What to do With the Wi-Fi Wild West

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Abstract

This document includes the specification of the second version of the Smart Access Point (AP) Solutions, which are being developed within WP3 of the Wi-5 project. After the Literature Review, a global view of the Wi-5 architecture is presented which includes not only the Smart AP Solutions but also the Cooperative Functionalities being developed in WP4.

Next, the Smart AP Solutions are described including the summary of the general approach being followed based on Light Virtual APs (LVAPs). The functionalities enabling Radio Resource Management (i.e. Dynamic Channel Allocation, Load Balancing and Power Control) are reported in detail and the current status of the implementation of the solutions is detailed, with a set of improvements aimed at integrating the support of different channels within the Wi-5 framework.

A multi-channel handoff scheme has been designed, requiring a good synchronisation between the different events, in order to make the LVAP switching happen at the same moment when the STA switches its channel. In addition, the beacon generation has been modified in order to improve the scalability and to give a better user experience during handoffs. Tests measuring the handoff delay are presented using three wireless cards from different manufacturers, and using as test traffic a flow of an online game with real-time constraints. The results show that fast handovers ranging from 30 to 200 milliseconds can be achieved.

The savings provided by frame aggregation, and its effect on subjective quality have also been studied. A methodology including subjective tests with real users has evaluated this effect, using *paired comparison*. The results indicate that bandwidth usage savings and especially significant packet rate reduction can be obtained without degrading players' Quality of Experience (QoE), as long as the overall latency is kept under 100ms. An important finding coming from these results is that the players do not register delay variation introduced by multiplexing.

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Glossary

AddBa	Add Block ACK Request
AP	Access Point
CAIDA	Center for Applied Internet Data Analysis
CCR	Comparison Category Rating
CDMA	Code Division Multiple Access
CRC	Cyclic Redundancy Check
CSA	Channel Switch Announcement
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DFS	Dynamic Frequency Selection
DHCP	Dynamic Host Configuration Protocol
D-ITG	Distributed Internet Traffic Generator
DOI	Digital Object Identifier
DTGCS	Distributed Traffic Generation Control System
ESS	Extended Service Set
ETSI	European Telecommunications Standards Institute
FF	Fittingness Factor
GSM	Global System for Mobile Communications
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IMUNES	Integrated Multiprotocol Network Emulator/Simulator
ISO	International Organization for Standardization
LCCS	Least Congested Channel Search
LLC	Logical Link Control
LTE	Long Term Evolution
LVAP	Light Vırtual Access Point
MAC	Media Access Control

MMORPG	Massively Multiplayer Online Role Playing Game
MOS	Mean Opinion Score
MPDU	MAC Protocol Data Unit aggregation
MSDU	MAC Service Data Unit aggregation
MTU	Maximum Transmission Unit
NFV	Network Function Virtualisation
PHY	Physical Layer
PLCP	Physical Layer Convergence Protocol
PPP	Point to Point Protocol
QoE	Quality of Experience
QoS	Quality of Service
RF	Radio Frequency
RFC	Request For Comments
RRM	Radio Resource Management
RTP	Real Time Protocol
RTT	Round Trip Time
SDN	Software-Defined Network
SDWN	Software-Defined Wireless Network
SINR	Signal to Interference plus Noise Ratio
SNAP	Subnetwork Access Protocol
SOHO	Small Office / Home Office
STA	Wi-Fi Station
TCP	Transmission Control Protocol
TCRTP	Tunnelling Compressed RTP
TPC	Transmit Power Control
UBS	User Behaviour Simulator
UDP	User Datagram Protocol
UrBBaN-Gen	User Behaviour Based Network Traffic Generator

USB	Universal Serial Bus
VoIP	Voice over Internet Protocol
WLAN	Wireless Local Area Network
WMM	Wi-Fi Multimedia

Executive Summary

This deliverable presents the second version of the specification for the mechanisms to be included in the Wi-5 Access Points (APs) to perform dynamic channel allocation, load balancing and power control. It also includes a definition of the policies to be employed when using packet grouping between the AP and the end device, as defined in 802.11n and 802.11ac. The integration with the coordination entities of the Wi-5 architecture and the interface with performance monitoring mechanisms are also be defined here.

The present document summarises the work carried out regarding the Smart Access Point Solutions during the second year of the Wi-5 project. This specifies the radio configuration capabilities allowing the use of resource management algorithms, including dynamic channel allocation, load balancing and power control. The mechanisms for including packet/frame grouping are also considered here. These functionalities describe a scenario where all the APs are managed by a controller, which has a global view of the network.

After the Introduction, the Literature Review and a global view of the Wi-5 architecture to understand the context, the main sections of this deliverable are devoted to explaining the functionalities enabling all the Wi-5 features, with additional information about their implementation:

- The framework being used for the implementation of the Wi-5 functionalities, based on the use of Light Virtual APs (LVAPs).
- The new horizontal handover scheme, integrating multi-channel APs with the LVAPs approach. This includes some tests of the handoff latency, illustrating that they can really be *seamless*, i.e. not disrupting the ongoing connections.
- Test software which has been developed for measuring the savings of frame aggregation mechanisms is presented, and used for testing.
- A set of subjective tests of the effect of multiplexing on the QoE, showing that, under certain conditions, the users may not notice the additional required delay.

A conclusions section surveys the work that has been carried out.

Two innovative aspects can be remarked: firstly, the combination of the use of LVAPs with multi-channel APs allow two key features at the same time: seamless handovers, and radio resource management. The obtained results show that the possibility of combining LVAPs with multi-channel is feasible, even with highly demanding services. And second, the fact of being able to aggregate packets without disturbing the users is also relevant, as this opens the possibility of grouping small packets in wireless environments, which can provide a significant improvement in efficiency.

1 Introduction

1.1 Background to project

The last few years have witnessed a significant increase in the use of portable devices, especially smartphones and tablets which, thanks to their functionality, user-friendly interfaces and affordable prices, have become ubiquitous worldwide. Most of these devices make use of IEEE 802.11 wireless standards, commonly known as Wi-Fi.

Given this increasing 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 in order to enhance its performance. For example, as Wi-Fi saturation increases in congested scenarios such as business centres, malls, campuses or even whole European cities, interference between these competing Access Points (APs) can negatively impact the user's experience.

At the same time, real-time services with tight latency constraints are becoming ubiquitous. For example, VoIP (Voice over Internet Protocol) services such as *Skype* are now very popular. Furthermore, some instant messaging applications (e.g. *WhatsApp*) also include VoIP features. Finally, online games are no longer exclusive of high-end desktops, but are also run on tablets or even smartphones. These real-time services share the same connection with "traditional" applications, such as e-mail and Web browsing, but have different requirements (tight latency constraints) in order to meet the Quality of Experience (QoE) demands.

In addition, the availability of these services in mobile devices has a consequence: whereas the mobility of a user with a laptop can be considered as *nomadic* (i.e. the user may move, but he/she will stay for a long time in the same place), smartphone and tablet users do walk while using these real-time services.

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 solutions able to efficiently reduce interference between neighbouring APs and provide optimised connectivity for new and emerging services. Cooperating mechanisms are being integrated at different layers of the protocol stack with the aim of meeting a demanding set of goals such as seamless hand-over, reduced congestion, increased throughput and energy efficiency. The project is developing a variety of different solutions, which are being made available in academic publications, in addition to other potential dissemination channels for industrial exploitation and standardisation.

1.2 Scope and structure of the deliverable

This deliverable presents the second version of the specification of the mechanisms to be included in the Wi-5 APs to perform dynamic channel allocation, load balancing and power control. It will also include a definition of the policies to be employed when using packet grouping between the AP and the end device, as defined in 802.11n and 802.11ac. The integration with the coordination entities of Wi-5 architecture, and the interface with performance monitoring mechanisms will also be defined.

Therefore, this report summarises the work carried out regarding the Smart Access Point Solutions during the second year of the Wi-5 project. This includes the radio configuration capabilities allowing the use of resource management algorithms, including dynamic channel allocation, load balancing and power control. The mechanisms for including packet/frame grouping are also included. These functionalities consider a scenario where all the APs are managed by a controller, which has a global view of the network.

Beyond the Introduction, the rest of this document is structured as follows. A Literature Review is first provided in Section 2, related to the topics covered here. Next, a global view of the Wi-5 architecture is presented, including the smart AP solutions described here and the cooperative functionalities. Section 4 is devoted to explaining the functionalities enabling all the Wi-5 smart AP features, with additional information about their implementation. The new horizontal handover scheme, integrating multi-channel APs with the Light Virtual APs (LVAPs) approach is presented and tested. The test software that has been developed for measuring the savings of the frame aggregation mechanism is presented and used for testing. In addition, subjective tests of the effect of multiplexing are presented. The document ends with a conclusion in Section 5.

1.3 Relationship to other deliverables

The five use cases and their requirements were reported in Deliverable 2.3, including the different scenarios, the applications and the services considered. The functionalities included in the present document will be in charge of enabling the accomplishment of these requirements.

The current version of the Wi-5 architecture is presented in Deliverable 2.5i "Interim Wi-5 architecture", which provides a global view of the whole set of solutions being deployed, including the Smart AP Solutions explained in this deliverable. The architecture is described according to the ISO-IEC-IEEE 42010 standard, and the requirements are presented in the context of the business and stakeholders' requirements.

Some features regarding Smart AP Solutions were already reported in the previous version of this deliverable (Deliverable 3.2 "Specification of Smart AP Solutions version 1"), so they will not be included again here. For example, the reader can find in Deliverable 3.2 the studies carried out with Simplemux. In some other cases, when the functionalities have experienced a significant update, new versions of some parts of Deliverable 3.2 are included in the present document.

The Wi-5 monitoring functionalities are reported in Deliverable 3.1 "Definition of the performance monitoring mechanisms", also released in MS4, which not only includes the features able to monitor the wireless environment, but also the tools for automatically detecting real-time services.

The Cooperative Functionalities, being deployed in WP4, are explained in detail in Deliverable 4.2 "Specification of Cooperative Access Points Functionalities version 2". These functionalities are tightly related with the Smart AP Solutions, since they have to run in an integrated and seamless way in order to provide the desired performance.

The document Deliverable 5.1 "Testbed description and definition of the tests" includes a description of the platforms for the evaluation tests, which will be carried out using the tools presented in the current document.

2 Literature Review

2.1 Use of Virtual Wi-Fi APs in Software-Defined Wireless Networks (SDWNs)

The SDN (Software-Defined Networking) concept aims to separate the network control and data plane, allowing an abstraction of the underlying technology for applications and services. It is becoming increasingly popular, since it provides a coordinated programmable interface for network managers. In combination with NFV (Network Function Virtualisation), it is becoming a concept considered not only in wired networks, but also in wireless environments [1]

Different high-level languages have been proposed for SDNs [2], [3], but they are mainly designed for wired networks based on the OpenFlow protocol [4] for data plane control. However, the work in [5] surveyed a set of abstractions for wireless networks, as OpenFlow does not itself capture all the issues appearing in wireless scenarios. For example, the "flow" abstraction proposed by OpenFlow does not reflect the stochastic nature of wireless links (which are very different from an Ethernet connection), so it does not suffice for network management in wireless environments.

One of these abstractions is the concept of the *Light Virtual Access Point* (LVAP), first proposed in [6]. It assumes that there is a central controller, to which all the APs are connected. The controller creates an LVAP for each terminal, which is dynamically assigned to the physical AP where the terminal is located at each moment. Therefore, the AP will use a different LVAP (which includes a specific MAC address) for communicating with each terminal. So, the terminal will only "see" a single AP even if it is actually moving between a number of them, thus avoiding the need for re-association (see Figure 1). In [7], a solution also based on LVAPs was presented, which is able to perform very fast handoffs between different APs controlled by a single entity. An open-source implementation (called *Odin)* was also developed.

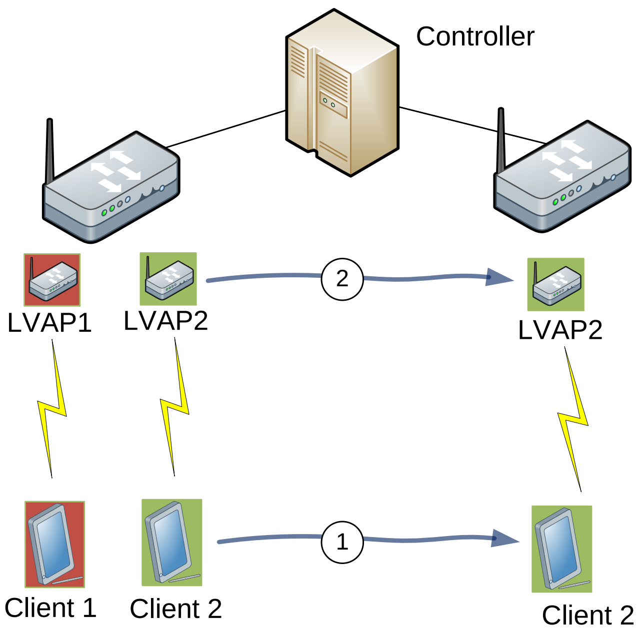


Figure 1: Scheme of a Wi-Fi network using LVAPs

In [8] the concept of *Multichannel Virtual Access Point* was introduced, adding to the LVAP the possibility of using different channels. This allows a STA to change its AP and channel at the same time, synchronising both events. The article proposed a protocol for the exchange of information between APs. For that aim, they used the *CSA (Channel Switch Announcement)* element of the 802.11 beacon. This message makes all the STAs associated to an AP move to a specific channel.

More research has recently been published which also uses the concept of LVAP, and can also provide fast handovers: in [9] a scheme called BIGAP is presented, which is based on the use of a mechanism below the Media Access Control (MAC) layer for handover, exploiting the Dynamic Frequency Selection (DFS) capability in 802.11. In a similar way to the solutions developed by Wi-5, it does not require any modifications to the STAs. However, it requires the support of 802.11n [10] or 802.11ac [11], including the IEEE 802.11h [12] amendment. In addition, it requires the existence of a sufficiently large number of available RF channels in order to allow the possibility of different channels being assigned to co-located APs. This is feasible in the 5GHz band (there are 25 channels with DFS), but it may not be feasible in the 2.4 GHz band.

Finally, it should be noted that the literature related to monitoring the wireless environment and service detection is summarised in Deliverable 3.1 and is not included here.

2.2 Resource Management in Wi-Fi WLANs

Radio resource management (RRM) approaches aim to design the appropriate strategies and algorithms for configuring wireless transmission parameters in order to efficiently utilise the limited radio resources. In the context of Wi-Fi networks, the RRM solutions in Wi-5 focus on three main issues: smart channel selection, dynamic transmit power control and load balancing. A literature review of these functionalities is provided hereafter. In the Wi-5 project, these functionalities aim at operating in scenarios where a large number of uncoordinated APs operate simultaneously to ensure more efficient resource reuse for the communication between APs and terminals. The aim of the Wi-5 architecture is to present an over-the-top implementation to interact with neighbouring APs, which jointly performs these three features to find the best overall configuration and thus minimise interference in a heterogeneous environment.

SDN approaches are becoming popular in wireless environments: for example, in [13] the authors used SDN and cloud computing ideas to manage interference in Cognitive Radio Network deployments in residential areas. Wi-5 also relies on the use of SDNs in order to achieve its goals.

2.2.1 Smart channel selection

Due to the limited number of orthogonal channels the 802.11 standard supports, high levels of interference are expected, which in the end will lead to a reduction in network efficiency and therefore in the Quality of Experience (QoE). In this context, in recent years several channel assignment schemes for infrastructure-based WLANs have been proposed [14]. Most of these works propose centralised algorithms that assume a network that belongs to one administrative domain [15], [16], [17], [18], [19]. 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. Some of these cases are covered by the Wi-5 use cases.

In some of these scenarios, channel assignment algorithms, where APs can be configured to manage their operating channels and their transmitted power level to minimise interference with adjacent APs, would be required. In this context, Least Congested Channel Search (LCCS) is a common feature provided by commercial APs [20] 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. This basic mechanism suffers from the so-called *hidden interference* problem (an AP not listening to another AP, but suffering interference from a client associated with that AP) and it does not take into account the traffic patterns of the devices, but only the number of devices. Other mechanisms trying to improve the performance of LCCS in an uncoordinated scenario have been proposed and evaluated through simulation [21], [22], [23]. In [24], a game-theoretic framework was utilised to construct a joint transmission power control and dynamic channel assignment scheme which reduces the total overlap area, thus reducing interference.

In [25] the authors introduced 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 analysed the relationship between network throughput and channel assignment by using partially overlapping channels in SINR interference model. Then, they proposed a heuristic algorithm in order to assign overlapping channels to the APs in the system such that the network throughput can be maximized.

The aforementioned studies exemplify the solutions with an overall network interference indicator set to be tracked that guides the assignment of the channels. The channels are also assumed to have predefined characteristics. However, 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 [26]. 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 of these networks. Subsequently, more recent studies tend to provide solutions explicitly proposed for specific use cases such as high density networks [27] and areas with uncoordinated interfering network elements [28] which are among the most challenging contemporary deployments of Wi-Fi networks.

In [29] the authors have proposed a solution for radio resource management in dense Wi-Fi deployments in residential scenarios. The proposal is that the AP performs an initial scan for other APs, allowing the exchange of some information between them. A secure point-to-point channel between the APs is then established through the wired Internet, which allows the execution of different resource management algorithms including the coordination for a better channel assignment. The authors have also implemented a proof of concept of the solution that includes a distributed channel assignment algorithm.

2.2.2 Dynamic transmit power control

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 RF output power. This may result in high levels of interference on the same channel, increasing the probability of packet collisions, making 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 also been proposed for 802.11 trying to reduce interference and improve spatial reuse in order to increase network capacity.

One of these methods is MiSer (Minimum-energy transmission Strategy) [30], an algorithm based on the link-quality estimation scheme defined for TPC in IEEE 802.11h. The WLAN station (STA) 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 attempt 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 of transmission failures, thus causing re-transmissions and eventually consuming more energy. The key point of MiSer is to combine TPC with PHY rate adaptation and pre-establish a rate-power combination table. At runtime, a wireless station determines the best transmit power as well as the PHY rate for each data transmission attempt based on the rate-power combination table. MiSer relies on communication between the clients and the AP in order to complete the table data, and hence it requires that the appropriate software must be running on both the AP and client stations in order for the technique to be used.

Another option is to use Contour-Slotted power control management [31]. Its main goal 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 where 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. However, Contour also needs GPS synchronisation, which is an important weakness for indoor deployments.

Symphony [32] considers 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 link and network throughput.

2.2.3 Load balancing

Since STAs independently select the APs to connect to, the traffic in WLAN networks can be unevenly distributed, which leads to inefficient use of the available resources. Load balancing techniques try to solve this problem by better distributing the traffic load in the network. In [33] a survey of both network- and wireless-station-based solutions is presented. For example, in [34] a combined metric consisting of the number of stations associated, and mean and instantaneous RSSI for each of the clients associated with this AP is used. A similar AP-assisted approach has been proposed by Cisco [35], to give associated client information about the load through beacons. Both these solutions require modifications on the client side. Murty *et al*. [36], and Chandra and Bahl [37], achieve fair load balancing between APs through a centralised management approach that aggregates AP workload, which requires changes in the wireless network infrastructure. No modifications in the STA are considered in Wi-5.

2.3 Packet/Frame Grouping at Different Layers

An inherent characteristic of packet-switched networks is the need for a number of headers, which are added to the payload in order to make it possible to transport the data from the source to the destination. This overhead is not a problem when the payload is big, but the inefficiency caused by very small payloads (in the order of tens of bytes) may become excessive in certain scenarios with limited resources.

However, small packets are ubiquitous in nowadays' networks. The first example, and perhaps the most evident one, is TCP Acknowledgements (ACKs), which are required by the traffic control mechanisms inherent to this Transport Layer protocol. These packets do not usually carry any payload, so they can be considered as 100% overhead packets. However, they are carried by the network in the same way as any other packet. In addition, emerging real-time services (e.g. VoIP, online games) also send high rates of small packets, required to meet the interactivity level demanded by the end users. Finally, small packets may also be present in Machine to Machine and IoT (Internet of Things) scenarios with limited network and energy resources.

As reported in [38], which used a traffic trace at a backbone link from the *CAIDA Anonymized Internet Traces* 2015 Dataset [39], a high number of small packets are present in the public Internet: 33.4% of the packets were 60 bytes or smaller, and 41.4% overall were 200 bytes or smaller. The presence of these levels of small packets has some drawbacks: first, the *overhead* drawback, i.e. the relative amount of header bytes required for sending a small payload is high. For example, a VoIP packet carrying 20 bytes requires at least 40 bytes corresponding to IP, UDP and RTP headers.

Second, when a small packet is passed to Layer 2, the MAC mechanisms make it necessary to define a number of waiting intervals until a host gets the channel. CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) is the mechanism employed in 802.11. This delay may be negligible in Ethernet (a preamble, a header and an inter-packet gap are only required), but it may become significant when packets are using a wireless technology such as 802.11.

The efficiency reduction in wireless networks is exacerbated for small packets. As explained in [40], when UDP and TCP packets of different sizes are sent following the 802.11 standard, a significantly low efficiency was observed when small packets (some tens of bytes) were sent, since the time required for medium access is in the same order of magnitude as the time required for the actual transmission of the data.

