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Abstract

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

The present document includes the specification of the first version of the Cooperative AP Functionalities, which are being defined within Work Package (WP) 4 of the Wi-5 project. In this deliverable after the Executive Summary and the literature review, the first version of the Cooperative Access Point Solutions are illustrated. In particular, a section with a general cooperative framework that jointly includes functionalities for an optimized AP channel assignment, Radio Resource Management (RRM) and smart AP allocation is presented. The optimized APs channel assignment enables an important improvement of the network performance in terms of SINR. Furthermore, the results analysed in this deliverable validate the flexibility and practicality of the proposed algorithm in different scenarios. The smart AP allocation solution introduces the innovative Fittingness Factor (FF) concept that efficiently matches the suitability of the available spectrum resource to the application requirements. Moreover, the basis required for a seamless mobility functionality in the framework is also included in the section. Next, a first assessment of the algorithms proposed in this deliverable is presented through the analysis of several performance results in a simulated environment. In detail, the AP channel assignment and the smart AP allocation algorithms are assessed and compared against other strategies found in the literature. Finally, a set of monitoring procedures to be conducted on the Wi-5 APs and on the Wi-5 controller are presented. These procedures will allow the correct deployment of the cooperative APs functionalities proposed in this deliverable. After summarising the main conclusions, the document ends with future work.

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Executive Summary

This deliverable describes the specification of the first version of the Cooperative Access Point (AP) Functionalities, which are being defined within 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, which aim to address the following challenges:

- To find an optimal radio configuration that minimises the level of interference and considers the QoS requirements of the applications running on the end-user's device.
- To guarantee the connectivity of the wireless device while the user is moving, hiding to him/her the authentication process.
- To allow the APs to find and select the most suitable AP that satisfies the QoS level required by the user.

These functionalities have been developed to be included in the Wi-5 architecture whose first version is presented in Deliverable D2.4. Hence, in order to address the challenges mentioned above in the Wi-5 architecture, the first version of a cooperative framework has been designed and presented in this deliverable. This framework implements a set of algorithms that cooperate to efficiently exploit the use of the radio resource, reducing interference between neighbouring APs and providing optimised connectivity for each user served by an AP. The algorithms have then been assessed in a simulated scenario demonstrating their efficiency through the analysis of different performance metrics.

Moreover, a set of monitoring procedures conducted on the Wi-5 APs and on the Wi-5 architecture defined within WP3 and detailed in Deliverable D3.2, have been also introduced in this document. These procedures will allow the correct deployment of the algorithms to be implemented in the cooperative framework in a real-time environment.

Hence, this deliverable provides a comprehensive description of an innovative cooperative framework that jointly addresses the following centralized capabilities:

- Optimized channel assignment based on an innovative utilisation function that reduces the magnitude of the interference affecting the whole system.
- The use of an interference-based utilisation function as a global quality indicator in the network alongside the per-user's experienced SINR to control the AP association procedure and APs' parameter adjustment such as transmission power control.
- A smart AP allocation solution based on a novel algorithm, which relies on the Fittingness Factor (FF) concept, whose target is to maximize a function that reflects the suitability of the available spectrum resource to the application requirements.

Furthermore, the aim of this framework is to guarantee satisfactory performance in terms of interference and QoS to both an individual user and the overall Wi-Fi network. A first comparison against other state-of-the-art solutions has been also presented in the deliverable that assessed the effectiveness of some of the functionalities implemented in the framework.

1 Introduction

1.1 Wi-5 background

The last few years have witnessed a significant increase in the use of portable devices, especially smartphones and tablets thanks to their functionality, user-friendly interface, and affordable price. Most of these devices use Wi-Fi Access Points (AP) where possible, in addition to 3G/4G, to connect to the Internet due to its speed, maturity and efficiency.

Given this demand, Wi-Fi is facing mounting issues of spectrum efficiency due to its utilisation of non-licensed frequency bands, so improvements continue to be added to standards in order to improve performance and adapt it to new demands. For example, as Wi-Fi saturation increases in areas, such as business centres, malls, campuses or even whole European cities, interference between these competing APs can begin to negatively impact users' experience. At the same time, real-time interactive services have grown in popularity and are now used across a range of mobile devices. These share the same connection with "traditional" applications, such as e-mail and Web browsing, but are far more bandwidth intensive and require consistent network capacity to meet user Quality of Experience demands.

In this context, the Wi-5 Project (What to do With the Wi-Fi Wild West) proposes an architecture based on an integrated and coordinated set of smart solutions able to efficiently reduce interference between neighbouring APs and provide optimised connectivity for new and emerging services. Cooperating mechanisms 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 hand-over to improve user experience with real-time interactive services.
- Develop new business models to optimise available Wi-Fi spectrum in urban areas, public spaces, and offices.
- Integrate novel smart functionalities into APs to address radio spectrum congestion and current usage inefficiency, thus increasing global throughput and achieving energy savings.

1.2 Scope of the deliverable

This deliverable presents the first version of the cooperative Access Points (APs) functionalities that cover cooperative Radio Resource Management (RRM) solutions, wireless hand-over, and smart wireless in the so-called "Wi-Fi jungle". These functionalities aim at operating in scenarios where a large number of uncoordinated APs run simultaneously in both indoor public areas, such as in a shopping mall, large apartment building or an airport, and outdoor areas such as Pico-cell street deployment, ensuring more efficient frequency reuse for the communication between APs and terminals. In urban scenarios, co-channel interference between neighbouring Wi-Fi APs with an Internet connection from different service providers may occur. The Wi-5 architecture will present an over-the-top implementation to interact with neighbouring APs to find the best overall configuration, thus minimising interference in a heterogeneous environment. This solution can also take into account legacy Wi-Fi APs as they are already operable with operators' remote management systems, including their channel allocation. Recent works on cooperative communications have shown that considerable network capacity and spectrum efficiency enhancements can be achieved through cooperative mechanisms such as network coding, relaying and forwarding, etc. [1]. Furthermore, past and ongoing

FP7 projects such as CODIV [2], iJOIN [3] and METIS [4] address the challenge of improving cellular network performance by using cooperation mechanisms.

1.3 Document structure

This deliverable describes the first version of the specification for cooperative AP functionalities proposed in Wi-5. In detail, in section 2 we describe the state-of-the-art found in the literature related to the functionalities proposed in this deliverable. In section 3 we discuss the cooperative functionalities framework, providing a set of algorithms for RRM in Wi-Fi jungle scenarios and Smart Connectivity. Section 4 presents a first assessment of the algorithms proposed in this deliverable through the analysis of several performance results in a simulated environment. While section 5 illustrates the set of monitoring procedures to be conducted on the Wi-5 APs and on the Wi-5 controller that will allow the correct deployment of the algorithms proposed in this deliverable. Finally, conclusions and future work are presented in section 6.

1.4 Relationship with other deliverables

The material in this document relates to the following deliverables.

D2.3: All the solutions developed in this deliverable conform to the functionalities and the performance requirements defined in deliverable D2.3.

D2.4: This deliverable describes the algorithms that will support the cooperative APs functionalities proposed in Wi-5 and implemented in the first version of the functional architecture described in deliverable D2.4.

D3.2: This deliverable will rely on the radio configuration functionalities and on a set of monitoring procedures developed in deliverable D3.2 for a proper deployment of the proposed algorithms.

1.5 Glossary

3GPP	3rd Generation Partnership Project
AP	Access Point
ACT	Assistance of Clustering Techniques
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CRN	Cognitive Radio Network
DPI	Deep Packet Inspection
DQCA	Distributed Queuing with Collision Avoidance
ET	Enemy Territory
FF	Fittingness Factor

FPS	First Person Shooter
GSM	Global System for Mobile communications
IEEE	Institute of Electrical and Electronics Engineers
ILP	Integer Linear Programing
IS-95	Interim Standard 95
KPI	Key Performance Indicator
LCCS	Least Congested Channel Search
LTE	Long Term Evolution
LVAP	Light Vırtual Access Point
MAC	Media Access Control
ML	Machine Learning
MCS	Modulation/demodulation and Coding Scheme
NE	Nash Equilibrium
QoE	Quality of Experience
QoS	Quality of Service
RF	Radio Frequency
RRM	Radio Resource Management
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RTP	Real-time Transport Protocol
SDN	Software Defined Networking
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
STA	Wi-Fi Station
SSID	Service Set IDentifier
TPC	Transmit Power Control
WLAN	Wireless Local Area Network
WiMAX	Worldwide Interoperability for Microwave Access

WP	Work Package

2 Literature Review

The cooperative functionalities introduced in Wi-5 focus on the management of the wireless spectrum and related resources such as APs, wireless channels, etc. Radio Resource Management (RRM) is an essential element of these cooperative functionalities, especially when addressing issues related to congested spectrum environments.

RRM has been a relevant topic also in previous FP7 projects such as BeFEMTO [5], OneFIT [6], and ARTIST4G [7], where the focus was on improving the performance of managed cellular networks and opportunistic networks, which are defined as extended infrastructures, temporarily created to serve specific regions. Moreover, previous research works such as in the FP6 project E2R [8], the FP7 project E3 [9] and recently-concluded efforts such as the FP7 project SEMAFOUR [10] have also considered RRM techniques to achieve global network performance optimisation of wireless communication systems. This section reviews relevant state-of-the-art developments in terms of RRM solutions in wireless networks and explains the novel contributions and the progress that will be made in the Wi-5 project.

2.1 Radio Resource Management in Wi-Fi

Due to the limited number of orthogonal channels that the 802.11 standard supports, high levels of interference are expected, which in the end leads to a reduction in the network efficiency and therefore lower Quality of Service (QoS) and degraded Quality of Experience (QoE). In this context, in recent years several channel assignment schemes for infrastructure-based WLANs have been proposed and a comprehensive survey can be found in [11].

Most of these works propose centralised algorithms that assume there is a network that belongs to one administrative domain [12], [13]. However, in most situations this is not the case for WLANs, which continuously evolve, generating heterogeneous scenarios where multiple WLANs are deployed by different owners and Wi-Fi access providers. In this scenario, channel assignment algorithms, where the operating channels of the APs can be self-configured and their transmitted power level can be managed in order to minimise interference with adjacent APs, should be required. For instance, Least Congested Channel Search (LCCS) is a common feature provided by commercial APs [14] for channel auto-configuration. With LCCS each AP scans all available channels, listens to the beacons transmitted by neighbouring APs and chooses the channel used by the least number of associated devices as its operating channel.

Elsewhere, in [15] the authors introduce a channel assignment solution that exploits the gain of using partially overlapping channels relying on the Signal to Interference plus Noise Ratio (SINR) interference model, which considers the accumulative interference of the environment from the receiver point of view. They first analyse the relationship between network throughput and channel assignment by using partially overlapping channels in the SINR interference model. Then, they propose a heuristic algorithm in order to assign overlapping channels to the APs in the system such that the network throughput can be maximized. The above-mentioned studies exemplify the solutions with an overall network interference indicator set to be tracked and that guides the assignment of the channels. The channels are also assumed to have predefined characteristics. In some other approaches the channel characteristics are considered to be dynamic. They are set to be adjusted locally to gain a desired impact on the network as well as meeting their local service quality [16].

Although the channel assignment solutions are proposed specifically for WLAN and Wi-Fi networks, they are not necessarily suitable for all new emerging and diverse use cases considered in the context of the Wi-5 project. More recent studies tend to provide solutions explicitly tailored for specific use cases such as high density networks [17] and areas with uncoordinated interfering network elements [18], which are among the most challenging contemporary deployments of Wi-Fi.

In addition to channel selection, transmission power control algorithms are also critically important in any wireless system. These mechanisms are commonly applied in cellular systems (GSM, IS-95 CDMA, 3G-W-CDMA, LTE) in order to ameliorate the near-far problem and minimise the interference to/from other cells and therefore improve the wireless systems' performance. However, in the context of WLAN networks, devices typically transmit at their highest Radio Frequency (RF) output power. This generates high levels of interference on the same channel, increases the probability of packet collisions, and makes more neighbouring transmitters defer their frames, thus reducing the overall throughput of the network. Because of these drawbacks, in recent years adaptive transmit power control methods have been proposed for 802.11 trying to reduce interference and improve spatial reuse in order to increase network capacity.

For instance, in [19] an algorithm is presented based on the link-quality estimation scheme defined for Transmit Power Control (TPC) in IEEE 802.11h. The WLAN station estimates the path loss between itself and the transmitter, updates the data transmission status, and then selects the proper transmission rate and transmit power for the current data transmission that attempts using a simple table look-up. The lower the transmit power or the higher the PHY rate (hence, the shorter the transmission time), the less energy is consumed in one single transmission attempt. However, this also increases the likelihood the transmission will fail, thus causing re-transmissions and eventually consuming more energy.

The main goal of the power control management defined in [20] is the minimisation of the interference level when different APs and WLANs are working in the same area. The algorithm defines a controlled WLAN communication scheme. The APs on different WLANs are synchronised in order to avoid asymmetric links. At any instant of time, all APs in the network operate at the same power level to avoid link asymmetry. Over time, by using different power levels, the system achieves per-client power control to maximise spatial reuse. Each AP can transmit to each of its clients at the lowest power level that minimises the interference to other APs' communications, while not affecting the performance perceived by the client.

