What to do With the Wi-Fi Wild West		
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Abstract

The H2020 What to do With the Wi-Fi Wild West (Wi-5) project combines research and innovation to propose a Software Defined Networking (SDN) architecture based on an integrated and coordinated set of smart Wi-Fi networking solutions. The resulting system will be able to efficiently reduce interference between neighboring Access Points (APs) and provide optimized connectivity for new and emerging services.

In this document we present a general overview of the testing and field trials work and then describe the setup of the system in PrimeTel and the planning and description of the different tests and trials that were carried out in the SOHO and community Wi-Fi scenarios. We also provide a thorough explanation of the testing process and the important observations and results from the field trials conducted, including some conclusions about each test and application that was included during the field trials.

In the final section we give a general assessment to the currently implemented Wi-5 applications regarding their functionality and performance. We also refer to the aspects of the system and functionalities of the system, in which, we believe that future work should aim at improving. Finally, we give a general recap of the problems and difficulties faced in the trials in an attempt to guide future work.

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Glossary

AP	Access Point
API	Application Interface
CSA	Channel Switch Announcement
HT	High Throughput
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISO	International Organization for Standardization
LCC	Least Congested Channel
LVAP	Light Vırtual Access Point
MAC	Media Access Control
MCS	Modulation and Coding Size
QoE	Quality of Experience
QoS	Quality of Service
RF	Radio Frequency
RRM	Radio Resource Management
RSSI	Received Signal Strength Indicator
SDN	Software-Defined Network
SEBoK	System Engineering Body of Knowledge
SINR	Signal to Interference Ratio
SMB	Small Medium Businesses
SOHO	Small Office Home Office
SSID	Service Set Identifier
TPC	Transmit Power Control
ISP	Internet Service Provider
Wi-Fi	Wireless Fidelity

1 Introduction

1.1 Wi-5 background

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

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

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

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

1.2 Scope of the deliverable

This document describes the testing done during the field trials for the Wi-5 System conducted by PrimeTel. The work in the field trials had two main goals. First we aimed to test all the available features and controller applications of the Wi-5 System and provide feedback to the project partners for improvements and fixes. The second goal was to validate the performance of the functionalities and the respective algorithms that are used in each application.

1.3 Document structure

In Section 2 we provide a general description of the Wi-5 project.

Section 3 is separated in two main parts. First we present the procedure of setting up the Wi-5 System, and secondly we give a detailed description on the important tests conducted by PrimeTel.

More specifically, in the first part we present the two scenarios of Wi-Fi use cases which we decided to follow when deploying the Wi-5 System. The setup of the system at the PrimeTel premises followed the wiki instructions provided on Git-Hub but we adjusted several aspects of the procedure to bring it more in line with production systems able to be deployed by an Internet Service Provider (ISP) in reality. Through the procedure of setting up the system, we were also able to provide feedback to our partners.

The second part of Section 3 describes the main tests and procedures that we followed to provide some meaningful results and conclusions. Several tools and techniques used in the tests are described here also. The tests we made in PrimeTel can be separated in two categories. The first category is represented by the tests conducted by the Engineers and focuses mainly on gathering Quality of Service (QoS) measurements under specific controlled conditions in order to evaluate the functionality and the performance of the Wi-5 System. The second category is represented by the Quality of Experience (QoE) evaluations by the final users of the system. For this part we engaged with volunteers as testers who provided feedback about the system performance. In the document we also tried to report on the changes made to the testing process. As the field trials were progressing, several limitations of the system and wrong assumptions on the test process made it necessary for us to adjust the field trials on several occasions. Nevertheless, the document provides our results from the final form of each test.

Section 4 provides the results of the field trials. Initially in this section we provide some general but important observations on deploying and operating the Wi-5 system in a real world setting. The majority of these observations include functional characteristics of the system, which also affected the reconfiguration and planning of the field trials. Furthermore, Section 4 presents the results corresponding to the tests described in Section 3. We also explain how we interpret the results and how we compare them in order to evaluate several aspects of the system and the different applications on the controller. For each test we include some final conclusions about it and the tested application.

In the final section, we give a general assessment to the currently implemented Wi-5 applications regarding their functionality and performance. We also refer to the aspects of the system and its functionalities, which we believe that future work should aim at improving. Finally, we give a general recap of the problems and difficulties faced in the trials in an attempt to guide future work.

1.4 Relationship with other deliverables

D5.3 is the final deliverable from WP5, along with deliverable D5.2. Specifically it describes the field trials, while D5.2 illustrates the integration and testing process conducted by AirTies. D5.2 and D5.3 come after deliverable D5.1, which provided an initial description and planning on how the field trials should be conducted. Several aspects of the planning of the trials were changed in practice in order to adapt to the challenges and results we had to deal with as the testing was progressing. Considering the feedback from AirTies and PrimeTel, the Wi-5 system and applications were continually updated, so this is another aspect where we had to adapt the trials to include testing for new or extended functionalities in the system.

WP5 in general has provided feedback to modify and develop the Wi-5 System. This deliverable includes useful results and conclusions for various aspects of the functionalities developed in WP3 and WP4 in order to improve the system. This deliverable also presents results that test the Smart and Cooperative functionalities developed in WP3 and WP4 and presented in deliverables D3.2, D3.3, D3.4, D4.1, D4.2 and D4.3.

2 Description of the Wi-5 SDN Platform

In this section, we present a summary of the Wi-5 SDN platform as a basis for our description of the integration work presented in sections 3 and 4. More detailed descriptions of this platform in terms of its specific functionalities can be found in deliverables D2.5 [1], D3.3 [2], and D4.2 [3].

The SDN-based Wi-5 architecture relies on the decoupling of the control plane from the data plane in Wi-5 APs and the dynamic programmability of the Wi-5 APs, which simplifies the development and deployment of network applications running on top of the Wi-5 controller. A global view of the Wi-5 SDN platform is depicted in Figure 1. According to Figure 1, the Wi-5 SDN Platform is composed of Wi-5 agents running in the APs and a Wi-5 master running in the Wi-5 controller.

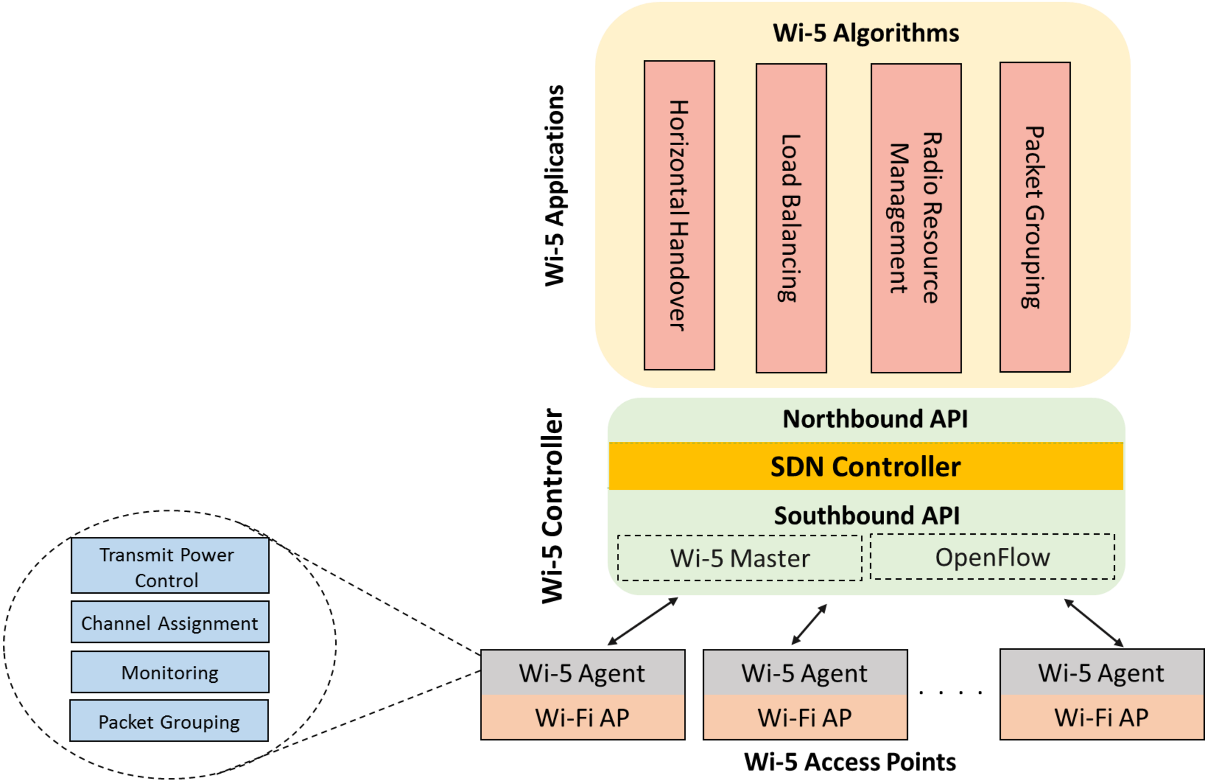


Figure 1: The global view of Wi-5 SDN platform

The Wi-5 APs are responsible for processing packets based on rules provided by the Wi-5 controller. The Wi-5 APs and Wi-5 controller communicate via the OpenFlow protocol. OpenFlow was developed by identifying common features in the flow tables of commercial Ethernet switches in order to facilitate vendors in providing a means to control their APs without exposing the code of their devices. In addition, Wi-5 agents deployed on each Wi-5 AP extend OpenFlow and are responsible for the configuration of the radio-specific parameters, monitoring of the wireless network status, and the Service Set Identifier (SSID) association process.

In the Wi-5 controller, the southbound API allows it to apply the necessary wireless network configuration generated by Wi-5 functionalities. In order to achieve this, an extension of the OpenFlow protocol, called the Wi-5 master, is deployed to communicate with the Wi-5 agents. The Wi-5 master provides the following additional control functions: transmit power control, channel assignment, monitoring of the wireless network status, seamless handover and packet grouping configuration.

The northbound API of the Wi-5 controller provides a programmable interface to allow the implementation of the Wi-5 functionalities, such as seamless handover, load balancing, smart connectivity and packet grouping. Besides the implementation of these algorithms, this API also allows the management, processing and storage of the monitoring information that is necessary for implementation of these functionalities. A more detailed description of the overall architecture is presented in deliverable D2.5.

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

- Smart Functionalities aim at enabling performance improvements in Wi-Fi networks by means of enhanced radio configuration capabilities including dynamic channel assignment, seamless handover, load balancing and power control. The use of packet grouping is also considered here. These functionalities consider a scenario where all the APs are managed by a central controller.

- Cooperative Functionalities will enable coordination between Wi-Fi networks under different management algorithms, in concert with the smart functionalities. These functionalities improve interference management in Wi-Fi jungle scenarios (i.e. including a high number of devices in the same zone), and the realisation of seamless horizontal and vertical handovers.

Both smart and cooperative functionalities are briefly summarized in the following subsections.

