed FF-based scheme provides better flow satisfaction than the Load aware-based and SINR-based solutions. From this figure we can observe that when all the 400 flows are connected to the network, our RAT selection scheme outperforms the Load aware-based strategy by around 16%, and the SINR-based solution by around 45%. This shows that our approach for RAT selection and the adopted FF metric reflect the satisfaction of the flows much better than the other approaches that rely on other metrics.

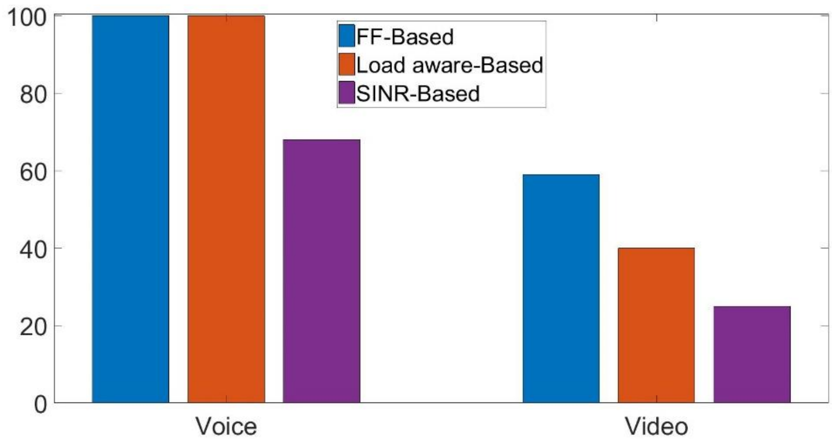


Figure 17: Percentage of flows with at least *Good MOS*

Although satisfying a wireless user's requirement is a main target of our solution, it is also necessary that this satisfaction is translated into an acceptable QoE. Figure 17 shows the performance results in terms of the percentage of flows that reach at least a *Good MOS* for the three approaches. The left hand side of the figure illustrates the performance achieved in the case of Voice, while the right hand side shows the performance obtained in the case of Video. The figure illustrates that in the case of Voice, our FF-based scheme and the Load aware-based one guarantee a *Good MOS* to all the flows connected to the network, both improving on the SINR-based solution, which guarantees a *Good MOS* to only approximately 68% of the flows. On the other hand, our RAT selection scheme outperforms the Load aware-based strategy by around 32%, and the SINR-based solution by around 58%, in terms of the percentage of flows requiring a connection for a video streaming and reaching at least a *Good MOS*.

In summary, from this performance analysis we can conclude that the proposed FF-based scheme gives the best fairness guaranteed by the suitability between the users' requirements in terms of the bit rate and the selected RAT. It also allows us to achieve the best performance in terms of satisfaction and *Good MOS* compared to the state of the art.

5 Integration of Smart AP Functionalities and Cooperative Functionalities

All the algorithms proposed in this deliverable have been evaluated via MATLAB-based simulations. In order to allow the correct deployment of the algorithms developed in the context of WP4 in a real-time environment, the set of smart AP functionalities developed on the Wi-5 APs and controller as defined in deliverables D3.1 [4], D3.2 [5], D3.3 [6] and D3.4 have been considered. Specifically, such functionalities have been exploited to validate and assess the channel assignment algorithm based on the interference impact, and the AP selection based on the Fittingness Factor (FF). The Wi-5 functionalities needed in the context of these algorithms and 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 power level sensed in each AP at the available channels in the considered frequency bands; (ii) the number of users/flows associated to each AP; (iii) the achievable physical bit rates, computed by the PQA functionality; and (iv) the RSSI detected in each AP from each connected STA. These monitoring mechanisms are crucial during the execution of the algorithms implemented in the Wi-5 controller.

Specifically, the monitoring of the power levels can support the algorithm implemented in the *Channel Assignment* process during the channel optimisation in two different cases: (i) during the initialisation of the Wi-Fi network, considering the interference impact 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 results of this algorithm are able to provide the Wi-5 agents with the channel allocated to each AP. The number of STAs associated to each AP, the achievable physical bit rates and the RSSI can support the *AP selection* process in the algorithm based on the FF executed when a new STA tries to join the network.