In [21] the authors consider a combination of power level control and rate adjustment for meeting the link quality requirements. Rate selection in WLANs is determined by an estimation of the channel conditions including packet loss, delivery ratio, throughput, or SINR estimation. Rate selection and transmit power control are tied together, since power control without considering the rate can reduce the SINR, leading to a reduction in the rate and hence the network throughput in the link. This solution considers the above problem and does not compromise the required rate. It takes into account the relationship between transmission rate and TPC, proposing an effective approach for dynamically controlling the transmission power. TPC also has an explicit impact on the scale of the interference between neighbouring APs with channel overlap or those which experience co-channel interference throughout the network. In [22] the authors propose a power control method which dynamically adjusts the 'per-user' transmission power aiming for adjacent and co-channel interference reduction. The proposed method is merely based on the link and client's status information available at the AP without the need for extra/out-of-band signalling between the client device and its corresponding AP.

2.2 Interworking between Wi-Fi and non-Wi-Fi technologies

The diversity of the available radio network technologies and the heterogeneity of the contemporary communication devices require support for interworking between these technologies as well as mobility management for multi-radio network interfaces and integrated solutions. Since the Wi-Fi/WLAN interface is a default capability in all communication devices, including the new emerging smartphones and laptops, numerous academic researches and industrial solutions have been dedicated to the study of Wi-Fi and non-Wi-Fi technologies' coexistence. These include the possibility of the interworking between Wi-Fi and non-Wi-Fi services, required mobility support and users scheduling processes. Wi-Fi-related interworking is also discussed under some other topics such as traffic offloading in mobile communication systems and multi-radio interfaces management.

Among the above mentioned topics, the interworking between mobile communication systems (e.g. 3GPP-3G and 4G) and Wi-Fi has specially become a characteristic capability of communication services in recent years [23]. Subsequently, Wi-Fi as an unlicensed-band network is an alternative to the short range cellular solutions, such as femto-cells, for cellular network traffic offloading [24]. However, the integration of a centrally controlled cellular network and a distributed, short range and decentralized Wi-Fi technology requires additional efforts to overcome the differences in making an efficient interworking process work [25]. IEEE 802.11, as the core standard of Wi-Fi technology, has also been updated with the possibility of interworking with non-Wi-Fi technologies and describes the requirements from a Wi-Fi point of view [26].

As an example of Wi-Fi and non-Wi-Fi interworking, some probable scenarios for a streaming service through a combined network of Wi-Fi APs and mobile network base stations (e.g. eNodeB in 4G-LTE) have been depicted in Figure 1. User1 in the range of AP1 can be served through its Wi-Fi air interface while it is directly supported by a dedicated broadband connection independent from the mobile network. For user2, the Wi-Fi interface can maintain connectivity of the user in the range of AP2.

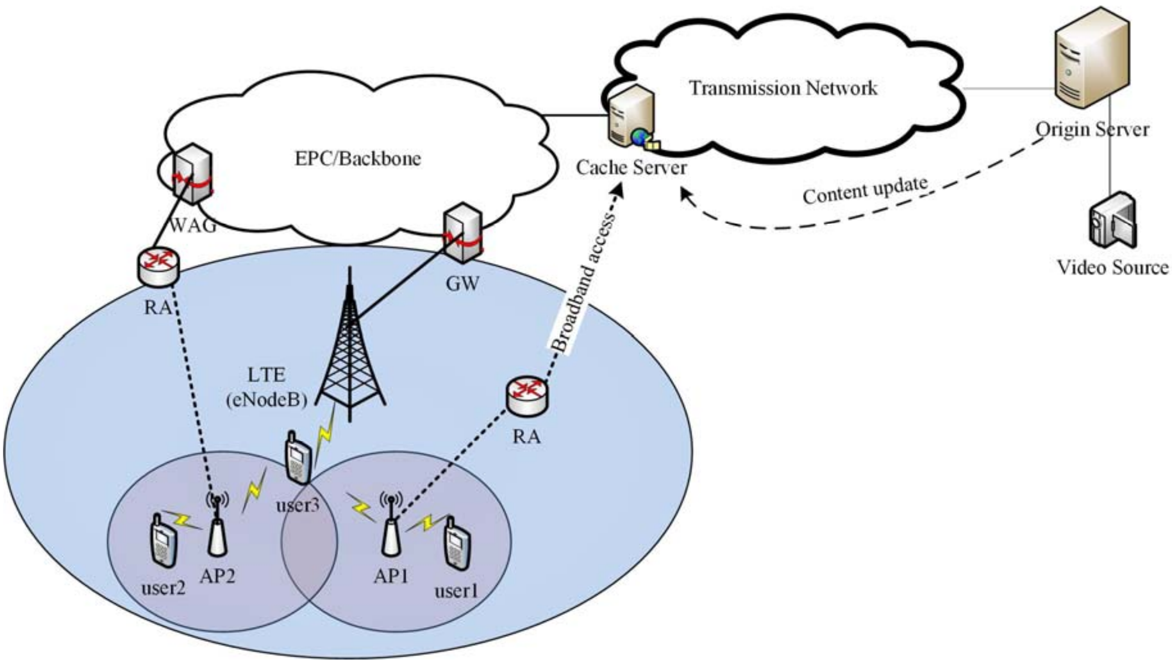


Figure 1: Example of streaming service scenarios through combined LTE-Wi-Fi air interfaces

However, AP2 shares signalling support through the backbone connection (e.g. for IP tunnelling) with the cellular network. User scheduling mechanisms can therefore be managed cooperatively in this case. User3 represents an edge position (from a Wi-Fi point of view) in which the user may be better served through the mobile cellular network. From the cellular network's point of view, user1 and user2 positions are opportunities for traffic offloading (i.e. from non-Wi-Fi to Wi-Fi). In contrast and from a Wi-Fi perspective, user3 position is an opportunity for vertical handover from Wi-Fi to a non-Wi-Fi interface.

It is also important to note that the appropriate management of the IP address is the main requirement for maintaining a smooth connection during the interworking process. This has been addressed under the title of 'IP-mobility' in IEEE and 3GPP standards [27]. The aim is to make the process transparent for the layers above the MAC layer so they do not need to adapt to the air interface changes. As shown in Figure 2, the IP-mobility and smooth transition between Wi-Fi and non-Wi-Fi interfaces can be handled in the user-side or the network-side of the connection. This depends on the chosen IP management approach [28]. This mechanism is less likely to be applied when the Wi-Fi AP is completely independent from the non-Wi-Fi network. However, a non-seamless switch between Wi-Fi and non-Wi-Fi air interfaces with a certain degree of quality provisioning is still possible in this case [29].

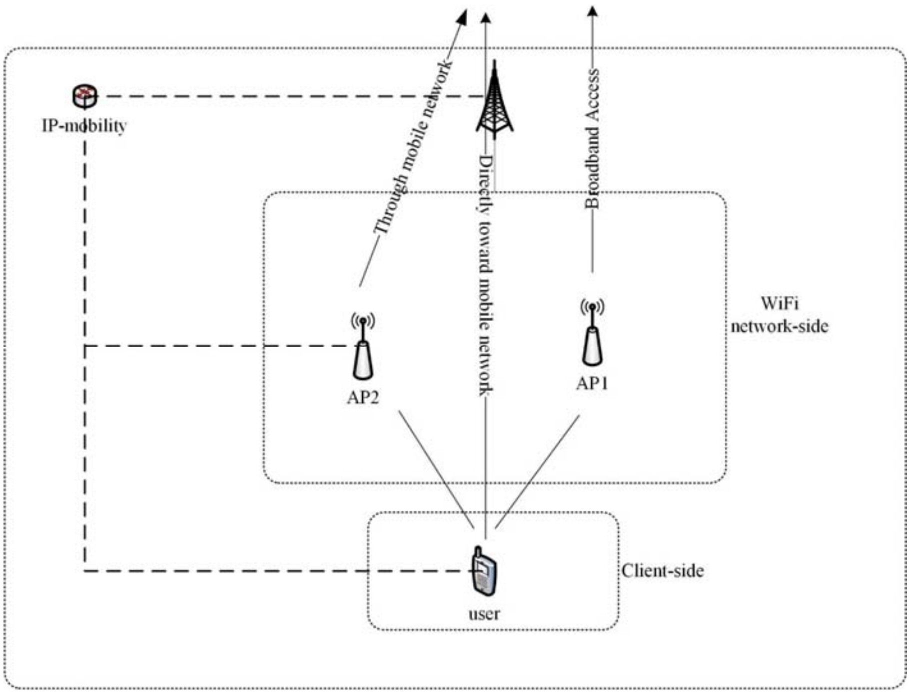


Figure 2: Interworking between Wi-Fi and non-Wi-Fi for smooth user transition

2.3 Quality-Aware Approaches and Smart Connectivity

In the context of the Wi-5 project, smart connectivity functionalities aim to assist wireless devices in the selection of the most suitable connection according to the application running on the device. In fact, the Wi-5 architecture is designed to provide the user with the opportunity to join a wireless network, not only according to the Received Signal Strength (RSS), under the assumption that APs with a stronger signal will offer better performance, but by also taking into consideration other application specific parameters and QoS metrics.

In the literature several AP selection strategies which aim to maximize the QoS of a particular user that tries to join a WLAN can be found. For instance, in the approach considered in [30] the authors propose an association metric called EVA (Estimated aVailable bAnd-width) that allows a user to be allocated to the AP that provides the maximum achievable throughput. Authors have showed that EVA-based association solutions increase the per-station throughput, balances the load of the APs, and consequently, enhances the aggregate network throughput. Other papers consider AP selection strategies relying on finding the best throughput under frameworks based on game theory. For instance, in the study proposed in [31] each user aims at maximizing its achievable throughput, which depends on the number of users that associate with the same AP and the data rates these users can achieve. The authors have proven the stability of this game (Nash Equilibrium, NE) and shown that the maximization of individual users' throughput improves the overall bandwidth fairness among the users.

In [32] an AP selection problem in Variable channel-width WLANs is investigated using an evolutionary game theoretical approach. In detail, the paper assumes that all the stations adopt the most efficient Modulation/demodulation and Coding Schemes (MCSs) to achieve their highest bandwidth efficiencies under the power constraints. The numerical results illustrated in the paper have validated the convergence and the effectiveness of the algorithm. Meanwhile, in [33] the author formulate the AP selection problem as a non-cooperative game where each user tries to maximize its utility function, defined as the throughput reward minus the fee charged by the AP. They have shown that the formulated game belongs to the class of congestion games and admits a pure NE.

In [34] the authors formulate the AP selection problem as a game where players are mobile wireless users and they choose radio APs to connect to the network. They define a new parameter called Access Point Selection Parameter (APSP) based on the SINR. Each selfish user chooses an AP which maximizes its APSP value that depends on both the distance to the AP and the total number of connected users in the AP. Authors have proven the NE in the model with and without users knowing each other's location. A SINR-based approach to maximize the QoS of the users is also considered in [35]. Here, the authors have proposed an SINR-based mechanism with QoS support for seamless handover and vertical handover for coexist heterogeneous WiMAX and Wi-Fi networks. The performance result of the proposed SINR-based algorithms have been evaluated in terms of the maximum downlink throughput.

On the other hand, in [36] the benefits that cross-layer solutions can provide in the association of users/flows with 802.11 APs are introduced. Moreover, the authors propose a metric based on the expected throughput that combines information from the physical and MAC layers to assist users/flows in their AP association decisions. In [37], a cross layer partner-based fast handoff mechanism, called PHMIPv6, is presented. PHMIPv6 exploits information obtained from the MAC and network layers in order to accurately predict for each user/flow which AP minimizes the handoff delay time and the packet loss rate. In [38] the authors have described handoff processes for Distributed Queuing with Collision Avoidance (DQCA) in a multi-cell environment considering different AP selection mechanisms. These mechanisms are based either on a single metric such as the Signal to Noise Ratio (SNR) or the traffic load, or on a cross-layer design by combining the information from different layers. Simulation results have shown that the best results in terms of throughput and delay are achieved by considering a cross-layer approach where both SNR and traffic load are used as inputs for the AP selection process.

2.4 Mobility and Hand-over

Mobility is a major characteristic of wireless user that might have an effect on the utilisation of the spectrum, the quality of the connection, and the capacity of the network. In Wi-5, we aim to provide a seamless mobility solution to minimise the effects of handover on the quality of the connection and the user's quality of experience while optimising utilisation of the spectrum.

Seamless mobility has been addressed in several publications in the past [39], [40] with the focus on improving the decision making when selecting the most suitable AP. Most of these contributions rely on the mobile terminal to trigger the handover process, and provide the performance metrics needed to assist the handover algorithm in choosing the most suitable AP during the handover. These performance metrics include: Received Signal Strength Indicator (RSSI), the network connection time, the available bandwidth, the power consumption and the transition cost. For instance, in RSS based algorithms [41], [42], [43], the decision to join a network is based on the RSS parameter whereas in bandwidth based algorithms [44], [45] the decision to join a network is based on the amount of available bandwidth which helps to achieve high throughput. Other contributions propose handover solutions that rely on functions that, in addition to RSS and available bandwidth, combine a number of other parameters such as: battery consumption, connection QoS, and latency [46], [47]. These solutions, however, have been designed with the assumption that the heterogeneous networks are under the same management entity. Moreover, the implementation complexity of these solutions makes them unsuitable for large infrastructure networks that consist of dozen to even hundreds of access points.

More recent contributions have tried to address the problem through distributed mobility management approaches based on mobile agents and virtualisation [48], [49], [50]. In [48], the authors propose to deploy an agent on the Wi-Fi APs and the mobile terminal to assist the vertical handover algorithm. The agent reports monitoring information such as signal strength, network security, available bandwidth, network load, QoS and user preferences, etc. The agent will also enable cooperation between APs and mobile terminal to select the appropriate AP as well as executing seamless mobility. Although, these distributed approaches provide a more robust vertical handover solution, they do not scale well, especially when implementing seamless mobility in highly dynamic Wi-Fi networks characterised by increasing network usage and high users' mobility. In [50], the authors propose to address mobility in large wireless networks through the concept of virtual APs. According to this concept, the complexity of the mobility management is implemented within the network infrastructure, where Virtual AP are created and associated with wireless stations. This provides a centralised yet efficient mobility management framework that optimise the network resources.