2.1 Smart Functionalities

These functionalities will equip Wi-Fi APs with the necessary capabilities that allow them to more effectively manage the wireless spectrum and adapt to changing conditions based on fine-grained radio resource configuration. The improved Wi-Fi APs will have the capability to adjust their transmission power, change their transmission frequency, or both, according to the observed spectrum utilisation and user bandwidth requirements. Another contribution of these functionalities is to optimise the utilisation of the spectrum through packet grouping. These smart functionalities can be summarised as follows:

- **Dynamic Channel Selection and Transmit Power Control**: This functionality will enable Wi-Fi networks to dynamically adjust their radio configuration including changing the transmission channel within the network and the transmit power between an AP and a wireless device.

- **Seamless Handover**: This functionality allows Wi-5 to seamlessly move STAs between different APs, even if they operate in different channels.

- **Monitoring**: This functionality allows Wi-5 to constantly gather detailed information about the state of the Wi-Fi network, its environment, operational parameters, and performance.

- **Load Balancing**: This functionality enables Wi-5 to make decisions on when to move user devices to a new AP or not to accept new association requests, with the aim of maximising the aggregate data rate of these networks.

- **Packet Grouping**: This functionality enables, disables, and configures packet grouping between the Wi-Fi AP and the wireless device on demand, which will result in significant overhead reduction and bandwidth and energy savings.

A detailed description of the Wi-5 smart functionalities is provided in deliverables D3.3 [2] and D3.4 [4].

2.2 Cooperative Functionalities

Enabling cooperation between Wi-Fi networks is critical to achieve efficient spectrum usage and flexible management. For instance, wireless networks should be able to share their spectrum with STAs from a different provider in order to provide seamless mobility. Interference management is another topic that can benefit from cooperative wireless networks. An optimal radio configuration that can minimise the effects of interference while maximising the network capacity, can only be achieved if the operators of the interfering networks cooperate with each other. The need for a cooperative environment in wireless networking is fulfilled in Wi-5 through a set of functionalities that can be summarised as following:

- **Radio Resource Management**: With this functionality, APs will cooperate to find an optimal radio configuration across the entire wireless network that reduces the effect of interference on the QoS of connected flows.

- **Smart AP Selection** This functionality assists a wireless device in choosing the most suitable connection according to the application running on the device. It takes into account the QoS requirement of the application, the quality of the link, the network capacity and the bit rate requirements.

- **Vertical Handover**: This functionality provides an access technology agnostic approach that allows devices to join and leave wireless networks without affecting the user experience, hence exploiting any underused Wi-Fi or 3G/4G capacity.

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

3 Wi-5 Field Trials Description

In this section we describe the Wi-Fi deployment scenarios that have been followed in the trials carried out at PrimeTel. We also describe the procedure of setting up these scenarios as well as some adjustments we made in order to deploy the system. The majority of this section describes the plan for a series of tests we designed for the trials at PrimeTel.

3.1 Field Trials Parameters and Setup

3.1.1 Field Trials Scenarios

The possible use cases of the Wi-5 project were introduced in D5.1 [6] as Large Home/SOHO, Airport, Pico-cell street deployment, Dense Apartment building and Community Wi-Fi Networks. However, in practice we could only test the project in the SOHO and Community Wi-Fi Networks due to a late partner change during the project, resulting in the non-availability of the other environments.

a) Small Office/Home Office (SOHO)

This scenario, which is described in deliverables D2.3 [7] and D5.1 [6], corresponds to a Large Residential or Professional Space in which more than a single AP are deployed in order to increase the Wi-Fi coverage in areas where the signal is weak or non-existent.

For our field trials related to this scenario, we considered a Wi-Fi network that consists of 4 APs deployed on the second floor of the PrimeTel Headquarters (HQ) office building. Therefore, we expected to have a relatively small number of business users and visitors who will use this Wi-Fi network. Figure **2** shows the location of the four Wi-5 APs used during the field trials, and the other non-Wi-5 Wi-Fi APs that will produce a congested environment with a lot of internal and external interference.

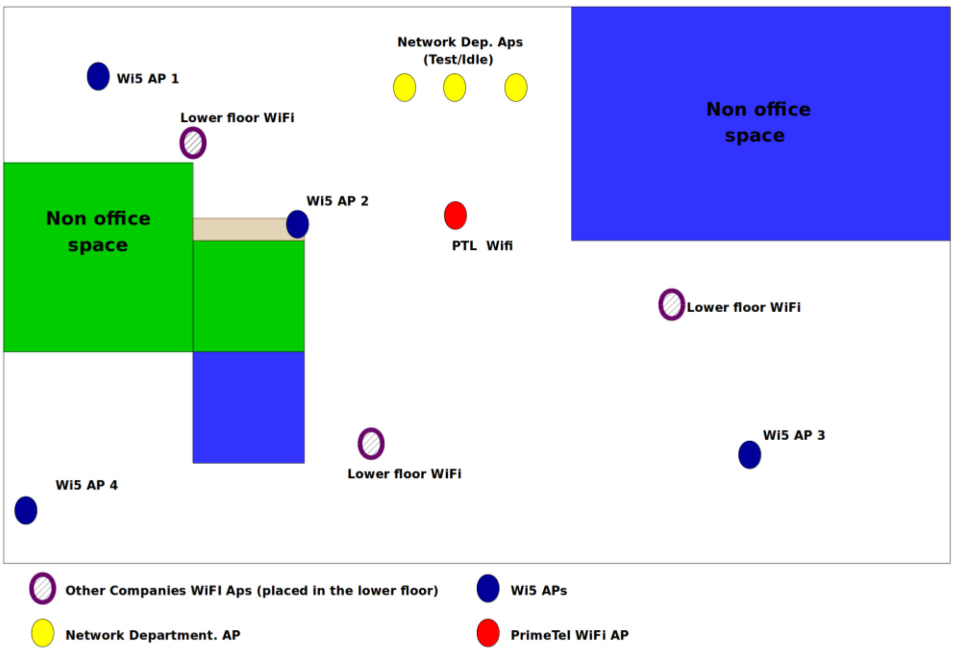


Figure 2: Top view plan of the SOHO setup at PrimeTel's office

b) Community Wi-Fi Scenario

This scenario refers to the cases where the Customer Premises Equipment (CPE) of a client, which is provided by the ISP, is used also to provide Wi-Fi connectivity to pedestrians in the vicinity of the network deployment.

Our field trial for this scenario was also set up at PrimeTel's HQ where 3 APs are deployed to act as the community Wi-Fi network. This network is open to access for pedestrians walking along the neighbouring main street just in front of the building. In Figure 3 we can observe the top view plan of the community, the location of the Wi-5 APs and the path covered by the users during the field trials. This scenario represents a busy wireless network with lots of users and mixed combinations of applications and data flows and has to consider supporting mobility as the users move around.

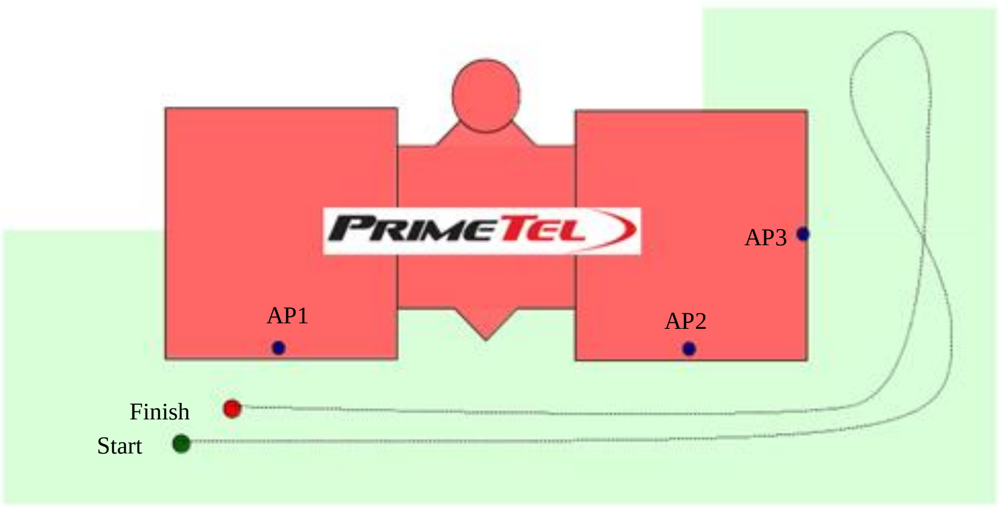


Figure 3: Top view plan of the community setup outside the PrimetTel building ground floor

3.1.2 Wi-5 System Field Trials Requirements

In order to run the field trials of Wi-5 based on the scenarios described above, a number of technical requirements need to first be considered. More specifically, the Wi-Fi networks deployed at the PrimeTel premises needed to be upgraded in order to meet the hardware and software requirements of Wi-5, according to the guideline described in the Wi-5 Wiki page[1].

The hardware requirements for these field trials can be summarised as following:

- Wi-Fi Access Points to provide connectivity.
- A server to act as a Wi-5 controller.
- USB drive to provide additional hard drive space for the Wi-Fi APs in order to install Wi-5 software.
- Auxiliary wireless interface to provide the Wi-Fi APs with the ability to monitor the network while at the same time providing connectivity to users.
- A DHCP server.
- Networking switch and cables.

[1] https://github.com/Wi5/odin-wi5/wiki

Table 1: Hardware Specification of the Components used during the trials

Field Trial Component	Hardware Specification
Wi-Fi Access Points	TP-Link Archer C7 AC1750 v2
Personal Computer	HP Server
Auxiliary wireless interface	TL-WN722N
DHCP server	Mikrotik routerboard 750
Networking switch	TL-SG108

The specifications of the hardware used for these field trials are summarised in Table 1. Once this has been obtained, some specific software also needs to be installed on these hardware components to support the Wi-5 functionality. More specifically the following software must be installed:

- OpenWRT, OpenVswitch, and Click Modular router need to be installed on the Wi-Fi APs to support the Wi-5 functionality.
- The Wi-5 controller software needs to be installed on the server.
- The Wi-5 agent should be installed on all Wi-Fi APs.

The system utilizes 3 different local area networks. The first network is for managing the devices. The second is the SDN Control network, which is used to connect the applications and the Controller in order to provide the control signals for the system. The third network is the Data network on which a user can connect by using the Wi-Fi provided by the APs. From the Data network, the user can use the Internet. These Networks need to be correctly configured on each AP so they can be used by the different components.

3.1.3 Wi-5 System Setup

Once the requirements described above are all satisfied, the Wi-5 System needs to be setup and properly configured.

The following steps describe the process to configure the Wi-5 APs:

1. Create a firmware image of OpenWRT, which was customised to include the OpenVswitch module and the drivers for the auxiliary wireless interface, and install it on the Wi-Fi APs.
2. Configure the wireless interfaces to support the Wi-5 Light Vırtual Access Point (LVAP) abstractions according to the description presented in deliverable D3.2 [2].
3. Configure the LAN parameters of the Wi-Fi APs before connecting them to the main network.
4. Configure the DHCP server, which also acts as the main LAN gateway.
5. For each Wi-Fi AP, upload the Click modular router image on the USB drive connected to it, and create a Click configuration file using a Python script[2].
6. For each Wi-Fi AP, upload and run the Wi-5 start script that initiates all the processes, so the Wi-5 System can work properly.