The role of the seamless handover functionality is to allow for horizontal handover between APs. This can be used for mobility management, i.e. when a user is walking and needs to be moved from one AP to another. In addition, it can also be useful when a static wireless user needs QoS requirements for a certain application but his/her current AP can no longer provide it. Moreover, the seamless handover functionality has been extended to enable the vertical handover, which allows us to 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 progress towards seamless handovers. Finally, we present the use of these functionalities during the execution of the algorithms developed in the cooperative framework here for their correct usage in real-time environments.

5.1 Monitoring Mechanisms

The solutions developed in the Wi-5 project have been integrated into an open-source implementation[5], built as a fork of the Odin framework [81]. As a result of Task 3.1 of the project, a series of parameters can now be gathered from the wireless network, and used as inputs for the algorithms implemented here. More detailed information about the gathering of these parameters can be found in deliverables D3.1 [4], D3.2 [5], D3.3 [6] and D3.4.

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

5.1.1 Monitored Parameters for RRM Algorithm

As we have detailed in Section 3, we defined a RRM algorithm that addresses interference in Wi-Fi networks through a combination of channel assignment and transmit power adjustment solutions. The transmit power adjustment provides the capability of setting the per-flow transmission power of the APs trying to satisfy QoS requirements of the flows, and maintain the level of interference in the network close to its optimal value defined through the channel assignment.

This solution has been initially designed and implemented in the MATLAB-based simulator detailed in deliverable D4.2 [2]. This initial design version exploits Transmit Power Control (TPC) request/report elements defined in the IEEE 802.11h standard, which allow a per-flow transmission power adjustment. However, these elements have only been implemented for 5 GHz frequencies. Therefore, since our focus in Wi-5 was to improve spectral efficiency in 2.4 GHz frequencies, the proposed per-flow power adjustment solution could only be assessed through simulations and its performance analysis could be found in deliverable D4.2 [2]. All the details on the design of the TPC included in the Wi-5 system, and its limitation in the Wi-5 APs can also be found in deliverables D3.2 [5] and D5.2. Hence, this section focuses on the use of the monitoring mechanisms during the execution of our channel assignment solution included in the RRM algorithm.

As we have explained in subsection 3.2.1, the main objective of the channel assignment algorithm is the optimisation of the interference impact that each AP causes to the other APs belonging to the Wi-5 network, and defined through equation (1). Specifically, the interference impact depends on the following parameters: (i) the location of the APs throughout the Wi-5 network; (ii) the transmission power of each AP; and (iii) the overlap between the RF channels that can be configured in the Wi-5 APs. The power level monitored in each AP at the available channels, introduced in the previous section, allows us to estimate the location of the Wi-5 APs, through the computation of the path losses among all of them programmed in the Wi-5 controller.

Figure 18 illustrates the process that allows us to compute these path losses. In detail, during a certain time interval, each Wi-5 AP sends beacons with a special Service Set IDentifier (SSID), named *odin_init* in the figure, which are heard by the rest of the Wi-5 APs. Each *odin_init* beacon is transmitted and received through an auxiliary wireless interface, which switches to the Industrial, Scientific and Medical (ISM) Channel 6 in all APs as illustrated in the figure. Then, each AP can calculate the average signal level with which they receive these beacons from other APs. Given N Wi-5 APs, the received average signal level, together with the transmission power of each Wi-5 AP available in the controller allows us to build a matrix where the element $x_{i,j}$ represents the path loss from AP i to AP j. For instance, given the received average signal level in dBm computed in AP j from AP i, i.e., Rx_j, and the transmission power in dBm of AP i, i.e., Tx_i, we can obtain $x_{i,j} = Tx_i - Rx_j$. The inclusion of the matrix with the path losses together with the transmission power of each Wi-5 AP, and the overlap between RF channels in the algorithm to optimise the interference impact will be explained in subsection 5.3.1.