The Software Defined Networking (SDN)-based architecture proposed in Wi-5, and presented in details in D2.4, offers a flexible platform to implement a scalable seamless mobility solution that can operate across different networks in a similar manner to the approach proposed in [50]. The only difference is that, by the using the SDN approach, Wi-5 will be able to create, move and manipulate virtual SSIDs instead of Virtual APs, which will result in lower overheads and near-real time performance.

3 Cooperative Access Point Solutions

One of Wi-5's most significant features is the cooperative approach it takes to address the lack of flexibility in wireless networks. Wi-5 introduces a number of functionalities into Wi-Fi networks, which are inherently cooperative in nature. These functionalities aim to address the following challenges:

- **Radio Interference in 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. Whereas the interference can be acceptable for certain applications, other applications, with strict QoS requirements, will not be able to work properly. Wi-5 will address this issue by enabling cooperation between APs to find an optimal radio configuration that minimises the level of interference and considers the QoS requirements of the applications running at the end-user's device.

- **Seamless Handover**: The wireless network flexibility addressed in Wi-5 covers the management of the wireless spectrum as well as the management of the end-user mobility. Wi-5 promotes the nomadic use of the wireless spectrum by tackling the problem of seamless mobility. Currently, seamless users' mobility is restricted to Wi-Fi networks to which the device can authenticate seamlessly. A seamless handover approach is introduced by Wi-5 whereby APs cooperate to guarantee the connectivity of the wireless device while the user is moving, and the authentication process is hidden from the user.

- **Smart Connectivity**: In Wi-5, Wi-Fi APs will assist the user to find the wireless network that offers the best QoS required by his/her application. This Smart Connectivity functionality will be built on cooperation between APs to find and select the most suitable AP that satisfies the QoS level required by the user.

3.1 Cooperative Functionalities in the Wi-5 Architecture

The aim of this subsection is to address the cooperative functionalities in the Wi-5 architecture, while its overall and detailed presentation has been included in Deliverable D2.4. The initial design of the Wi-5 architecture relies on the separation of control and data planes in the Wi-Fi APs. This approach has been considered in order to have a single point where all the control operations can be integrated. The most important entity of the architecture is the Wi-5 controller, which has a global view of the network under its control, and is capable of running different algorithms for optimising the network traffic. Therefore, all the functionalities included in WP3 and WP4 can run as applications on top of the controller as depicted in Figure 3. Moreover, the cooperative functionalities developed in WP4 will use the smart functionalities developed in WP3 in order to manage the radio resources at the APs. These functionalities will be implemented through the northbound API of the Wi-5 controller, as presented in D2.4. The configuration issued by the different cooperative functionalities will be sent to the APs through the Wi-5 controller southbound API, as illustrated in Figure 3.

The use of the Spectrum Usage Broker to provide inter-operator cooperation (see Deliverable D2.4) is not discussed in the context of the functionalities presented at this stage. This feature is not finalized in the initial Wi-5 architecture as the details of its business role and operation are still being refined within WP2, with the cooperation of the Wi-5 Operator Board. Once this is complete, the Spectrum Usage Broker and its interoperation with Interference Management, Smart Connectivity, Seamless Handover, and the other Wi-5 functionalities will be described in detail.

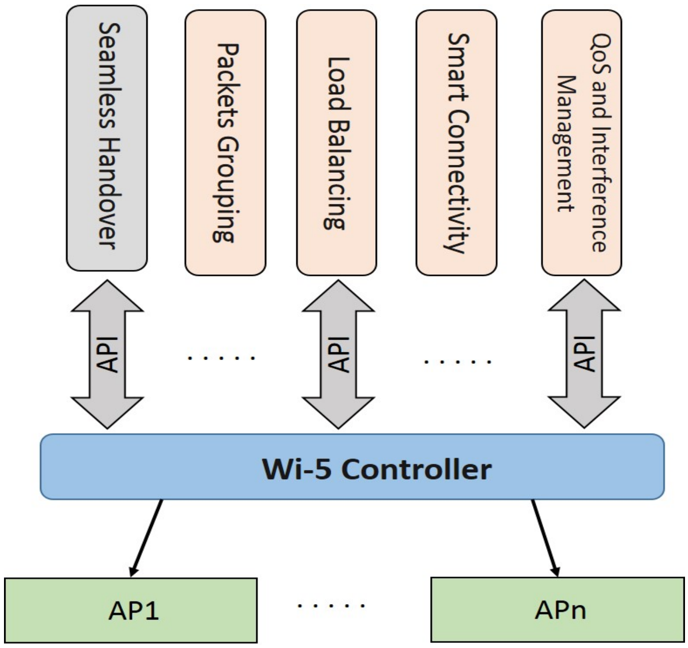


Figure 3: Scheme of the Wi-5 architecture design including the Cooperative Functionalities

3.2 Cooperative Functionalities Framework

This section describes a framework, which has been designed to be implemented in the Wi-5 controller in order to provide the first version of the Wi-5 cooperative APs algorithms. In detail, this framework has been designed 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. Moreover, the proposed framework will exploit the radio configuration functionalities presented in D3.2 dealing with dynamic AP channel selection and transmit power control, in order to extend the assessment of the framework in real-time environments. The framework presented in this section and illustrated in Figure 4, implements a set of algorithms that cooperate to achieve the following objectives:

- Defining an optimized channel assignment algorithm, which will reduce the radio interference throughout the Wi-Fi network.
- Defining a smart AP allocation algorithm that will assist users/flows in selecting the most suitable AP according to the application running on the station in terms of QoS requirements. Moreover, the allocation of the APs will aim to provide satisfactory performance for both an individual user/flow and the overall Wi-Fi network.
- Defining a transmit power control mechanism which will assist the channel assignment algorithm to achieve the user’s required quality, maintaining an acceptable level of interference in the network and providing a tool for energy saving.

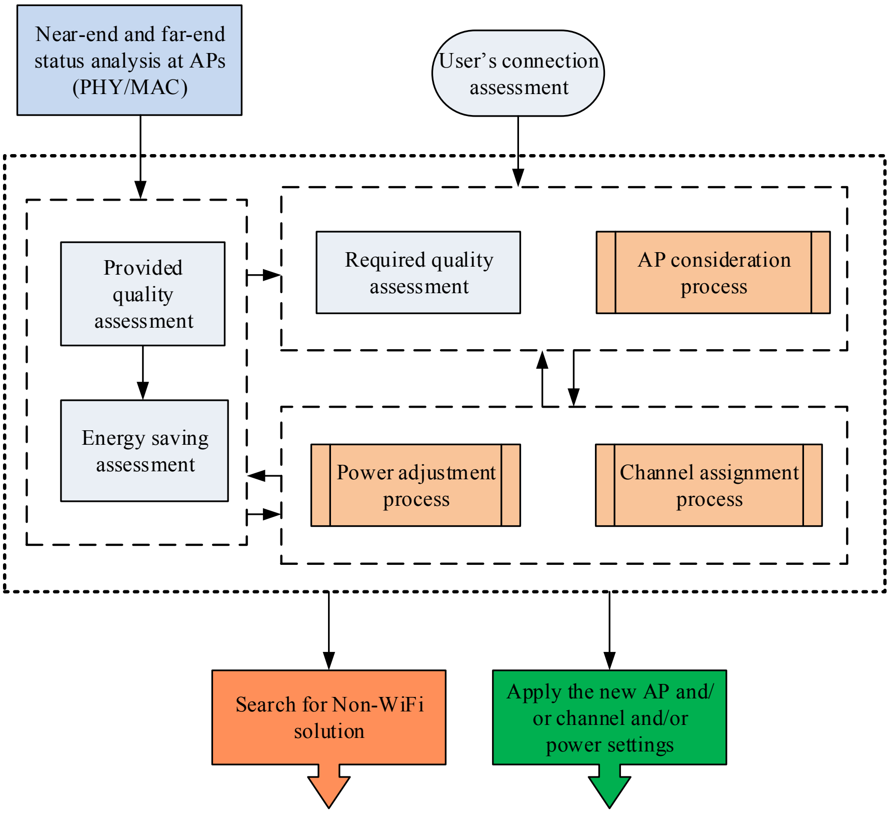


Figure 4: Cooperative Functionalities Framework

The *Channel assignment process* in Figure 4 allows Wi-5 controller to select the channels for the different APs in a network based on the Wi-Fi system properties (e.g. IEEE 802.11's standard channel characteristics), the actual network topology (the AP distribution throughout the network), and the desired resource management criteria (the assigned channels, interference related QoS, or handover requirements). The configuration adjustments per user/flow or group of users/flows will be processed and applied in the network of APs coordinated by a central controller.

The *Power adjustment process* provides the capability of setting the transmission power on the lowest possible level that maintains the quality demanded by the user as well as the overall energy savings constraint.

The *AP consideration process* implements a smart connectivity algorithm based on the Fittingness Factor (FF) in charge of smartly associating an AP to each new user/flow taking into consideration the bit rate requirements.

The *Provided quality assessment* functionality will exploit the monitoring tools detailed in D3.2 to detect the interference levels and compute the achievable QoS requirements for the stations in each AP. This functionality will support the *Channel assignment process* and the *AP consideration process* as explained in the next subsections.

The *Required quality assessment* functionality will use the monitoring tools presented in D3.2 to compute the required QoS by a station. This functionality will support the *AP consideration process* during the smart connectivity algorithm based on the FF executed for a smart AP association.

The *Channel assignment process* and the *Power adjustment process* implement the RRM algorithm illustrated in section 0 and will be able to trigger a possible reconfiguration of certain AP's working parameters, such as the transmit power or the modulation and coding scheme, making use of *Dynamic Channel Allocation* and *Transmit Power Control* functionalities illustrated in D3.2.

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

3.2.1 Channel assignment approach and optimisation model

For its optimisation process, the channel assignment approach proposed in this project exploits the following principles:

- The topology of the network and the arrangement of the APs will be represented in a matrix (based on the graph interpretation of the network) with the interfering APs represented by the conflicting edges.
- Distribution of the utilised channels throughout the network represented by an assignment table.
- The interference status around APs for the whole available spectrum of Wi-Fi. The characteristics of the channels in IEEE 802.11 and their overlaps will be taken into account.

The above mentioned principles will be combined in this subsection to define a utilisation function which represents the magnitude of the interference in the whole system and provides a base for the optimisation algorithm of the proposed channel assignment approach.

The overall interference in the system actually encompasses the APs' conflict in each specific channel and reflects the APs' inter-relation from an overlapping coverage point of view. Let us define $I_i^{F\times 1}$ as the a-priori unit of interference expected around access point i using each of the F available channels for that AP. Furthermore, let us describe U_i as a function which represents the interference conflict throughout the network (around all APs) due to the assigned channel in AP i. These two parameters (i.e., U_i and I_i) are related through a weighting factor W, which scales the conflict related to each channel taking into account all other APs which may utilize that channel simultaneously. W can be defined using the network arrangement descriptor G, and the channel assignment A, for N access points and F available channels as follows:

$$U_i = WI_i\,, W = GA^T \;\rightarrow U_i = GA^T I_i \;\rightarrow U = diag(GA^T I) \qquad (1)$$

Where $G^{N\times N}$, $A^{F\times N}$ and $I^{F\times N}$ are respectively the representatives of the network topology, channel assignment and the a-priori interference (per channel per AP). U represents the total interference conflict throughout the network due to the assigned channels in all APs. '*diag*' describes the diagonal values in (1). 'G' is a binary matrix defined as:

$$G \in \{0,1\}^{N\times N} \rightarrow$$

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

'A' is also defined as a binary matrix which describes the channels which are assigned to the APs:

$$A \in \{0,1\}^{F\times N} \rightarrow$$

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

Since I is a matrix with real values ($I \in \mathbb{R}^{F \times N}$), U in (1) will also be a real value ($U \in \mathbb{R}$). Given the utilisation function in (1), we can see that:

$$U \equiv \underbrace{\overbrace{\underbrace{G}_{\substack{\text{represents the APs' interrelations} \\ (\text{with or without interference conflict})}} \quad A^T}^{\substack{\text{encapsulates the scale by which APs} \\ \text{conflict in each specific channel}}} \quad I}_{\substack{\text{represents the magnitude of the interference} \\ \text{which the whole system is facing}}} \quad (4)$$

So, for a given network topology (i.e., G) and an a-priori interference status (i.e., I) we may find an optimal assignment of channels (i.e., A^*) to reduce the magnitude of the interference which the whole system is facing, i.e.:

$$\forall i \in \{1, .., N\}; \quad A_i^* = \min_{A_i} \|U_i\|_1 \quad (5)$$

$\|.\|_1$ represents the 1-norm or the summation of the elements of $U_i \in \mathbb{R}_+^F$ (values are in real power not in dB). More accurately the optimisation system for all the network can be expressed as:

$$\begin{cases} A^* = \min\limits_{A} \ \|diag(GA^T I)\|_1 \\ \quad A \in \{0,1\}^{F \times N} \\ \quad \left\|A(:,i)\right\|_1 = 1 \\ \forall\, a_{ij} \in A: \ \sum\sum a_{ij} = N \end{cases} \quad (6)$$

The values which are reflected in I for each channel in each AP are actually a prediction of the conflict due to using that channel for that AP given the current state of the network. This approach needs a central controller as well as access to the observed status of the network.