The Wi-5 controller is installed on a ProxMox hypervisor[3] virtual machine which runs in the HP server, but a laptop was also used in some early trials.

[2] https://github.com/Wi5/odin-wi5-agent/blob/master/agent-click-file-gen.py
[3] https://www.proxmox.com/en/

Figure 4 presents the topology of the deployed networks for the SOHO scenario. The Community Wi-Fi scenario was exactly the same except for the element in the top right titled ‘PrimeTel Office’.

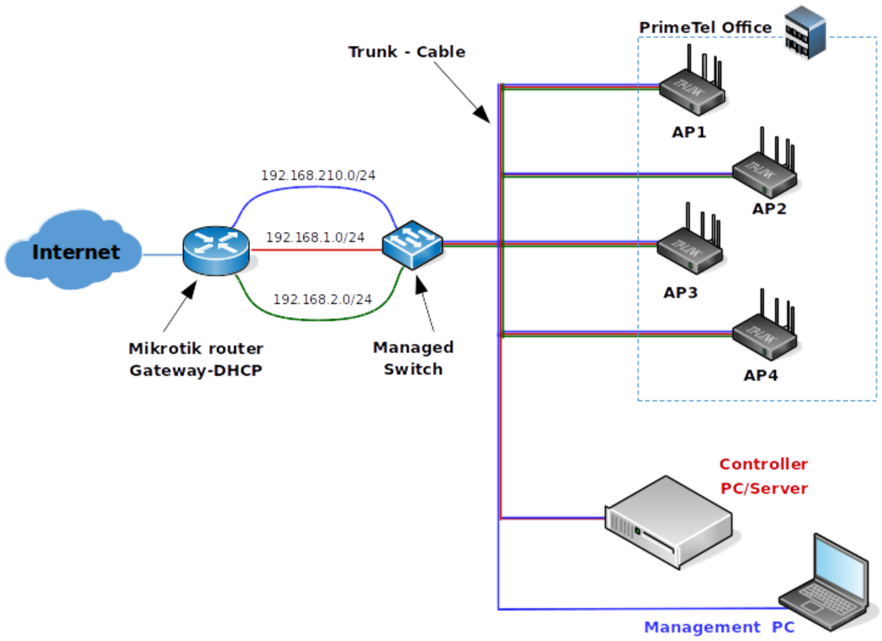


Figure 4: Network topology of the Scenarios

3.1.4 Technical challenges - problems and improvements

During the initial setup process when PrimeTel Engineers started to deploy the Wi-5 system, the AP OpenWRT internal network was configured to use 3 of the external Ethernet ports of the TP-Link Archer router. The internal switch of the Archer was configured in such a way that port 0 was used as a trunk port, handling more than 1 VLAN and thus keeping the LAN of each external port separated. We also discovered that the OpenWRT OS on the Archer machine already uses a VLAN interface with the HW interface being eth1.

After careful study of the capabilities of the Archer AP and OpenWRT, we proceeded using port 5 of the internal switch, which corresponds to the Ethernet port 4 in the device as a trunk port in the same way as port 0 in the internal switch. This is very useful for setting up the system in a production environment, particularly for PrimeTel’s setup of the SOHO and community trial, as it would be very difficult to install the system in a real network without the use of VLANs.

Another problem we experienced was related to the auxiliary interface. In detail, sometimes when we tried to reboot the Archer devices, the auxiliary USB wireless interface was not created properly. As a consequence, when we tried to run the start script on the applications, we obtained the following output.

Setting variables
Setting interfaces
ifconfig: SIOCGIFFLAGS: No such device
command failed: No such file or directory (-2)
ifconfig: SIOCGIFFLAGS: No such device
ifconfig: SIOCSIFMTU: No such device

ifconfig: SIOCGIFFLAGS: No such device
Restarting OpenvSwitch
Now you can launch the Wi-5 odin controller and press Enter

This issue appears after one reboot and is repeated after subsequent reboots. In order to solve this problem we have to disable and enable the USB port on which the auxiliary device is placed. To do this we execute the commands below:

echo 0 > /sys/class/gpio/gpio21/value

echo 1 > /sys/class/gpio/gpio21/value

After these commands were run, we rebooted the Archer AP again and the problem was fixed. If the problem persisted, we repeated this process again until the USB interface was detected.

These issues caused considerable challenges for us to overcome but were expected given the proof of concept nature of the Wi-5 System. Our findings here were provided as feedback to the project and documented in the implementation wiki on GitHub.

3.2 Functionalities Considered in the Field Trials

The field trials focused on two main Wi-5 functionalities, namely the Radio Resource Management and Smart AP Selection, as these two applications have been designed to improve spectral efficiency, ease spectrum congestion, and satisfy users' Mobility and QoS requirements. Other Wi-5 functionalities could not be tested in the field trial because they were not implemented, as in the case with Packet Grouping (see deliverable D5.2), or due to the lack of resources, as in the case with the Vertical Handover.

Note that as explained in deliverable D5.2, the implementation of the Radio Resource Management functionality of Wi-5 does not support Per-Flow Transmit Power Control, and therefore represents only the Channel Assignment Functionality.

The Smart AP Selection has been implemented to support three operational modes:

- **RSSI Mode**: In this mode the application manages mobility and handover of the STAs.
- **Load-Balancer Mode**: In this mode the application allows us to manage the load of traffic and STAs that each AP serves and balances in order to avoid overloading some APs at the expense of others.
- **FF Mode**: This mode enables the application to connect the STA to an AP that best serves its QoS requirements according to the Fittingness Factor metric [3], [8].

3.3 Tests performed during Field Trials

The tests carried out during these trials aimed to assess the performance of the Smart AP Selection and Channel Assignment functionalities in the SOHO and community Wi-Fi scenarios. Although many components of this performance evaluation could be assessed automatically without external input, certain aspects could only be assessed by requesting users' opinion and experience. In this section we describe both categories of assessment and explain the Wi-5 functionality performance that they helped to measure.

3.3.1 Automated Tests

This category of tests focuses on performance metrics that could be measured automatically, according to the Wi-5 functionality considered in the trials.

In the case of the Channel Assignment functionality, the automated tests helped to achieve the following:

- Assess the reactiveness of the Channel Assignment functionality to interference.
- Evaluate the improvement in terms of throughput and thus spectral efficiency in the case of channels assigned by the Wi-5 Channel Assignment functionality.

In the case of the Smart AP Selection functionality, the metric that could be measured automatically is the throughput at the wireless station, which helps to assess the adaptability of Wi-5 to changes in the QoS requirements and movement of the wireless users.

a) Description of Chanel Assignment Assessment

The aim of these tests was to first evaluate the reactiveness of the Channel Assignment application to interference so we used three APs from the Community Wi-Fi scenario to emulate inter-AP interference. Since our objective here was to measure the reaction to internal interference, we setup the three APs to operate on the following channel assignment configuration: 1-6-6. We connected one STA to each AP and generated downlink traffic between a server and the STAs using *iPerf*, and then measured the throughput at each AP, while also monitoring any changes in the channel assignment configuration.

We then tested and assessed the performance of this application in the SOHO scenario as it exhibits spectrum interference conditions similar to the ones that the RRM algorithm has been designed to address. In these tests, the following practices were adopted:

- Four APs were deployed: AP1, AP2, AP3, and AP4.
- One STA was connected per AP.
- Downlink traffic was again generated using *iPerf* installed on a server connected to the main LAN.
- During the different performance measurements, STAs are static and do not change location.

We measured the throughput achieved at each STA under the following channel assignment configurations:

1. Channel assignment configuration where all APs are on the same channel: 6-6-6-6
2. The following Channel assignment configuration where the APs are on different but overlapping channels: 1-2-3-4
3. Channel assignment produced by the Wi-5 Channel Assignment application: 1-6-4-11

b) Description of Smart AP Selection Tests

As described previously, we aim through these tests to assess the performance of Smart AP Selection in terms of its adaptability to changes in the mobility of wireless users and their QoS requirements, and in connecting the user to the best AP.

In the context of mobility, the Smart AP Selection functionality is designed to take into account the received signal strength indication (RSSI) to connect a STA to the best AP in terms of RSSI. In this case, the functionality monitors a threshold set by the system administrator, and connects the STA to another AP when the RSSI falls below this threshold, while measuring the throughput at the STA. This test has been performed in the SOHO scenario.

In the context of QoS, the Smart AP Selection functionality is designed to take into account the Fittingness Factor (FF) to find the most suitable AP for a STA in the Community scenario.

During the test of the RSSI based Smart AP Selection, the STA is moved from the vicinity of one AP to the other at walking speed. To generate traffic at the STA, we used a number of tools, including:

- iPerf
- D-ITG
- Local - Web server http download
- Ftp from Local server
- Internet - web server http download

Note that in these tests, only one STA was considered, as we tried to avoid having multiple STAs interfering with each other, thus affect the performance measurements.

3.3.2 User -Based Tests

In this section we describe the tests that were carried out in which user opinions were the main measurement criteria. More specifically, these measurements focused on gathering users' information using questionnaires that could help us to assess their quality of experience and overall satisfaction with the Wi-5 network.

a) SOHO User-Based Trial

The SOHO scenario provides Wi-Fi connectivity to PrimeTel employees. Although most of these employees work on PC desktops, many of them access the Wi-Fi network via their laptops or smartphones.