There is another drawback related to the limited processing capacity of the machines managing the packets. Datasheets of commercial devices often report the performance both in terms of bandwidth and packets per second. For example, a commercial 50-Port switch [41] has *"13.6 Gbps switching capacity, 10.1 million pps".* This means that, for 100-byte packets, the throughput of the switch would in fact be limited to 8.08 Gbps. Other hardware drawbacks may also appear: for example, the energy consumed by a router is expected to rise not only with the generated and received throughput, but also with the amount of packets per second it is managing.

In this context, the aggregation (multiplexing) of a number of small packets of frames, to form a single and bigger one can be seen as a means to jointly overcome these drawbacks. Some initiatives aimed to increase the average size of the Internet packets are already in place. For example, Ethernet Jumbo Frames, with an MTU of 9000 bytes instead of 1500, present some advantages in terms of throughput, and even in the TCP window growth speed [42]. Furthermore, in Wi-Fi networks, frame aggregation was added as an option to 802.11n, and it is compulsory in 802.11ac.

Aggregation can be deployed in Layer 2 or in upper layers, but there are some differences between these two possibilities. If frames are multiplexed at Layer 2, they will traverse only a single link together, and then they will be de-aggregated. If the common path includes a number of links, a demux-mux process will be required at each node. However, if multiplexing is deployed at the upper levels, packets can travel together during the whole path, thus reducing the processing in the intermediate nodes, at the cost of adding a tunnelling header which allows end-to-end delivery. If aggregation is not available at Layer 2 (e.g. legacy devices not implementing Wi-Fi frame aggregation), Layer 3 mechanisms can be employed.

Regarding Layer 2, two frame multiplexing policies are included in 802.11n (and subsequent versions), namely MAC Service Data Unit aggregation (A-MSDU) and MAC Protocol Data Unit aggregation (A-MPDU). Aggregation has become even more important in 802.11ac, where all the frames must have an A-MPDU format, even if they include a single sub-frame. The former allows multiple MSDUs to be sent to the same receiver, as a single MPDU. The latter is able to join a number of MPDU sub frames sharing a single leading PHY header. The main difference is that A-MPDU works after the MAC header encapsulation. This presents two advantages: a higher bandwidth reduction, and the fact that each sub-frame includes its own CRC (Cyclic Redundancy Check), which avoids the need for discarding the whole frame because of an error in a single sub-frame: if a sub-frame is wrong, only that one will be retransmitted.

A number of research works have studied the achievable savings when using 802.11 aggregation. In [40], the authors presented an analytic model for estimating the improvements of A-MPDU and A-MSDU. Their findings showed a significant efficiency increase, and a better performance of A-MPDU, which was stressed when the packet-error rate was high. In [43] a scheduler for selecting the packets to be multiplexed together was proposed, taking into account that the 802.11 standard only specifies the frame format, but scheduling schemes are left as the vendor's choice. An optimal frame size was calculated, and packets were grouped trying to fit this size. In [44], the number of aggregated sub-MAC protocol data units was optimised and adjusted dynamically according to the sub-frame size, the maximum aggregation level allowed and the real-time channel bit-error-rate, thus increasing the throughput.

Multiplexing at higher layers has been studied in some works: [45] and [46] presented different proposals for VoIP optimisation, trying to keep a good voice quality. The adaptation of TCRTP for other real-time services such as online games has also been proposed [47]. Aggregation has also been proposed in SDNs: relying on the flow identifier of OpenFlow, many of the fields that are repeated in all the packets of a flow can be avoided, and a number of packets can also be aggregated [48]. Different standard protocols for multiplexing packets at higher layers do exist, such as TMux [49], PPPMux [50], or TCRTP (Tunnelling Compressed RTP) [51], which combine header compression with multiplexing and tunnelling, in order to optimise VoIP RTP flows.

2.4 Wi-5 innovation challenges

Different gaps in the existing work have been identified that can be addressed as part of the Wi-5 objectives. For example, the integration of LVAPs with multichannel in a centralised scheme was seen as convenient, since the available solutions considered that all the APs are in the same channel, which is not compatible with frequency planning. The results obtained in the subsequent sections show that this is feasible, since very fast handovers have been demonstrated in the Wi-5 setup between APs in different channels, without disrupting the connections and avoiding the need for re-association (see Subsection 4.2.1). However, this will introduce some complexity as an additional wireless interface is required in order to detect STAs in other channels which are approaching the AP. In addition, the scalability problems that may appear when using an LVAP approach (i.e. multicast beacons cannot be used) have to be solved. As we will see, the use of two different inter-beacon time intervals (one for regular beacons and other one for sending the beacons after a handoff) can solve the problem.

Regarding packet aggregation, current solutions do not consider the kind of service in order to limit the maximum additional delay. Different queues, with different priorities, are used according to the service but a mechanism to limit the additional delay caused by aggregation is not considered. As a result, the savings in terms of bandwidth and efficiency may come with the counterpart of a reduction in the subjective quality perceived by the users. A very challenging scenario, with players of an online game with real-time constraints, will be used for carrying out a *paired comparison* test, in which the users have to run a service twice, without knowing if the aggregation is active or not. In contrast to other works, we will not directly try to map the impact of specific network parameters onto players' QoE, but we aim to investigate whether traffic optimisation based on aggregation can be performed without QoE degradation (see Subsection 4.4.3).

3 Global view of the Wi-5 Architecture

In this section, we provide a global view of the Wi-5 architecture to describe how the work presented here fits in this context. A more detailed explanation of this can be found in deliverable D2.5i "Interim Wi-5 architecture."

The design of the Wi-5 architecture relies on the separation of control and data planes in Wi-Fi APs based on the SDN approach. We have followed this approach in order to have a single point where all the control operations can be integrated. The most important entity is the Wi-5 controller, having a global view of the network, and being able to run different algorithms for optimising the network traffic.

An SDN approach, relying on OpenFlow [4] protocol, is being used so the Wi-5 controller runs within an OpenFlow controller. Therefore, certain functionalities (e.g. load balancing, channel selection) run as applications on top of the controller (see Figure 2).

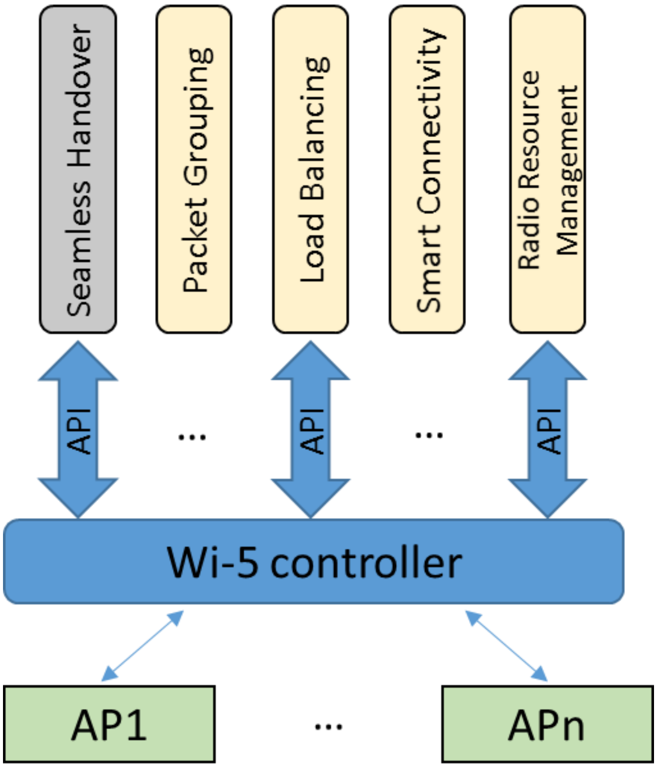


Figure 2: Scheme of the Wi-5 architecture design

In order to make it possible for the controller to manage all the APs, new functionalities have been included on each of them, i.e. their internal switch must become an OpenFlow switch, and a Wi-5 agent is added in order to interact with the Wi-5 controller. Something similar has been done with the OpenFlow controller, where new features have been added in order to interface with the Wi-5 functionalities.

Figure 3 shows the scheme of the Wi-5 entities, indicating the place where they are implemented, and how they interact between them. Monitoring functionalities run in the Wi-5 agent included in each AP, but a centralised approach is also considered for e.g. detecting the kind of application. Decisions about resource management (channel selection, power control and load balancing) are made by the central controller. Decisions about packet grouping can also be made by the controller, but the frame aggregation takes place at the AP. It should be noted that the present document is complemented by deliverable D3.1 “Definition of the performance monitoring mechanisms,” where all the monitoring functionalities required for the Wi-5 optimisations are described.

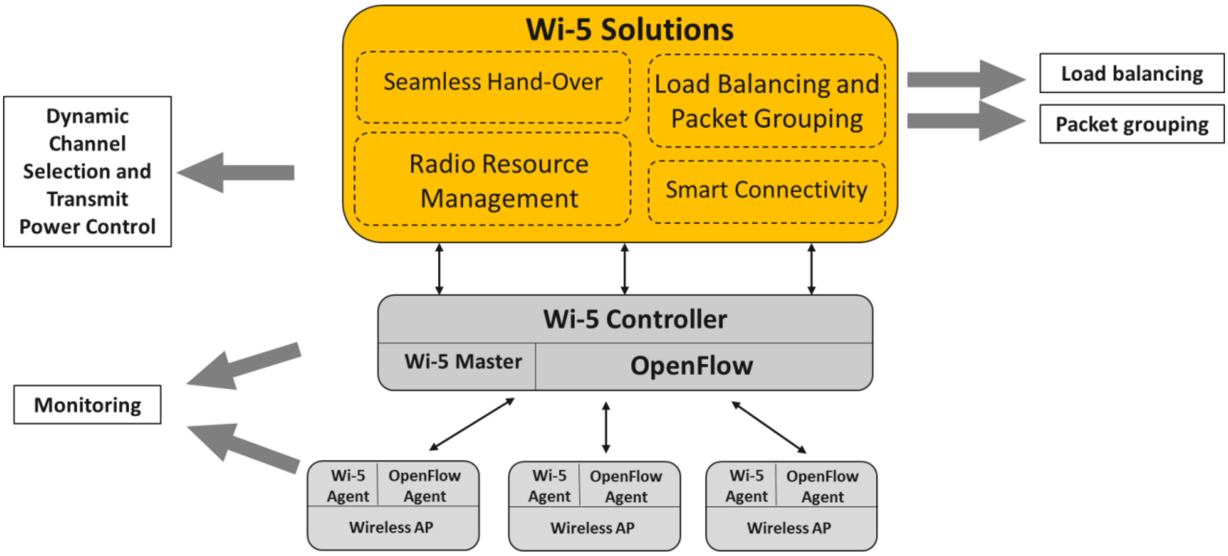


Figure 3: Scheme of the Wi-5 entities

One of the aims of the Wi-5 project is to make it possible for a set of APs to support real-time applications (e.g. VoIP, online games) with quality. This includes resource management algorithms that take into account the nature of each flow, and its coexistence with other services. In addition, seamless handovers between APs are not only required for supporting user mobility, but also for the optimisation of radio resources. The use of LVAPs implementing a virtual Wi-Fi network (see Figure 4) enables seamless handovers [40], which may be acceptable even for users of real-time applications with tight delay constraints. The handovers can be from one AP to another (horizontal), but the possibility of handing off a STA to the 3G/4G network (vertical handover) is also under consideration, if it is required to provide the quality level demanded by the user.

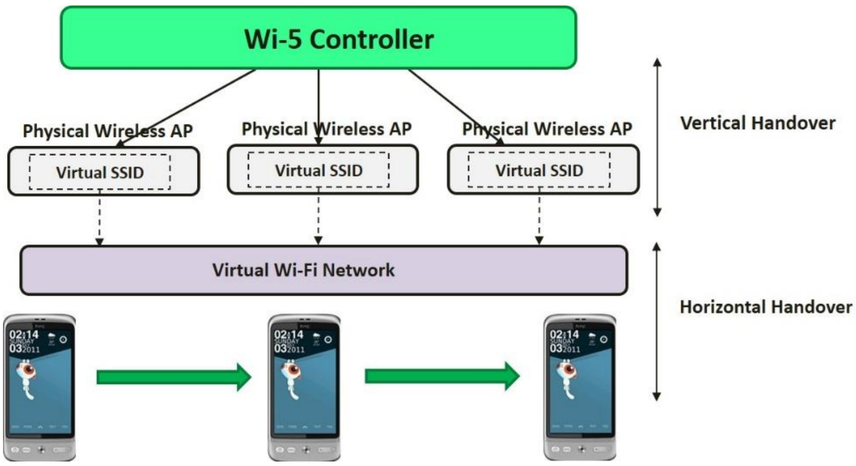


Figure 4: Seamless Handover using Wi-5 Architecture

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

- *Smart Access Point Solutions*, aimed to enable the improvement of Wi-Fi networks by means of radio configuration capabilities and resource management algorithms, including dynamic channel allocation, load balancing and power control. The use of packet/frame grouping is also considered. These functionalities consider a scenario where all the APs are managed by a controller.

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

Figure 5 illustrates how the different Wi-5 solutions work together to deliver optimised Wi-Fi services. The diagram presents the flows among the different components and solutions included in Wi-5: the STA requests connectivity from the wireless AP, and also sends and receives traffic. The monitoring module of the AP transmits a series of parameters (e.g. power, interference level, etc.) to the controller's monitoring module for aggregation and analysis with those from other APs in the network. The resulting information can then be used by the algorithms to make decisions about load balancing, activation (or de-activation) of packet grouping, radio resource management, etc. The decisions are implemented by the network configuration module in the controller and may affect a number of APs, which will each be implemented by means of their AP network configuration modules. Finally, in some cases, these decisions will also affect some STAs, which may have to modify their channel or be handed off to another AP.

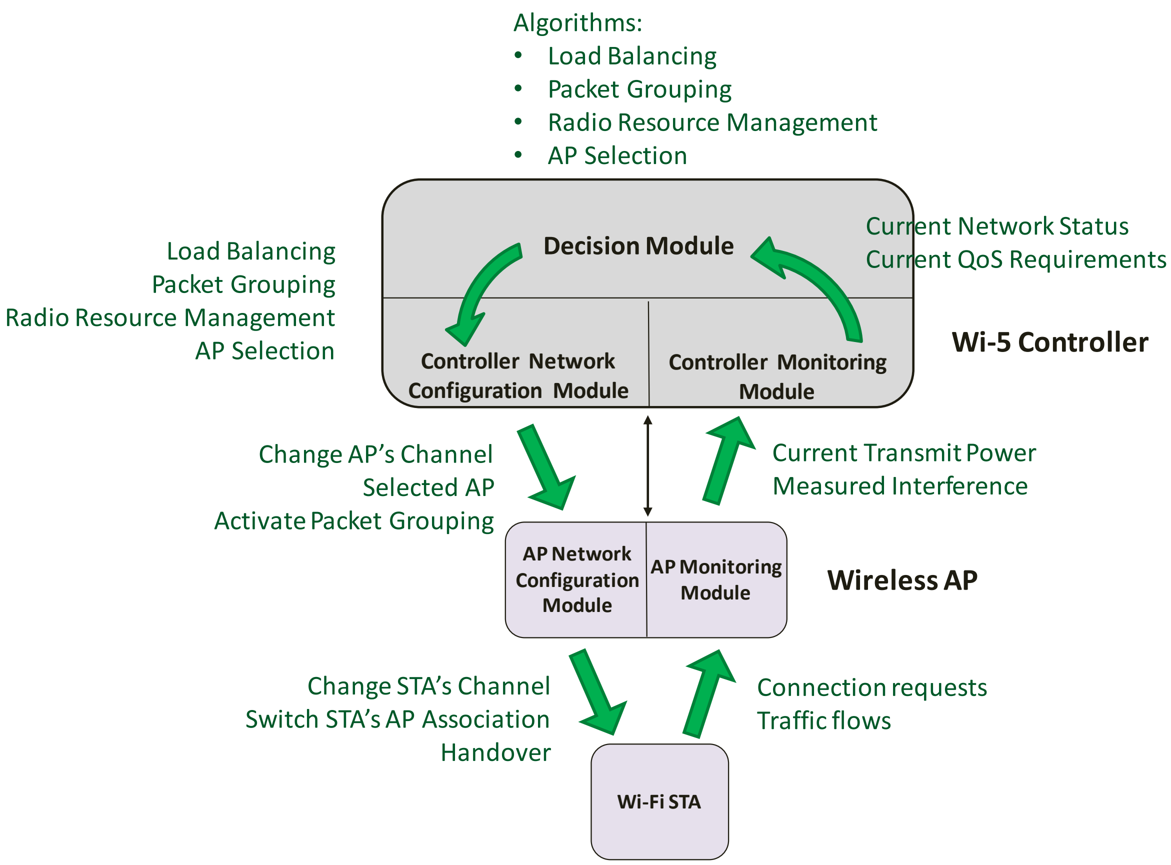


Figure 5: Relationship between the different Wi-5 components

3.1 Smart Access Point Solutions

This subsection provides a brief summary of the solutions that will be explained in more detail in Section 4. The Wi-5 Smart AP Solutions are a set of improvements being developed in WP3 considering a centralised cooperation between APs. As shown in Figure 6, a number of APs are connected to a central controller using a wired network as a backhaul. This controller is able to manage the radio parameters of the APs, and to perform load balancing of users. The power of the signal of the AP can also be centrally tuned, in order to reduce the interference level and to save energy. Monitoring elements are also placed in every AP, which report the status of the network to the controller.

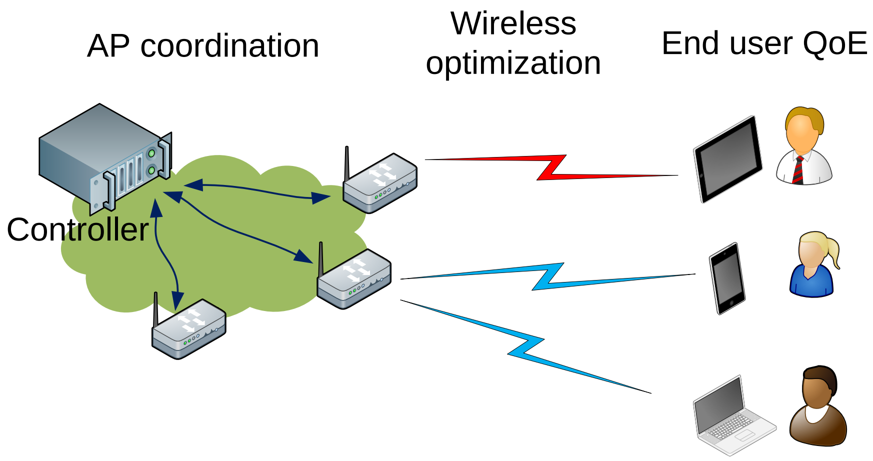


Figure 6: Basic scheme of the smart APs architecture

The functionalities can be summarised as:

- Performance monitoring, including two capabilities: firstly, an automatic detection feature able to identify the flows with real-time requirements. Secondly, the scanning of the radio environment in order to have accurate information about the interference level on each channel, the power being sent by the STA, etc.
- Radio Resource Management. This includes mechanisms allowing a good performance of the algorithms being deployed in the Wi-5 architecture: (i) Dynamic Channel Allocation, looking for an optimal distribution of the channels of the APs, in order to reduce the interference; (ii) Load Balancing, looking for an optimal distribution of the users between the APs; (iii) Power Control, trying to keep the level signal as low as possible, in order to save energy and to reduce the interference.
- Packet grouping, considering smart scheduling policies enabling a better use of the aggregation policies already included in 802.11n and subsequent versions. This alleviates the airtime inefficiency caused by the STAs requesting the shared channel before being able to send actual data. For legacy devices not including aggregation at Layer 2, multiplexing packets at Layer 3 can also be a solution.

3.2 Cooperative Functionalities

This section presents a summary of the second version of the algorithms designed to efficiently exploit the use of the radio resources, reducing the interference between neighbouring APs and providing optimised connectivity for each user/flow that is served by an AP in the considered scenarios. A more detailed explanation of the developed algorithms has been included in deliverable D4.2 *"Specification* *of Cooperative Access Points Functionalities version 2"*. In more detail, several improvements have been developed with the aim of achieving the following purposes:

- Defining a RRM algorithm to address interference in Wi-Fi networks by combining both channel assignment and transmit power adjustment techniques. The proposed approach aims to improve the application flow QoS, while at the same time considering the effect of the configuration on the rest of the network.
- Defining an enhanced AP allocation algorithm that will assist users/flows in selecting the most suitable AP according to the application running on the STA in terms of QoS requirements.
- Defining a preliminary version of a strategy that extends the AP selection towards vertical handover between Wi-Fi and 3G/4G mobile networks.

3.2.1 Radio Resource Management algorithm

The RRM algorithm presented in D4.2 is composed of channel assignment and transmit power adjustment strategies. The channel assignment process is based on an objective function which reduces the magnitude of the interference in the whole system. In detail, this strategy allows the Wi-5 controller to find an optimised channel distribution, in terms of interference for the different APs, in a network based on (i) the Wi-Fi system properties (e.g. IEEE 802.11's standard channel characteristics); (ii) the logical network topology (the AP distribution throughout the network); and (iii) the desired resource management criteria (the assigned channels, interference related QoS, or handover requirements). At the same time, the power adjustment process provides the capability of setting the transmission power of the APs such that the QoS requirements of the flows are met, and the interference level in the network is maintained close to its optimal value defined through the channel assignment process.

3.2.2 Access Point Selection Algorithm

The AP Selection algorithm implements a smart connectivity, based on the Fittingness Factor (FF) concept, in charge of associating an AP to each new user/flow, taking into consideration its bit rate requirements. This algorithm extends the *Network Fittingness Factor* metric introduced in Deliverable D4.1, which efficiently addresses the QoS requirements of both a flow joining the network and other active flows in the network. Note that the FF inherently considers the heterogeneity of the requirements for the different STAs accessing the network, so that not all the APs are equally appropriate for all the users/flows depending on the application needs.