By elementwise expansion of matrices in (6) and redefining all elements of A in an unknown vector x, a binary Integer Linear Programing (ILP) interpretation of (6) leads to the desired solution and can be expressed as:

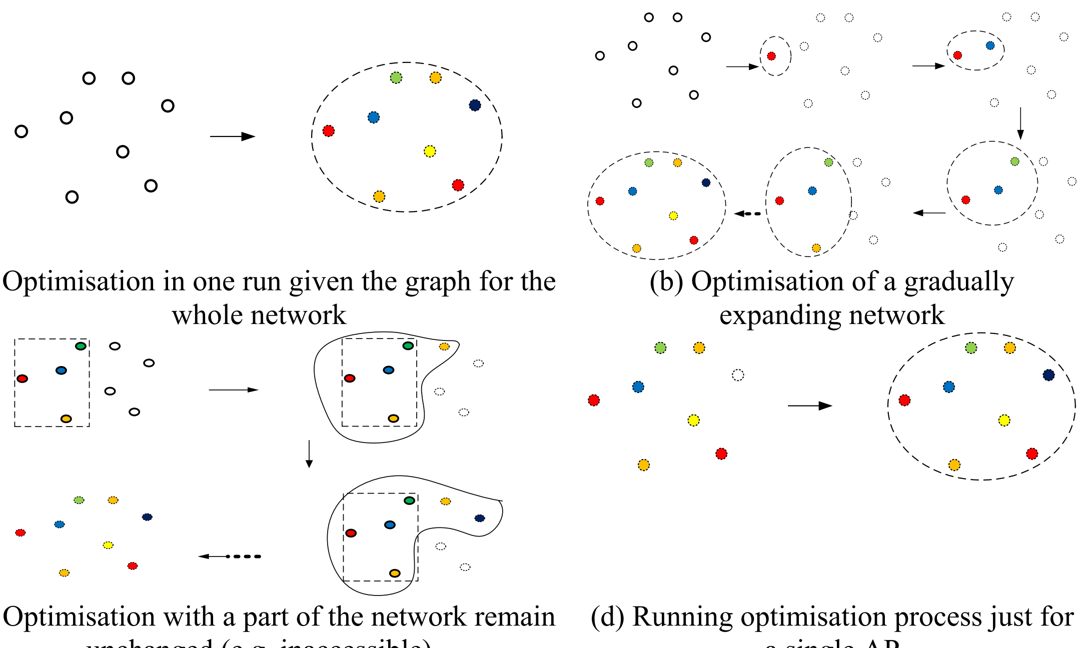
$$\begin{cases} x^* = \min_x c^T x \\ Bx = b \\ x_i \in [0,1]\,, \ \forall i\!: \ 1 \le i \le N \times F \end{cases} \qquad (7)$$

$$c = f(A, I), \ \ B = \begin{pmatrix} 1\,1\dots1 & 0\,0\dots0 & \dots & 0\,0\dots0 & 0\,0\dots0 \\ 0\,0\dots0 & 1\,1\dots1 & \dots & 0\,0\dots0 & 0\,0\dots0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0\,0\dots0 & 0\,0\dots0 & \dots & 1\,1\dots1 & 0\,0\dots0 \\ 0\,0\dots0 & 0\,0\dots0 & \dots & 0\,0\dots0 & 1\,1\dots1 \end{pmatrix}^{N\times(F\times N)}, b = 1^{N\times 1}$$

where c is actually a coefficient matrix resulted from elementwise expansion of (6) and x provides the desired channel assignment (i.e., the elements of matrix A^*).

3.2.2 Radio Resource Management Algorithm

As depicted in Figure 5-a and in the case of access to all information required in I, the optimised assignment of the channels can be achieved for all APs at one run of the algorithm (7) based on (6). In practice, re-running the optimisation procedure may be required after any major change of the network status such as the change of the network topology or APs' transmission powers. An interference indicator value can be used to detect a major deviation from the optimum value and to trigger the optimisation process. However, in most of the occasions, especially at the initial setup or re-initialization of the network, the required information to create G and I is not fully achievable. The disruptive effect of the recurrent channel assignment is also an important factor which needs to be taken into account. So, a gradually expanding model of the problem as depicted in Figure 5-b will be more desirable. The channel assignment procedure, in this case, starts from an AP and continues by adding other APs one by one.



(a) Optimisation in one run given the graph for the whole network

(b) Optimisation of a gradually expanding network

(c) Optimisation with a part of the network remain unchanged (e.g. inaccessible)

(d) Running optimisation process just for a single AP

Figure 5: Provided possibilities for channel assignment using the proposed model

The assigned APs in each run provide the information required for *I* in the next step. There is also the possibility of assigning/re-assigning the channels for a single AP (Figure 5-c) or a subset of the APs (Figure 5-d) leaving the rest of the APs unchanged. Figure 6 depicts the implemented algorithm which supports these scenarios. In order to provide a complete RRM framework that supports interference management as well as smart connectivity, we combine the proposed channel assignment model, transmit power adjustment and energy saving.

Figure 6 depicts the flow chart of a smart connectivity procedure which exploits the channel assignment functionality to achieve a per client quality, while maintaining a global quality indicator of the network. Matrix G will be created based on its definition in (2) with a predefined and configurable threshold representing the margin of the overlapping coverage among APs. This threshold is proportional to the APs' receiver sensitivity. Matrix I can be assessed based on the observations in the central controller using an assessment approach such as that explained in subsection 5.1.2 with the considerations discussed in subsection 5.2.

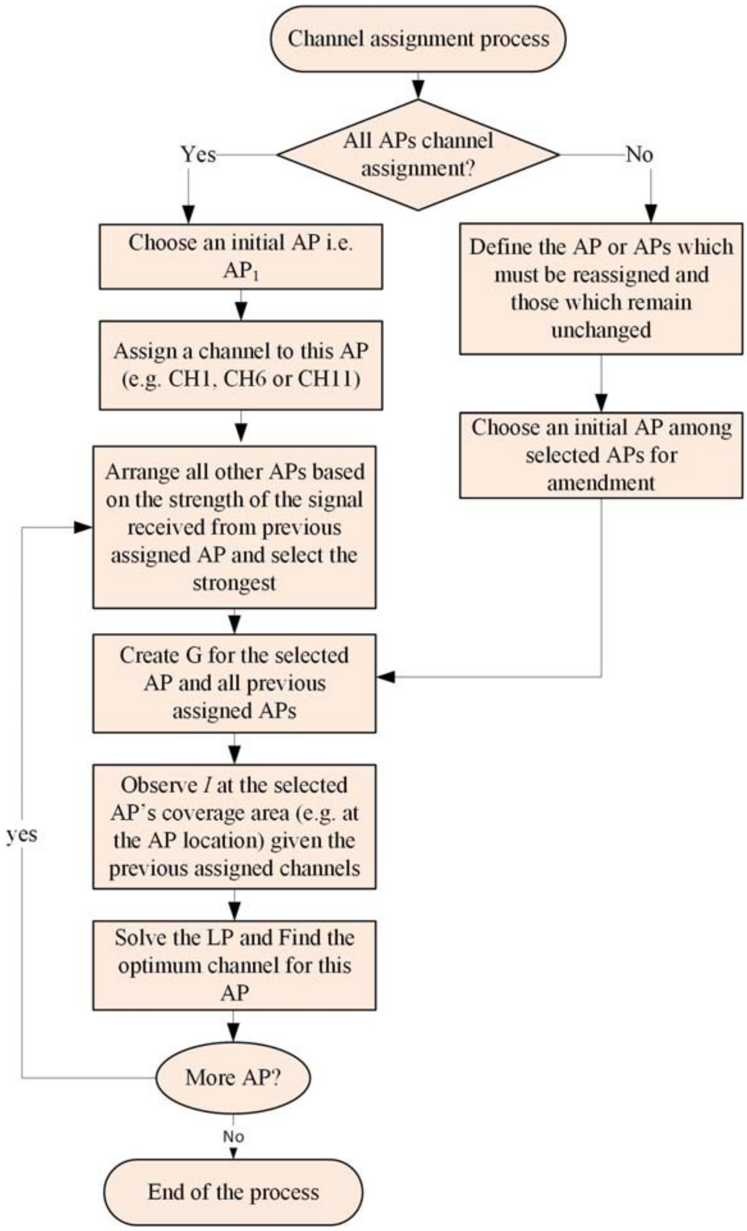


Figure 6: Flow chart of a smart connectivity procedure

The value of the utilisation function in (1) can also be used as a global quality indicator in the network. As an example, Figure 7 provides the detail of a power adjustment procedure which controls the request for increasing the AP transmission power when it is needed to achieve a certain SINR in an AP and the utilisation function in (1) plays the role of a global quality indicator alongside the desired SINR as a local quality indicator around that AP. The power adjustment process sets the transmission power in a way that 1) is high enough to provide the required SINR for the served stations and 2) maintains the overall interference in the network (i.e. the subsequent global quality indicator value denoted by U') as close as possible to the latest optimised value U. The maximum acceptable deviation of U' from U has been defined through the ratio σ.

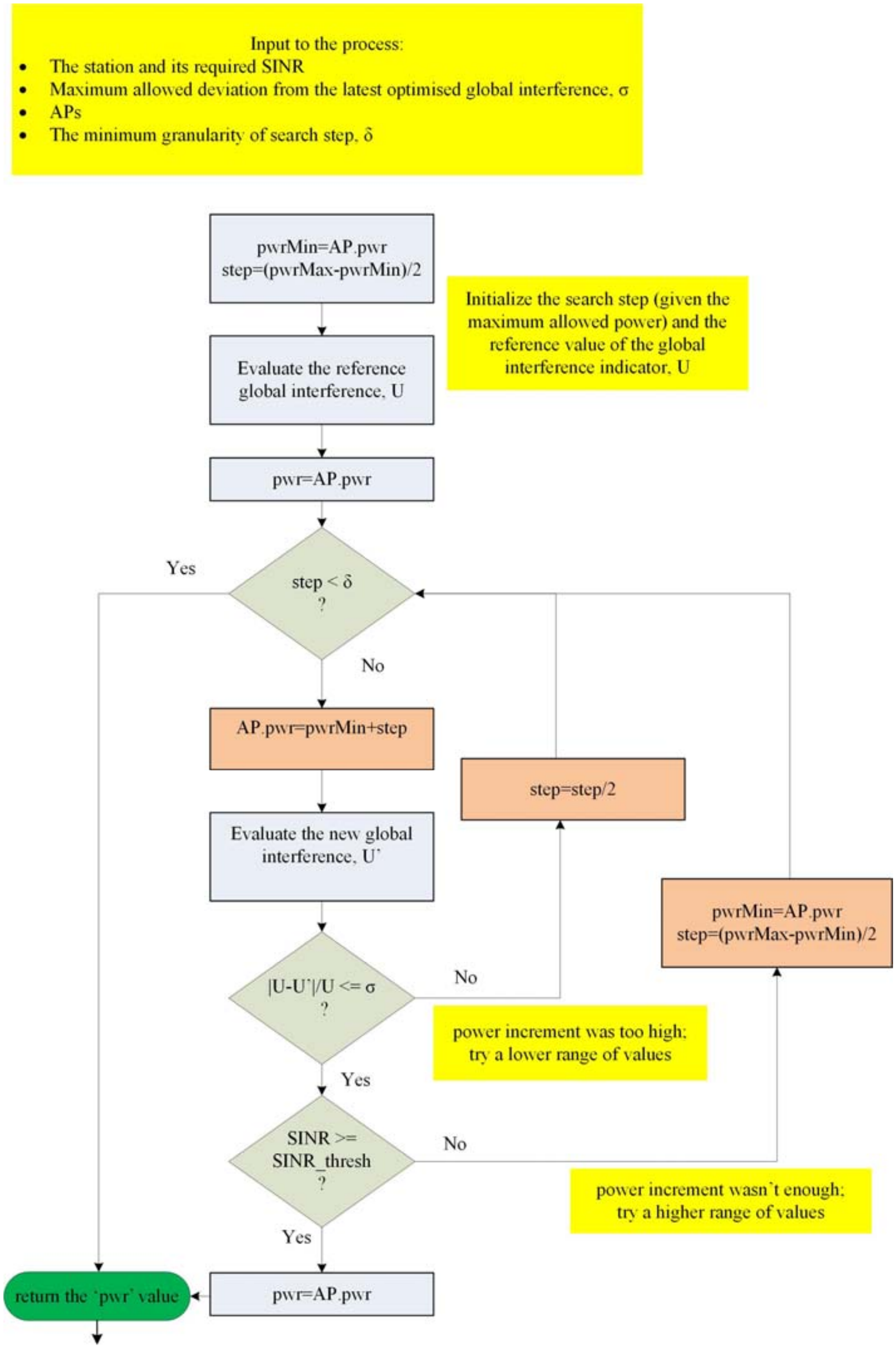


Figure 7: an example of power control with simultaneous local and global quality indicators represented by SINR and utilisation function, U.

3.2.3 Smart Connectivity and Selective AP Association

One objective of Wi-5 is to address the lack of flexibility in Wi-Fi with regards to the QoS requirements of the different flows travelling from the APs to the wireless station. In fact, IEEE 802.11 standard suggests to consider the RSS to establish which AP a station should join. Notwithstanding, this approach can lead to different problems in the efficiency of the spectrum resources or achieved throughput. Starting from this consideration, the smart connectivity functionality proposed in Wi-5 aims to recognise the heterogeneity of the requirements for the different stations accessing the network; hence, not all the APs characterized by the strongest RSSs are equally appropriate to serve a specific station with specific QoS applications.