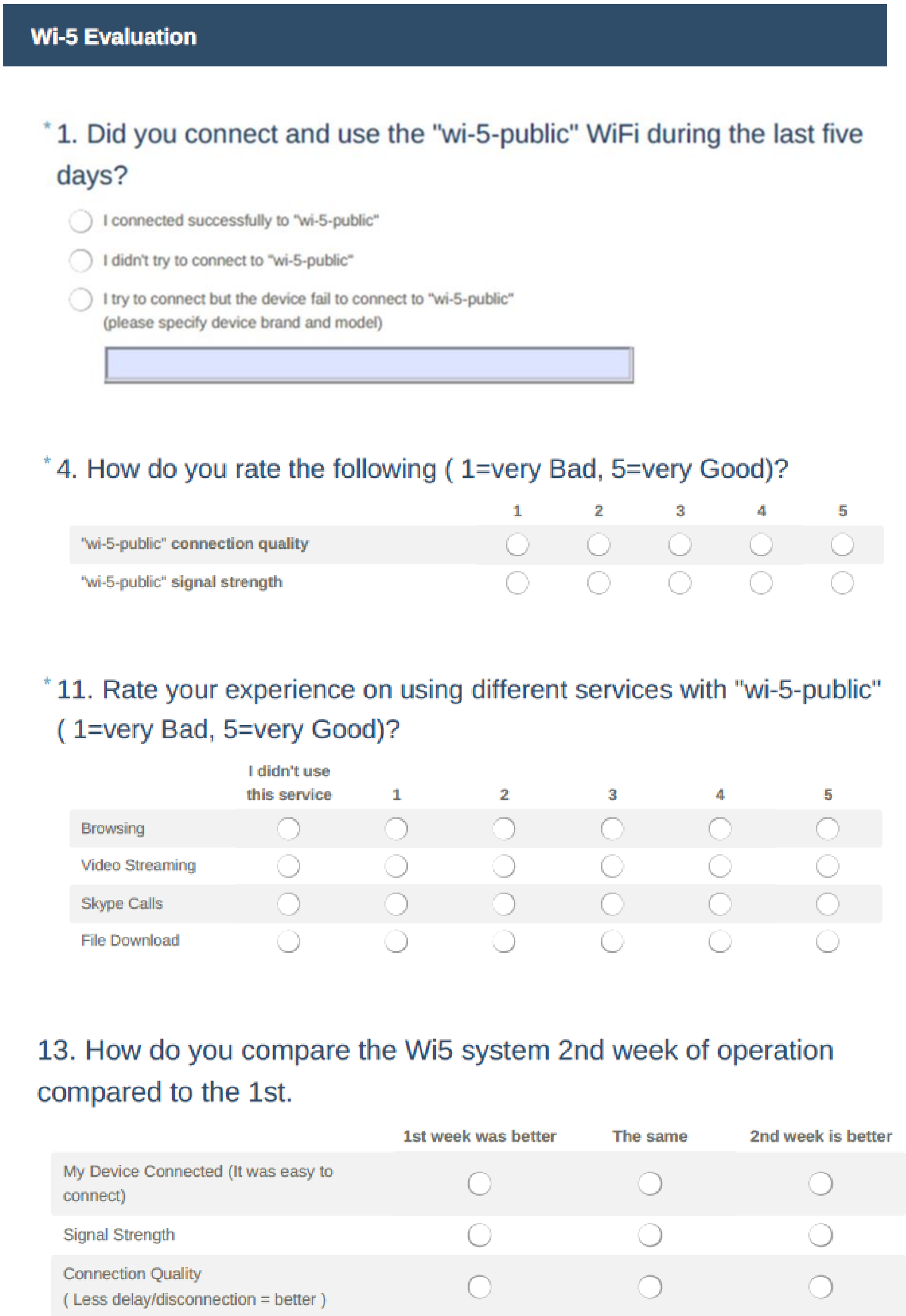
The goal of this trial was to measure the users' QoE and we therefore used simple questionnaires to perform the evaluation via Survey Monkey[4]. This questionnaire allows the users to evaluate the Wi-Fi connection in terms of a set of metrics such as signal strength, connection quality, jitter and delay. Note that the connection quality is a subjective opinion of the users, based on general observations that can be affected by latency, throughput, connectivity issues, etc. The questionnaire was created on this website and a link was sent to the employees who have access to the trial Wi-5 network. The important questions of the questionnaire are presented in Figure 5. The rest of the questions were not taken into account for the results analysis in section 4.3.1 and therefore are not presented here.

The assessments consisted of two periods: in the first one, Wi-5 was running but without the Smart AP Selection functionality running, and in the second, Smart AP Selection was operational. The details of the tests during each period are summarised in Table 2.

[4] https://www.surveymonkey.com/

To be able to compare those periods effectively we had to collect feedback from users separately for each period. In the second questionnaire, the users were also directly asked to compare the two periods of operation.

Based on how we organized the SOHO trials, as the trials were progressing we had the chance to increase the number of periods and the system features/configuration to be tested. Unfortunately because of some setbacks described in Section 4.3.1 we decided not to extend the SOHO trials further.



Wi-5 Evaluation

* 1. Did you connect and use the "wi-5-public" WiFi during the last five days?

- I connected successfully to "wi-5-public"
- I didn't try to connect to "wi-5-public"
- I try to connect but the device fail to connect to "wi-5-public" (please specify device brand and model)

* 4. How do you rate the following (1=very Bad, 5=very Good)?

	1	2	3	4	5
"wi-5-public" **connection quality**					
"wi-5-public" **signal strength**					

* 11. Rate your experience on using different services with "wi-5-public" (1=very Bad, 5=very Good)?

	I didn't use this service	1	2	3	4	5
Browsing						
Video Streaming						
Skype Calls						
File Download						

13. How do you compare the Wi5 system 2nd week of operation compared to the 1st.

	1st week was better	The same	2nd week is better
My Device Connected (It was easy to connect)			
Signal Strength			
Connection Quality (Less delay/disconnection = better)			

Figure 5: Questions from the questionnaire for the SOHO scenario

Table 2: Description of User-based tests for SOHO Field trial

Period #	Dates	Channels	Conditions
# 1	5-9 Feb	1, 6, 1, 11	Wi-5 without Smart AP Selection
# 2	12-23 Feb	1, 6, 1, 11	Wi-5 with Smart AP Selection

b) Community User-Based Trials

Similarly to the SOHO User-Based trials, the tests here focus on assessing the users QoE, and we therefore again used a questionnaire. In contrast to the SOHO trials, users connect to the network using a device (STA) provided by PrimeTel, in order to avoid potential differences in terms of device hardware and software performance affecting the results of the tests.

The Field Trials for each user included several iterations or tests of similar conditions by the User. For the different iterations the Wi-5 system was configured differently by enabling the AP selection application in different modes and other configuration changes. For practical reasons of not confusing the users and keeping the user trials fairly simple, we decided to set the max number of repeated tests to 4. The configuration for each of the 4 tests is shown in Table 3.

Table 3. Description of User-based Tests

Test#	Application running	Mode	Congestion
Test1	No application	--------------------------	No
Test2	Smart AP Selection	RSSI	No
Test3	Smart AP Selection	RSSI	STA to AP2 – 3 Mbps download
Test4	Smart AP Selection	BALANCER	STA to AP2 – 3 Mbps download

The definition of the 4 repeated tests also serves the purpose of evaluating the Wi-5 System's mobility features. The first two tests are directly compared to evaluate the improvement in the experience of the user under the use of Smart AP selection. Under the first test the STA follows the sticky client policy and remains connected to the first AP while moving as a result of no Wi-5 application running on the controller. This is then compared to the second test where AP selection is enabled in the RSSI mode. In the third and fourth tests we evaluate the improvement of the system using the Balancer mode under congested conditions caused by generating traffic towards an additional STA connected to AP2. The idea is that the Balancer mode will move the STAs to different APs in order to avoid disruption of the video streaming service on the user's STA.

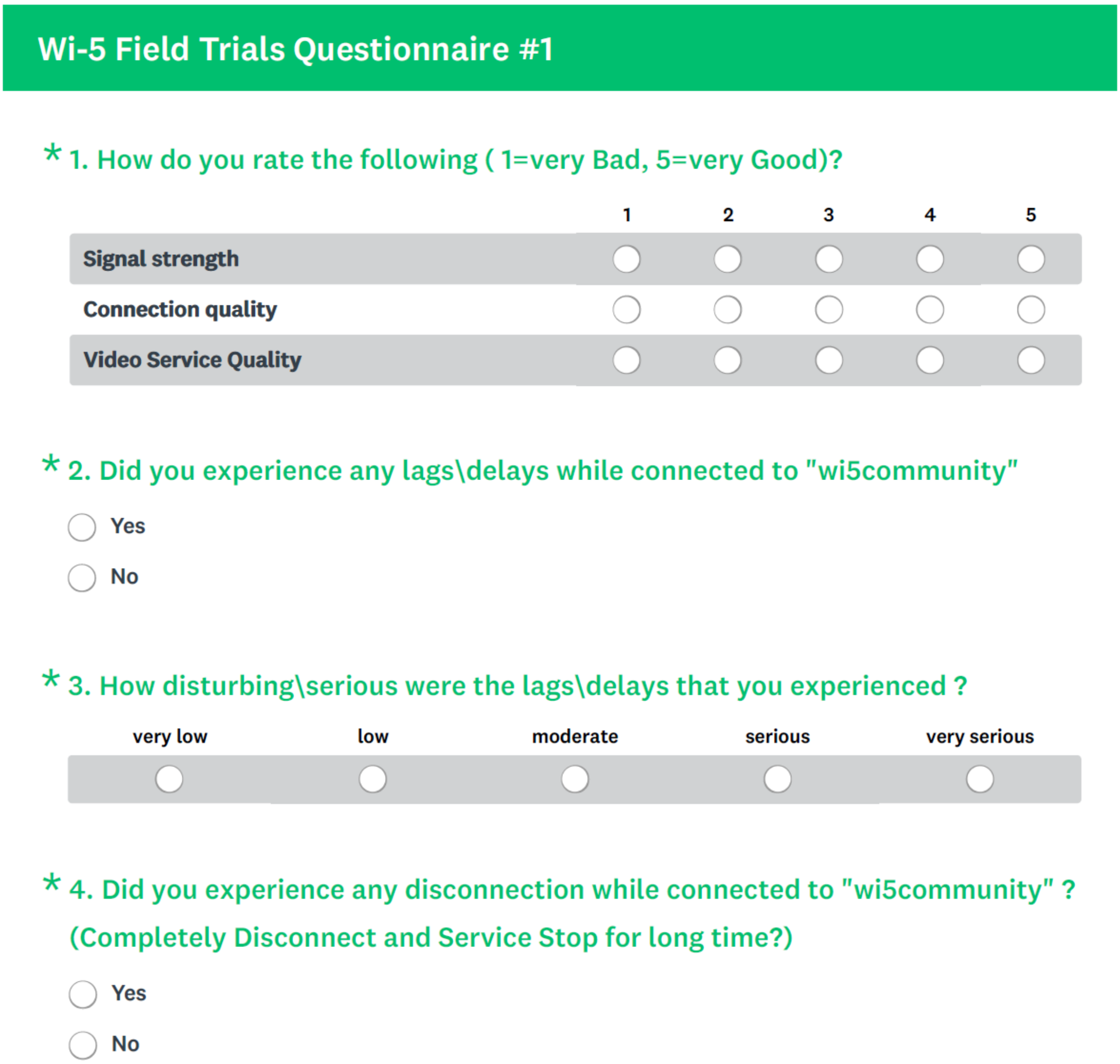
During each iteration the user walks along the predefined path illustrated in Figure 3 and is given guidance to monitor the signal strength which the STA is receiving. The user should also observe for possible Wi-Fi disconnections through each test. In addition, the user should continuously use a service in order to evaluate their experience using that service in the different tests. Specifically, we used VLC[5] on a local server to send a video stream over the HTTP protocol. The client which ran Ubuntu also used VLC to receive and play the stream. In order to have a smooth test and avoid glitches because of minor

[5] https://www.videolan.org/

packet loss, we increased the Network caching value of VLC to 10000ms. The Network caching was increased for every iteration to have fair conditions on each test.

So, for each complete test, each user should complete 4 test/iterations by walking along the same path and using VLC to stream a video over the Wi-5 system. After each test the user completes a small Questionnaire to provide a rating to its experiences. Since the first two tests and the last two tests should be directly compared, we included extra questions on the questionnaires for the 2nd and 4th iterations so that the user could say directly if its experience in the second iteration was better than the first and if its experience in the fourth was better than the third.