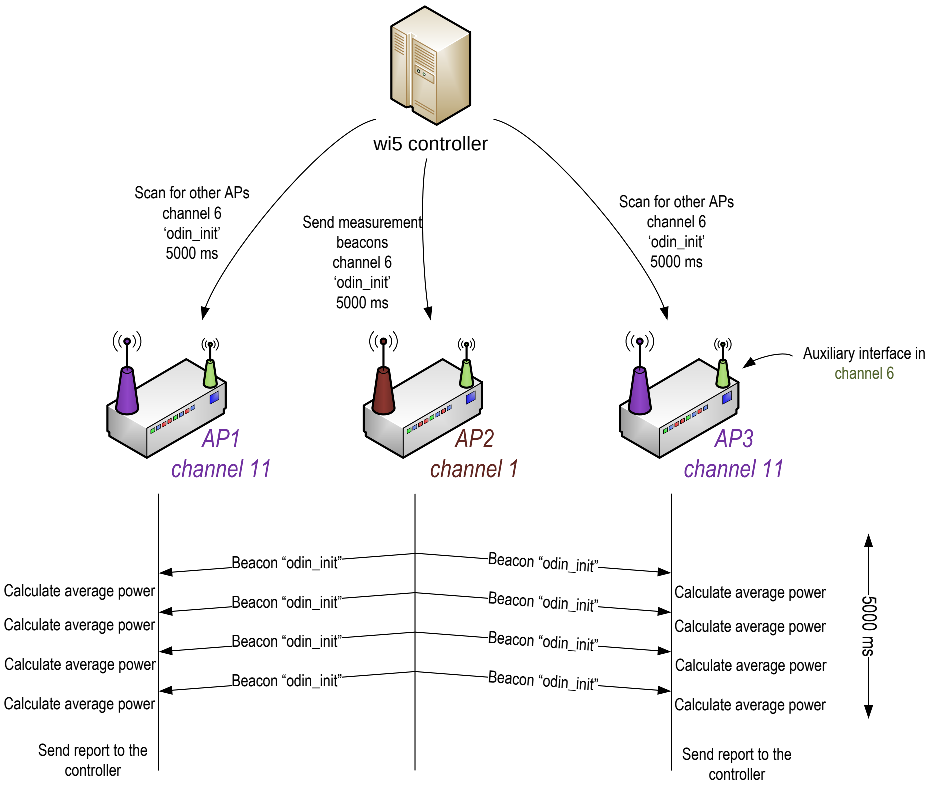


Figure 18: Process that allows to compute the path loss between Wi-5 APs

5.1.2 Monitored Parameters for AP Selection and Horizontal Handover

A key element of the AP Selection algorithms designed in the context of WP4 is the FF. Specifically, this parameter is used in the algorithms presented in D4.1 [1] and D4.2 [2], and based on the *Potential Game* proposed in this deliverable, respectively. In this subsection we will present all the information available in the Wi-5 controller that allows the computation of the maximum FF for a new STA in the available APs in real-time environments. As we have explained in subsection 3.2.2, the FF depends on the following parameters used in equations (4) and (5): (i) the link capacity available between an STA and a Wi-5 AP; (ii) the number of STAs connected to a certain Wi-5 AP; (iii) the maximum capacity in bps available in the Wi-5 APs; and (iv) the STA's QoS requirements in terms of the bit rate. Note that the monitored achievable physical bit rates and RSSIs in each AP from each connected STA, introduced in the previous section, allow us to define the link capacity available for an STA in any Wi-5 AP.