The smart connectivity functionality proposed in this deliverable uses a *reward* concept that consists of a metric between 0 and 1 according to the suitability of an AP to serve a new user's data flow. The suitability of an AP is determined using the data bit rate required by the new flow and the bit rate that the AP can achieve.

Several possible definitions of the reward metric as a function of the bit rate may exist such as utility functions, linear functions or Fittingness Factor (FF). The effectiveness of the FF approach has been demonstrated in [51] against the utility function; while, in [52] the authors have extended the FF function for efficient spectrum selection in the presence of external interference variations in Cognitive Radio Networks (CRNs). The reward function considered in this approach is based on the FF formulated in [52]; the performance results illustrated in section 4.2 demonstrate the effectivness of the FF function in the context of the smart AP allocation against another common approach found in the literature. [52]The smart connectivity algorithm based on the FF also makes use of a standard deviation factor of the rewards computed in each available AP in the network. This standard deviation factor ensures that the performance of the overall network is maintained as much as possible when an AP starts serving a new flow. The reward metric for an AP *n*, which serves a flow *j* is given by the following formula:

$$r_{j,n} = \frac{1-e^{-\frac{\Gamma \cdot U_{j,n}}{\varrho \cdot \left(R_{j,n}/R_{req,j}\right)}}}{\lambda} \quad (7)$$

Here, $R_{req,j}$ is the bit rate required for flow *j* and obtained using the *Required quality assignment* functionality. $R_{j,n}$ denotes the bit rate served by AP *n* when serving flow *j* and computed using the *Provided quality assessment* functionality. $U_{j,n}$ is the utility function used to depict the QoS perceived by the users in a wireless network. In this context the function refers to the bit rate achievable by the user *j* from the AP *n* with the requested bit rate, and it is defined by the following formula:

$$U_{j,n} = \frac{\left[\varrho \cdot \left(R_{j,n}/R_{req,j}\right)\right]^{\xi}}{1+\left[\varrho \cdot \left(R_{j,n}/R_{req,j}\right)\right]^{\xi}} \quad (8)$$

Γ, ξ and ϱ are parameters that reflect the different degrees of elasticity of the required bit rate, while λ is a normalization factor given by:

$$\lambda = 1 - e^{-\frac{\Gamma}{(\xi-1)^{1/\xi}+(\xi-1)^{(1-\xi)/\xi}}} \quad (9)$$

The standard deviation of the rewards can then be computed in each accessible AP. The formulation of the standard deviation includes both the rewards of all the previous flows active in the AP n and $r_{j,n}$ computed using equation (7), and is given by:

$$\sigma_{j,n} = \sqrt{\frac{\sum_{f=1}^{F}\left(r_{f,n}-\overline{r_n}\right)^2}{F}} \; where \; \overline{r_n} = \frac{1}{F}\sum_{f=1}^{F} r_{f,n} \qquad (10)$$

Note that the standard deviation defines the variation in terms of the average reward that serving a new flow causes on each AP. Each time a new user tries to join the network, the smart connectivity algorithm based on the FF, selects through equation (11) the AP represented by the so-called *network reward* (i.e., *net_r*$_j$) that optimises the following parameters:

i. The reward metric that identifies the APs that can serve best the flow requirements of the new user.
ii. The standard deviation factor that maintains the performance of the overall network as much as possible.

This optimisation problem, formulated in equation (11), means that the smart connectivity algorithm based on the FF proposed in this deliverable aims to optimise the individual performance of the AP associated with the new user while trying to safeguard the overall network performance.

$$net\_r_j = \arg max_{n\in\{1,\dots,N\}} \left\{r_{j,n}\left(1-\sigma_{j,n}\right)\right\} \quad (11)$$

Each time that a new flow joins the network, the *AP consideration process* will execute the smart connectivity algorithm based on the FF through eq. (7)-(11) making use of the quality information obtained from *Provided quality assessment* and *Required quality assessment* functionalities introduced in figure 4. Note that the rewards of all the previous flows active in each AP and used in eq. (10) are updated in the *AP consideration process* each time an AP is allocated to a new flow. After the computation of the optimized *network reward* parameter achieved through eq. (11), if such a value will be above a threshold to be defined, the corresponding new flow will be allocated to the selected AP. Otherwise, the *AP consideration process* will trigger a reassessment of the required quality to the *Required quality assessment* functionality.

3.2.4 Seamless Mobility

In Wi-5, we address the limitations of existing mobility solutions, described in section 2.4, by proposing a novel seamless mobility functionality that exploits the flexibility and scalability offered by the SDN approach adopted in Wi-5. The main objective of this functionality is to offer the user the possibility to move between Wi-Fi networks without affecting its QoE.

Initially, as described in the deliverable D2.4, the Wi-5 controller creates Virtual SSIDs on the APs. Each STA that connects to the Wi-Fi network is, initially, associated with a unique Virtual SSID.

Since the Wi-5 controller receives regular messages from APs and STAs by using the monitoring functionality specified in D3.2, it can detect a change in the RSS of a moving STA. If the change in the RSS exceeds a certain threshold RSS_{th}, it triggers the seamless mobility algorithm, which receives monitoring information collected by the Wi-5 controller through the monitoring agents, including the RSS detected by the STA from each neighbouring AP. Once the Wi-5 controller selects the appropriate AP to which the mobile STA will be associated, it moves the Virtual SSID to the new AP.

However, it is possible that the new AP is operating on a different channel than the previous AP which means that the STA and the new AP will be operating on separate channels. In such a case, the Wi-5 controller will change the channel of the Virtual SSID when moved from the former AP to the new AP, and will also ask the STA to switch channel. This operation will be performed using the dynamic channel switching smart functionality specified in D3.2.

In the context of the Wi-5 project the client mobility is implemented using Odin [53], which is an architecture using the SDN concept. The Odin WLAN Management Framework, described in D2.4, provides a reactive Mobility Management application for Wi-Fi networks. In this application, the Odin controller first registers all the APs, in order to receive monitoring information related to the presence of STAs. If an AP hears a new client with a signal strength higher than a threshold, it reports the event to the controller. Once the mobility event is triggered, the Mobility Management application moves the Light Virtual Access Point (LVAP) corresponding to the STA from the origin AP to the destination AP.

However, currently Odin exhibits many limitations and requires a series of extensions that have been presented in D2.4 before it can support Wi-5 functionalities, including Seamless Mobility. Firstly, Odin does not support dynamic channel switching which is necessary when the STA is associated to an AP operating on a different channel. Secondly, Odin monitoring mechanisms are still limited to basic RSS metrics and do not support QoS and resource related metrics such as: bandwidth usage, energy, etc. Note that although in its current version the Wi-5 seamless mobility algorithm is based on RSS metrics, we also plan to extend it to support a combination of QoS and resource related metrics in order to complement the smart connectivity functionality presented in the previous section. In fact, although RSS represents a common method considered in the context of the mobility management, it can lead to unbalanced loads between APs, poor throughput and other performance metrics. Therefore, the *network reward* parameter introduced in section 0 will be evaluated as a key potential candidate for improved mobility management under the assumption that APs with a stronger signal will not always offer better performance.

Note that since the Wi-5 seamless mobility solution heavily relies on other functionalities, such as the monitoring tool and dynamic smart channel switching developed in WP3, it is currently a work in progress.

4 Performance Evaluation

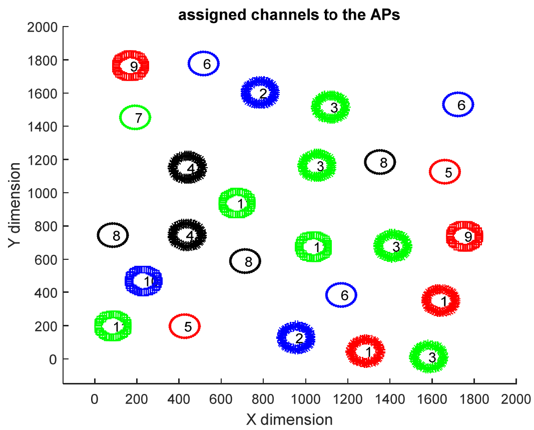
The aim of this section is to provide the first assessment of the algorithms proposed in this deliverable through the analysis of several performance results in a simulated environment. The MATLAB-based simulator developed for this purpose comprises the required network elements and functionalities including the Wi-Fi AP entities, a central controller and user stations together with the implemented resource management functionalities. It also supports the consideration of the wireless channel characteristics, AP association process, and connection quality control. 25 APs are considered to be deployed in an area of 1800m×1800m at a minimum centre-to-centre distance of 300 meters (i.e. 150m coverage radius) where the transmit power is set to be adjusted between 10dBm to 25dBm. We also consider a free space path loss model with path loss exponent 2.

4.1 Evaluation of the Channel Assignment Algorithm

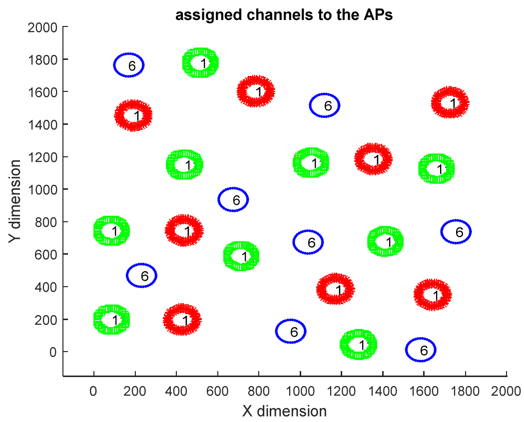
We evaluated the performance of the channel assignment algorithm in terms of achieved SINR, in a dense Wi-Fi network represented by the scenario previously introduced. The performance of the channel assignment algorithm is compared against the initial random assignment of the channels as a reference of comparison. The obtained results, presented in Figure 8 and Figure 9, show the expected improvement in the achievable SINR.

Figure 8(a)-(e) depict the location of the APs and the arrangement of their allocated channels in each scenario (different channel numbers are represented by different colours). Figure 8(a) shows the initial random allocation of the channels. The optimised channel assignment based on the algorithm introduced in subsections 3.2.1 and 0 is depicted in Figure 8(b). Figure 8(c) represents a situation in which the status of the network has changed and the previously optimised assignment needs to be revised. Since APs are likely to experience an interruption during the channel assignment process, some of them may need to be excluded from repetitive optimisation processes on some occasions. This scenario has been shown in Figure 8(d). And finally, a full re-optimisation of the assigned channels of the network status in Figure 8(c) has been shown in Figure 8(e).

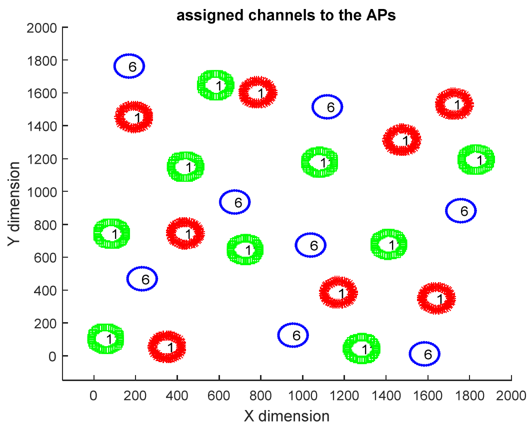
Figure 9 summarises the comparison of the performances of the network in the above explained scenarios in terms of the Cumulative Distribution Function (CDF) of the achieved SINR in each case. These results show the improvement of the network performance using the proposed optimisation algorithm during the network initialization (represented by the shifted CDF toward the higher SINR values in the case of the optimised channel assignment). In contrast, the results reveal the degradation of the performance due to the changes in the network status (e.g. changes in the transmit powers and the locations of some of the APs) compared to the optimised assignment. Furthermore, the results demonstrate the flexibility and practicality of the proposed algorithm to include all the APs or just some of them in the subsequent re-assignment process. It must be noted that the CDFs which do not cross each other represent an absolute improvement (or degradation) of the performance of one of them in the whole range of the SINR values. In contrast, CDFs with crossing points depict a situation in which the improvement or degradation of the performances are not consistent for the whole range of the SINR values. For example, the comparison between the initial channel assignment and the optimised assignment reveals an absolute improvement of the optimised values in the whole range of the SINR while the partial re-optimisation and full re-optimisation scenarios have a non-consistent performance comparison around SINR=6dBm.