3.2.3 Vertical Handover

The Vertical Handover policy that has been introduced in D4.2 includes strategies that will allow the most suitable connection for each new user/flow between Wi-Fi APs and 3G/4G mobile stations for dual-interface devices.

3.2.4 Monitoring Tools and Radio Configuration

The functional blocks defined in the Wi-5 architecture which will implement RRM, AP selection and vertical handover algorithms will rely on a set of monitoring tools included in the Wi-5 APs and in the Wi-5 controller.

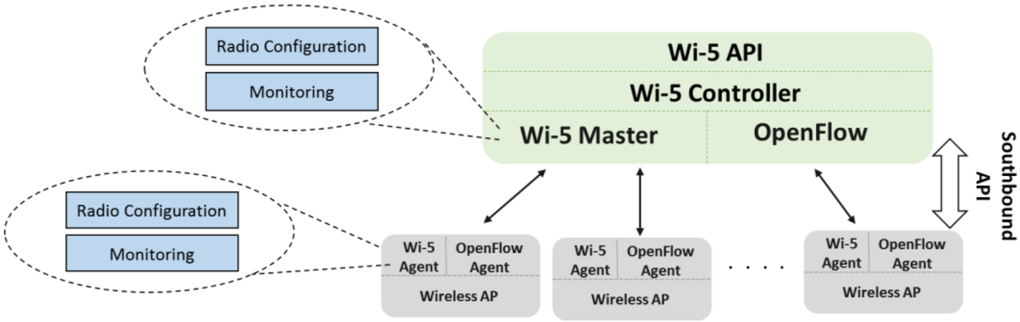


Figure 7: Radio configuration procedures

The role of these tools 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 with each AP; (iii) automatic identification of different kinds of user services in terms of bit rate requirements (e.g. a combined PHY and MAC layers process at the APs). These monitoring mechanisms are helpful during the decision-making process at the Wi-5 controller. For instance, monitoring the interference levels can support the channel assignment process implemented in the RRM algorithm during the initialisation of the Wi-Fi network, or during a possible reassignment of the channels due to a change of status in the network. This functionality provides the Wi-5 agents with the channel allocated to each AP. Moreover, the information on the interference levels supports the AP selection procedure when a new user/flow tries to join the network. Therefore, the results of these algorithms may trigger a reconfiguration of a certain AP, providing the Wi-5 agent in the allocated AP with the appropriate radio configuration parameters through the southbound API, as illustrated in Figure 6.

4 Wi-5 Smart Access Point Solutions

The Wi-5 architecture includes a series of improvements for AP cooperation (be it intra or inter-operator). Therefore, a number of functionalities and procedures have been defined in WP3 in order to enable the different considered optimisations. This section details the current design and definition of these features. These functionalities are exploited by the radio resource management algorithms, and also in the cooperative functionalities summarised earlier and detailed in D4.2.

4.1 Light Virtual APs for the coordination in Wi-5

Odin [7] has been selected for the implementation of the Wi-5 functionalities, as discussed in Deliverable D2.4 *"Wi-5 initial architecture"*. The main reason for this selection is that it is based on LVAPs, so it is suitable for supporting load balancing, dynamic channel and power configuration and other interesting features in multi-channel WLANs. There is an additional advantage: in regular Wi-Fi, the handover is usually triggered by the user device so it is not controlled by the network, and it may require 1 or 2 seconds to perform [5]. In contrast, this SDWN solution allows the network to control the mobility and to select the best moment for the handover, which can be very fast.

Some initial measurements were performed with the aim of testing the Odin handover. They were published in [52] and presented as a demonstration paper in NetGames 2015[1], a conference about network support for online games. An online game with very strict delay limits was selected because it is a good example of a real-time application with tight latency constraints. The tests showed that handovers can be really fast, to the extent that a player cannot detect if his/her device is being switched from a Wi-Fi AP to another. However, these tests were based on a single-channel approach, i.e. all the APs were in the same channel. The present document expands this initial approach for its use even with APs in different channels.

As explained in the Literature Review (subsection 2.1), Odin proposed and implemented an LVAP-based wireless LAN solution. It includes a central *controller*, and a set of *agents* (i.e. the APs). The system is based on commodity OpenWrt APs with a single radio using OpenFlow.

OpenWrt is a Linux distribution for embedded devices. It does not create a single, static firmware, but it provides a fully writable file system with package management. This enables application selection and configuration. As said in the project web page[2]: *"For developer, OpenWrt is the framework to build an application without having to build a complete firmware around it; for users this means the ability for full customization, to use the device in ways never envisioned."* More than 1000 Wi-Fi devices are currently supported by OpenWrt (see http://wiki.openwrt.org/toh/start). Many of these devices are low-cost APs, typical of SOHO (Small Office / Home Office) wireless scenarios.

Odin uses OpenFlow to control the internal switch of each of the wireless APs in a network. In addition, *Click Modular Router* [53] is used in the AP, adding a specific Odin module, which interacts with the Odin controller when required. The use of *Click* enables the possibility of directly managing the traffic. In addition, *Open vSwitch*[3] is installed, thus making the internal switch of each AP behave as an

[1] NetGames 2015, The 14th International Workshop on Network and Systems Support for Games (In co-operation with ACM SIGCOMM and ACM SIGMM, Technically co-sponsored by IEEE Communications Society), http://netgames2015.fer.hr/, [Accessed Dec 2016].
[2] OpenWrt, Wireless freedom, https://openwrt.org/, [Accessed Dec 2016].
[3] Open v Switch, http://openvswitch.org/, [Accessed Dec 2016].

OpenFlow switch. The controller runs a Floodlight OpenFlow Controller[4] in order to manage all the switches of the APs. The resource management algorithms are added as applications on top of the controller.

Although Odin represented a good starting point, it has many limitations for the aims of the Wi-5 project. The first limitation is that Odin assumes that all the APs are using the same channel, as this makes it possible for an AP to hear all clients in the vicinity, even if they are associated to other APs. Although this enables a relatively simple mobility management, it also represents a severe limitation, since frequency planning for the different APs would not be possible.

Many features are therefore being added to Odin in order to make it capable of supporting the requirements of Wi-5, i.e. building solutions for resource management in real scenarios. The new code is being shared in the Wi-5 GitHub repository[5], including the Odin controller (written in Java) and the Odin agent (written in C++).

The original Odin scheme has also been improved by the addition of an auxiliary interface (`mon1`, mainly used for monitoring purposes) and the real separation between control and data planes. A detailed explanation of this work is presented in D3.1. Here we describe the resulting scheme of the entities and interactions (see Figure 8), including the agent, the controller and all the flows that are exchanged between them.

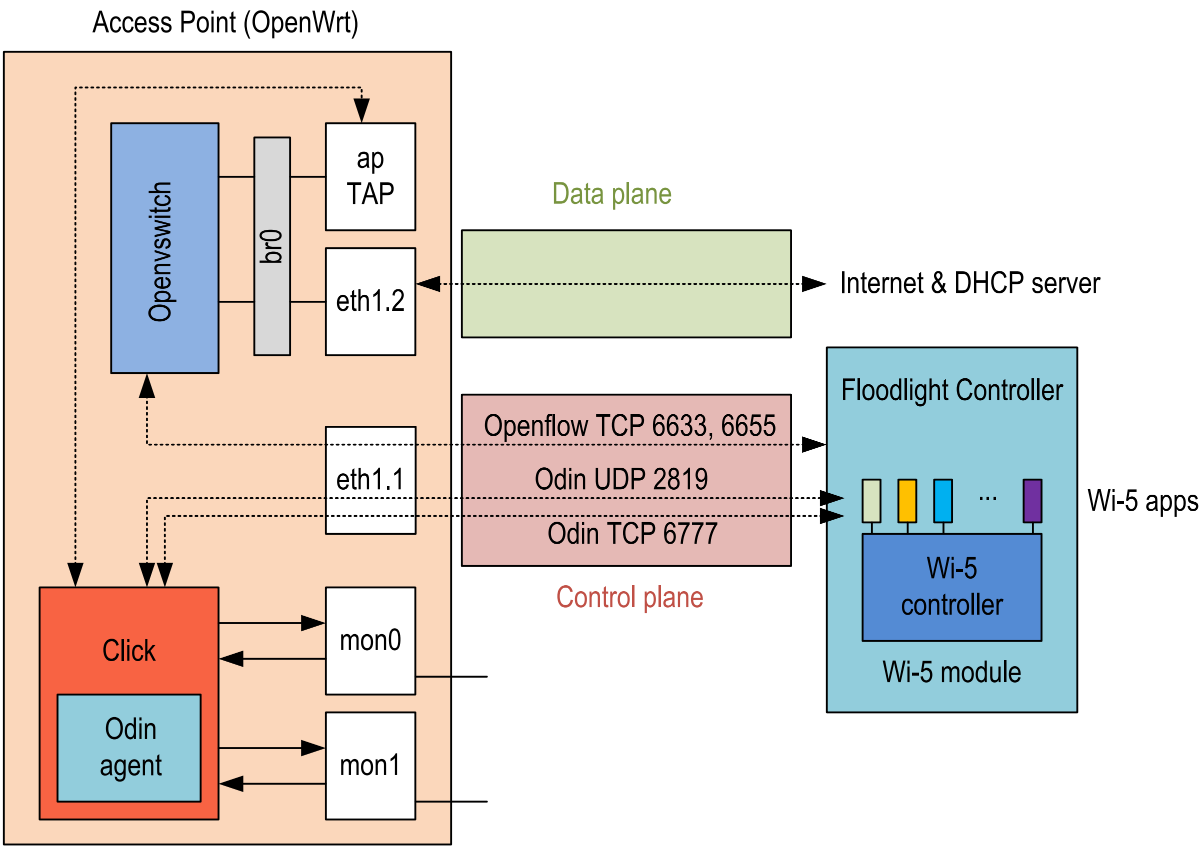


Figure 8: Entities and communications between the Wi-5 elements

[4] Floodlight SDN Controller: http://www.projectfloodlight.org/floodlight/, [Accessed Dec 2016].
[5] Wi-5 GitHub code repository, https://github.com/Wi5

As can be seen from Figure 8, the controller and the AP exchange control information that is used for the implementation of the resource management features. This includes:

- OpenFlow: uses TCP ports 6633 and 6655 to control the internal switch of the AP, as it is an OpenFlow switch using *Open vSwitch*.
- *Click control socket* and *Click chatter socket*: they use TCP ports 6777 and 6778.
- Odin agent: uses UDP port 2189 in order to transmit messages to the controller, including e.g. monitoring results, power level of the different heard STAs, etc.

A summary of the implementation-specific details follows. A virtual Linux `tap` [6] interface called `ap` is added to the internal switch of the controller (called `br0`), which communicates with the Click module. The Click module includes a new entity called *Odin Agent*, which is in charge of communicating with the controller and performing all the functionalities implementing the LVAPs. A patch has to be added to the 802.11 driver (Atheros *ath9k*) of the AP in order to support different virtual MAC addresses in a single real interface. The wireless network interface is set to *monitor* mode, so its name is no longer `wlan0`, but `mon0`. In D3.1 the scheme for the adaptation of a commercial AP for its use with the Wi-5 solution is presented.

4.2 Handover and Power Control

The scenario we are assuming consists of a number of APs covering an area, under a single controller. However, it is possible that other 802.11 devices (APs and STAs), not managed by the controller, may operate in the same area, thus producing a certain degree of interference. The monitoring capabilities included on each AP provide detailed information about the state of the AP and its environment, and this is used to perform coordinated resource allocation. According to the proposed centralised architecture, all these algorithms run in the Wi-5 controller.

We assume a dense scenario where there are several APs working in different channels, and typically most of the zones will be covered by more than a single AP. This will make it possible that a STA is attended by more than a single AP in different channels. Therefore, the Wi-5 controller will also be able to make the decisions on which STA and which channel is assigned to which AP, as defined in the Wi-5 architecture.

4.2.1 Horizontal Handover between APs in Different Channels

As identified above, the original design of Odin, in which all the APs are located in the same channel, is not suitable to build deployments in big scenarios, since the interference level would be very high. Therefore, new functionalities for managing APs in different channels are required. First, inter-channel handover has to be enabled. In addition, fast and seamless handovers are an essential part of this solution because it must be possible to dynamically redistribute the STAs between the APs.

In order not to interrupt the user’s session, seamless AP re-assignment can be very convenient when a user is walking, or whenever a load balancing decision is made. In this context, we developed and tested a centralised solution able to provide seamless handovers between APs in different channels, meeting the QoS requirements of real-time services. In order to consider it as a good solution, the next conditions have to be accomplished:

[6] TAP enables layer 2 frame reception and transmission for user space programs in Linux.

- No changes should be required in the terminal and only low-cost APs can be used (i.e. the ones that operators place in the households of their subscribers).
- As the users may move while using real-time services, the handoffs must work correctly at walking speed. Therefore, the solution must meet the quality demands of real-time services with tight latency constraints.
- The input parameters for the handoff decision should not be limited to the signal level; i.e. the use of other parameters must also be possible.
- The APs must be in different channels, to reduce the scalability issues caused by the beacon generation for each STA, as reported in [7]; so inter-channel handoffs must be possible.

All in all, the solution must allow the network to control the mobility and to select the best moment for the handoff. The proposed solution should also be able to separate the control and data planes, allowing an abstraction of the underlying technology for applications and services, making it able to interact with other technologies (e.g. 3G or 4G).

4.2.1.1 Proposed handoff scheme

The proposed handoff scheme and the tests and results have been published in a Journal Paper "Building a SDN Enterprise WLAN Based on Virtual APs," appeared in IEEE *Communications Letters* [54], published online in November 2016. It should be noted that using a number of different channels introduces a new degree of complexity. In addition, in order to consider the possibility of using different channels, the CSA (Channel Switch Announcement) element in an 802.11 beacon will be employed (as done in [8]) to make the STAs associated to an AP move to a specific channel.

A number of additional elements have been incorporated in the present approach:

- An extra Wi-Fi interface has been added to the APs in order to monitor traffic in other channels, without interrupting the normal operation of the AP. More details about the monitoring setup and process are given in D3.1.
- Different metrics for making the handoff decision can now be used [55], and they can be evaluated and weighted in the controller, as it has access to all the information. Therefore, the handoff is controlled by the network, and it does not only depend on power measurements in the STA.
- The controller has a map including the coordinates of the APs, so it knows the channels of other APs in the vicinity of a certain one. This information is useful for initiating scans in correct channels whenever the signal of a STA fades (as a consequence of user's movement).
- The beacon generation has been modified in order to improve the scalability and to give a better user experience during handoffs.

Figure 9 shows the proposed handoff scheme, in which we suppose that an STA is associated to *AP1* (in channel *A*). *AP2* is in channel *B*. Besides this, an Ethernet control plane connection is used to communicate between the controller and the APs. The handoff scheme has been designed according to the following process:

- First, the controller establishes different "subscriptions" in the APs, in order to raise an event whenever a threshold (noise level, power, etc.) is reached by an STA.
- When the STA moves (1) away from the Origin AP (*AP1* in channel *A*), it detects that the signal is below a threshold and sends a *PUBLISH* message to the controller (2).
- According to its AP map, the controller sends a *Scan Request* message to the neighbouring APs (3).

- For a short period of time, all neighbouring APs switch their auxiliary interfaces to channel *A* and listen to packets originated by the STA. If an AP successfully hears the STA's packets, it sends a *Scan Response* message to the controller (4).
- Once the controller has received the *Scan Response* messages from the APs, it runs its algorithms (5) and selects the best suited one for the STA. The decision is: "*move STA to AP2.*" Next, the controller tells *AP1* (6) to send a series of CSAs to the STA (7). They are understood by the STA like a countdown, meaning "*after N beacons, switch to channel B*".
- When the countdown ends, three events must occur in a specific order: a) the STA switches to channel *B* (while *AP1* does not) (8); b) the controller sends an *Add LVAP* message to *AP2*, which starts sending beacons to the STA in channel *B* (9), and c) a *Remove LVAP* message is sent to *AP1* (10).

After that moment, the STA starts receiving beacons from *AP2* in channel *B*. The synchronization of these events is the most critical part of the handoff, as we will see in the subsequent tests and measurements. It should be noted that the STA interprets this as a channel switch carried out by the same AP, so Layer 3 and upwards are not aware of the handoff. Therefore, on-going communications are only interrupted briefly due to the channel switching.

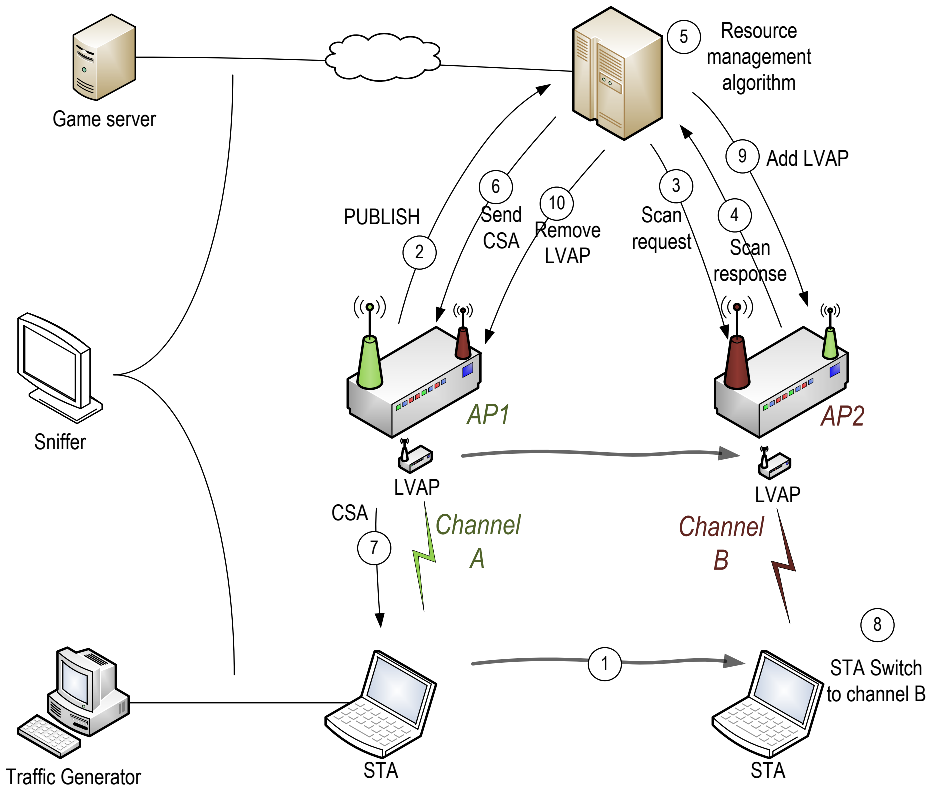


Figure 9: Scheme of an inter-channel reactive handoff using LVAPs

Scalability issues may appear when running resource management algorithms, taking into account that the decisions will be made by a central controller. Therefore, the signalling traffic (e.g. monitoring, power control) in the wireless network has to be limited. Something similar will happen in the wired network connecting the APs and the controller, where the signalling traffic should not interfere with the data generated by the clients. In the present case, the control and data planes have been separated, so this can be easily achieved. The required processing capacity will also have to be taken into account, as low-cost APs with limited capabilities are being used. This could also be a limitation in the central controller, depending on the number of APs it is managing.

4.2.1.2 Tests and results

The test setup in Figure 9 includes two APs (TP-Link 1043NDv2 with OpenWrt 14.07) configured in different channels (4 and 9, in the 2.4 GHz band); the controller runs Debian 8 (Linux kernel 3.16.0.4) and the STA runs a Fedora 23 workstation (Linux kernel 4.4.5.201). Finally, a DHCP server and a router to access the Internet are included.

The aim of the tests is to analyse the effect of the handoff on the quality of real-time services, in terms of delay and packet loss. As an example of a service with tight latency constraints, we have selected the client-to-server traffic of an online game (*Quake* 3, a popular First Person Shooter using UDP), generated by D-ITG [73].

In order to avoid common issues while capturing in the radio channel (mainly the *missing-rate* problem, see [56]), we have included a sniffer (see the left of Figure 9), so we can accurately obtain the transmitted and received traces by measuring in both (wired) ends of the communication [57]. In addition, the traffic is not generated by the STA itself, but by another machine which sends it to the STA's Ethernet interface, which forwards it to its wireless interface. This setup avoids any degradation of the performance of the applications and allows us to test different Wi-Fi devices with minimal changes.

We have chosen a real environment instead of an interference free scenario. The tests were run in a lab inside a university building, which constitutes a harsh environment with about 15 APs producing interference (see a capture of the environment in Figure 10).