The questions that are relevant to this assessment are presented in Figure 6, Figure 7, and Figure 8. Figure 6 represents the questions from the first questionnaire, which are included in all 4 questionnaires for each test. Figures 7 and 8 show the comparative questions from questionnaires 2 and 4, respectively. Note that the rate of the Video Service Quality illustrated in Figure 6 allows us to measure the QoE in terms of Mean Opinion Score (MOS) [9], which is one of the metrics used to assess the AP selection algorithm based on the FF presented in deliverable D4.3. Specifically, the MOS can be obtained by the results of the tests in which the users rate the Video Service Quality from 1 (very bad/worst) to 5 (very good/best). Further details on this metric can be found in D4.3 [5].



Wi-5 Field Trials Questionnaire #1

* 1. How do you rate the following (1=very Bad, 5=very Good)?

	1	2	3	4	5
Signal strength					
Connection quality					
Video Service Quality					

* 2. Did you experience any lags\delays while connected to "wi5community"

Yes

No

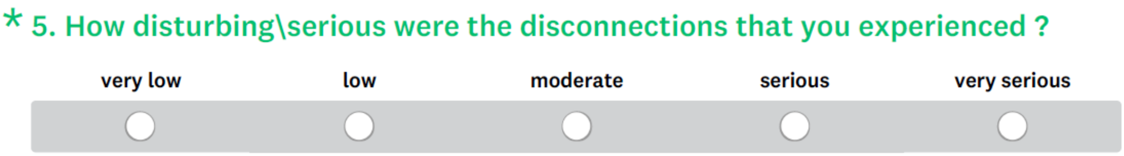
* 3. How disturbing\serious were the lags\delays that you experienced ?

very low | low | moderate | serious | very serious

* 4. Did you experience any disconnection while connected to "wi5community" ? (Completely Disconnect and Service Stop for long time?)

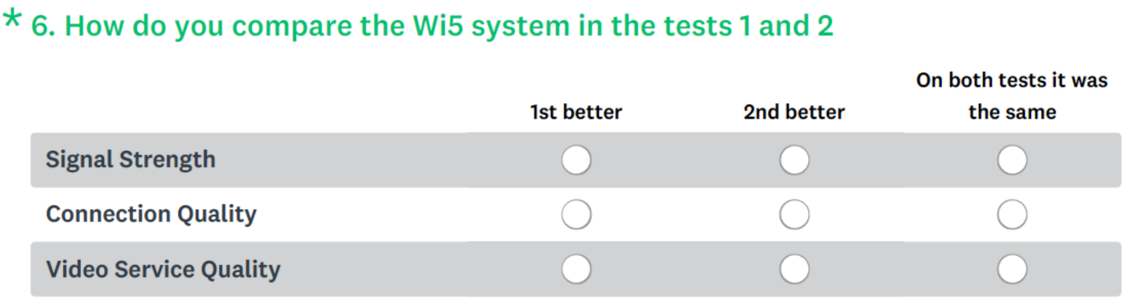
Yes

No


* 5. How disturbing\serious were the disconnections that you experienced ?

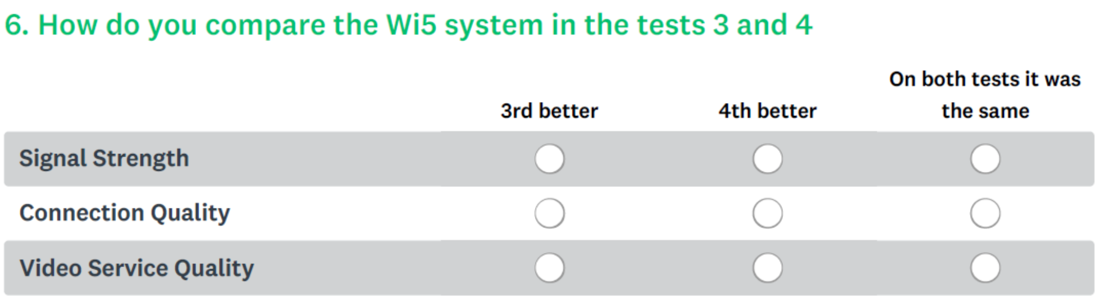
very low	low	moderate	serious	very serious
○	○	○	○	○

Figure 6: Questions from the questionnaire of the first iteration from Survey Monkey


* 6. How do you compare the Wi5 system in the tests 1 and 2

	1st better	2nd better	On both tests it was the same
Signal Strength	○	○	○
Connection Quality	○	○	○
Video Service Quality	○	○	○

Figure 7: Question 6 from the questionnaire of the second iteration from Survey Monkey


6. How do you compare the Wi5 system in the tests 3 and 4

	3rd better	4th better	On both tests it was the same
Signal Strength	○	○	○
Connection Quality	○	○	○
Video Service Quality	○	○	○

Figure 8: Question 6 from the questionnaire of the fourth iteration from the Survey Monkey

4 Field Trials Results

4.1 General Observations

From the initial tests, as the Wi-5 System was being setup at PrimeTel, we did some detailed analysis to study the behaviour of the network in operational conditions. Specifically, regarding the connectivity of devices to the system, we observed that there were glitches when some devices tried to connect and other devices were not able to connect at all. Below we give a ranking list among the Operative Systems (OSs) starting from the one that worked the best based on the R&D engineers' observations. We have to note that the ranking was among the cases (devices) where we observed at least one successful connection.

- Android – many devices connected and were stable
- Ubuntu – most devices connected but experienced some unreliability
- Debian – some devices connected but experienced unreliability
- iOS – fewer devices could connect
- Windows – fewer devices could connect

The devices with the best overall behaviour with the Wi-5 System are the following:

- Samsung galaxy s7
- Samsung s9
- HP pavilion with Ubuntu desktop 16.04.3
- Wi-Fi card: Broadcom corporation BCM4313 802.11bgn rev 01

Some devices that could not manage to connect at all were also used by at least one user in the SOHO user trials and therefore are presented in the Section 4.3.1. Other problems include the disassociation of an STA from the Wi-5 System for no reason. A frequent message associated with the removal of an STA was the following:

Controller output: disconnection of an STA.

```
08:30:59.804 [pool-3-thread-6] INFO  n.f.odin.master.OdinMaster - Clearing Lvap [redacted] from agent:/192.168.1.12 due to deauthentication/inactivity
```

We suspect this issue might be caused as a result of MAC randomisation being applied by the terminal as a privacy measure. However, this issue requires more study in the future to determine the ultimate cause and develop functionality in the Wi-5 system to prevent the disassociation of an STA if it actually disconnects.

We also observed problems with some applications when using the Smart AP Selection functionality. In some cases the controller was showing that the STA was connected to the system when in reality it was disconnected, whereas in others the STA remained connected to the system but this was not indicated by the controller.

4.2 Automated Tests Results

This section presents the controlled test, representing the QoS measurements conducted by the research Engineers at PrimeTel. In this series of tests there is no volunteer user involvement.

4.2.1 Channel Assignment Tests Results

The first set of tests were carried out to assess the performance of the Channel Assignment application, focused on the reactiveness of the application to the presence of interference as well as the throughput and spectral efficiency that could be achieved.

a) Reactiveness to Interference

The aim of these tests was to evaluate the reactiveness of the Channel Assignment application to interference and for that we used the three APs from the Community Wi-Fi scenario to emulate inter-AP interference. We then used *iPerf* to generate downlink UDP traffic from a server connected to the main internal LAN towards two STAs connected to two different APs: AP1 and AP2, as illustrated in Figure 3. Initially, the three APs used in the tests were set to the channels 1, 6 and 11, respectively.

Sometime during the tests, we create interference among the APs by changing the channel assignment configuration to the following: 1, 6 and 6. As shown in Figure 9, in the period between 0 and 40 seconds we can see the throughput before the channel change in AP3. However, in the interval between 40-73 seconds we can see a drop in the throughput due to the additional interference. After a few seconds later, the Channel Assignment application is triggered which assigns a new channel combination of 1, 6 and 11 again corresponding to APs 1, 2 and 3. This change results in an improvement in the throughput between 73-90 seconds, as shown in Figure 9.

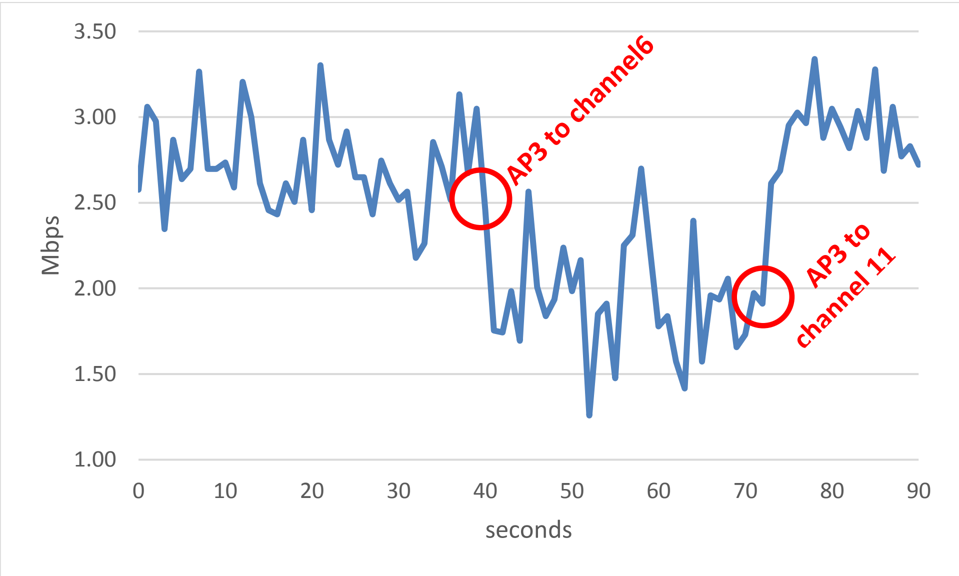


Figure 9: Measured throughput before, during, and after interference

b) Throughput and Spectral Efficiency

For this test we used 4 devices (STAs), one connected to each AP from the SOHO scenario, and we followed the procedures described in Section 3.3.1.a.

We used 1 Samsung S7 and 3 laptops with Ubuntu 16.4. During these trials for this test we faced some difficulties because of misbehavior of the STAs which can be summarised as follows:

- In many cases we had difficulty to keep the devices connected to the system. Usually when we were connecting all 4 devices the last one had a problem to connect.
- In other cases an STA already connected to the system was suddenly disconnecting and reconnecting.
- The algorithm was assigning a device to an AP other than the one closest to it.
- Sometimes the throughput measured for an STA was presented as degraded even if we were measuring the throughput for that STA separately from the other STAs. This demanded a reset of the system to bring it back to normal operating conditions.

The output below shows some typical output of the system that illustrates these issues.