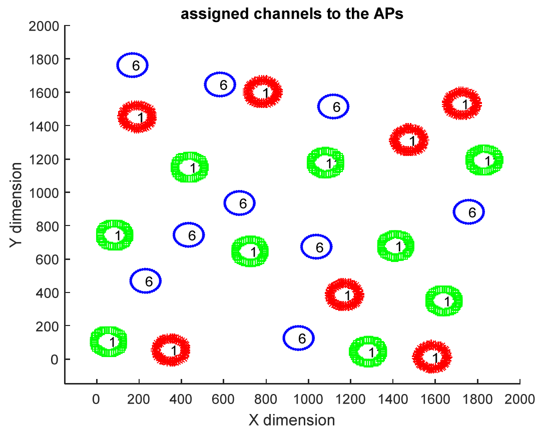
(a) Random assignment



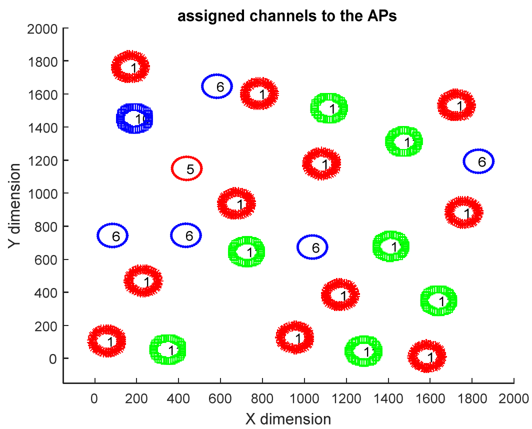
(b) Optimised



(c) Some change (e.g. power change and displacement)



(d) Partial re-assignment of (c)



(e) Full re-optimisation of (c)

Figure 8: Performances comparison of the network before and after various optimisation scenarios

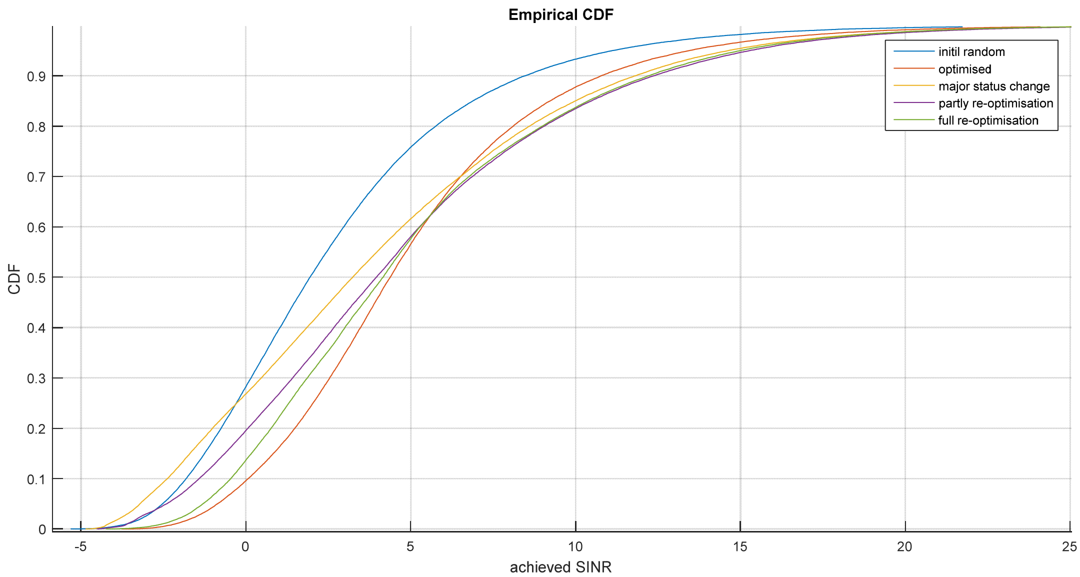


Figure 9: Performances comparison in terms of SINR

4.2 Evaluation of the Smart Connectivity Functionality

In order to evaluate the performance of the Smart Connectivity Functionality, we simulated a simplified version of the framework depicted in Figure 10. This simplified version focuses on the *AP consideration process* of the framework, as illustrated in Figure 10.

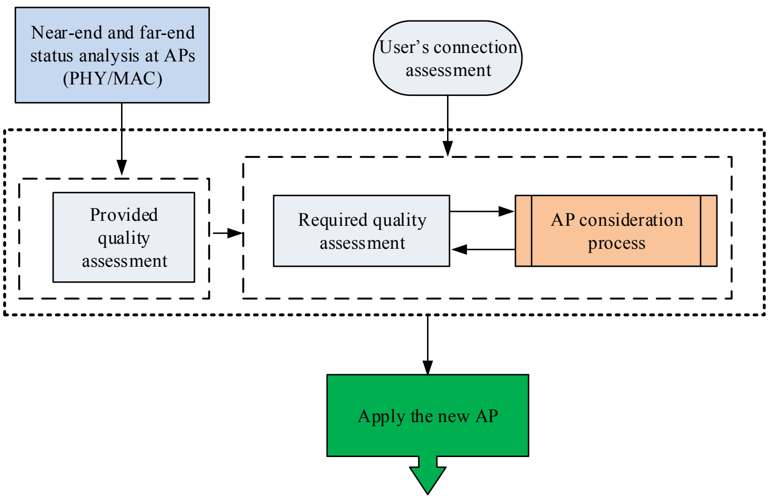


Figure 10: Simplified framework that implements the AP consideration process

In the scenario previously introduced, we simulated an STA trying to connect to the network every 3 minutes from different and random positions within the network area. We also simulated an application on the STA trying to receive a flow of data with different bit rate requirements, as summarised in Table 1. In this table we introduce a Quality Grade (QG) which reflects the class of the traffic the application is receiving once connected to the Wi-Fi network, with QG=1 meaning that the traffic has the lowest requirement, and QG=3 meaning that the traffic has the highest requirement.

The *AP consideration process* starts by considering the highest requirement (QG=3) traffics. For a flow j, the algorithm computes net_r_j for all the APs accessible from the STA requesting connection. If $net\_r_j \geq net\_r_{th}$ (where net_r_{th} is the selected threshold), the AP n will be associated with the STA receiving flow j. If no AP satisfying the quality requirement threshold, net_r_{th}, is found, the *AP consideration process* downgrades the quality requirement of the flow to the class below it, i.e. QG=2, and repeats the computation process of net_r_j. The process is repeated until either an AP that satisfies the flow requirement is found, or the quality requirement class reaches QG=1. A high value of net_r_{th} in the algorithm would lead to needless downgrades of the QG and to a consequent user dissatisfaction. Therefore, considering that the value of net_r_j ranges between 0 and 1, net_r_{th} has been set to 0.6 in these simulations.

Application	QG	Bit rate (Mbps)
Video streaming	1	1.5
	2	3
	3	6

Table 1: Bit rate requirements

For the sake of comparison and in order to evaluate the performance of the smart connectivity functionality, we devised another AP allocation strategy that acts as a comparison candidate. This strategy associates an AP to an STA according to the SINR achieved by each AP, as proposed in [35].

The evaluation of the smart connectivity is based on the following performance metrics:

1. ***Congested APs***: This is the number of congested APs which is updated for each new flow trying to join the network.
2. ***Achieved SINR***: This metric is measured in terms of its Cumulative Distribution Function (CDF).
3. ***Data bit rate***: This metric represents the data rate in terms of kbps achieved by each new flow trying to join the network and averaged for all the flows.
4. ***Extra Bandwidth***: This metric represents the average extra bandwidth served to all the flows which had their bit-rate requirements satisfied.
5. ***Station Satisfaction***: This metric is the ratio of the assigned bit rate by the required one (i.e., the value corresponding to QG=3 in case of the FF-based algorithm) averaged for all the flows.

Figure 11 shows the number of congested APs as a function of the number of flows that join the network in the case of both algorithms, FF-based using the Smart Connectivity and SINR-based. From this figure, it can be observed that the FF-based strategy provides a better result in terms of congested APs. In particular, in the SINR-based approach, 420 flows congest all the available APs, while the same number of users only congest 7 APs under the FF-based strategy. This is due to the better distribution of the flows obtained by the FF-based algorithm, as it helps in finding and associating the most suitable AP to a flow, which does not necessarily correspond to the one guaranteeing the highest data rate.

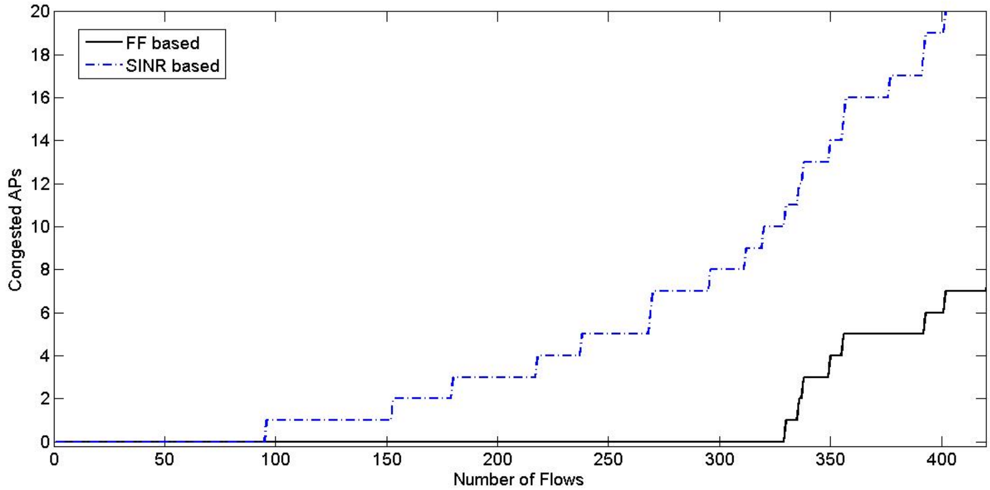


Figure 11: Congested Access Points

Figure 12 and Figure 13 show, respectively, the CDF of the achieved SINRs and the data bit rates when the demand on the network is at the maximum, in the case of 420 simultaneous flows. These figures show that the SINR-based algorithm achieves better performance than the FF-based one in terms of the SINR and data bit rate. This result could be expected, as the SINR-based algorithm aims to achieve the maximum SINR and bit rate.

Finally, Figure 14 and Figure 15 show the performance results of both algorithms in terms of extra bandwidth and station satisfaction in the case of the FF-based and SINR-based algorithms. From Figure 14 it can be noticed that the SINR-based algorithm tends to offer flows more extra bandwidth than the FF-based algorithm. Figure 15 shows that the bandwidth saved by the FF-based algorithm does not affect the stations satisfaction, and offers a better station satisfaction than the SINR-based algorithm. This proves the bandwidth allocation efficiency of the FF-based algorithm. Note that the lower the number of flows, the greater the improvement of the performance results in terms of saved bandwidth in the FF-based solution with respect to the SINR-based algorithm thanks to its better distribution of the flows. Moreover, as was expected, the averaged performance results of both algorithms get worse with the increase of the number of flows. Notwithstanding, the efficient distribution of flows among the APs in the case of the FF-based algorithm allows it to maintain better performance results with respect to the SINR-based solution.