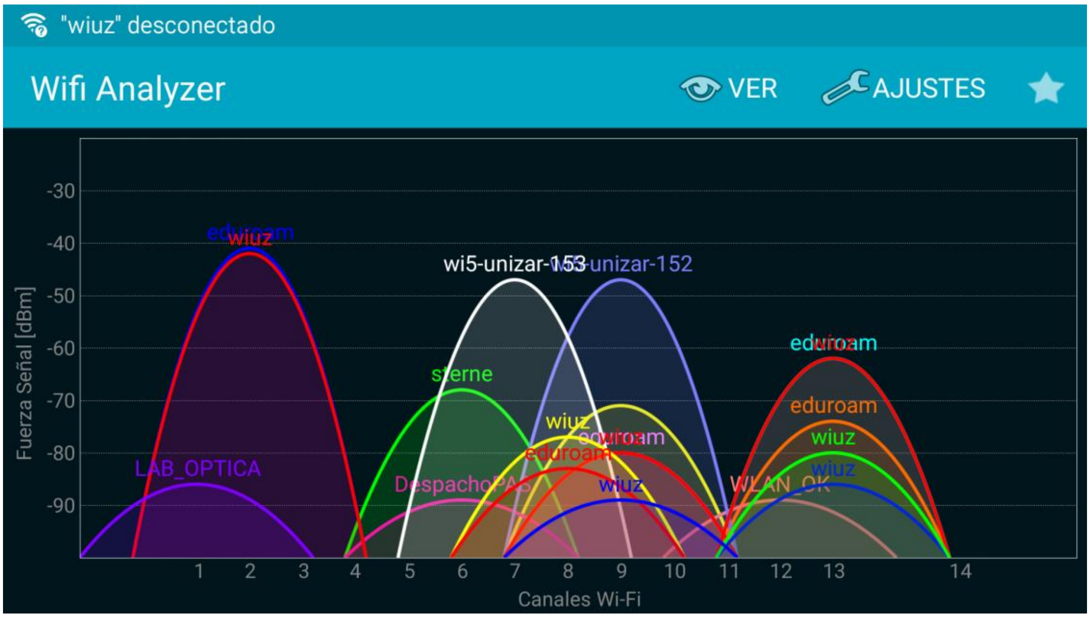


Figure 10: The wireless environment in the lab, obtained with the App Wi-Fi Analyzer[7]

Three different wireless cards have been used in the STA (Linksys WUSB54GC, WiPi WLAN USB b/g/n, and TP-LINK TL-WN722N), see Figure 11.

[7] WiFi analyzer, https://play.google.com/store/apps/details?id=com.farproc.wifi.analyzer&hl=es, [Accessed Nov 2016].

Figure 11: The three wireless cards used (from left to right): TP-LINK TL-WN722N, WiPi WLAN USB b/g/n and Linksys WUSB54GC

Our initial tests showed the following behaviour: when the STA switches its channel, it remains idle for a period. The duration of this period depends on the hardware characteristics, the driver and the network implementation. After receiving a certain number of beacons in the new channel, the STA continues the sending of packets. For this reason, the inter-beacon time has to be kept low in order to obtain a fast and seamless handoff.

A trade-off appears: on the one hand, a smaller inter-beacon time permits a faster handoff. On the other hand, high beacon rates can negatively impact the network performance, since broadcast beacons cannot be used, as each STA receives the frames from the AP with a different MAC (the one included in its LVAP).

The solution we propose to solve this trade-off consists of defining two different beacon rates: a *low frequency* one, to be used when the STA remains in the same AP; and a *high frequency* one, used for sending a burst of beacons during the handoff. Therefore, when the controller makes a handoff decision, it instructs the destination AP to send a burst of beacons using the high rate. Thus, the wireless card of the STA will hear the required number of beacons in the new channel, and continue its normal operation.

The values of these frequencies have to be selected properly. In the case of the low frequency, we have followed the vendor's recommendations (between 50 and 100ms). For the *high frequency*, tests with different inter-beacon times, namely 5, 10, 20, 30, 40 and 50ms, have been performed, in order to observe the effect of this parameter and to adjust the beacon frequency during the handoff.

Some tests have been run (Figure 12), in which the controller has been configured to force an STA handoff every 30 seconds; every test includes 20 handoffs. The results are reported in terms of packet loss and delay. The packet loss rate can be easily obtained because all transmitted and received traces are known. We can differentiate two causes of packet loss: (i) some packets are lost during the handoff and (ii) others are randomly lost due to wireless issues such as interference, packet injection errors and others. The sniffer also allows us to obtain the delay for each packet.

We estimate the handoff time, from the application's point of view, as follows: when the STA starts the channel switch, the wireless interface drops some UDP packets during certain period while switching, and then a number of packets are dropped in a burst. Therefore, we calculate the handoff time as the gap between the last transmitted packet in the *transmitted trace* and the first received packet in the *received trace*.

Figure 12 shows the obtained delay for each packet for a 600s transmission when the frequency of the burst of beacons is set to 10ms. The results are presented for the three wireless cards mentioned above. Vertical lines have been included in order to show the moments in which the handoffs occur. In Figure 12 a, we can identify all 20 handoffs, but in Figure 12 b and Figure 12 c, there are cases in which handoffs are undetectable. A handoff cannot be detected in these cases because: a) no packets are lost, or b) we cannot distinguish between packets lost by the handoff or by the wireless channel. These undetectable handoffs represent a switch between APs with very good quality. On the other hand, we can observe that the handoff does not increase packet delay; i.e. peaks of delay are not correlated with the moments when handoffs happen.

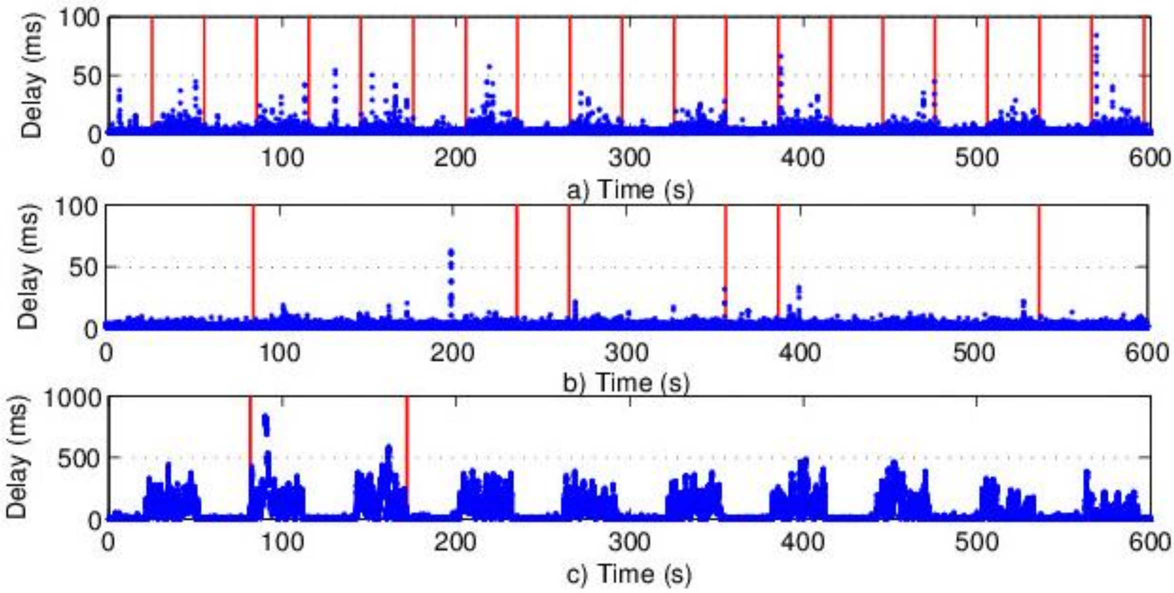


Figure 12: Packet loss (total and caused by the handoff) comparison for different Wi-Fi devices: a) Linksys; b) WiPi; c) TP-Link

In Table 1, the total packet loss rate and the loss rate caused by the handoff are shown, using different values for the frequency of the burst of beacons. The devices behave in different ways, depending on the beacon frequency: for the Linksys and WiPi devices, we can observe a very low level of packet loss attributable to the handoff, especially when the inter-beacon time remains in the lowest levels. However, in the case of the TP-Link, all the losses can be attributed to the handoff, and random loss is zero.

Table 1: Packet loss (total and caused by the handoff) comparison for different Wi-Fi devices

Burst (ms)	Packet loss (%)					
	Linksys		WiPi		TP-Link	
	Total	Handoff	Total	Handoff	Total	Handoff
5	9.10%	0.03%	1.24%	0.01%	0.31%	0.31%
10	5.64%	0.00%	1.09%	0.01%	0.33%	0.33%
20	4.11%	0.05%	1.39%	0.05%	0.36%	0.36%
30	2.61%	0.01%	0.80%	0.07%	0.40%	0.40%
40	1.43%	0.05%	0.16%	0.14%	0.48%	0.48%
50	0.08%	0.04%	0.30%	0.26%	0.60%	0.60%

Table 2 shows the handoff times for each burst inter-beacon time, and the cumulative percentage of the detected handoffs (e.g. for the Linksys device, when the inter-packet time of the burst is set to 10 ms, 90% of the handoffs last less than 73.80 ms). Again, we can see different behaviours depending on the used device: while the TP-Link has the longest handoff time, the other devices show significantly lower values.

Table 2: Percentage (Acc) of times that handoff time can reach a time value

Burst (ms)	Handoff time					
	Linksys		WiPi		TP-Link	
	Acc* (%)	Time (ms)	Acc* (%)	Time (ms)	Acc* (%)	Time (ms)
5	90.00%	223.89	80.00%	28.55	0.00%	89.86
10	90.00%	73.80	70.00%	22.29	0.00%	87.01
20	75.00%	53.13	65.00%	35.44	0.00%	89.98
30	70.00%	59.00	50.00%	30.96	0.00%	92.58
40	35.00%	46.26	35.00%	43.27	0.00%	93.10
50	10.00%	66.80	10.00%	61.80	0.00%	109.10

We have observed that the behaviour of each wireless device differs in terms of handoff time and packet loss. In some devices the handoff time is very small, which produces a small packet loss rate comparable to the loss produced by the normal interference when the STA is in the same AP. In these cases, it is not possible to determine the moment when a handoff occurs, nor how long it lasts. There exist other cases in which no packets are lost, due to the combination of a fast handoff and the optimal radio channel conditions.

In order to illustrate the different behaviour of each wireless device, the next figures present the inter-packet time histograms of the traffic used for the tests (traffic of the online game *Quake* 3). The grey graph represents the histogram of the original traffic, as generated by D-ITG. The other graphs represent the traffic received by the destination (the game server) after the traffic has gone through the wireless link (see the scheme in Figure 9). Different values of inter-beacon time are used.

In Figure 13 the results obtained when using the Linksys wireless card are shown. It can be seen that the histogram in reception has significantly changed with respect to the one in transmission. This can be caused by the existence of an internal buffer in the wireless card, which flattens the histogram. The modification means that more delay and jitter have been introduced in the game (e.g. the delay peak in 12ms is now extended to 15ms).

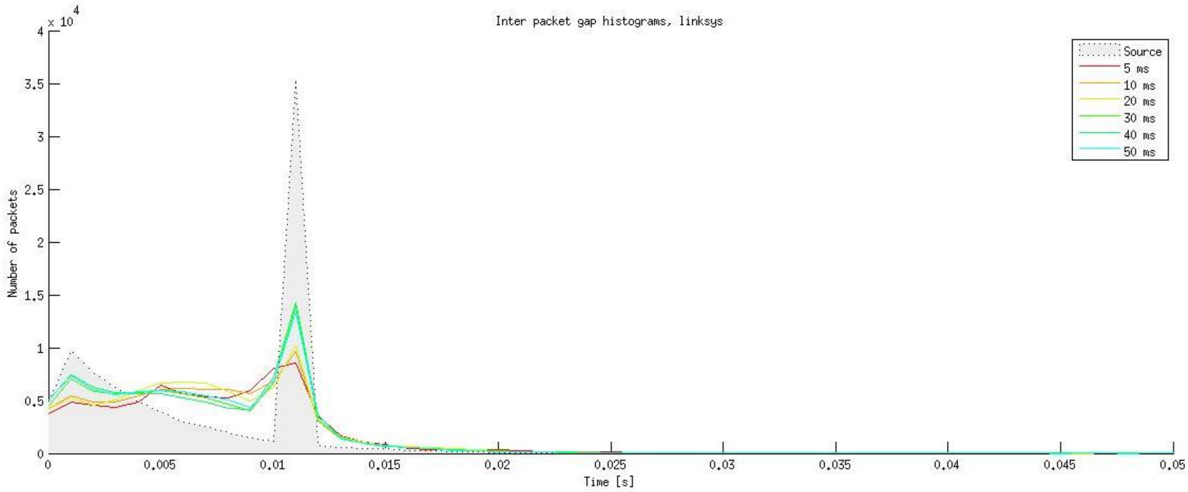


Figure 13: Inter-packet time histogram for the Linksys wireless card

However, the results reported in Figure 14 and Figure 15, which correspond to the WiPi and the TP-Link devices respectively, report better behaviour. The histograms of the traffic received are quite similar to the one of the original traffic, except for some dispersion of the main peak, which means that some jitter is being added to the traffic.

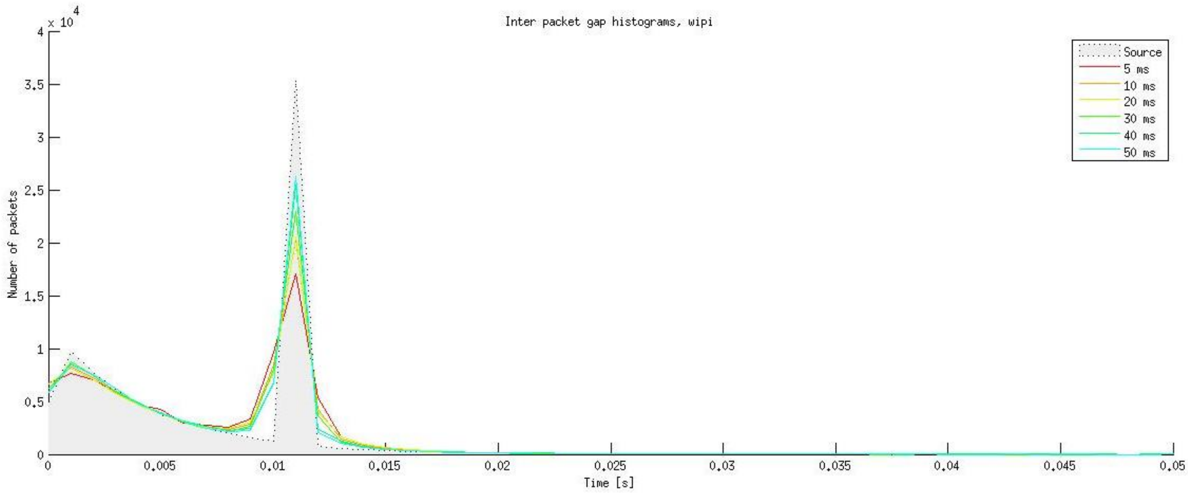


Figure 14: Inter-packet time histogram for the WiPi wireless card

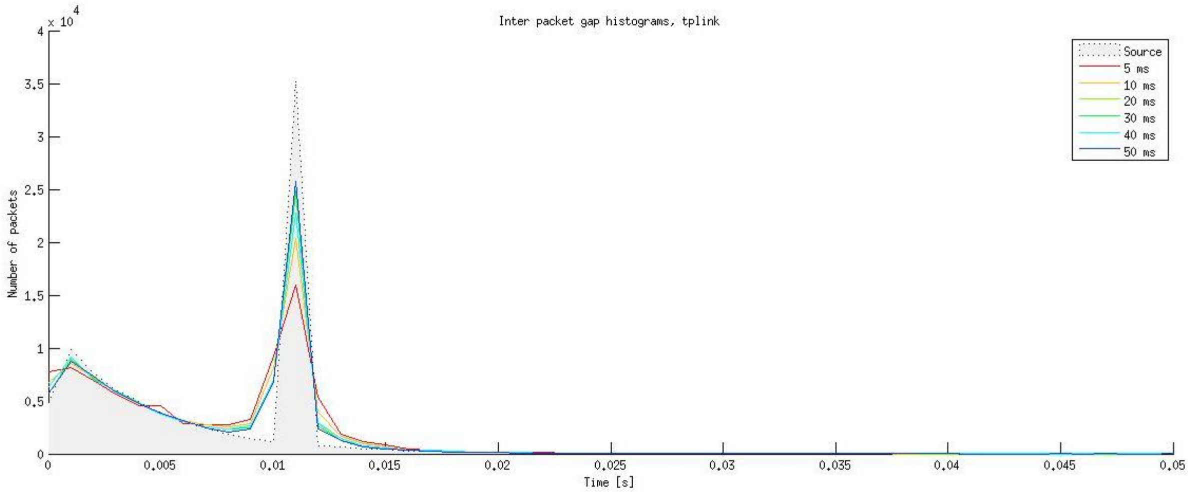


Figure 15: Inter-packet time histogram for the TP-Link wireless card

In order to estimate the QoE for this traffic, we have utilised the G-Model, proposed in [58]. It is based on some subjective experiments with real players, which allowed the authors to devise a formula for producing an estimation of the QoE, based on delay and jitter. Table 3 presents the estimated MOS (Mean Opinion Score, which varies from 1: 'bad' to 5: 'very good') for each test. The results show that the Linksys adapter could not provide a good quality. In the WiPi and TP-Link adapters, the value of 4 is reached and exceeded in most of the cases, which would be more than enough for a smooth playing experience.

Table 3: QoE estimation (G-Model) for different Wi-Fi devices

Burst (ms)	**G-Model**		
	Linksys	**WiPi**	**TP-Link**
5	1	4.19	4.06
10	1.10	4.23	4.16
20	1.15	4.17	4.25
30	1.21	4.28	4.25
40	1.37	4.26	3.89
50	2.72	4.28	4.29

After performing the experiments, we can conclude that this seamless handoff solution works well for the WiPi and TP-Link adapters, while the Linksys adapter performs poorly for real-time services, but it can be good enough for other types of services without real-time constraints. The proposed handoff mechanism has been found to work correctly, and the beacon interval change does not significantly affect the tested wireless adapters.

4.2.2 Vertical handover

The Wi-5 proposal not only considers the possibility of handing an STA from a Wi-Fi AP to another Wi-Fi AP (horizontal handover), but the idea of handing an STA from a Wi-Fi AP to a 3G/4G cell should also be allowed. In D4.2, a strategy is proposed for a preliminary solution that will determine the most suitable connection for each new user/flow between Wi-Fi APs and 3G/4G mobile stations, based on the Fittingness Factor (FF) concept. This is currently a part of the future work to be carried out by the Wi-5 project.

The complete handover solution includes the parameters and decision elements of the algorithm, to be developed in WP4. In this document, we will outline the following two steps considered in order to include vertical handovers in the Wi-5 implementation:

1) A simple approach will be first considered, which consists of just disconnecting the STA from the Wi-Fi network (i.e. the controller would remove the LVAP), so the STA will automatically move to the mobile network. This assumes that the STA connectivity features connect to the mobile only if there is no known Wi-Fi network available. This assumption is not unlikely, as the vast majority of current terminals implement this mechanism (e.g. in Android it is called "Smart network switch"; in iOS it is called "Wi-Fi Assist"), which allows the phone to fall back to cellular data when Wi-Fi in the area fades.

2) In the second case, the vertical handover should be run depending on the currently services running in the STA, giving a special weight to the fact of having a real-time flow. These flows present very strict delay constraints that, depending on the status of the Wi-Fi network, may not be possible to accomplish. The capabilities for detection of real-time flows, presented in section 3.6 of D3.1, will be leveraged for this aim. Having access to this information, the Wi-5 controller will be able to make the correct decision about handing off an STA from the Wi-Fi to the mobile network.

4.2.3 Adjustment of the transmission power

The work has been focused on the 2.4 GHz band, avoiding the consideration of other bands (5 GHz, 60 GHz), as the proposed coordination solutions are generally applicable and can mitigate the shortage of spectrum despite the considered frequency. Therefore, Wi-5 mechanisms do not rely on *TPC request / report* elements, defined in IEEE 802.11h, to adjust the transmission power of each AP towards each STA, as they are not available in the 2.4GHz band. Thus, all the measurements will be done in the APs themselves. Different mechanisms for measuring the interference level between Wi-5 and non-Wi-5 APs are reported in D3.1.

This information will be made available in the controller, in order to be used as input for the power control algorithms. As for the Wi-5 APs, information about which APs can potentially interfere among them if they use the same channel and the current load of those interfering APs will be required to properly assign both channels and users. In addition, reports about the interference level caused by non-Wi-5 devices will be important to avoid those channels presenting a high level of activity.

Two ways for implementing power control have been explored:

4.2.3.1 Modification of the power at AP-level

In this case, the algorithm's output is limited to the definition of the power level for the whole AP, so all the associated STAs would be affected in the same way. The best approach for implementing these decisions has been investigated here and we present a summary of the tests below.

4.2.3.1.1 OpenWrt 14.07[8]

In OpenWrt 14.07, a test has been run with a TP-Link Archer C7 in AP mode. The power has been modified using the `iw` command[9] `(#iw dev wlan0 set txpower 1800`, which means a power level of 18dBm). It can be observed (using a device hearing in monitor mode) that the power transmitted by the AP does get modified by the `iw` command.

[8] Released October 2014, see https://forum.openwrt.org/viewtopic.php?id=51940, [Accessed Dec 2016].
[9] Linux Wireless, About iw, https://wireless.wiki.kernel.org/en/users/documentation/iw, [Accessed Dec 2016].

We run another test with the same router, but this time it runs in the monitor mode (using Odin). We modify the power with `#iw dev mon0 set txpower fixed 180` and `#iw dev wlan0 set txpower fixed 180`, but none of these commands is able to modify the power of the AP. We can therefore conclude that this command works in the AP mode, but not in the monitor mode.