Wi-5 system output: Example of disconnection and reconnection to the system from controller logs:

08:30:59.804 [pool-3-thread-6] INFO n.f.odin.master.OdinMaster - Clearing Lvap [redacted] from agent:/192.168.1.12 due to deauthentication/inactivity
08:31:00.506 [pool-3-thread-13] INFO n.f.odin.master.OdinMaster – Client [redacted] connecting for first time. Assigning to: /192.168.1.12
08:31:21.414 [pool-3-thread-6] INFO n.f.odin.master.OdinMaster - Client [redacted] completed the association

To make sure we had valid conditions for the testing, the engineers at PrimeTel had to constantly monitor that all the STAs were connected to the appropriate AP. In addition, we were constantly measuring throughput to each STA alone to ensure that the system is operating normally.

From the results illustrated in tables 4, 5, and 6 below, we can see that we have greater throughput in the channel combination obtained through the Wi-5 channel assignment, i.e. [1, 6, 4, 11]. We also see that we have the lowest throughput when all the APs are in the same channel.

Table 4: Throughput for the Wi-5 Channel Assignment (Mbps)

	Channels 1 6 4 11					Avg.
Sta1	2.69	2.98	2.76	2.80	2.86	3.02
Sta2	0.96	1.49	1.27	1.29	1.32	1.34
Sta3	1.48	1.73	2.27	2.23	2.01	1.92
Sta4	3.62	3.20	3.22	3.24	2.98	3.16
Avg.	2.19	2.35	2.38	2.39	2.29	2.36

Table 5: Throughput for Channel Assignment using the same channel (Mbps)

	Channels 6 6 6 6					Avg.
Sta1	0.12	0.13	2.90	2.83	2.80	1.76
Sta2	1.58	1.45	0.48	0.68	0.86	1.01
Sta3	0.16	0.35	0.43	0.07	2.39	0.68
Sta4	1.78	1.77	0.62	0.86	0.07	1.02
Avg.	0.91	0.92	1.11	1.11	1.53	1.12

Table 6: Throughput for third Channel Assignment (Mbps)

	Channels 1 2 3 4					Avg.
Sta1	2.66	2.52	2.68	2.65	2.65	2.75
Sta2	0.09	0.81	0.03	0.10	0.09	0.18
Sta3	0.25	0.07	0.27	0.23	0.22	0.21
Sta4	2.24	2.54	2.21	2.22	2.38	2.29
Avg.	1.31	1.48	1.30	1.30	1.33	1.36

Moreover, Table 7 shows the improvements in terms of average spectral efficiency obtained by the Wi-5 channel assignment.

Table 7: Average Spectral Efficiency for all the Channel Assignments (bit/s/Hz).

	Spectral Efficiency
Wi-5	0.118
Same Channels	0.068
Third Option	0.056

4.2.2 Smart AP Selection Tests Results

As explained above, through these tests we aim to assess the performance of the Smart AP Selection algorithm in terms of its adaptability to changes in the mobility of wireless users and their QoS requirements, and in connecting the user to the best AP. In planning this test we took several traffic generating tools into consideration. However, the main results presented in this section were obtained when using FTP and *iPerf* UDP traffic. This choice is justified by the fact that these applications could generate traffic at a steady rate, which was not the case with *iPerf* TCP and D-ITG.

Figure 10 shows the UDP throughput measured at the STA when moving, with the mobility handover decision managed by the STA itself. The results obtained in this figure show that the throughput drops to zero for a long time (between 40 and 90 seconds) before increasing again. This interval corresponds to the time it takes for the STA to manage the handover from one AP to the other, which is often referred to as the Sticky Client problem.

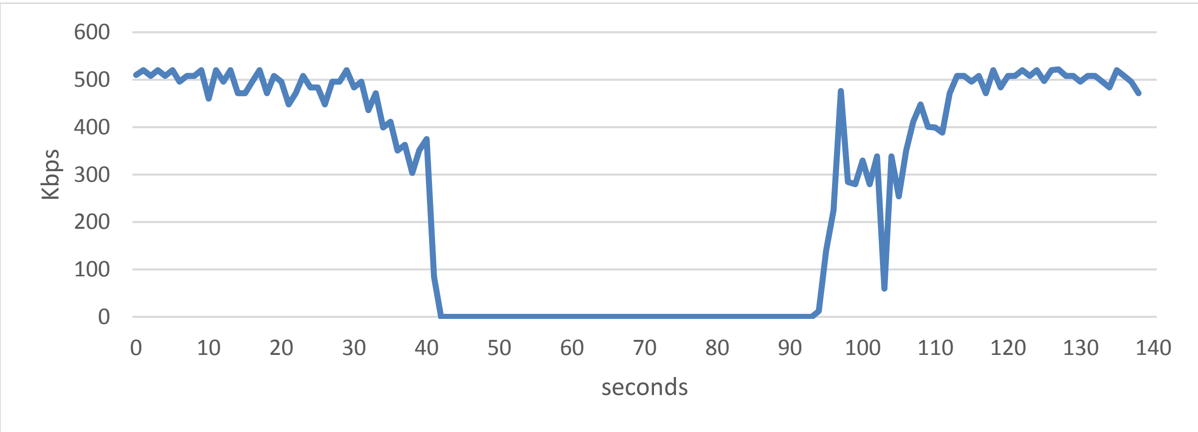


Figure 10: UDP traffic with STA managing handover decisions during mobility

Figure 11, Figure 12, and Figure 13 show the measured throughput for the same STA when the Smart AP Selection is used in the RSSI mode for different types of traffic. From these figures, we can observe that the traffic drops during certain periods and reaches the value zero during the handover. However, these time intervals are much shorter in comparison to the previous results.

In these trials we tried many tools with different conditions, including tests with different channels assigned to the APs (Figure 13) or where every AP is in the same channel (Figure 12). After the initial tests using small UDP traffic, we tried to use real services to evaluate the system. For that purpose we tried both FTP and HTTP to download of a file from local servers. We concentrated on tests with FTP because this produced more steady traffic when the STA was stationary and because there were some problems in HTTP during movement. After many tests we saw that the FTP service stops after some packet loss. The small packet loss was initially caused by the AP handoff of the Smart AP Selection but we have to note that there was no disconnection of the STA.

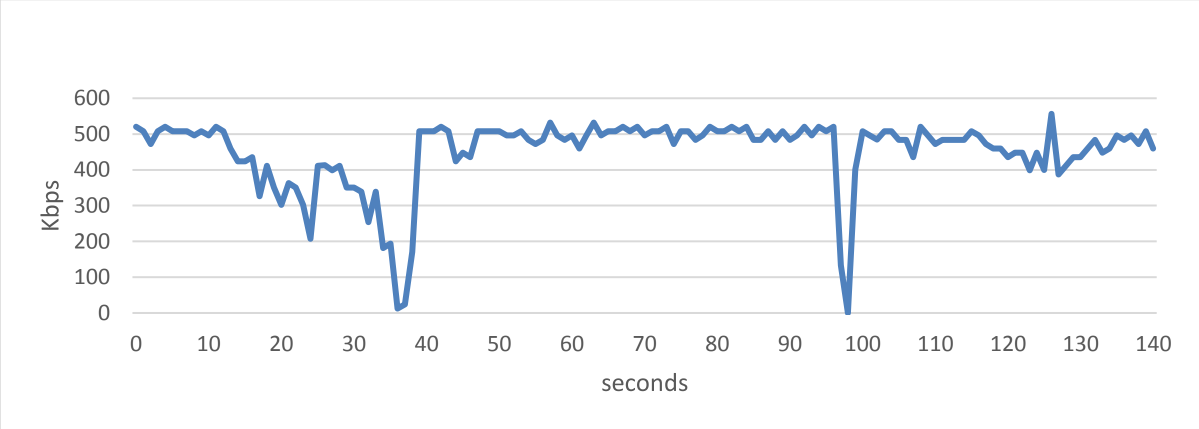


Figure 11: UDP traffic on STA during mobility test withWi-5 Smart AP Selection in RSSI mode

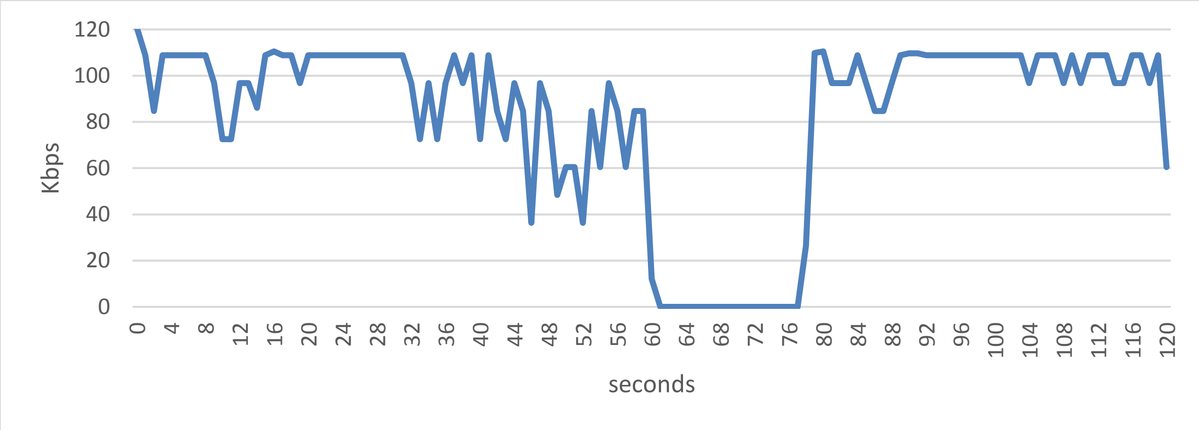


Figure 12: UDP traffic (106 kbps) on STA during mobility test with Wi-5 Smart AP Selection in RSSI mode with APs on the same channel

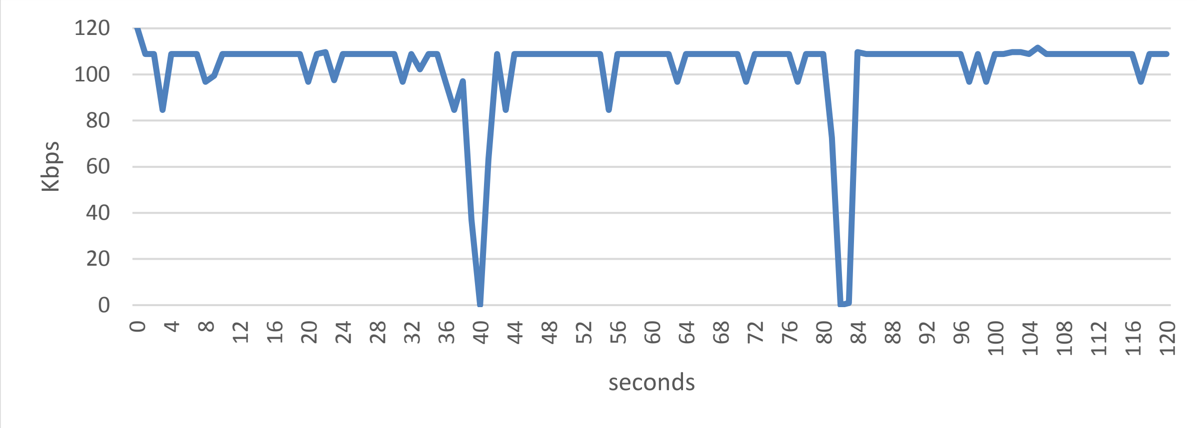


Figure 13: UDP traffic (106 kbps) on STA during mobility test with Wi-5 Smart AP Selection in RSSI mode with APs on different channels

After more tests we saw that the freezing of FTP was observed much more frequent when the APs were in different channels (Figure 14) than when the APs are all in the same channel (Figure 15). We concluded that the reason of the freezing was that, in the case of different channels on the APs, the STA has to change channel during handoff which may affect the internal state or the upper layer protocols, as this is the only extra thing that needs to take place to create the problem.