Focusing on the monitored parameters used for the computation of the FF, each of the Wi-5 APs is able to gather different statistics from the associated STAs. In detail, the Wi-5 agent running in each AP receives and sends frames to/from the associated STAs and stores different averaged statistics of each of the exchanged packets (e.g., average size, number of packets, average rate, average power, etc.). The Wi-5 controller can periodically send a query to request these statistics from the agent. Every time the statistics are sent to the controller, the agent resets them and starts gathering the information again. As an example, an application called `ShowStatistics.java` was built in the Wi-5 controller[6], which shows the results of these statistics gathered from the APs. We next show the output of this application, when

[6] See https://github.com/Wi5/odin-wi5-controller/blob/development/src/main/java/net/floodlightcontroller/odin/applications/ShowStatistics.java

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
```

From these statistics we can obtain the downlink physical bit rate available between the STA and the Wi-5 AP, i.e., the parameter called *avg rate* and equal to 12 Mbps in the example. Moreover, we can obtain the RSSI in AP `192.168.101.9` from STA `192.168.1.200`, i.e., the parameter called *avg signal* and equal to -34.47 dBm. Through these statistics, the number of active STAs in each Wi-5 AP can be detected and used for the computation of the FF. Note also that the maximum capacity of the Wi-5 AP is 54 Mbps in this case, as 802.11g is being used. Finally, the STA's QoS requirements in terms of bit rate is available in the Wi-5 controller as we have described previously.

The use of the abovementioned parameters for the computation of the FF included in our AP selection algorithm, together with a further explanation of the STA's bit rate requirements available in the Wi-5 controller, will be explained in subsection 5.3.2.

5.2 Seamless Handover Capability

The crucial radio configuration functionality developed in the context of WP3 is the seamless handover. In fact, one of the most important features of our solution is the possibility of seamlessly handing STAs between different APs, even if they operate in different channels. For that aim, the concept of the Lightweight Virtual AP (LVAP) is used. Specifically, the LVAP is an abstraction associated to each STA, which is moved by the Wi-5 controller between Wi-5 APs and includes: (i) SSID of the STA; (ii) STA IP address; (iii) STA MAC address; and (iv) the virtual MAC address used by the AP to communicate with the STA.

A detailed study of the seamless handover between Wi-5 APs, which is a smart functionality, was presented in Deliverable D3.3 [4] and published in [69]. It includes the novelty of considering a multi-channel handoff scheme, requiring an efficient synchronisation in order to make the LVAP switch occur at the same moment when the STA switches its channel. In addition, the beacon generation process has been modified in order to improve the scalability and provide a better user experience. Tests using three different wireless cards from different manufacturers were carried out, and the results showed that fast handovers, ranging from 30 to 200 ms, could be achieved. All the latest progress on the seamless handover functionality is presented in Deliverable D3.4 [5].

In the Wi-5 project we have also studied real-time vertical handover from a Wi-Fi network to a wireless network that operates on a different RAT, which could be useful in certain spectrum congestion scenarios. In such scenarios, for instance, a cellular network could provide the wireless user with better connectivity than the Wi-Fi network where the user is initially connected to. The vertical handover solution proposed in Wi-5 provides a seamless handover of the user terminal to another network without significantly affecting the quality of the connection. Realising this solution, however, requires cooperation between the Wi-Fi network and the receiving network.

In this deliverable we have illustrated and assessed through simulations a RAT selection algorithm that allows Wi-5 to handle vertical handovers where wireless users could be moved from a WLAN to a 4G network and vice-versa. The performance analysis of our solution illustrates the benefits from a centralised optimisation possible only through the cooperation between the two networks.

However, the Wi-5 project scope is limited to the Wi-Fi networking technology, and as such we have limited the design of the Wi-5 architecture and its implementation through a real-time testbed to the hand off part of the Wi-Fi network. In the deliverable D5.2, we present an experiment that demonstrates the feasibility of removing a user in the Wi-5 network based on the output of a decision-making module and the performance improvement of the Wi-Fi network.