4.2.3.1.2 OpenWrt 15.05[10]

We then flash the next version of OpenWrt into the same AP and run the same test in the monitor mode. In this case, it can be observed that the power transmitted by the AP does indeed get modified if we run the command `#iw dev wlan0 set txpower 1800` or `#iw dev mon0 set txpower 180`. So, we can conclude that `iw` can be used for modifying the power level of an AP if OpenWrt 15.05 is used.

4.2.3.2 Modification of the power at flow-level

The possibility of a power control mechanism that can be associated to each packet is seen as very beneficial as it could perform a more fine-grained control, thus allowing the sending of the frames with different power levels to each STA. This is usually called *per-packet TPC* (Transmit Power Control). Therefore, the possibility of doing this in our implementation has been explored. This includes the power management features in Click Modular Router, and it also has some implications related to the used drivers, which can be different when operating in monitor mode.

In Click, *annotations* are elements added to a packet, which are not part of the packet itself [11]. Click has an annotation element (called `SetTXPower`) which sets the Wi-Fi Tx Power of a packet[12].

Therefore, if the Click element `odinagent.cc` sets this annotation for each packet, and it places it in the queue (outputs `0` and `2` of the `odinagent` element, see Figure 16 where the scheme of the Click elements used by the agent is shown), per-packet TPC would be possible. In addition, we would have to add a `SetTXPower` box in the `.cli` scheme of Odin, after the `SetTxRate` and before the `RadioTapEncap` box (see Figure 16). Finally, the `RadiotapEncap` box would read the annotation and pass the packet to the device according to the power level established in the annotation.

[10] Released September 2015, see https://forum.openwrt.org/viewtopic.php?id=59528, [Accessed Dec 2016].
[11] For further information, see http://read.cs.ucla.edu/click/packet?s[]=annotation#annotations, [Accessed Dec 2016].
[12] For further information, see http://read.cs.ucla.edu/click/elements/settxpower?s[]=power, [Accessed Dec 2016].

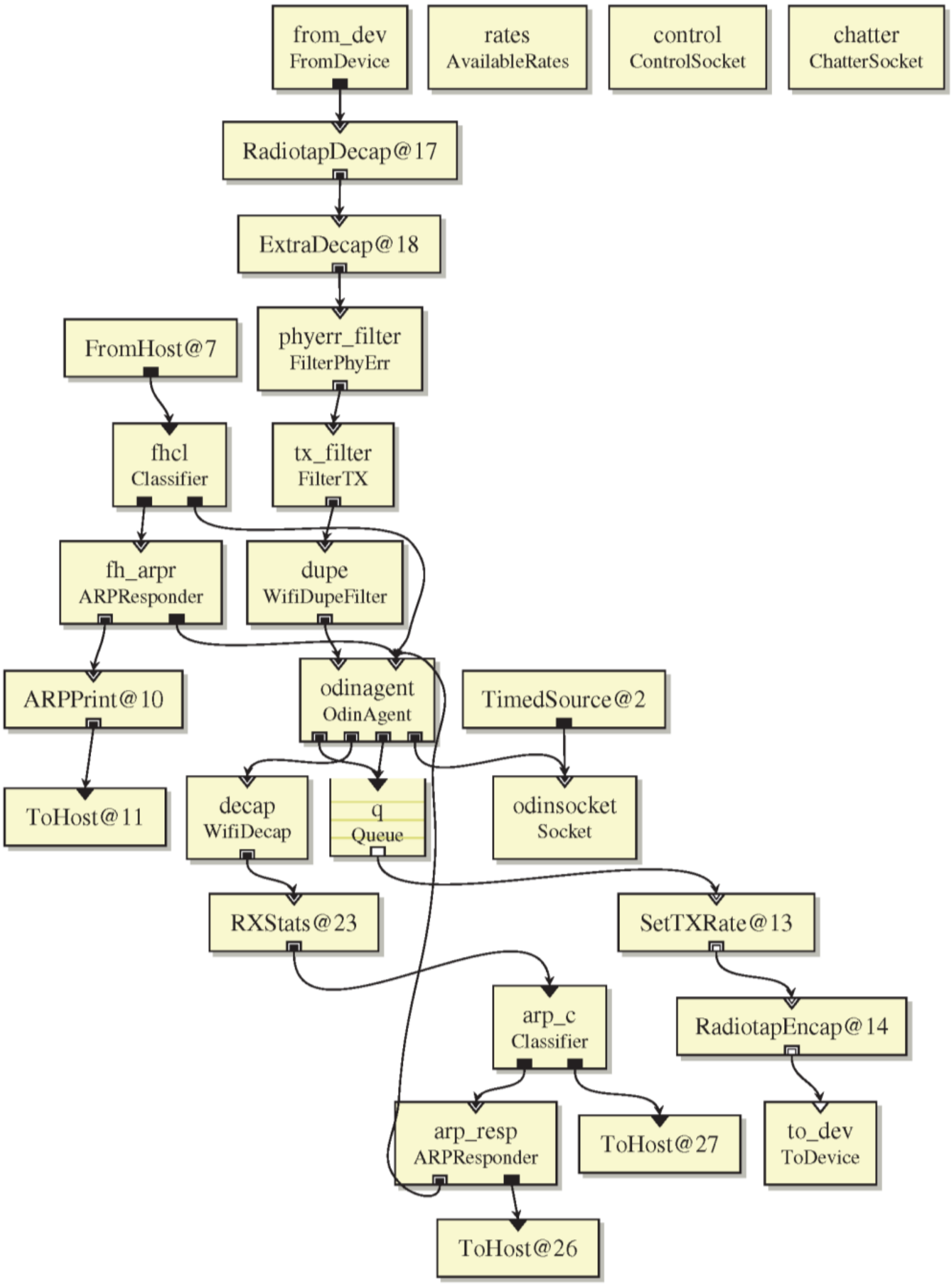


Figure 16: Scheme of the .cli script used for the Wi-5 Agent

In order to check if this would work in our setup, we have run a simple Click script including settings for the rate and the power. This script generates an IP packet every 0.333 seconds, and sends it with a power level of 0 dBm and a rate of 2 Mpbs (4*500kbps), using the `mon0` interface:

```
source::TimedSource(INTERVAL 0.333)
-> Queue()
-> EtherEncap(0x0800, E8:DE:27:FB:EF:5D, 10:68:3F:60:2A:F2)
-> WifiEncap(0x02, E8:DE:27:FB:EF:5D)
-> SetTXPower(0)
-> SetTXRate(4)
-> RadiotapEncap()
-> PrintWifi()
-> ToDevice (mon0)
```

We can observe that if we modify the value given to the `SetTXRate` element, we can generate traffic with different rates. However, we have also observed that although Click Modular Router does pass the information to the driver of the wireless card, the value of the Tx power is not supported by the driver. The problem is that the part of the driver that is parsing the Radiotap header is ignoring the Tx power field. The Linux kernel used by OpenWrt 15.05 does not parse the power level set in the Radiotap header[13].

As a conclusion, we have found that with our current implementation, and with the current state of the art, it is possible to modify the power of an AP in the monitor mode, but not per-frame. Different approaches for overcoming this limitation can be explored: first, avoiding the use of Click, taking into account that this software was mainly developed for academic purposes and not for operational environments. Second, avoiding the use of the interfaces in the monitor mode. This would require the inclusion of these features in the Linux kernel, which would require a significant effort that we consider beyond the scope of our demonstration platform. Another way would be to patch OpenWrt in order to read the Tx power field of the Radiotap header.

4.3 Load Balancing

This functionality enables Wi-5 networks to make decisions on when not to accept new association requests, and also the possibility of moving some STAs from one AP to another in the neighbourhood. This is aimed to maximise the aggregate data rate of these networks. The centralised approach makes this relatively straightforward, since all the association requests have to be approved by the central controller, and the controller can also run periodic algorithms for load balancing. These algorithms can be reactive, i.e. run after some event (a new STA has been associated, a STA has started/finished a real-time service, etc.), or they can be proactive, i.e. run periodically to optimise the load distribution of the network.

Taking into account that we have opted for a solution based on LVAPs, the controller has the freedom to assign an STA to any Wi-5 AP, and to move it seamlessly from one Wi-5 AP to another, even if they are working on different channels. Moving an STA to a new Wi-5 AP or changing the operating channel in the Wi-5 APs does not require a Layer 3 re-association, so the algorithms can consider a relatively high level of movement between Wi-5 APs.

This has been enriched with the possibility of each AP being in a different channel, so now the APs will use their auxiliary interfaces for performing the scanning. In addition, all the functions used for moving a STA from one AP to another have been improved with the automatic consideration of the multi-channel scheme: if the function for moving an STA is invoked, it will automatically check if a channel switch is required, as it will perform the required actions (e.g. sending the CSA frames to the STA). The scheme including the multi-channel support is shown in Figure 17.

[13] More information can be found in this discussion http://librelist.com/browser//click/2014/12/3/click-raw-packet-injection-and-ath9k/#e72da523b5725b40377a6d7a6209e673, [Accessed Dec 2016].

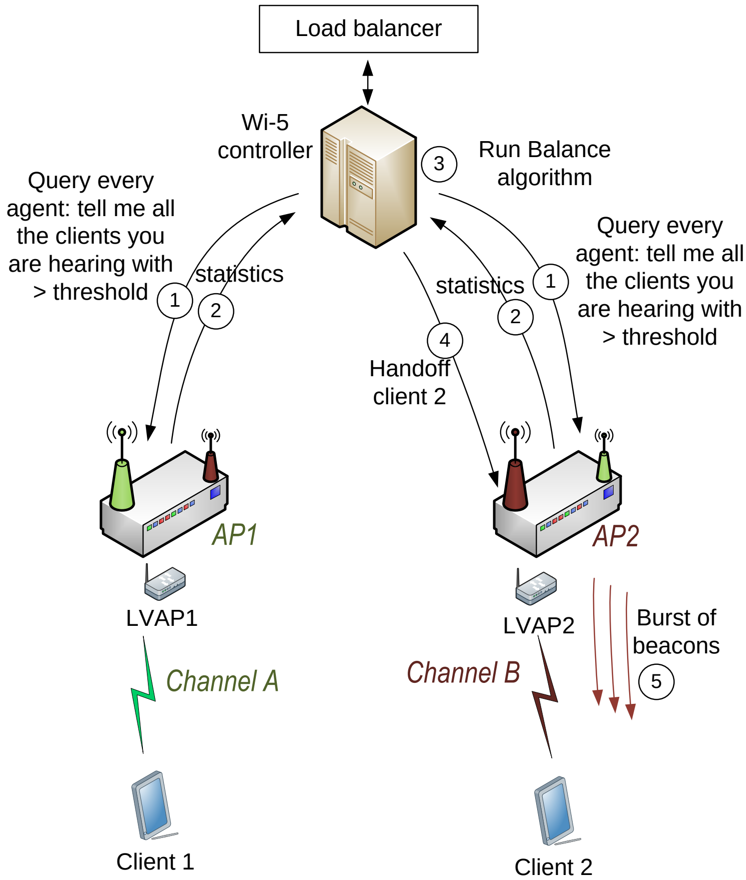


Figure 17: Scheme of Load Balancer application with multi-channel support

The Load Balancer algorithm works this way: it is run every e.g. 60 seconds when the controller requests (1) a "hearing table" from every AP. This table is built by each AP using the auxiliary interface, and sent to the controller (2). Then, the balancer algorithm is run (3), and the changes are implemented in the network, handing off the STAs to other APs when required (4). If necessary, a burst of CSA beacons is sent to the client, when it has to be handed off to an AP in another channel (5), as described above. This would be the process followed:

```
Every 60 seconds
{
        // build the "hearing table"
        For every agent
        {
               obtain the IPs and MACs heard above a threshold
        }
        // result: updated map of agents and clients they hear

        // run balance() function
        For every client
        {
               find the most suitable AP
               handoff the client if necessary
        }
}
```

The development of the load balancing functions themselves is not within the scope of this deliverable. We are only addressing the ways that permit them to work properly, i.e. to get the information and to implement their decisions in the network, once the algorithm has been run. This way, different load balancing functions can be added to the Wi-5 controller in order to allow an intelligent distribution of the network load, also in cooperation with the rest of functionalities.

4.4 Packet Grouping

The objective of this functionality is to define and implement the mechanisms for packet grouping between the AP and the end device as specified in the IEEE 802.11n [10] and 802.11ac [11] standards. Two forms of frame aggregation are explored: Aggregated Mac Service Data Unit (A-MSDU), and Aggregated Mac Protocol Data Unit (A-MPDU). In addition, Layer 3 optimisation has also been explored: in certain scenarios, legacy 802.11 devices (prior to 802.11n) exist, so this optimisation is not possible at Layer 2.

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

In this deliverable we include two studies: first, a detailed study of the achievable savings when using the aggregation functionalities of 802.11, including the development of testing software that can aggregate frames at Layer 2. Second, a study of the impact of aggregation on subjective quality. This test has been run in cooperation with the University of Zagreb, and includes tests with real volunteers playing a real-time service (an online game) while the packets were aggregated. The study was published in [59].

4.4.1 Layer 2 optimisation mechanisms

A normal 802.11n frame has the same structure (Figure 18), including the PLCP (Physical Layer Convergence Protocol) headers, the MPDU, some tail bits and padding. An MPDU includes the MAC addresses, and the MSDU, which is the “payload” being carried.

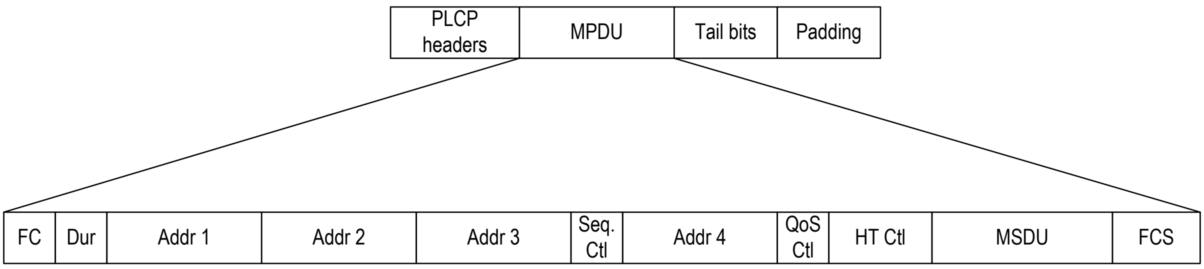


Figure 18: Structure of a normal 802.11 frame

In order to improve efficiency, new versions of Wi-Fi (from 802.11n) include mechanisms for frame grouping: A-MPDU and A-MSDU (see Figure 19):

- A-MPDU: a number of MPDU delimiters each followed by an MPDU.
- A-MSDU: multiple payload frames share not just the same PHY, but also the same MAC header.

Finally, it should be noted that both aggregation mechanisms can also be combined (*Two Level Aggregation).*

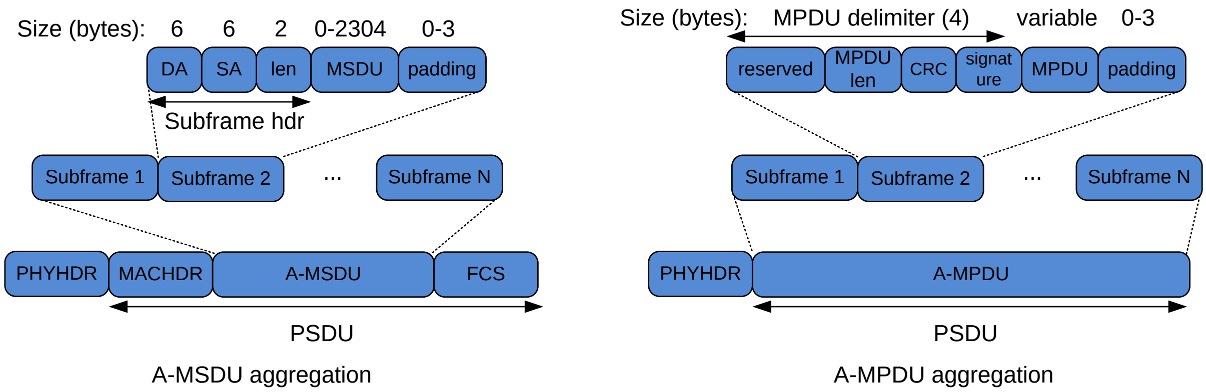


Figure 19: Frame aggregation schemes in 802.11n: a) A-MSDU; b) A-MPDU

Frame aggregation is becoming a common feature. In fact, in 802.11ac all the frames must have an A-MPDU format, even when a single sub-frame is transported. This success of A-MPDU is because in lossy environments, when a number of subframes travel together and some of them are received in the wrong way (i.e. the CRC does not match), only the wrong ones have to be sent again. That is not the case of A-MSDU, which requires the whole multi frame to be sent again. Therefore, our study will mainly focus on A-MPDU, as it is the most used aggregation mechanism.

A frame including a number of A-MPDUs has the structure shown in Figure 20, with a number of subframes sharing the same PLCP headers. A *delimiter* and a *padding* have to be added for each of the MPDUs being carried. The delimiter includes the length of the MPDU that comes next.

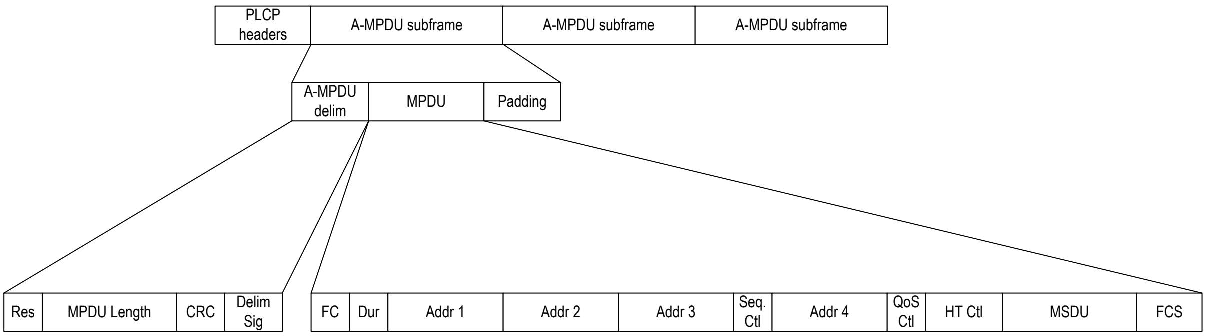


Figure 20: Structure of an A-MPDU 802.11 frame with many subframes

Wi-Fi Multimedia (WMM) [60]) is a subset of the IEEE 802.11e specification [61] that adds quality of service (QoS) functionalities by prioritising data packets according to four categories, namely *Voice*, *video*, *best-effort* and *background*, each of them with different values for the *interframe space*, CW_{min}, and CW_{max} values. Only frames belonging to the same category can be aggregated together

The efficiency increase achievable when aggregating frames is significant. Figure 21 shows an example: we have used the analytical model developed in [40] in order to represent the efficiency increase when these two aggregation mechanisms are used. The packet size considered is 1500 bytes. It should be noted that A-MPDU allows a higher number of frames to be aggregated. The efficiency can increase up to 90% for UDP packets, and 80% for TCP.

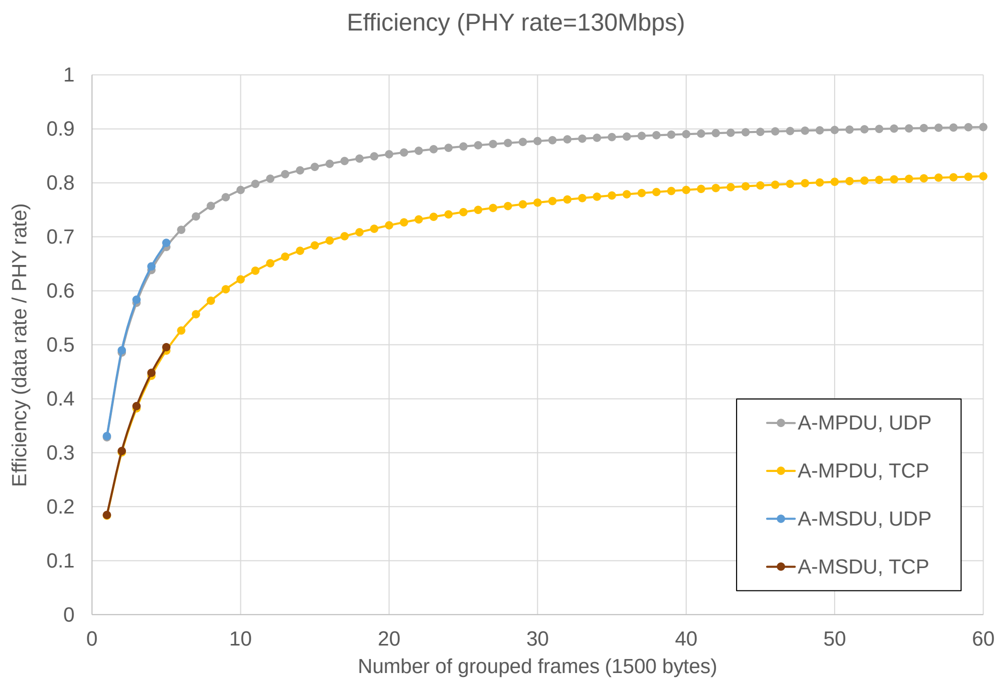


Figure 21: Efficiency improvement in 802.11 when using aggregation schemes

However, these results are only analytical, and we wanted to corroborate them with real 802.11 traffic. Towards that aim, we have built a software tool able to reproduce the whole process of sending A-MPDU frames. It had to work in user space and use the interfaces in the monitor mode. This mode allows a wireless interface to monitor all traffic received from the wireless network. Therefore, packets can be captured without having to associate with an AP or an ad hoc network first. In addition, we also need the frames to be injected in the monitor mode.