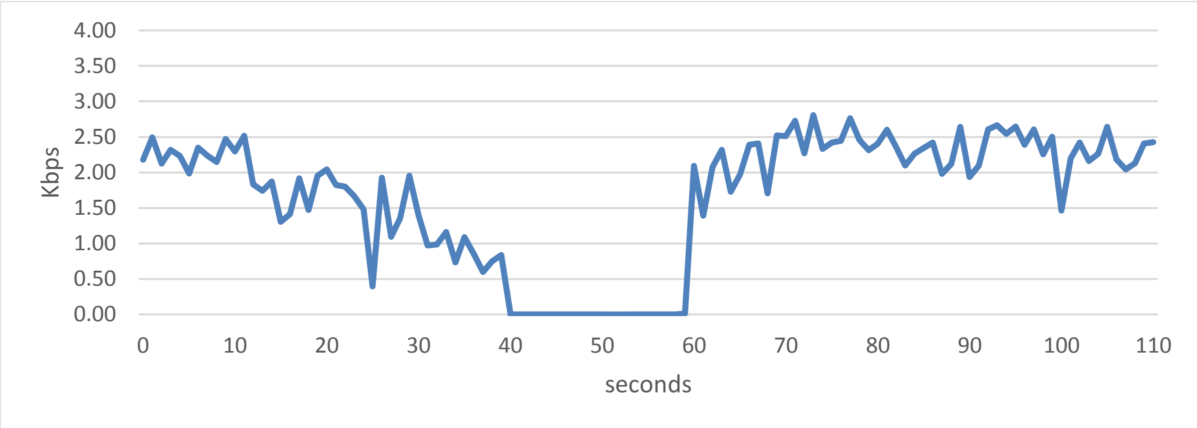


Figure 14: FTP traffic on STA during mobility test – different channels to APs

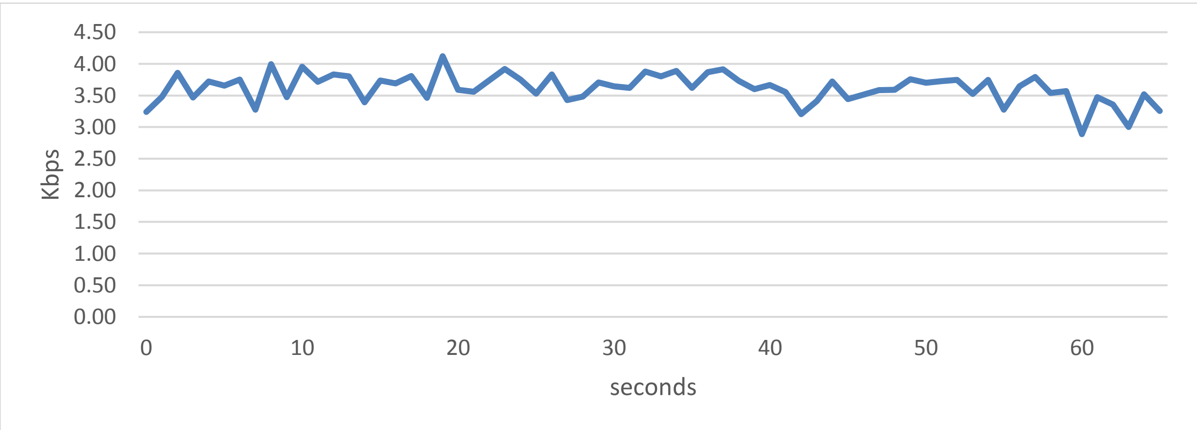
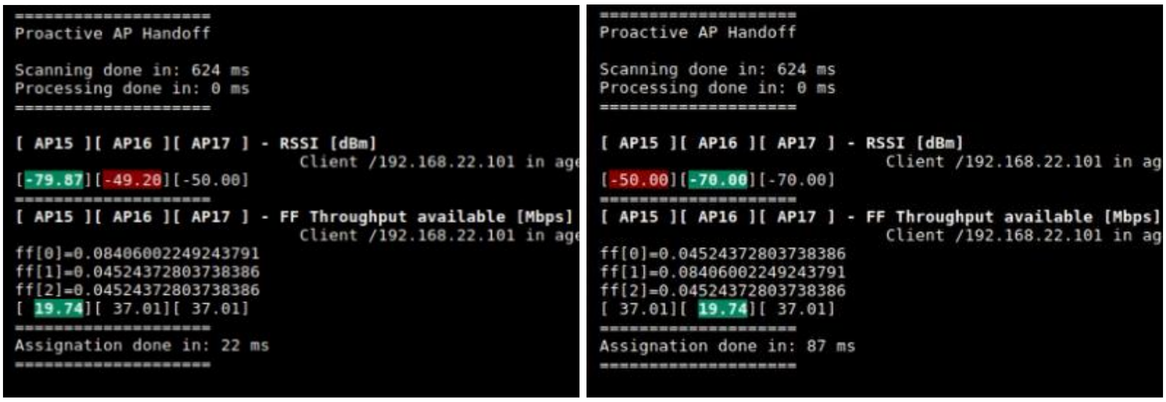


Figure 15: FTP traffic on STA during mobility rest – same channels to APs

In the final stage, we tested the Smart AP Selection based on the Fittingness Factor in the FF mode with the aim to assess its performance. We used a Samsung S7 as the STA and set the QoS requirements for a throughput of 1Mbps.

From the initial observations we noticed some uncommon behaviour of the application. Specifically, the AP to which the STA was assigned was not the one with the best throughput despite the fact that there were no other devices connected to the Wi-5 system. This behaviour is illustrated in the screenshots in Figure 16 where AP1, AP2 and AP3 of the Community scenarios are named AP15, AP16 and AP17, respectively. In detail, Figure 16 shows the AP selection results when the STA is closer to AP16 (Figure 16(a)), and to AP15 (Figure 16(b)), respectively. Note that in the figure the RSSI reached by the STA in its assigned AP is green marked, whereas the highest RSSI is red marked. In Figure 16(a) we can observe that when the STA is closer to AP16, it is assigned to the AP providing the highest FF, i.e. AP15 where the achieved FF is 0.084 and the throughput is 19.74 Mbps. Figure 16(b) shows that when the STA is closer to AP15, it is assigned to AP16, which also provides the highest FF of 0.084 and 19.74 Mbps throughput. These assignments do not reflect typical AP selection behaviour that connects a STA to the AP providing the highest RSSI. On the other hand, this result validates the AP selection based on the FF implemented in the Wi-5 system, with the further details given in deliverables D3.4 [4], D4.3 [5] and D5.2 [10].



(a) STA closer to AP16 (b) STA closer to AP15

Figure 16: Images from the controller running Smart AP Selection - Fittingness Factor mode

Moreover, we noticed that the achieved throughput for the associated AP was changing rapidly and at some times the application on the STA even indicated 0 Mbps throughput. Hence, we decided to measure the throughput of the downlink traffic on the STA connected to AP15 using *iPerf3* from the local server in our system in three experiments. The results of these experiments are illustrated in Table 8. From these experiments we can see that the value of achievable throughput estimated during a 624 ms scanning period shown in Figure 16 is not close to the real throughput measured using *iPerf3* and shown in Table 8. Therefore, from these experiments we can conclude that the scanning time considered to compute the achievable throughput used as an input for the AP selection based on the FF should be accurately analysed and selected to ensure optimal AP selection. However, the AP selection algorithm would provide the same allocation described in Figure 16(a) based on the realistic results illustrated in Table 8. In fact, such throughput values are still the most suitable metric for an STA requiring a 1 Mbps throughput for its application.

Table 8: Throughput measurements with STA connected to AP15

Downlink Throughput measurements			Average
1.02Mbps	0.960 Mbps	0.910 Mbps	0.963 Mbps

4.3 User-based Tests Results

In this section we present the results obtained through the questionnaires that were distributed to the users who accessed the Wi-5 network for both the SOHO and Community scenarios.

4.3.1 SOHO Tests Results

The SOHO user-based assessments consisted of two periods: in the first period Wi-5 was running but without the Smart AP Selection, and in period 2 Smart AP Selection was operational.

Due to the voluntary nature of these tests we could not motivate enough PrimeTel employees to connect and use the network, who worked on the floor of the building where the Wi-5 system was deployed. Moreover, many employees who volunteered had difficulties to connect to the network. Most of these connection issues occurred with the devices listed in Table 9 as outlined in section 4.1. As a result, the participation in these user-based tests was moderate, which made it difficult to draw definitive conclusions about the users' overall satisfaction and their perceived QoE.

Table 9: Devices that could not associate with the Wi-5 System

Device
Lenovo A806
OnePlus 5T (Cannot obtain IP address)
Xiaomi Mi Note 3
Samsung Galaxy J3 (2016)
Lenovo ZUK Z2
Iphone 5c

The results obtained for the first period of the user-based tests, where Smart AP Selection was not enabled, are shown in Figure 17, Figure 18, and Figure 19 as well as in Table 10 and Table 11.

Question 1: Did you connect and use the "wi-5-public" Wi-Fi during the last five days?

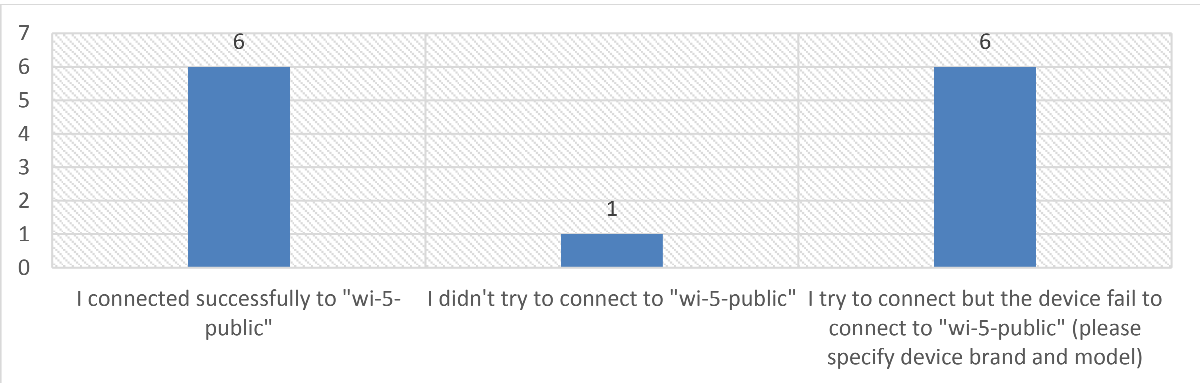


Figure 17: Participation in the SOHO user trials.