The obtained results indicate that such a vertical approach is possible and therefore, if implemented, the cooperation between Wi-Fi networks and 4G networks could yield very promising gains in terms of spectral efficiency.

5.3 Deployment of Wi-5 Smart AP Functionalities in the Cooperative Framework

5.3.1 RRM Algorithm

The channel assignment optimisation designed in the context of WP4 is to minimize the *interference impacts* for *N* APs and *F* available channels. Therefore, the interference impact is first computed for each Wi-5 AP and then optimised through our channel assignment algorithm explained and assessed in detail in D4.1 [1] and D4.2 [2]. Specifically, the optimisation problem is defined as follows:

$$A^* = \min_{A} \sum_{i \le N} \sum_{f \le F} G \times A^T . I \tag{12}$$

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

$$g_{ij} = \begin{cases} 1, & \text{average power strength of } AP_i \text{ around } AP_j \\ & \text{exceeds a given threshold} \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

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

$$a_{ij} = \begin{cases} 1, & \text{if channel } i \text{ is assigned to } AP_j \\ 0, & \text{otherwise} \end{cases} \tag{14}$$

$I \in \mathbb{R}^{N\times F}$ in (12) is the matrix of the *interference impacts* where each element $I_{i,f}$ is defined through equation (1) detailed in subsection 3.2.1. The optimisation problem is first executed during the initialisation of the Wi-5 network, considering the interference impact between the APs caused by the default transmit power. Therefore, each element $I_{i,f}$ expressed by (1) and included in matrix I is computed considering the following conditions:

- The Wi-5 controller requests from Wi-5 AP *i* its transmission power level;
- The average power strength from Wi-5 AP *i* to all the other Wi-5 AP *k* with $k = 1, \ldots, N$ and $k \neq i$ is computed through the abovementioned transmission power and the path loss $x_{i,k}$ introduced in subsection 5.1.1.
- The overlaps between the RF channels that can be configured in the Wi-5 APs varies from 0 to 1 and their values are based on [2], [17] and [78].

After the computation of matrix *I*, our Channel Assignment algorithm is executed by providing the optimised interference impact through (12). Then, the value of the optimised interference impact is stored in the Wi-5 controller and can be monitored periodically. When one or more APs cause a change of the status in the network, e.g., a channel is changed in one of the Wi-5 APs if the optimised interference impact suffers a significant decrease, the channel assignment is triggered again in the Wi-5 controller in order to assign the optimised channel configuration to the APs. Details on the monitoring of the interference impact and its effect in possible reassignment of the channels to Wi-5 APs are provided in deliverables D3.4 and D5.2.

Note also the possible effect of non-Wi-5 equipment in the environment, e.g., APs which are not managed by the Wi-5 controller, can be included in the optimisation problem defined through equation (12). The details on the computation of non-Wi-5 equipment effect have been addressed in deliverable D3.4.

5.3.2 Smart AP Selection and Horizontal Handover

In this subsection we provide a detailed explanation of the computation of the maximum FF for a STA *i* trying to connect to the Wi-5 network. For each new STA we first need to compute the link capacity between the STA and all the available Wi-5 APs. STA *i* connects initially to the first heard AP *j*, and the Wi-5 controller achieves the link capacity in AP *j*, which corresponds to the monitored physical bit rate *avg rate* illustrated in subsection 5.2.1. While for all the other APs *k*, with $k = 1, \ldots, N$ and $k \neq j$, the Wi-5 controller is able to estimate the link capacity. Specifically, this estimation is executed through the following steps:

- **Step 1**: The RSSI in STA *i* from AP *k*, named here $RSSI_{i,k}$, is computed based on the *avg signal* illustrated in subsection 5.2.1 and called $avg\_signal_{i,k}$ through the following formula [82]:

$$RSSI_{i,k} = avg\_signal_{i,k} + 10log\left(\frac{P_T^{AP,k}}{P_T^{STA,i}}\right) \tag{15}$$

  where $P_T^{AP,k}$ and $P_T^{STA,i}$ are the transmission power of AP *k* and STA *i*, respectively.
- **Step 2**: The SNR in STA *i* from AP *k* is computed including the background noise.

- **Step 3**: the link capacity of AP *k* is estimated by mapping the obtained SNR to the OFDM data rate illustrated in Table 6[7].

Table 6 – Mapping between SNR and available data rate

SNR (dB)	<4	4-5	5-7	7-9	9-12	12-16	16-20	20-21	≥21
Link capacity (Mbps)	0	6	9	12	18	24	36	48	54