The developed software, which is available in the GitHub repository of the Wi-5 project (see https://github.com/Wi5/wi5-aggregation), was initially based on a test program[14] able to create a so-called *"fake* AP*,"* i.e. a computer that mimics the behaviour of an AP (see Figure 22). Its functionality was initially limited to the sending of *Beacons* and to the perception of *Probe Request* frames from the clients. As we will see, it has been extended in order to support the whole association process and the sending of the A-MPDUs. Additional documentation has been included in a README file in GitHub, with a setup, some examples of how to use the software and other details.

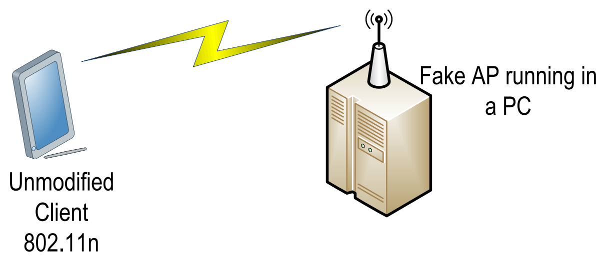
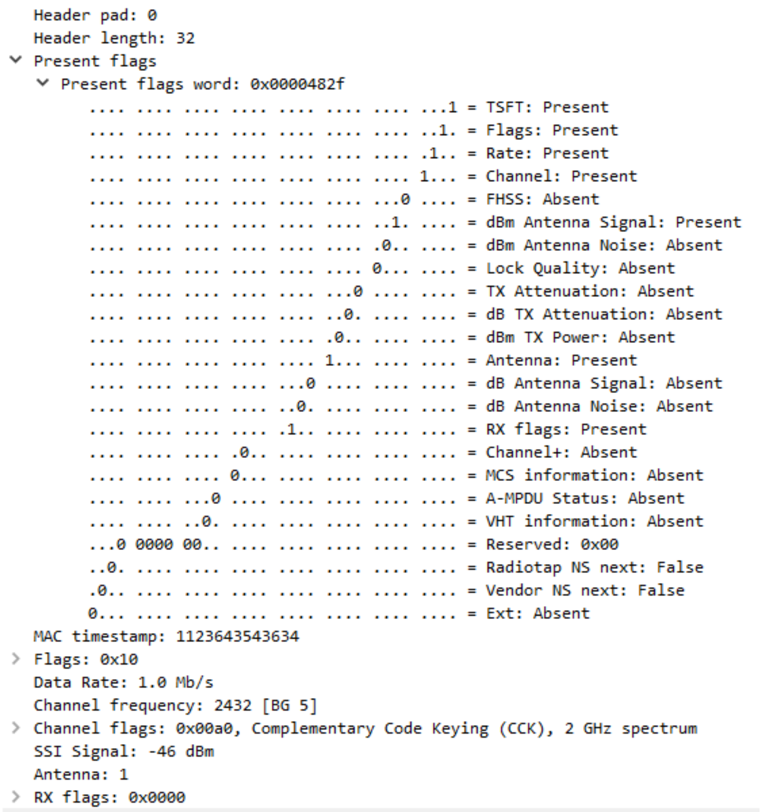


Figure 22: Scheme of a *"fake AP"* running in a PC

[14] Evan Jones, Fake Access Points. http://www.evanjones.ca/software/fakeaps.html, [Accessed Dec 2016].

The program is written in C. It uses the libraries `sys/socket.h` in order to open a *raw socket*[15] which lets it inject frames. Radiotap[16] headers are used, as they are the *de facto* standard for frame injection in different Operating Systems (FreeBSD, Linux, NetBSD, OpenBSD and Windows with AirPcap). The libraries `ieee80211.h` and `ieee80211_radiotap.h`[17] are also required, as they include the structures of the physical and link headers that we need. The Radiotap header permits us to obtain additional information from the received frames (channel, power, etc.). When sending, it also allows a number of parameters to be specified. This provides more flexibility than other options such as *Prism*[18]. The specification of these parameters is done by means of a bit mask that is in the header. In Figure 23 we show the scheme of the Radiotap header, as shown by Wireshark.



```
  Header pad: 0
  Header length: 32
v Present flags
  v Present flags word: 0x0000482f
      .... .... .... .... .... .... .... ...1 = TSFT: Present
      .... .... .... .... .... .... .... ..1. = Flags: Present
      .... .... .... .... .... .... .... .1.. = Rate: Present
      .... .... .... .... .... .... .... 1... = Channel: Present
      .... .... .... .... .... .... ...0 .... = FHSS: Absent
      .... .... .... .... .... .... ..1. .... = dBm Antenna Signal: Present
      .... .... .... .... .... .... .0.. .... = dBm Antenna Noise: Absent
      .... .... .... .... .... .... 0... .... = Lock Quality: Absent
      .... .... .... .... .... ...0 .... .... = TX Attenuation: Absent
      .... .... .... .... .... ..0. .... .... = dB TX Attenuation: Absent
      .... .... .... .... .... .0.. .... .... = dBm TX Power: Absent
      .... .... .... .... .... 1... .... .... = Antenna: Present
      .... .... .... .... ...0 .... .... .... = dB Antenna Signal: Absent
      .... .... .... .... ..0. .... .... .... = dB Antenna Noise: Absent
      .... .... .... .... .1.. .... .... .... = RX flags: Present
      .... .... .... .0.. .... .... .... .... = Channel+: Absent
      .... .... .... 0... .... .... .... .... = MCS information: Absent
      .... .... ...0 .... .... .... .... .... = A-MPDU Status: Absent
      .... .... ..0. .... .... .... .... .... = VHT information: Absent
      ...0 0000 00.. .... .... .... .... .... = Reserved: 0x00
      ..0. .... .... .... .... .... .... .... = Radiotap NS next: False
      .0.. .... .... .... .... .... .... .... = Vendor NS next: False
      0... .... .... .... .... .... .... .... = Ext: Absent
  MAC timestamp: 1123643543634
> Flags: 0x10
  Data Rate: 1.0 Mb/s
  Channel frequency: 2432 [BG 5]
> Channel flags: 0x00a0, Complementary Code Keying (CCK), 2 GHz spectrum
  SSI Signal: -46 dBm
  Antenna: 1
> RX flags: 0x0000
```

Figure 23: Scheme of the Radiotap header

In Annex 1 we have included detailed information about the whole process required for sending aggregated frames.

In Annex 2 a guide for the use of the developed test software is included.

4.4.2 Results obtained with the aggregation test software

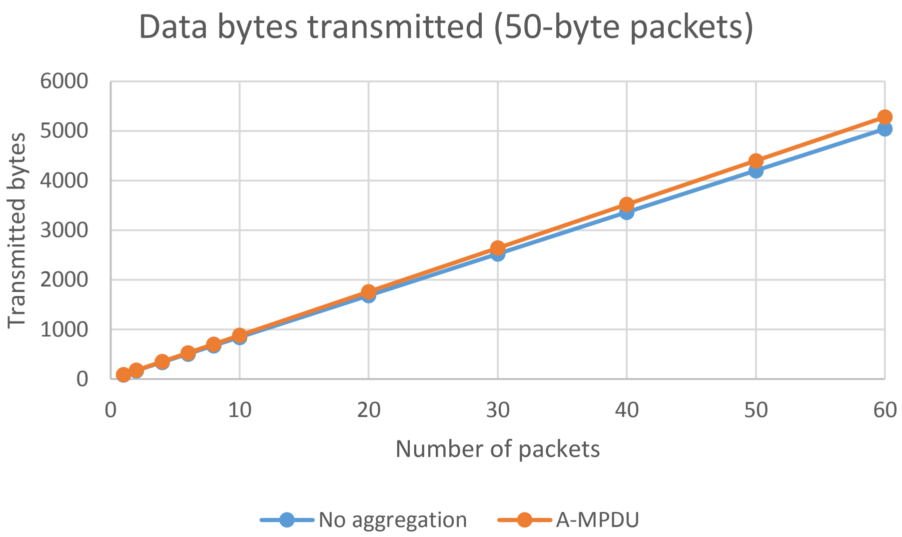
We have used the developed software in order to obtain some graphs of the total amount of bytes transmitted, which are separated into data bytes (the size of all the frames generated by the sender) and ACK bytes (the size of all the ACK frames generated by the receiver). The graphs are illustrative of the

[15] A *raw socket* is a kind of Linux socket which permits the sending of packets not following a protocol. For example, it permits to generate IP packets from user space.
[16] Radiotap, http://www.radiotap.org/, [Accessed Dec 2016].
[17] They can be obtained at http://ieee80211.sourceforge.net/#downloads, [Accessed Dec 2016].
[18] LINKTYPE_IEEE802_11_PRISM: http://www.tcpdump.org/linktypes/LINKTYPE_IEEE802_11_PRISM.html, [Accessed Dec 2016].

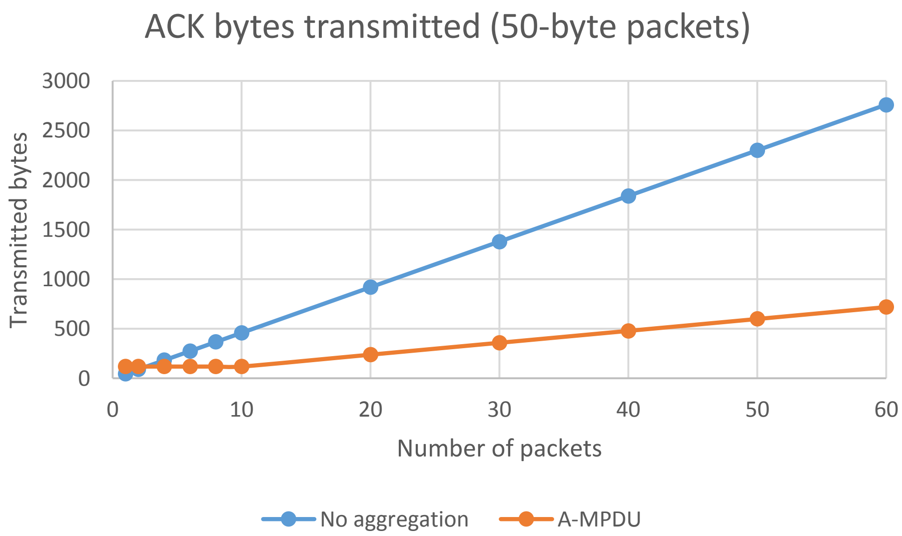
savings in terms of bytes. However, in order to have a clearer idea of the improvement this produces, a graph similar to Figure 21 could be generated. For that aim, an isolated environment would be necessary, in order to have no interference and no frame loss.

In Figure 24 we have represented the total amount of bytes sent in data frames including packets of 50 bytes at IP level (a), in the ACK frames (b) and the sum. It can be observed that A-MPDU aggregation may even send some more bytes in data frames when the packets are very small, as the size of the separators is in the same order of magnitude of the frames (a). However, the amount of bytes sent in ACKs is reduced (b), as Block ACKs can now be employed, which means that a single frame can acknowledge a number of frames. This results in an overall saving of the amount of bytes to be sent (c).

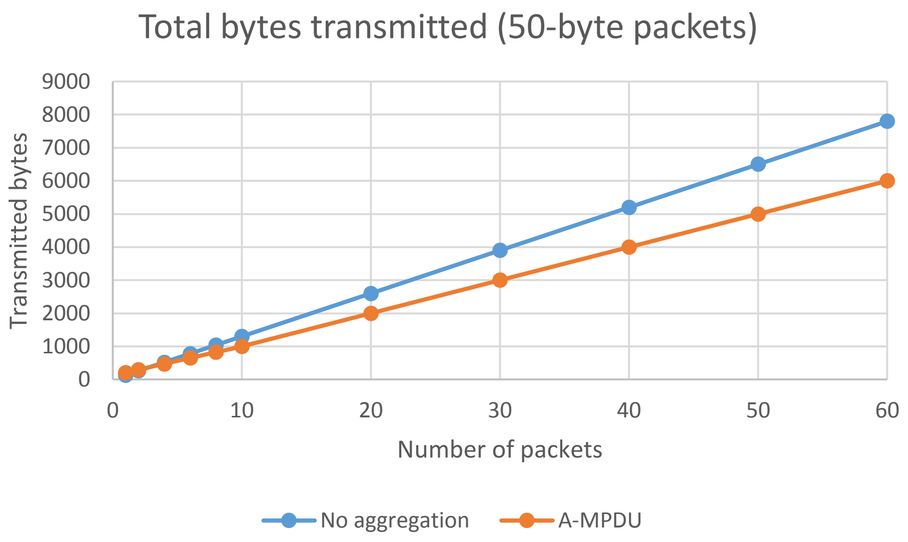
It should be noted that the MTU of our network setup has made it impossible to send more than 10 packets into a single aggregated frame, and this has made the savings worse than those expected.



(a)



(b)



(c)

Figure 24: Amount of bytes transmitted for 50-byte packets: a) data; b) ACK; c) total

In the next figures we represent the total amount of bytes sent when data packets of different sizes are sent. We have chosen 78, 228 and 528 byte sizes (corresponding to 50, 200 and 500 bytes of UDP payload respectively). The results are shown in Figure 25, Figure 26 and Figure 27. It can be observed that the savings are reduced as the packet size increases.

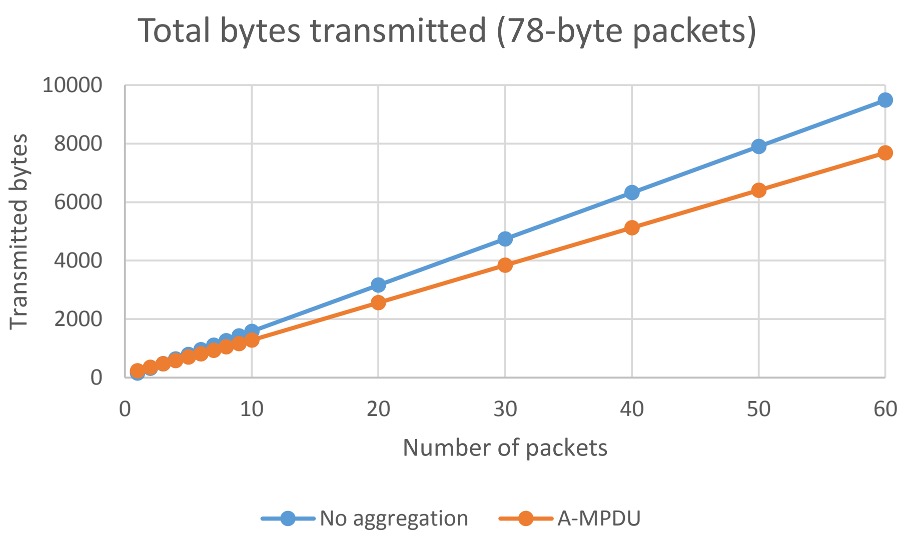


Figure 25: Total amount of bytes transmitted for 78-byte packets

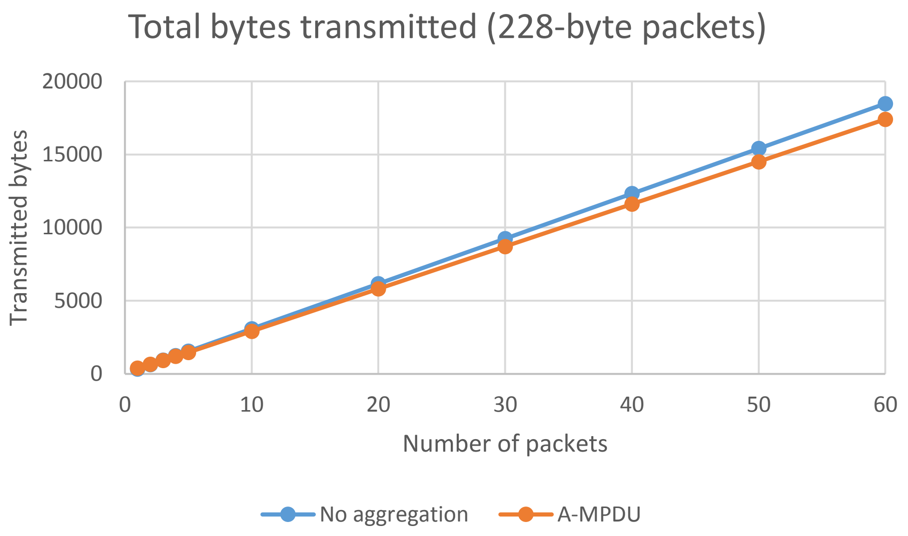


Figure 26: Total amount of bytes transmitted for 228-byte packets

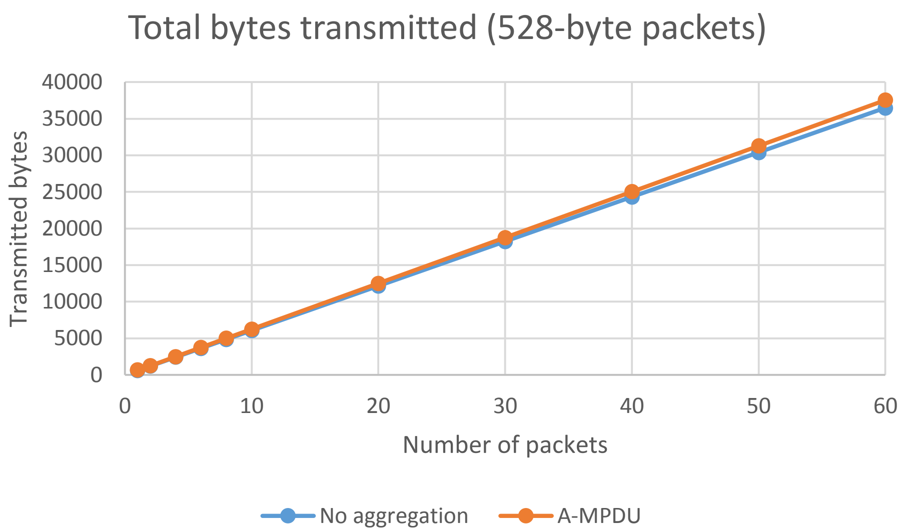


Figure 27: Total amount of bytes transmitted for 528-byte packets

Finally, in Figure 28 we have depicted the global savings that can be obtained when aggregating. It can be observed that aggregating small packets is clearly beneficial in terms of bandwidth. If the number of frames aggregated is small, the savings may become null, especially for small data packets. However, as soon as the number of packets grows, the achievable benefits become more noticeable.

However, as said before, the existence of a MAC layer in which the STAs have to compete for the channel, can make the benefits much higher. As shown in Figure 21, the efficiency improvement can be up to 80 or 90% if the effect of the MAC mechanisms is also taken into account. The present graphs have been included as an example of the results that can be obtained with the developed software. An isolated environment (or a wireless channel emulator) could be employed to obtain the results of the real achievable savings.

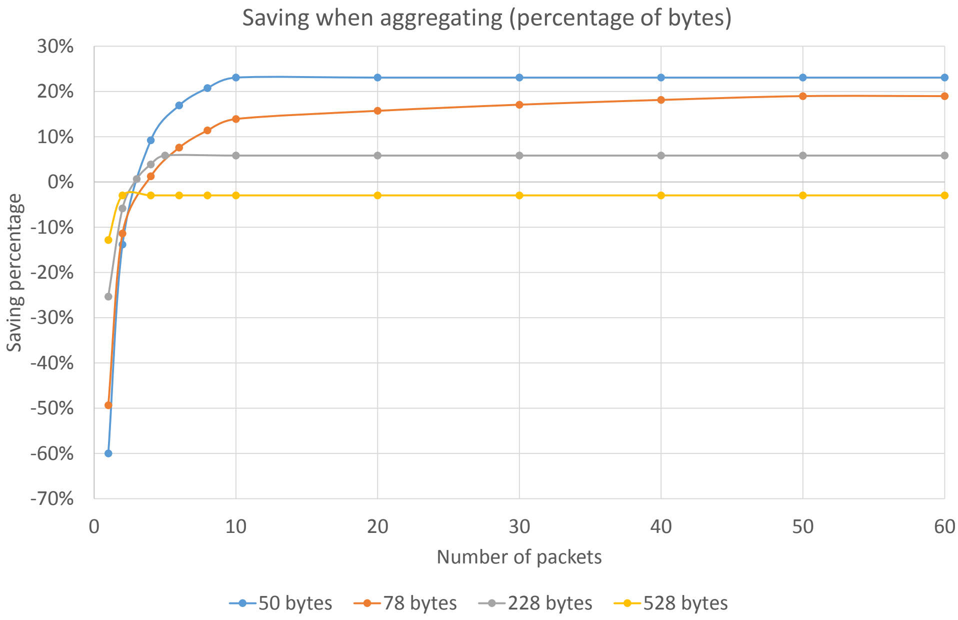


Figure 28: Global savings obtained when aggregating

4.4.3 Impact of Packet Grouping on subjective quality

As we have seen, frame aggregation is a means for improving efficiency, in terms of bandwidth utilisation, reduction of packets per second, and improvement of airtime utilisation. However, it should be noticed that frame or packet aggregation introduces some additional queuing delays, required for gathering a number of packets that will be sent together. Therefore, the effect of this new "aggregation" or "multiplexing" delay on subjective quality has to be studied in order to define its limits and the values that allow an acceptable level of subjective quality.

This section studies the impact of traffic aggregation on QoE, for a service with strict delay constraints, namely a Massively Multiplayer Online Role Playing Game (MMORPG). The results reported in this section have been published in the paper "Impact of Simplemux Traffic Optimisation on MMORPG QoE," see [59].