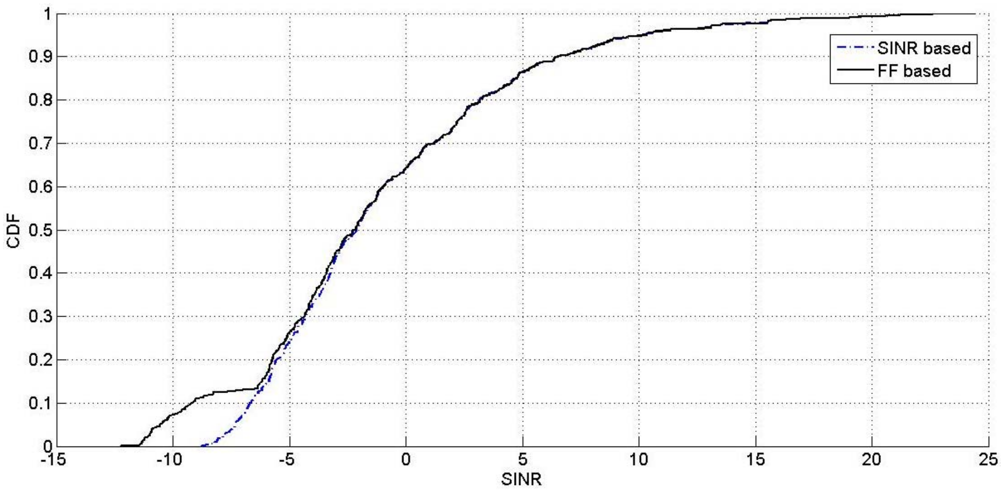


Figure 12: CDF of achieved SINRs

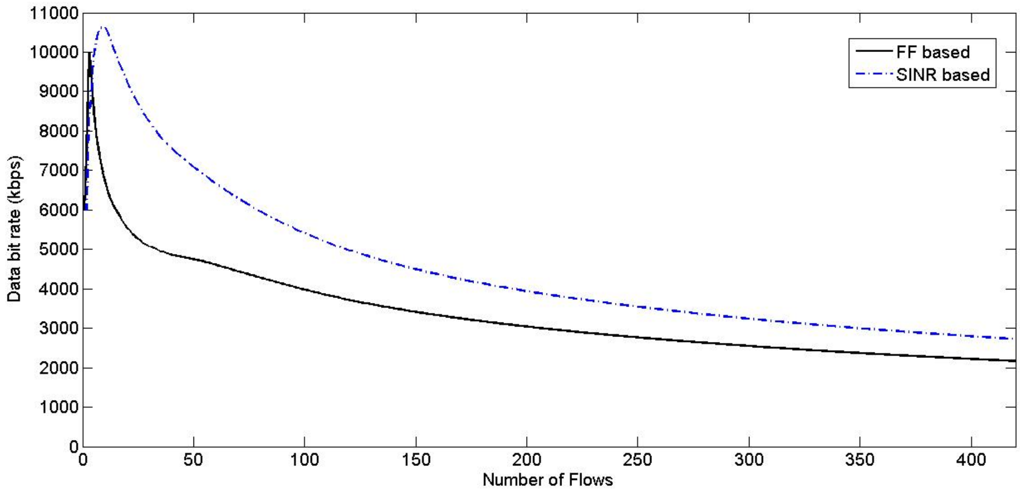


Figure 13: Data Bite Rate

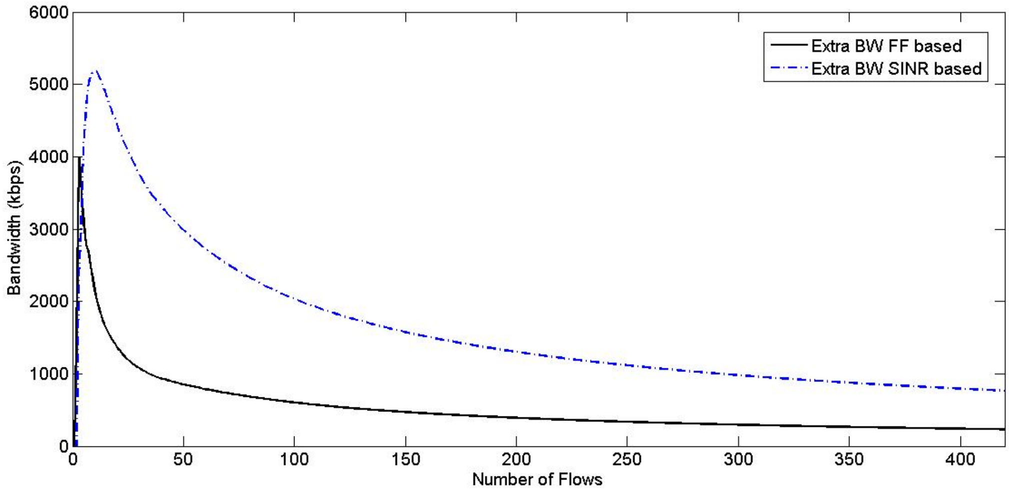


Figure 14: Available Bandwidth

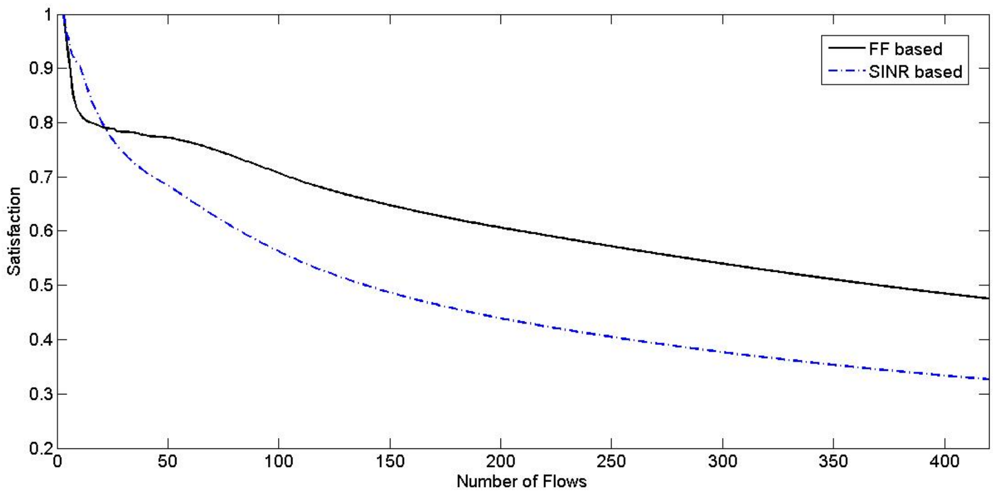


Figure 15: Station Satisfaction

The main findings derived from the simulations illustrated in this section can be summarized as follows:

- The proposed optimisation algorithm for channel assignment allows satisfactory network performance in terms of SINR during the network initialization.
- The results show the flexibility and practicality of this algorithm to include all the APs or just some of them in the channel re-assignment process.
- The assessment of the AP selection algorithm based on the FF concept demonstrates that this approach enables an important bandwidth saving compared against the solution that associates an AP to a user according to the SINR achieved by each AP.
- The bandwidth saved through this algorithm does not affect the user satisfaction; in fact, it provides a better satisfaction than the SINR-based algorithm.

5 Network Status Observation and Required Measurements

In order to allow the correct deployment of the procedures presented in section 3, the set of monitoring procedures conducted on the Wi-5 APs and on the Wi-5 controller and illustrated in D3.2 will be considered. The role of these procedures is to provide information on: (i) the interference level sensed from each AP at the available channels in the considered frequency bands; (ii) the number of users/flows associated to each AP; and (iii) identification of users' service requirements, e.g. in terms of the demanded bit rate or run-time perceived quality by the users. This could actually be a combined PHY and MAC layers process at the APs in cooperation with the central controller. These monitoring mechanisms will be helpful during the decision-making process at the Wi-5 controller and they also contribute to the optimal AP channel assignment and the smart AP allocation to each new user/flow joining the network.

In detail, the monitoring of the interference levels will support the algorithm implemented in the *Channel assignment process* during the radio configuration optimisation in two different cases: (i) during the initialization of the Wi-Fi network considering the interference between the APs caused by the default transmit power; and (ii) during a possible reassignment of the channels to one or more APs due to a change of status in the network. The changes comprise any alterations in the APs arrangement, transmission powers and/or their served users' statistics. The result of this algorithm will provide the Wi-5 agents with the channel allocated to each AP. Moreover, the monitoring of the interference levels will allow the controller to estimate the achievable requirements for the flow j in the AP n, computed by the *Provided quality assessment* functionality and exploited by both the *Channel assignment process* and *AP consideration process* (see Figure 4). The number of flows associated with each AP and the detected bit rate requirements computed in the *Required quality assessment* block will support the *AP consideration process* block during the smart connectivity algorithm based on the FF executed for a smart AP association, when a new flow tries to join the network. Finally, the result of the combined channel assignment and power control algorithm illustrated in section 0 will trigger a possible reconfiguration of a certain AP's working parameters, and subsequently, it will provide the Wi-5 agent of that AP with, for example, an appropriate modulation and coding scheme parameters.

5.1 Network Status Acquisition and Measurement Processes

The Wi-5 architecture proposes cooperative AP functionalities in order to maintain seamless handover, smart wireless connectivity and cooperative RRM solutions. These functionalities depend on statistics which have to be gathered from a set of measurements and that will be conducted on the Wi-5 controller and on the Wi-5 APs. As discussed earlier, the set of measurements should provide information on:

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

In the following, a brief summary on the measurement framework considered in the context of Wi-5 is presented, which will be used to collect the required information. Then, the measurement processes to achieve the required information are illustrated. A detailed description of these procedures can be found in deliverable D3.2.

5.1.1 Measurement Framework

Two main approaches used to measure the parameters of wireless systems can be found in the literature. The first approach is taking passive measurements through carefully placed sniffers [54], [55]; while, the second approach is based on placing specialized measurement capabilities into regular Wi-Fi APs. Therefore, implementing the second approach gives the opportunity of observing various wireless properties in-line [56].

The Wi-5 measurement framework will use the second approach and it is illustrated in Figure 16. It will rely on the monitoring information collected by Wi-5 agents, running on the Wi-5 APs and will be implemented using the *Click modular router* [56]. Wi-5 agents will be the extended version of the Odin agent, which is a part of the Odin SDN framework, and considered to support the programming of radio resources on Wi-5 APs. Wi-5 agents will supply the monitoring information to the Wi-5 controller as an input to the implemented cooperative RRM algorithms, through the southbound API. Detailed information on the SDN framework of the Wi-5 architecture can be found in deliverable D2.4.

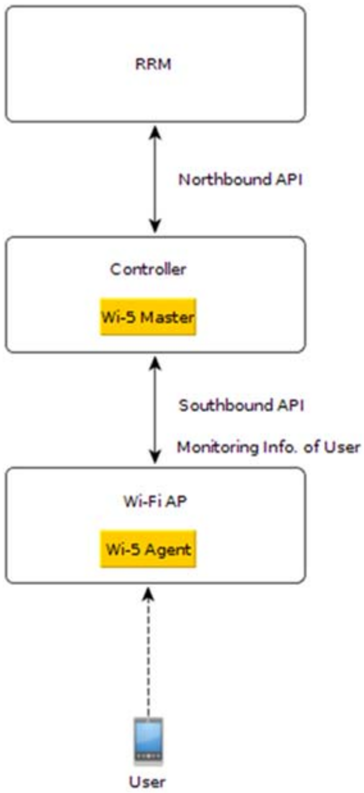


Figure 16: Wi-5 Measurement Framework

In order to expose the freedom of full customization, Wi-5 APs will use Wi-Fi cards based on the *ath9k* [58] driver, running the OpenWRT Linux distribution. Therefore, the Linux wireless subsystem will be used to gather information on the wireless transmission quality. In order to gather information on the wireless transmission system, the wireless subsystem of Linux offers two different options [59]. In the first option, a snapshot of the status of the wireless connection can be fetched via the *nl80211* interface. In the second option, it is possible to get detailed information for each transmitted and received data packet by using the monitor mode of the wireless subsystem.

When in the monitor mode, the monitor device adds a special header to the 802.11 frames, named *radiotap* header. The *Radiotap* header format is a mechanism to supply additional information about frames from the driver to userspace applications such as the Click modular router, and from a user space application to the driver for transmission. The *Radiotap* header includes detailed information on each packet, like the signal strength or the data rate of the captured packet. Detailed information on the fields of a *radiotap* header can be found in [60].

Wi-5 agents will run on top of the Wi-Fi network interface running in the monitor mode, to receive all frames including both management frames and data frames, along with per-frame reception information exposed using a *radiotap* header. The information used to measure the quality of the wireless link will include the signal strength of the reception, the bit rate or the MCS of the transmitted frame and the noise. On a per source basis, Wi-5 agents will save this information and will keep track of the timestamps for each source as well.

5.1.2 Measurement Process

A set of measurements should be conducted to provide information on interference levels, the number of associated clients with each AP/flow, and the service type of clients. In the following, both the required parameters to measure and the measurement processes of these parameters will be explained.

5.1.2.1 Interference Measurements

In order to reduce the interference level sensed from both the APs and STAs, cooperative RRM solutions should be maintained by the Wi-5 architecture. Interference measurement includes the measurement of the STA's transmitted power and the airtime utilization. To monitor the transmitted power of the STA, some IEEE standards, namely IEEE 802.11h and IEEE 802.11k, can be exploited. The detailed information on the monitoring process of this parameter can be found in deliverable D3.2.

One method to measure the airtime utilization is the micro-sensing method proposed in [61]. According to this method, first, the AP randomly selects a centre frequency and channel bandwidth and then it computes the list of all bands that can potentially interfere with the current band and randomly selects a sampled band. The AP then tunes each of these bands for a short amount of time and the AP comes back to the operating band between each individual scan. In order to not disrupt the traffic, the time spent in out-of-band sensing should be suitably small, but it must also be large enough to efficiently monitor the band. Since the time required to send a packet at a given rate is inversely proportional to the channel bandwidth, this amount of time also depends on the bandwidth of the channel currently being scanned. The whole time required to scan the channel can be calculated by summing the time spent for sensing the channel and twice the switching time. The reason of the multiplication of switching time by 2 is the switching back and forth requirement of the micro-sensing operation between the operational and monitoring bands. According to the paper [61], the time spent for sensing the channel is set to $240/b$ ms, where b is the bandwidth of the scanned channel in MHz.

During each micro-sensing period, the AP monitors the band and collects the link statistics. The AP records the corresponding band and the source-destination MAC address pair of each link. It also keeps an estimation of the airtime ratio consumed by the packet which is computed from the length of the packet, physical transmission rate and the occupied bandwidth.

In the Wi-5 architecture, Wi-5 agents will collect the PHY parameters from the *radiotap* header, which is required to infer the length of the packet. In order to calculate the length of the packet, *NetMate Meter* [62], an open source network tool for network measurement can be used.

The physical transmission rate and occupied bandwidth can be directly gathered from the *radiotap* header which is injected to the packet by the driver of the Wi-Fi network interface card. According to [60] the second bit of the header is assigned to the physical transmission rate field whereas the 19^{th} bit is assigned to the MCS field. The first flag of the MCS field indicates the occupied bandwidth.

The interference monitoring process can be handled by an auxiliary interface which is added to each AP. This approach can be beneficial for implementing the channel scanning and switching without affecting the other STAs. The feasibility of both the method proposed in [61] and the approach of adding the second interface should be investigated through measuring the time required for scanning and switching.

5.1.2.2 Monitoring of Number of Associated Clients

In order to assess the smart connectivity of wireless clients, the number of users/flows associated with each AP should be tracked by the Wi-5 controller. The Wi-5 Master, which will be implemented in the Wi-5 controller, will probe the Wi-5 agent for gathering the list of LVAPs hosted by the Wi-5 Agent, based on the Odin implementation. There is a single LVAP corresponding to each client, so each client has the illusion of owning its own AP. The MAC addresses, IP addresses and LVAP SSIDs of the clients are also provided along with the list of LVAPs. Since every Wi-5 AP hosts its own Wi-5 agent, the Wi-5 controller through the list of LVAPs hosted by each agent will collect the associated clients of each Wi-5 AP. The Wi-5 Master will send periodical requests in order to retrieve this information from the Wi-5 agents. In the Odin framework, this period is equal to 60 seconds.

5.1.2.3 Monitoring of Service Type of Users

The Wi-5 architecture promises to provide a good quality to real-time services with very tight latency constraints. Detection of traffic flows with the AP, where they are present, can be the first step for this aim. One candidate solution is to use the *Diffuse* (DIstributed Firewall and Flow-shaper Using Statistical Evidence) framework [63], in order to identify a kind of a traffic. This solution is based on the packet size and inter-packet time. Detailed information on detection of user traffic types can be found in D3.2.