Afterwards, the link capacity available for STA *i* in each AP, the number of all the STAs connected to each AP, and the maximum capacity of the APs are used to compute the available bit rate for STA *i* following the radio resource allocation algorithm presented in [83] and used to compute the FF through equation (5). As we have illustrated in equation (5), a further input for the computation of the FF is the bit rate required by the STA. The computation of this parameter is out of the scope of this project; however, using a traffic detection software, such as NetFlow, a mapping between the kind of application and the suitable bit rate requirements can be easily addressed. For instance, in [84] the authors illustrate typical bit rate requirements for Skype calls.

After the computation of the FFs available for STA *i* in each Wi-5 AP, our AP selection algorithm is executed to connect the STA to the AP providing the maximum FF. Note that the selected AP providing the maximum FF to the STA does not necessarily correspond to the first heard AP. Therefore, the seamless handover functionality developed in the context of WP3 allows us to efficiently move a STA from the first heard AP to another one guaranteeing the maximum FF when needed. Note that this procedure needs to be repeated each time the STA changes to another application with different QoS requirements, or the bandwidth offered by the AP diminishes due other STAs connecting to it. An experiment that illustrates the connection of a STA to the AP providing the maximum FF is presented in deliverable D5.2.

[7] ttps://www.cisco.com/c/en/us/td/docs/wireless/technology/mesh/7-3/design/guide/Mesh/Mesh_chapter_011.pdf (last access March 2018).

6 Conclusions and Future Work

This deliverable has presented the final 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, which is presented in deliverables D2.4 and D2.5. After that, the final version of the cooperative framework, which includes innovative functionalities for RRM solutions, an AP allocation strategy and 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 so-called interference impact, 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 a centralised potential game that optimisoptimises a utility function 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. Furthermore, this AP selection algorithm has been extended towards a vertical handover functionality, including 4G networks.

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 AP selection algorithm have demonstrated that the solution based on the potential game obtains significant improvements in terms of the distribution of the data rate among the users, their satisfaction and Quality of Experience (QoE) compared against the previous version of our AP selection algorithm and the strategy proposed by the IEEE 802.11 standards. Moreover, we have investigated through simulation the impact of our AP association algorithms in large scale WLANs through the study of a shopping mall use-case. In order to highlight the efficiency of the proposed solutions, a comparison has been performed against the AP selection strategy suggested by the IEEE 802.11 standards, demonstrating that our AP selection solutions yield better performance. Moreover, we have shown that the strategy based on the *Potential Game* outperforms the solution based on the *Network Fittingness Factor* at the cost of increased complexity. Then, the proposed algorithm for vertical handover has been evaluated via simulation to enable its comparison against a scheme based on the 3GPP and IEEE 802.11 standards, and another solution considered in the literature based on the best throughput estimation. The evaluation results have demonstrated that our solution achieves significant improvements over both schemes in terms of the distribution of the data rate among the users, user satisfaction, and QoE.

Moreover, the set of smart AP functionalities implemented on the Wi-5 APs and the Wi-5 controller and their use in the proposed algorithms have been illustrated. Specifically, we have provided a detailed explanation of these functionalities and how they can enable the correct deployment of the channel assignment and AP selection functionalities in realistic scenarios.

For the future work, the research conducted in WP4 and presented in this deliverable suggests some possible directions to further exploit the developed AP cooperative functionalities by including new technologies into the Wi-5 system. Specifically, as a part of the future work, a full cooperation between Wi-5 APs and 4G nodes, such as Macrocell LTE base stations (eNodeBs), managed through the Wi-5 controller will be investigated. This cooperation will allow us to implement in real-time the RAT algorithm proposed for vertical handover in this deliverable to provide potential benefits for both Wi-Fi networks and other networks such as LTE.

In addition, the study of the inclusion of APs compliant with the newest 802.11 standards, such as h/n/ac working on the 5 GHz bandwidth, could be considered for the Wi-5 system. The inclusion of such technologies would allow us to exploit in real-time the potentiality of our per-flow TPC solution included in the RRM algorithm proposed in this deliverable.

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