The effect of aggregation we are studying here is limited to the additional delay, i.e. the latency required to gather a number of packets that will travel together. This latency is the same, despite the fact of performing the aggregation at Layer 2 or Layer 3: as explained in [62], aggregation using a period (i.e. an aggregated bundle is sent at the end of each period) is translated into an additional delay with an average of half the period, and a jitter (the value of the standard deviation of the delay is $period/\sqrt{12}$).

In the subsequent tests, Simplemux [63] Layer 3 aggregation has been used to send together a number of packets of different game flows, sharing the overhead of a common end-to-end tunnel. As a counterpart of the reduction in terms of bandwidth usage and packet rate, an additional delay and delay variation are introduced. Subjective studies with real people have been conducted, combining artificially created network flows of the game, with traffic of real users, and this mix has been aggregated with Simplemux, using a publicly available implementation. In this way we have simulated a case scenario in which a number of flows share a common network path. As we will see, two parameters are modified: the number of active game flows, and the multiplexing period. We have examined if the players notice any degradation in their game experience, by comparing two situations: when aggregation is active or not. The goal is to investigate whether users' QoE is degraded by packet multiplexing.

4.4.3.1 Context of the study

From a network point of view, interactive applications, such as online games, have to send updates at a very fast pace to maintain the perception of responsiveness. The content of each update is relatively small, so the traffic profile of these services consists of small packets. As a result, these applications produce traffic flows comprised of high rates of small packets. Similar traffic features can also be observed in non-real time applications such as instant messaging or Machine to Machine (M2M) services. This results in a reduction of the overall network efficiency, as their payload-to-header ratio is very low so effective application-level bandwidth usage is reduced.

In the present case, we examine the effect of multiplexing on subjective quality for *World of Warcraft* (WoW) which is a TCP-based MMORPG. There are some reasons for selecting this game: it is a very popular title and, in addition, a number of academic works have been carried out using it [64], [65], [66]. To illustrate the problem of small packets in the network, in Figure 29 we present the packet-size distribution of a traffic trace from WoW. It can be observed that the size distribution of client-to-server packets ends in 200 bytes, with a significant amount of pure TCP ACKs (40 bytes). In contrast, the size of server-to-client packets has a wider range, although a significant amount of them are also small.

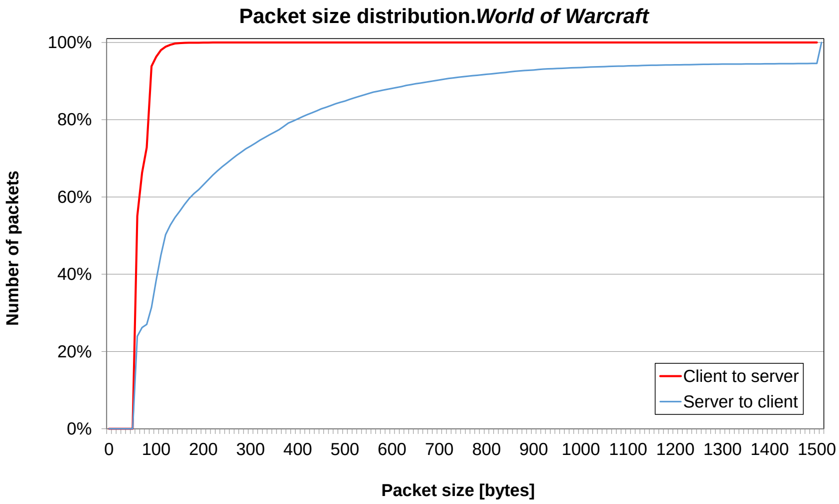


Figure 29: Packet size histogram of a traffic trace of *World of Warcraft*

In our use case we optimise traffic flows from one server of an MMORPG, and specifically look at the influence at the user level. In the study we keep the round trip time (RTT) under 100ms at all times, which is considered as *good* even for more interactive games such as First Person Shooters [67]. For MMORPGs there are conflicting results regarding the impact of delay on the player's QoE [68, 69], but the most conservative results suggest that for Mean Opinion Score (MOS) above 4, RTT should be kept under 120ms [68]. As regards to variation of delay, the same work [68] stated that the variation of delay of 10ms has a significant impact on QoE.

A subjective user's study has been conducted, in which the players compare their QoE in the case where aggregation is run versus a case in which no optimisation occurs. The goal is to evaluate whether the QoE of the players is degraded when the optimisation is used, but always maintaining the overall RTT low enough (below 100 ms, including the delay introduced by Simplemux). In another case, based on the scores of the evaluation parameters, multiplexing parameters could be adjusted to ensure high QoE.

Different subjective quality estimators have been proposed for real-time services. They are based on tests with real users who, after performing a test with the service, are invited to fill in a form reporting their subjective experience. Network conditions are modified (in terms of delay, jitter or packet loss) in order to capture the influence of each parameter on their subjective experience. Finally, a formula is devised based on the subjective data. As an example, the ITU E-Model [70] was proposed to estimate subjective quality of VoIP. Some models have also been proposed for games as e.g. [58] for a First Person Shooter or [68] for an MMORPG.

The present tests differ from those subjective studies as we do not directly try to map the impact of specific network parameters onto players' QoE, but we aim to investigate whether traffic optimisation based on aggregation can be performed without QoE degradation. If the QoE is not degraded for a real-time service such as an MMORPG, this means that such optimisation can be easily applied to other services which do not have such tight delay requirements.

There are different policies that can be employed for aggregating small into large packets: 1) *fixed number* of packets - once a fixed number of packets has arrived, a multiplexed packet is created and sent; 2) *size limit* - once a size limit is reached (e.g., next to the MTU of the underlying network), a multiplexed packet is sent; and 3) *period* - a multiplexed packet is sent every time period. The combination of *size limit* and *period* policies enables control of the additional delay introduced by multiplexing while maintaining high bandwidth usage savings: a multiplexed packet is sent at the end of each period but, if the size limit is reached, a multiplexed packet is sent immediately, and the period is reset. Thus, the added delay is for the worst case scenario equal to the defined period.

When multiplexing is based on a time period, a sawtooth-shaped delay is added to the packets [71], i.e., those arriving at the beginning experience a big delay, whereas those arriving at the end are sent almost immediately. The average delay is half the period, and some jitter is also added.

4.4.3.2 Methodology

4.4.3.2.1 Laboratory testbed

To enable testing we have first integrated Simplemux into the Integrated Multiprotocol Network Emulator/Simulator[19] (IMUNES) [72], developed by Ericsson Nikola Tesla and the University of Zagreb. IMUNES was originally built on a FreeBSD platform, but a Linux-based implementation is also available. Using IMUNES, complex network architectures can be simulated inside one machine, so there is no need for a physical testbed comprising multiple PCs and routers.

As we previously stated, as a use case MMORPG we use WoW. To generate realistic network flows associated with a WoW server, the User Behaviour Based Network Traffic Generator (UrBBaN-Gen) architecture [65] has been used which generates traffic following player behaviour. UrBBaNGen consists of three main components: User Behaviour Simulator (UBS), Distributed Traffic Generation Control System (DTGCS), and Distributed Internet Traffic Generator (D-ITG) as a module for creating packets [73]. Both physical and simulated environments are presented in Figure 30, which depicts the testbed.

[19] See http://imunes.net/

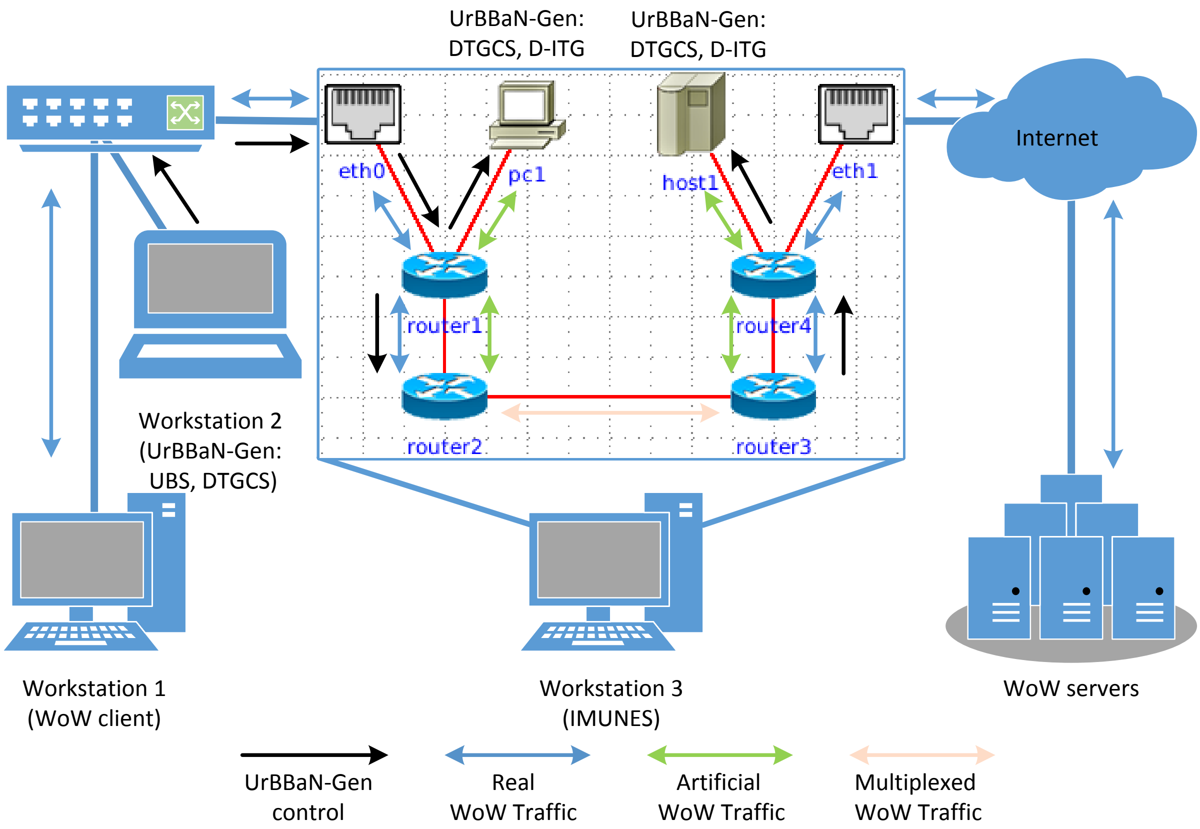


Figure 30: Laboratory testbed used for these experiments

A WoW client is run on *Workstation 1*, and in the testing procedure the players play on this device. *Workstation 2* hosts two parts of UrBBaN-Gen: UBS and the server part of DTGCS. Both workstations are connected via an Ethernet switch with *Workstation 3* which has two network interfaces (*eth0* and *eth1*) and runs IMUNES. These two interfaces are included into the simulation and their traffic can also travel to other machines outside IMUNES. Within *Workstation 3*, other elements of UrBBaN-Gen are run: part of DTGCS and D-ITG network traffic senders (on the simulated *host1)*, and part of DTGCS and D-ITG network traffic receivers (on the simulated *pc1*).

In this way, the real WoW traffic flowing from the client to the server and back (blue arrows) shares the network path with the artificially generated flows (green arrows) within the simulation environment. Based on the data from UBS, DTGCS controls the D-ITG network traffic senders and receivers which are run within the IMUNES simulation. In the simulation, server-to-client traffic of different action categories[20] is generated, as defined in [74]. The traffic is aggregated on the shared path using Simplemux between *Router 2* and *Router 3*.

4.4.3.2.2 Subjective tests

The experiments focus on users playing WoW and testing whether they notice the difference between a scenario in which aggregation is run, compared to the scenario in which it is not. We simulate different numbers of active artificial flows (10, 20, 30, 50 and 600 flows), as well as different multiplexing periods (10, 20, 30, 50 ms). We refer to each combination of numbers of artificially generated flows

[20] The term "action categories" refers to the different kinds of activities that can be performed when playing an MMORPG, e.g. *Questing, Player vs player, Trading, Dungeons*, etc. Each activity generates a different kind of traffic, following different patterns of inter-packet time or packet size, corresponding to the different levels of interactivity and the number of players simultaneously involved in the action.

and the multiplexing period as a “scenario”. The scenarios that have been tested are listed in Table 4. The participants of the study were 10 males, aged from 22 to 33. All the test participants were experienced gamers. The testing procedure lasted between 30 and 35 minutes on average. Each participant has tested all the scenarios.

Table 4: Tested scenarios

Scenario	No. of generated flows	Aggregation period [ms]
1	600	10
2	50	50
3	50	10
4	20	20
5	20	10
6	10	50
7	10	30

For comparison of gameplay between the case in which Simplemux is used and the one in which it is not, we used *paired comparison*, as defined in ITU-T P.800 [75] and ITU-R BT.500-13 [76]. In the Comparison Category Rating (CCR) method, testers are presented with a pair of samples on each scenario. The order of the affected and unaffected sample is randomly chosen for each scenario. In the CCR procedure, the 7pt. comparison scale, presented in Table 5, is used to judge the quality of the second sample relative to that of the first one.

Table 5: 7 pt. comparison scale

3	Much Better
2	Better
1	Slightly Better
0	About the Same
-1	Slightly Worse
-2	Worse
-3	Much Worse

The procedure for testing is as follows: first, the testing user would create a new character in WoW and play the game for a few minutes to get familiar with the commands. Then, the testing procedure would start. In each scenario, two different settings have been tested (i.e., aggregation on and off). Between both settings, the player has to be disconnected from the virtual world as the initialisation/shutdown process for Simplemux resets network interfaces within IMUNES, so the connection with the WoW servers is interrupted. The duration of gameplay for each setting was one minute. After one scenario was completed (i.e., both settings were tested for every scenario), the user would: 1) compare the QoE of the gameplay of the second setting with the first one on the 7pt. scale described above, and 2) answer whether he/she would continue playing in these conditions. Additionally, RTT was noted for each setting (as reported by the WoW client).

4.4.3.3 Results

The order in which each player performed both tests was random. Therefore, for the presentation of results, we normalised the CCR scores so as to present all scores considering aggregation as the second setting (i.e., we reversed the algebraic sign in the scenarios in which aggregation enabled was the first setting within a scenario).

The results for scenarios 1-6 are depicted in Figure 31. For scenario 7 we do not display the data, as all CCR scores were 0 *("About the same")*. It can be observed that in every scenario at least 7 test participants did not discriminate between both settings. No CCR score of 3, -3, and -2 was given, meaning that in the worst case, the setting in which Simplemux was active, was graded as *"Slightly worse"*. What is interesting is that in two cases the scenario in which aggregation was active was graded as *"Better"* (CCR score 2) than the scenario without it. The results indicate that for the majority of the time (81.43%) the users were not able to appreciate the difference. What is more important, all users in all scenarios stated that they would continue playing under these conditions. Therefore, we can conclude that the use of aggregation in our scenarios did not introduce degradation at a scale that would impact players' willingness to play.

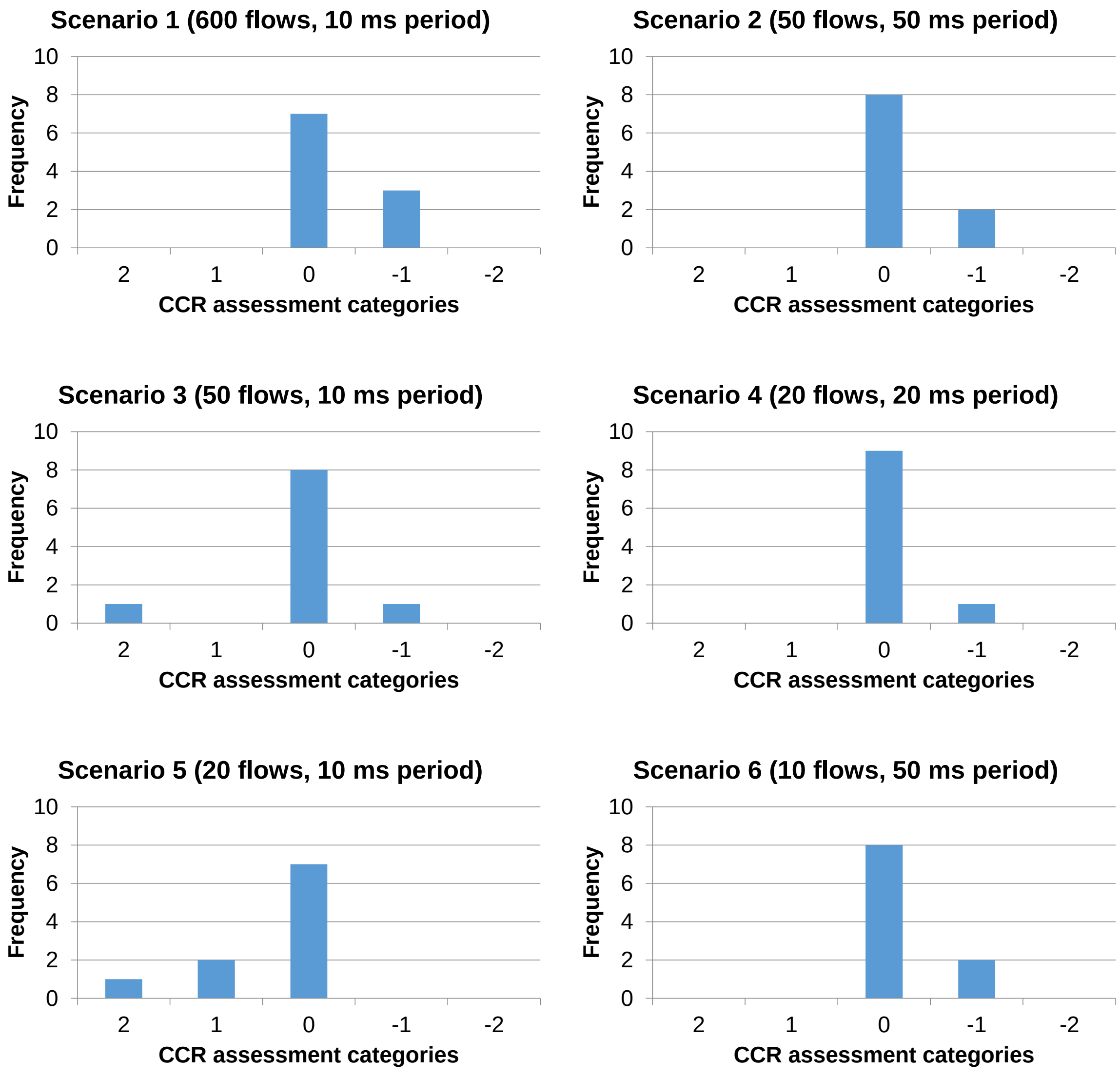


Figure 31: Subjective scores for scenarios 1-6

The RTT from our laboratory to the WoW server was 38ms (as reported by the WoW client) when the optimisation was not enabled (*base RTT*). In Figure 32 we present the average RTT measured in every scenario. It should be noted that RTT never reached 100ms for any user. Half of the multiplexing period is added as delay in one direction, resulting in an average latency increase of one multiplexing period. The added latency also depends on the number of generated additional flows, so it is lower in cases with higher number of users, where the MTU can be reached. When comparing CCR results with the introduced latency, no clear correlation is observed, meaning that the users do not notice the discrepancies in the latency. This could be expected, as one of our goals was to keep the latency below 100ms. Another important finding coming from these results is that delay variation introduced by multiplexing is also not registered by the players in our scenarios.

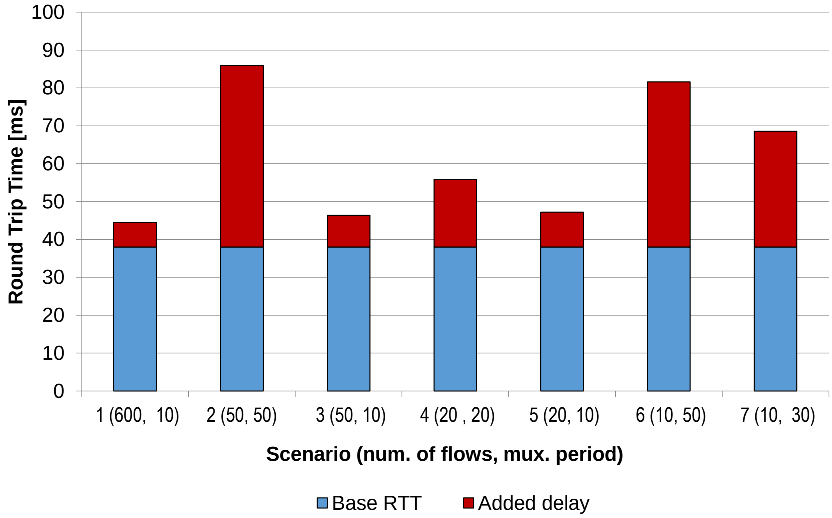


Figure 32: RTT for all scenarios

The results regarding bandwidth usage savings and reduction of the packet rate were obtained by capturing network traffic on the *Router 2*, before and after multiplexing. Reduction of the bandwidth usage (bitrate) and packet rate is depicted in Figure 33. Very significant packet rate reduction (up to 88%) can be observed, and bandwidth usage reduction can be up to 68%. The higher the number of concurrent flows that are multiplexed, the better both the bandwidth usage savings and the packet rate reduction. All in all, the results indicate that large bandwidth usage savings and especially significant packet rate reductions can be obtained without degrading MMORPG players' QoE, as long as the overall latency is kept under 100 ms.