In order to measure the packet size and inter-packet time, the *radiotap* header mechanism is exploited again. *NetMate Meter* [62], an open source network tool, can be used as a network measurement tool in the Wi-5 agents.

5.2 Measurement Process Limitation, Delay and Inaccuracy (Scalability and Reachability)

Given the Wi-5 functionalities such as channel selection, power adjustment and general status monitoring processes, the possible limitations of the measurement process have to be described, including the effect of the monitoring delay and its possible inaccuracy, as well as the scalability and reachability aspects of the process.

5.2.1 Automatic Traffic Detection

One of the objectives of the Wi-5 Project is to improve the subjective quality of the users of real-time network services. In these services, the throughput is not the main objective. Other parameters, mainly a reduced latency, are also of importance and may vary depending on the service [64]. Therefore, an automatic detection of these real-time services will be of primary importance in order to manage them in a proper way.

As reported in [63], Machine Learning (ML) based tools are able to automatically detect real-time flows in the network. In the ML literature, two metrics are often used, namely *Recall* and *Precision*, ranging from 0% (poor) to 100% (optimal). High Precision is only useful when the classifier achieves good Recall, and vice versa. In ML, inputs are divided into two or more *classes*. After being trained, the learner must produce a model that assigns unseen inputs to one or more of these *classes*. In the case of automatic traffic detection, a *class* means a kind of traffic, e.g. "VoIP with codec G729a", "*Quake 3* game traffic", "Web browsing", "file download", etc. Therefore, the metrics are defined as follows:

- Recall: Percentage of members of class *X* correctly classified as belonging to class *X*, among all members of class *X*:

$$Recall = \frac{True\ Positives}{True\ Positives + False\ Negatives}$$

- Precision: Percentage of those instances that truly belong to class *X*, among all those classified as class *X*:

$$Precision = \frac{True\ Positives}{True\ Positives + False\ Positives}$$

The presented work used the following network traffic *features*, calculated with *Netmate Meter,* in the forward and reverse directions:

- Inter-packet arrival time.
- Inter-packet length variation.
- IP packet length.

They computed minimum, maximum, mean, and standard deviation values. The use of these parameters is interesting because it avoids the need of inspecting the contents of the packets: the service can be detected just by observing the packet size and inter-packet time. No Deep Packet Inspection (DPI) is required, which may be important for maintaining user privacy and network neutrality.

Two real-time applications were tested in [63], which correspond to some of the applications of interest to the Wi-5 project:

1) First Person Shooter (FPS) game traffic: These are fast-paced games where the objective is to eliminate all the enemies. Each player's avatar has a gun, and the movements are fast. Accuracy and aims are of primary importance, and network latency has to be maintained very low [65]. The authors chose *Wolfenstein: Enemy Territory* (ET), as a representative of this genre.

2) VoIP Traffic: They used Real-time Transport Protocol (RTP) flows (92% G.711 and 8% GSM) collected on a home network. Calls' durations ranged between 19 and 8207 seconds, with a total of 7061 packets in both directions.

In addition, the tests included interfering (non-ET and non-VoIP) traffic, taken from two daily data traces collected by the University of Twente [66]. The interfering traffic datasets were built by extracting flows belonging to a range of common applications. The application types were inferred from the well-known default port numbers, since the payloads were missing for privacy reasons.

One of the goals of the article [63] was to classify online game and VoIP traffic in less than a second. Different training methods were tested. In addition, a parameter *M* was used to denote the offset of the first packet of the flow of interest from the beginning of the flow (i.e. *M* is the position of the first packet fed to the classifier). Finally, *N* denotes the number of packets of the flow of interest used in each detection test. The authors trained the algorithm with multiple sub-flow positions and Assistance of Clustering Techniques (ACT), representing an unsupervised technique for clustering in ML.

a) Precision and recall

The results reported in the paper when the algorithm is trained this way were acceptable: for the FPS game, 98% of recall and 90% precision were achieved. The results were even better for VoIP: always above 95%.

b) Detection delay

The delay between the beginning of the flow and the detection was smaller than a second, showing that these ML techniques are suitable to be used for this aim. Once the algorithm has detected a real-time service, the latency derived from the communication to the Wi-5 controller would be negligible, taking into account that we are assuming that all the APs are connected to the controller through a wired network.

c) Scalability

The ML tools may act in a Classification Node, i.e. a node that simply detects and somehow marks the traffic, and also as an Action Node, meaning that it sends the packet to one queue or another depending on its detected class. As reported in [67], an Action Node requires more hardware resources than a Classification Node. However, in the case of Wi-5, there is a central controller in charge of resource management, so the classifier should only act as a Classification Node.

5.2.2 STA’s Power measurement

The Power Control algorithms running in the Wi-5 controller will require different inputs. First, the APs may report the power they are sending to the STAs. However, in order to know the power sent by the STAs, other mechanisms are required. The AP only knows the received power, but this may vary depending on both the sent power and the channel conditions.

Therefore, the ***TPC Request* element** defined by the 802.11-2012 standard [68] will be used as a “request for a STA to report transmit power and link margin”. The STA should answer with a ***TPC Report* element** containing “transmit power and link margin information sent in response to a TPC Request element or a Link Measurement Request frame. A TPC Report element is included in a Beacon frame or Probe Response frame without a corresponding request.”

The information obtained from this report includes the power the STA is transmitting at, and the *link margin*: the difference between the receiver's sensitivity (i.e. the received power at which the receiver will stop working) and the actual received power.

This information will be used for the Power Control algorithms: in the uplink (STA to AP), if the power transmitted by the STA and the power received by the AP are known, we can estimate the channel conditions. In the downlink (AP to STA), although we will not know the power received by the STA, we will have an estimation of the margin, so we will know to what extent the power can be reduced.

a) Precision

The precision of the measurements provided by the STA will have to be measured. Taking into account that the STA may have different network interfaces and drivers, this may strongly vary between different devices. Therefore, a number of tests including a variety of devices will have to be run in order to check if, for example, the communication gets worse or the power is reduced according to the *link margin* reported by a STA.

b) Delay

The delay (and the overhead) incurred between the sending and the reception of these requests and reports will have to be measured in order to have an estimation of the delay associated with this procedure.

c) Scalability

This process will imply a certain consumption of airtime, so an estimation of the number of users per AP will be required in order to calculate the airtime percentage this would imply, and to adjust this trade-off accordingly.

5.2.3 Wireless Environment Scanning

In order to make correct decisions, the Wi-5 controller has to periodically monitor the radio environment for two reasons: firstly, other Wi-Fi devices in other administrative domains may be present; secondly, scanning is necessary in order to detect STAs coming from other APs, thus enabling handoffs between APs in different channels.

As illustrated in Figure 17, a client may move from one AP to another, and in this process AP_2 will have to scan Channel A at a certain moment. The handoff process will be triggered by AP_1, which observes a reduction in the signal level received from the client. Then, it reports this to the controller which, in turn, sends a scanning request to all the APs in the neighbourhood (including AP_2).

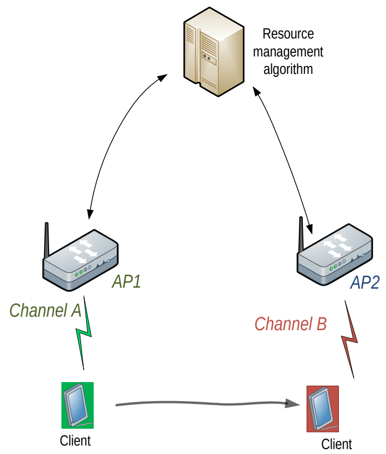


Figure 17: Need for scanning in other channels to trigger hand-offs

a) Precision

The scanning time will have to be long enough in order to detect a number of packets generated by the STA in Channel A, thus avoiding the possibility of missing a STA nearby.

The time between scans will also be carefully defined, considering the speed of a pedestrian, the distance between APs, etc.

b) Delay

In the Wi-5 architecture, all the information has to be available in the controller, so the delay associated with this information exchange not only has to include the delay associated to the connection between the AP and the STA, but the interaction between the Wi-5 controller and the AP. The latter component is expected to be very low (probably negligible in a first approach), taking into account that these components are connected through a wired network (typically 100 Mbps, 1 Gbps or maybe higher).

c) Scalability

Obviously, if AP_2 switches to the scanning mode, it will not serve its clients for a period of time. Therefore, depending on the number of users in the system and their mobility patterns, an excessive amount of scanning requests may harm the QoS of the users. Therefore, different measures will have to be considered and studied in order to avoid these situations:

- Defining hysteresis periods after a handoff;
- Setting an upper bound to the time devoted to scanning in an AP;
- Scanning only in the channels where a user is expected to be (in the figure, AP_2 would only scan in Channel A).
- Using an additional network interface in the AP, only for scanning purposes; etc.

5.2.4 Other scalability considerations

The use of a central controller implies a set of requirements, in terms of the network capacity of the *distribution network* (the wired network connecting the controller with the APs) and the processing capacity of the controller.

a) Network capacity

The information to be exchanged between the controller and each AP includes:

- OpenFlow protocol: Each new flow has to be added to the internal switch of the AP.
- DHCP: Each new STA has to request an IP address. One requirement of Odin is that this information has to go to the controller.
- Power requests and reports to/from the STAs.
- Information associated to the Odin protocol: Subscriptions (events to be triggered by APs); handovers (including moving LVAPs); load balancing, including re-association of STAs to new APs; modification of the parameters of each AP (Channel assignments, power adjustment, etc.).

The overhead caused by these traffic flows (control plane) in the wired network will have to be measured, in order to ensure that it does not pose any limitation for the data plane information, which carries users’ traffic.

b) Processing capacity

The Wi-5 controller must be able to simultaneously run a number of functions:

- OpenFlow controller.
- All the resource management algorithms, including Channel Assignment, Load Balancing, Power control.
- Handoff the clients as a consequence of mobility.

It must be noted that the data acquired from the network with the above described limitations of the measurement processes may require further estimation, prediction and updating processes. These can span the PHY and MAC layers and even higher layers if necessary.

Some pre-processing of the reports sent by the STAs will also be needed before feeding them into the resource management algorithm: measurement filtering, interpolation, estimation of some values from others, etc.

The main conclusions deriving from possible limitations of the measurement processes can be summarized as follows:

- Automatic detection of real-time services based on ML allows us to achieve encouraging results in terms of precision and delay. Moreover, the ML tools will be able to rely on the Wi-5 controller that detects and marks the traffic enabling a reasonable level of scalability.
- Mechanisms to detect the power sent by the STAs will need to compute the precision of the measurements provided by the STA and the delay due to processing the requests. Furthermore, an estimation of the number of users per AP will be needed to compute the consumption of airtime due to these mechanisms.
- The radio environment scanning will have to be long enough in order to detect a number of packets generated by the STA in a certain channel. The delay associated with all the information will also have to include the delay associated to the interaction between the Wi-5 controller and the APs. Moreover, several measures will have to be considered to avoid the detriment of the QoS of the STAs during the scanning process.

6 Conclusions and Further Work

This document has presented the first version of the Cooperative APs Functionalities, which have been developed within the Work Package (WP) 4 of the Wi-5 Project. A detailed literature review has been firstly provided, including several research works in the context of RRM, AP channel assignment, transmit power control, Smart Connectivity and Seamless Handover.

Then, the cooperative functionalities have been addressed in the Wi-5 architecture, whose first version has been presented in detail in Deliverable D2.4. After that, the first version of a cooperative framework has been illustrated, which jointly includes innovative functionalities for an optimized AP channel assignment, RRM and smart AP allocation. In particular, this framework has been designed to efficiently exploit the use of the radio resource, reducing interference between neighbouring APs and providing optimised connectivity for each user that is served by an AP. Therefore, a set of algorithms designed and implemented in the cooperative framework have been presented.

The first algorithm has been designed to allow an optimized channel assignment, which reduces the radio interference throughout the Wi-Fi network. The optimized APs channel assignment enables encouraging results of the network performance in terms of SINR. Furthermore, the results analysed in this deliverable validate the flexibility and practicality of the proposed algorithm in different scenarios. Moreover, a transmit power control mechanism with the aim to assess the channel assignment algorithm, has been also included to achieve the user's required quality, maintaining the acceptable level of interference in the network and providing a tool for energy saving.

Then, another algorithm has been developed to assist the users in the selection of the most suitable AP according to the application running on the station in terms of QoS requirements. The selection of the AP is based on the innovative Fittingness Factor (FF) concept that smartly associates an AP to each new user taking into consideration their bit rate requirements. Furthermore, the allocation of the APs has the purpose to provide satisfactory performance to both an individual user and the overall Wi-Fi network.

After the presentation of the algorithms, a first assessment of these solutions has been provided through the analysis of performance results in a MATLAB-based simulated environment. The results of the assessment of the optimized channel assignment have shown an improvement of the network performance in terms of SINR during the network initialization and after the degradation due to changes in the network. Moreover, the results have demonstrated the flexibility and practicality of the proposed algorithm to include all APs or just some of them in each channel assignment process.

The assessment of the AP selection algorithm based on the FF concept has shown that this solution allows an important bandwidth saving compared against another solution that associates an AP to a user according to the SINR achieved by each AP. Moreover, it has been demonstrated that the saved bandwidth does not affect the user satisfaction, and offers a better satisfaction than the SINR-based algorithm. This proves the bandwidth allocation efficiency of the FF-based algorithm.

As a part of future work, the cooperation framework will be extended to also cover the spectrum mobility functionalities illustrated in this deliverable. Moreover, further performance results analysis will be carried out to assess the overall framework through new metrics representing the whole network performance such as the energy saving.

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

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