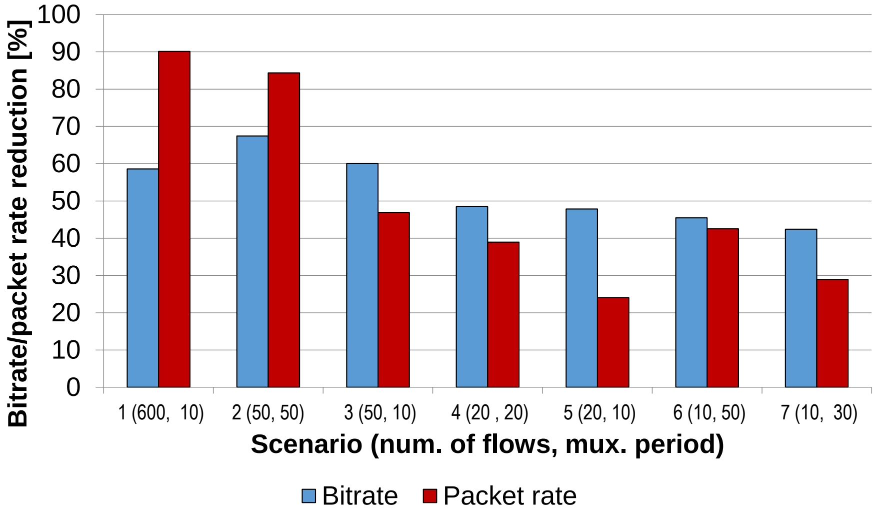


Figure 33: Reduction of the bitrate and packet rate per scenario

The results of the study showed that even with a small number of flows (such as 10), and 50 ms multiplexing period, the aggregation of packets results in a reduction of bandwidth usage and packet rate up to 40%, without degrading the players' QoE. In cases where the multiplexing period must be kept low to maintain overall latency below 10 ms, bandwidth savings of 45% and packet savings of 20% can still be achieved, with only 20 players. Another important finding is that the introduced latency variation, which can be up to half of the multiplexing period, does not prove to be a problem for the players, who do not notice it.

5 Conclusions

This document has presented the second version of the Smart Access Point Solutions being developed within the WP3 of the Wi-5 Project. After the Introduction, a Literature Review has been presented including the different research fields such as the use of virtual Wi-Fi APs combined with SDN; the resource management in Wi-Fi WLANs and packet/frame grouping for improving network efficiency.

A global view of the Wi-5 architecture was then provided, including the different entities and the description of the functionalities being considered here. An approach based on the use of SDN is being followed which considers a central controller, to which all the APs are connected. It also uses an abstract LVAP, and the controller creates an LVAP for each terminal, which is dynamically assigned to the physical AP where the terminal is located at each moment. Therefore, the AP will use a different LVAP (which includes a specific MAC) for communicating with each terminal, which will only "see" a single AP, even if it is moving between different APs, thus avoiding the need for re-association.

The original solution has been extended by the inclusion of support for APs in different channels. This has required the addition of an auxiliary wireless interface on each AP for scanning without interrupting the running connections. In addition, the full separation between the control plane and the data plane makes it possible to use different network interfaces for each kind of traffic.

Then, a detailed description of the work regarding Smart AP Solutions was presented. First, a set of improvements aimed at integrating the support of different channels within the Wi-5 framework were presented. A multi-channel handoff scheme has been designed, and good synchronisation is required between the different processes in order to make the LVAP switch happen in the same moment when the STA switches its channel. In addition, the beacon generation process has been modified in order to improve the scalability and to give a better user experience during handoffs

Tests measuring the incurred delay have been presented, using three wireless cards from different manufacturers, and using a flow of an online game with real-time constraints as test traffic. The results show that fast handovers can be achieved, ranging from 30 to 200 ms. Some differences have been observed depending on the wireless card used and its internal scheme, especially regarding the added delay to the traffic traversing it.

Some other tests aimed at exploring the feasibility of power control in our setup have been reported. In some cases (e.g. per-packet power control), the experimental setup does not allow them, so our tests could be limited to a proof-of-concept in an isolated environment. The way to perform load balancing in our multi-channel setup has also been explained.

Finally, packet grouping policies have been discussed. Proof of concept test software has been built, in order to implement frame aggregation in a device running in the monitor mode. The software creates a sort of *fake* AP, which is able to accept connections from STAs in the environment, and then sends a number of aggregated frames, according to the user's commands. The software has been used for running some tests of the savings obtained at Layer 2 when grouping frames of different sizes.

The effect of packet grouping on subjective quality has also been studied. A methodology including subjective tests with real users has evaluated this effect, using *paired comparison*, as defined in ITU-T P.800 and ITU-R BT.500-13. The users played an online game in two different conditions (with aggregation active or non-active) and then they had to evaluate their experience in both cases. The users do not notice the discrepancies in the latency. The results indicate that bandwidth usage savings and especially significant packet rate reductions can be obtained without degrading players' QoE, as long as the overall latency is kept under 100 ms. An important finding coming from these results is that delay variation introduced by multiplexing is not registered by the players in our scenarios.

Regarding the most innovative aspects of this work, two of them can be remarked: firstly, the combination of LVAPs with the use of multi-channel APs, which allows two key features at the same time: seamless handovers, and radio resource management. The obtained results, in terms of handover delay, are relevant, as they show that the possibility of combining LVAPs with multi-channel is feasible, even with highly-demanding services. The results have been published in a relevant journal, as it was the first time they have been proposed.

Second, the fact of being able to aggregate packets without disturbing the users is also relevant, as this opens the possibility of grouping small packets in wireless environments, which can provide a high efficiency improvement. It is our objective to study this issue in more depth, in order to achieve relevant results which illustrate the high efficiency improvement, using realistic traffic flows.

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Annex 1. Reproducing the whole Aggregation process with our test software

In order to send A-MPDUs, we first need to associate an STA to an AP. So we first had to extend the software in order to reproduce the whole association process of 802.11 (see Figure 34: Association process in 802.11), including the sending of *beacons*, the reception of *Probe Request* and the subsequent sending of *Probe Response*. Next, the *Authentication Request* and *Response* are exchanged and finally the *Association Request* and *Response* are sent. Different Layer 2 ACKs are also needed in order to acknowledge all these frames. Note that the developed program only implements the AP part (the left side of the figure). The STA can be any device including an 802.11 wireless card.

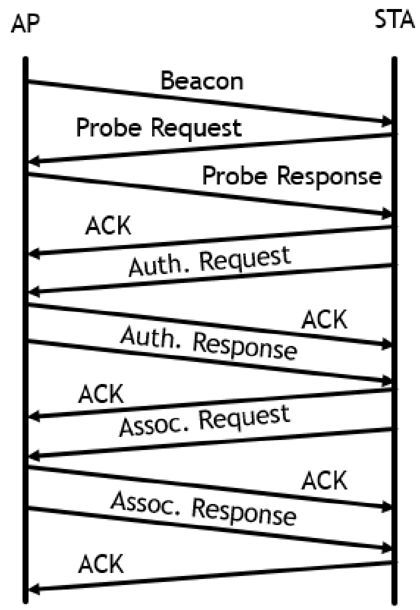
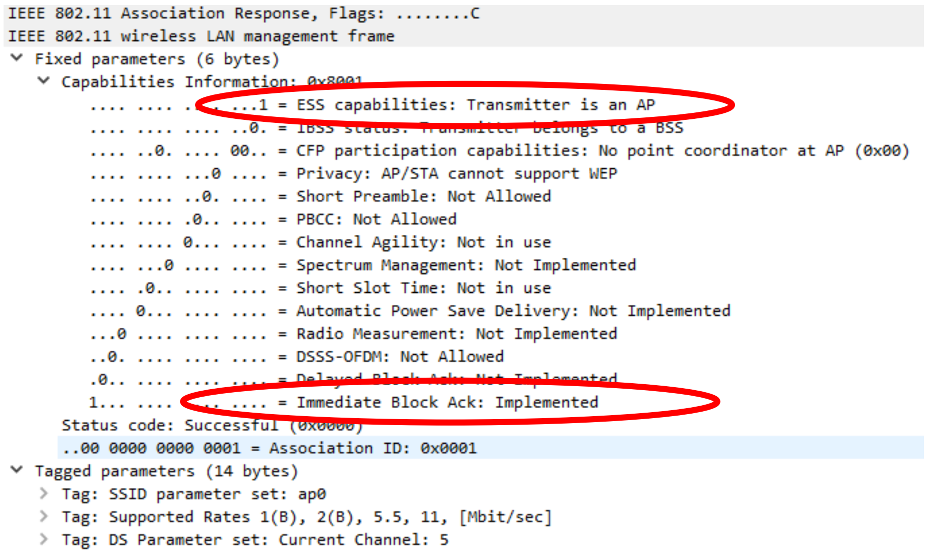


Figure 34: Association process in 802.11

The software is able to reproduce all of this process. However, different fields have to be added in order to make possible the subsequent sending of A-MPDUs. For example, in the *beacon*, the field *capabilities* must have the *ESS* (Extended Service Set) enabled, indicating that the transmitted is an AP; and also the *Immediate Block ACK* capability has to be enabled, as it is needed for frame aggregation. These fields have also to be present in the *Association Response*.

In Figure 35 we show a capture of the *Association Response* obtained with Wireshark. It can be observed that the *Immediate Block ACK* is implemented, and the *ESS* is set.



```
IEEE 802.11 Association Response, Flags: ........C
IEEE 802.11 wireless LAN management frame
  Fixed parameters (6 bytes)
    Capabilities Information: 0x8001
      .... .... .... ...1 = ESS capabilities: Transmitter is an AP
      .... .... .... ..0. = IBSS status: Transmitter belongs to a BSS
      .... ..0. .... 00.. = CFP participation capabilities: No point coordinator at AP (0x00)
      .... .... ...0 .... = Privacy: AP/STA cannot support WEP
      .... .... ..0. .... = Short Preamble: Not Allowed
      .... .... .0.. .... = PBCC: Not Allowed
      .... .... 0... .... = Channel Agility: Not in use
      .... ...0 .... .... = Spectrum Management: Not Implemented
      .... .0.. .... .... = Short Slot Time: Not in use
      .... 0... .... .... = Automatic Power Save Delivery: Not Implemented
      ...0 .... .... .... = Radio Measurement: Not Implemented
      ..0. .... .... .... = DSSS-OFDM: Not Allowed
      .0.. .... .... .... = Delayed Block Ack: Not Implemented
      1... .... .... .... = Immediate Block Ack: Implemented
    Status code: Successful (0x0000)
    ..00 0000 0000 0001 = Association ID: 0x0001
  Tagged parameters (14 bytes)
    Tag: SSID parameter set: ap0
    Tag: Supported Rates 1(B), 2(B), 5.5, 11, [Mbit/sec]
    Tag: DS Parameter set: Current Channel: 5
```

Figure 35: Capture of an 802.11 *Association Response* generated by our test software

Once the association has been completed (i.e. the STA is associated with the "fake AP"), a new message exchange has to be run in order to send A-MPDUs, which is shown in Figure 36.

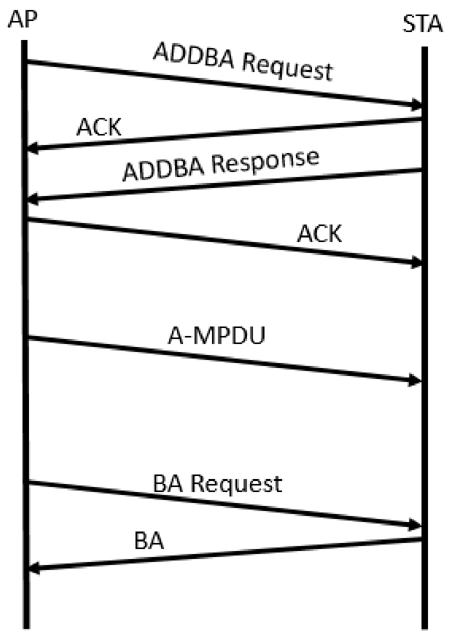


Figure 36: Frame exchange for grouping in 802.11

First, the sender has to send an *AddBa Request*[21], an *Action* frame where it is negotiated whether the receiver is able to receive A-MPDUs. In addition, their characteristics are negotiated: the maximum number of frames to be aggregated, if A-MSDUs can be included, and other options. The scheme of this frame is shown in Figure 37. It can be observed that it is an *Action* frame, with the correct *Action Code*.

[21] *AddBa Request* (*Add Block* ACK *Request*): This frame is used for the negotiation of *Block* ACK and therefore for A-MPDUs. It shares the characteristics which will be used when managing the *Block* ACK messages.

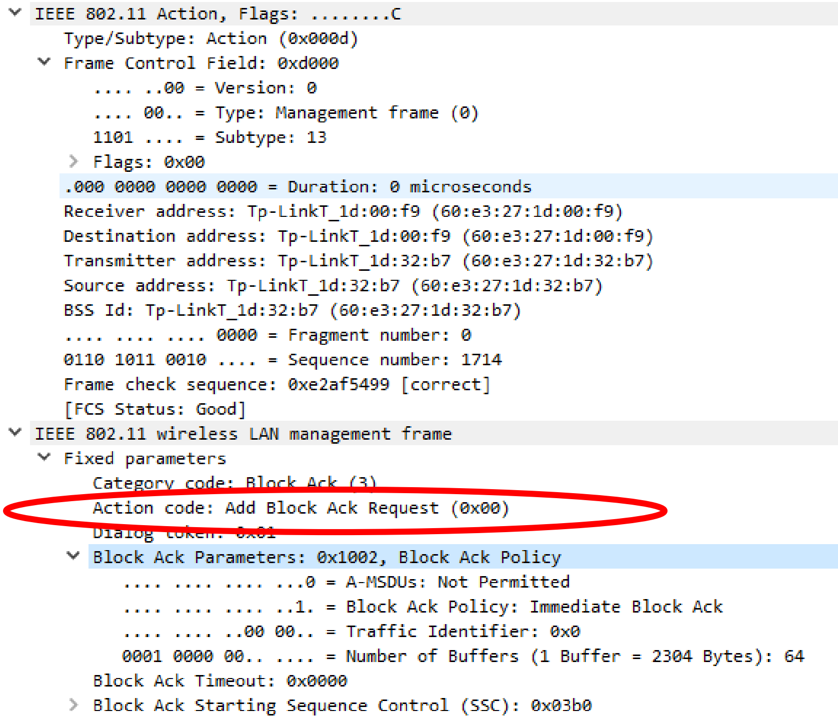


Figure 37: Scheme of an *AddBa Request* in 802.11, generated by the test software

If the receiver has the hardware and the software required to decode these kinds of frames, it will answer with an *AddBa Response*[22] frame. From that moment, it will be possible to send A-MPDUs in that sense. If a bidirectional exchange is desired, the negotiation also has to be carried out by the STA.

The test program sends IPv4/UDP packets within the A-MPDUs. The *LLC*[23] and *SNAP* [24] headers have to be filled in order to express that what comes next is an IPv4 packet (IPv4 header, UDP header and payload, which is filled with the character ‘0’).

Once this exchange has successfully been completed, the AP can start sending A-MPDUs. When it is finished, it will send a *Block ACK request*, i.e. a frame where it tells the STA to acknowledge those frames that have arrived correctly. The *Block ACK* includes a bitmap expressing which frames have arrived correctly.

[22] *AddBa Response* (*Add Block* ACK *Response*): This frame is an answer to the *AddBa Request,* where the receiver tells the sender which are its capabilities related to *Block* ACK. In addition, if it agrees with those received, it will be able to start using *Block* ACK.
[23] LLC (*Logical Link Control*): Is the highest layer of the *data link* defined by IEEE and it is in charge of error and flow control.
[24] SNAP (*Subnetwork Access Protocol*): It is an extension of LLC to distinguish a higher number of protocols of the upper layers.

Annex 2. Use of the aggregation test software

As said before, the program has been implemented as a user space application written in C. Once compiled (e.g. with `gcc`), the user can specify a number of parameters. This is the help message that the user will get if the program is invoked without parameters:

```
fakeaps [raw device name (e.g. 'wlan0')] [802.11 channel] [Packet size at IP level]
[number of frames in each A-MPDU (0 means 'no frame aggregation')] [number of A-MPDUs
to send] [destination IP address using (.)] [destination MAC address using (:)]
```

An example of usage would be:

```
./fakeaps wlan0 5 500 2 10 192.168.7.2 f4:f2:6d:0c:9d:aa
```

This is the meaning of the above parameters:

- `wlan0`: name of the interface where you are creating the *"fake AP."* It has to be in the monitor mode.
- `5`: number of the Wi-Fi channel where you are creating the *"fake AP."*
- `500`: packet size at IP level (including IP header).
- `2`: number of packets that are going to travel in an A-MPDU.
- `10`: number of A-MPDUs that will be sent.
- `192.168.7.2`: IP address of the STA that is going to connect. It will be the destination of the A-MPDUs to be sent.
- `f4:f2:6d:0c:9d:aa`: MAC address of the STA that is going to connect. The MAC is used as a filter. Only this MAC is allowed to connect to the *"fake AP."*

Therefore, the previous command would do the following things:

- Create a *"fake AP"* (called by default `ap0`) and start sending beacons in the broadcast mode in channel `5`.
- Wait for the STA with MAC `f4:f2:6d:0c:9d:aa` to associate, and then send `10` A-MPDUs, each of them containing `2` packets of `500` bytes, to the IP address `192.168.7.2`.

We next present the output of the program, when used to send 3 multi-frames, each of them containing 2 IP packets of 40 bytes:

```
$ ./fakeaps wlan0 5 40 2 3 192.168.7.2 f4:f2:6d:0c:9d:aa

##### Multi-frame #1
Sub-frame #1: MPDU size: 76 bytes
Sub-frame #2: MPDU size: 76 bytes
00:9d:1e:00:04:00:10:00:6c:60:e3:27:1d:32:b7:d0:
03:01:82:00:00:01:00:00:00:00:00:00:01:00:4c:00:
47:4e:88:02:00:00:f4:f2:6d:0c:9d:aa:60:e3:27:1d:
32:b7:60:e3:27:1d:32:b7:f0:03:00:00:aa:aa:03:00:
00:00:08:00:45:00:28:00:05:de:00:00:ff:11:77:00:
c0:a8:07:01:c0:a8:07:02:1a:0a:21:ae:00:14:b2:00:
30:30:30:30:30:30:30:30:30:30:30:30:00:00:4c:00:
47:4e:88:02:00:00:f4:f2:6d:0c:9d:aa:60:e3:27:1d:
32:b7:60:e3:27:1d:32:b7:00:04:00:00:aa:aa:03:00:
00:00:08:00:45:00:28:00:05:df:00:00:ff:11:7d:00:
c0:a8:07:01:c0:a8:07:02:1a:0a:21:ae:00:14:b2:00:
30:30:30:30:30:30:30:30:30:30:30:30:00:00:
```

```
Block ACK Request 1 sent

##### Multi-frame #2
Sub-frame #1: MPDU size: 76 bytes
Sub-frame #2: MPDU size: 76 bytes
00:86:1e:00:04:00:10:00:6c:86:71:e3:62:7f:00:00:
03:01:82:00:00:01:00:00:01:00:00:00:01:00:4c:00:
47:4e:88:02:00:00:f4:f2:6d:0c:9d:aa:60:e3:27:1d:
32:b7:60:e3:27:1d:32:b7:10:04:00:00:aa:aa:03:00:
00:00:08:00:45:00:28:00:05:e0:00:00:ff:11:4c:00:
c0:a8:07:01:c0:a8:07:02:1a:0a:21:ae:00:14:b2:00:
30:30:30:30:30:30:30:30:30:30:30:30:00:00:4c:00:
47:4e:88:02:00:00:f4:f2:6d:0c:9d:aa:60:e3:27:1d:
32:b7:60:e3:27:1d:32:b7:20:04:00:00:aa:aa:03:00:
00:00:08:00:45:00:28:00:05:e1:00:00:ff:11:45:00:
c0:a8:07:01:c0:a8:07:02:1a:0a:21:ae:00:14:b2:00:
30:30:30:30:30:30:30:30:30:30:30:30:00:00:

Block ACK Request 2 sent

##### Multi-frame #3
Sub-frame #1: MPDU size: 76 bytes
Sub-frame #2: MPDU size: 76 bytes
00:86:1e:00:04:00:10:00:6c:86:71:e3:62:7f:00:00:
03:01:82:00:00:01:00:00:02:00:00:00:01:00:4c:00:
47:4e:88:02:00:00:f4:f2:6d:0c:9d:aa:60:e3:27:1d:
32:b7:60:e3:27:1d:32:b7:30:04:00:00:aa:aa:03:00:
00:00:08:00:45:00:28:00:05:e2:00:00:ff:11:75:00:
c0:a8:07:01:c0:a8:07:02:1a:0a:21:ae:00:14:b2:00:
30:30:30:30:30:30:30:30:30:30:30:30:00:00:4c:00:
47:4e:88:02:00:00:f4:f2:6d:0c:9d:aa:60:e3:27:1d:
32:b7:60:e3:27:1d:32:b7:40:04:00:00:aa:aa:03:00:
00:00:08:00:45:00:28:00:05:e3:00:00:ff:11:7b:00:
c0:a8:07:01:c0:a8:07:02:1a:0a:21:ae:00:14:b2:00:
30:30:30:30:30:30:30:30:30:30:30:30:00:00:

Block ACK Request 3 sent
```

As the program dumps the packets by the screen, this information can be used for checking the results and to measure the benefits obtained when aggregating.