Question 4: How do you rate the following (1=very Bad, 5=very Good)?

Table 10: Participants who answer question 4

	Answers
"wi-5-public" connection quality	6
"wi-5-public" signal strength	6

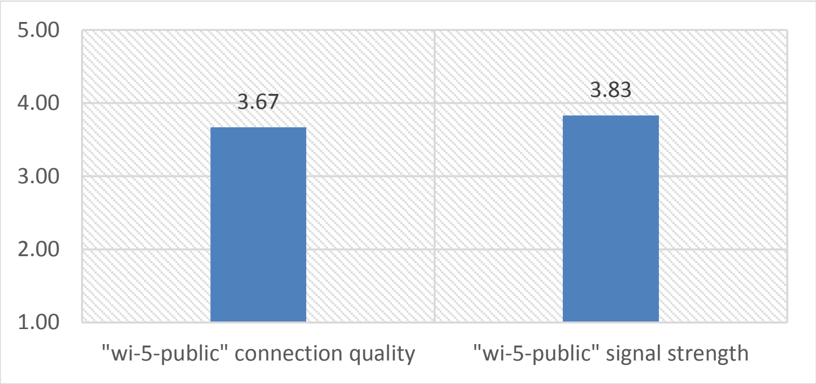


Figure 18: Results of the question 4 for the period 1

Question 11: Rate your experience on using different services with "wi-5-public" (1=very Bad, 5=very Good)?

Table 11: Participants who answer question 11

	Answers
Browsing	6
Video Streaming	4

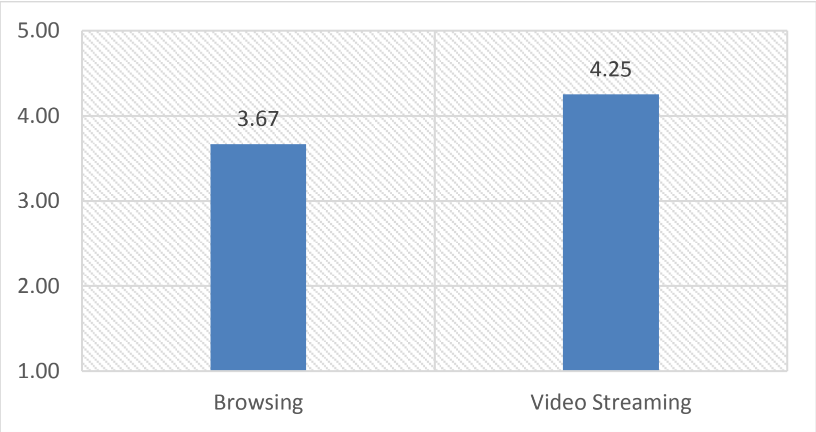


Figure 19: Results of the question 11 for the period 1

The results obtained for the period two of the user-based test, where Smart AP Selection is running, are shown in Figure 20, Figure 21, and Figure 22 as well as in Table 12, Table 13, and Table 14.

Question 1: Did you connect and use the "wi-5-public" Wi-Fi during the last five days?

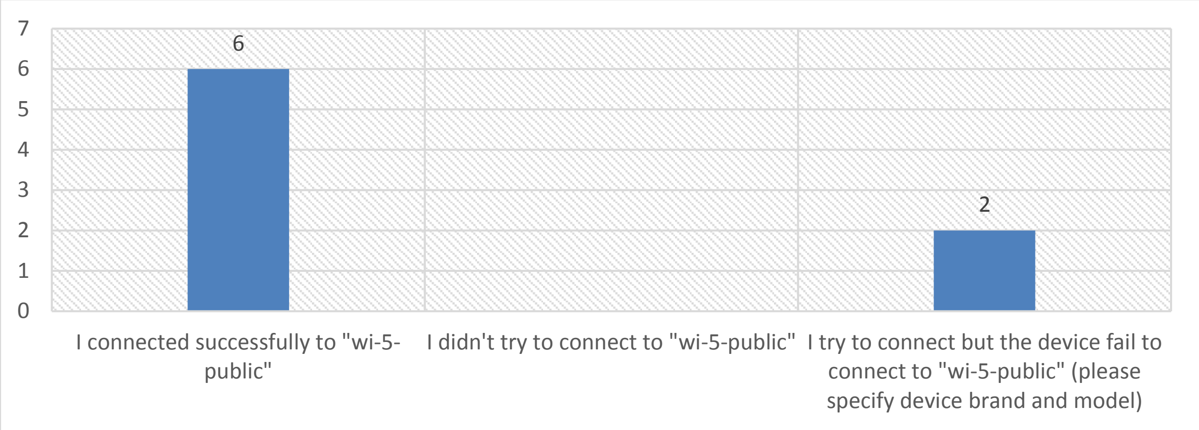


Figure 20: Results of the question 1 for the period 2

Question 4: How do you rate the following (1=very Bad, 5=very Good)?

Table 12: Participants who answer question 4

	Answers
"wi-5-public" connection quality	6
"wi-5-public" signal strength	6

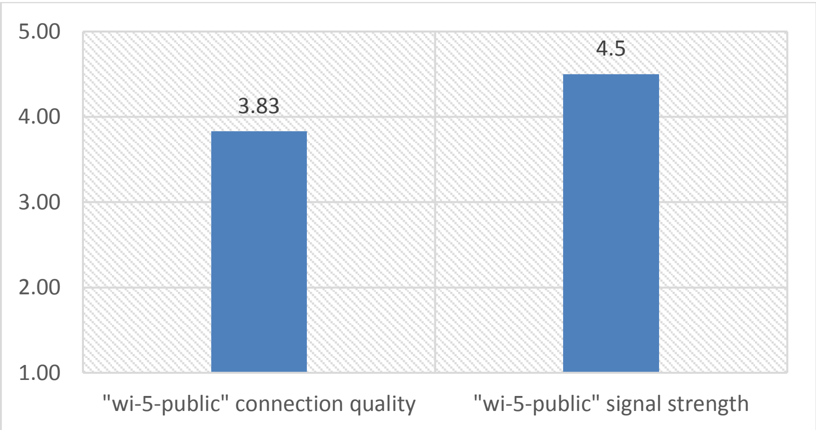


Figure 21: Results for the question 4 for the period 2

Question 11: Rate your experience on using different services with "wi-5-public" (1=very Bad, 5=very Good)?

Table 13: Participants who answer question 11

	Answers
Browsing	6
Video Streaming	4

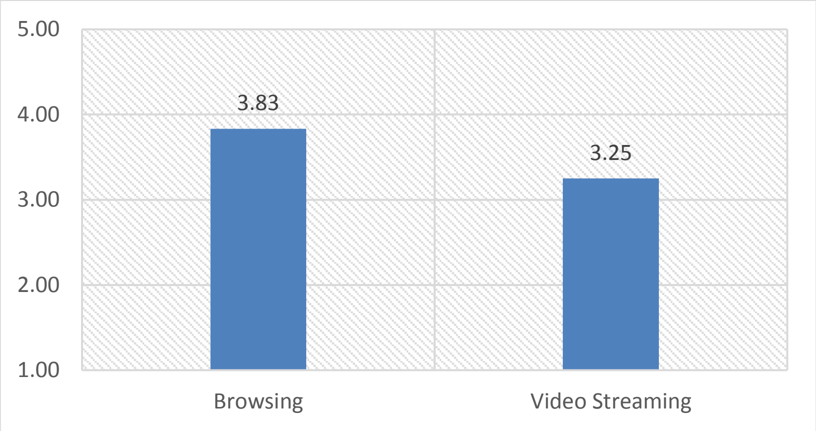


Figure 22: Results for question 11 for the period 2

Question 13: How do you compare the Wi-5 system in the 2nd week of operation compared to the 1st one?

Table 14 : Results of the question 13 for the SOHO user trials

	1st week was better	**The same**	**2nd week is better**
Signal Strength	0.00%	50.00%	50.00%
Connection Quality (Less delay/disconnection = better)	25.00%	25.00%	50.00%

From the results presented we can see that the signal strength and connection quality were evaluated better in the second period. The browsing experience was also evaluated better in the second period but not the video which was evaluated better in the first period. However, as we already mentioned, the low participation meant we could not extract safe results.

4.3.2 Community Tests Results

The community field trials with users were conducted as described in Section 3.3.2b. The total number of users that participated in this test was 21. The majority of the volunteer users were employees of PrimeTel and other companies near the premises. The users were usually taking their break in the outdoor area which is covered by the Wi-5 network.

a) Observations and Adjustments

Before we started these user trials, an R&D engineer evaluated the test that the volunteers would carry out in order to tune the system and observe any misbehaviour that was potentially caused by other factors in the environment. Therefore, when the user was walking along the path, he/she was escorted by the R&D engineer in order to observe the behaviour of the system and get any extra feedback from the user. From those tests we made some observations that we will explain here, some of which are expected and others were not expected but were rarer.

From our initial observations we saw that the video was sometimes freezing during the handoff. We saw that this can be easily fixed by increasing the network caching in the VLC client. On the other hand, we decided not to increase the caching value too much in order to be able to observe the behaviour during congestion. Moreover, during potential disconnections we didn't want the video to run for too long from the cache, and we wanted it to stop after approximately 10 seconds from disconnection. In order to improve the behaviour of the system we put all the APs in channel 6 which, as we have seen above, means that the LVAP can move from one AP to another AP without the STA being forced to change channel. We decided to do this because in these trials we wanted to evaluate the applications taking the decisions for the handoff and not the handoff mechanism itself. Therefore this was a valid measure to take in order for the effect of the algorithms to be clearer in the tests.

The test proceeded from 1 to 4, each with different functionalities enabled as illustrated in Table 3.

During the first test, the video was freezing as expected since the STA was getting too far from AP1 at some point. In the second test we sometimes observed some jitter in the video and sometimes the video was freezing but we could immediately restart the video stream. In the third test the video was freezing after the STA was connecting to AP2 since there was data traffic towards an additional STA in AP2. We have to mention that the STA on the second and third tests was only connecting to AP2 and not to AP3 since the RSSI was not falling below the threshold. This threshold was set to -68 dBm after we observed the signal strength in the middle points between the AP1 and AP2, which were farther away. At that point the worst signal we were getting from both APs was around -64 dBm. Therefore we set the threshold slightly above that, so when the RSSI of AP1 gets worse than AP2 the application would permit the change. In the fourth test, we rarely saw freezing in the video. However, it is again important to note the movement of the STAs between APs here. Sometimes the STA of the test user was assigned to AP3 from AP2 where the extra STA was connected. Sometimes the STA of the test user was assigned to AP2 before the extra STA was assigned to AP3.

b) Obtained Results

The users gave their feedback through the questionnaires outlined in section 3.3.2.b describing their experience through each of the tests. The results are shown below. The same questions/answers from questionnaires 1, 2, 3 and 4 are grouped together here in order to compare the results from the different tests. The results for questions 1, 2, 3, 4, and 5 are presented in figures 23, 24, 25, 26 and 27, respectively.

Question 1: How do you rate the following (1=very Bad, 5=very Good)?

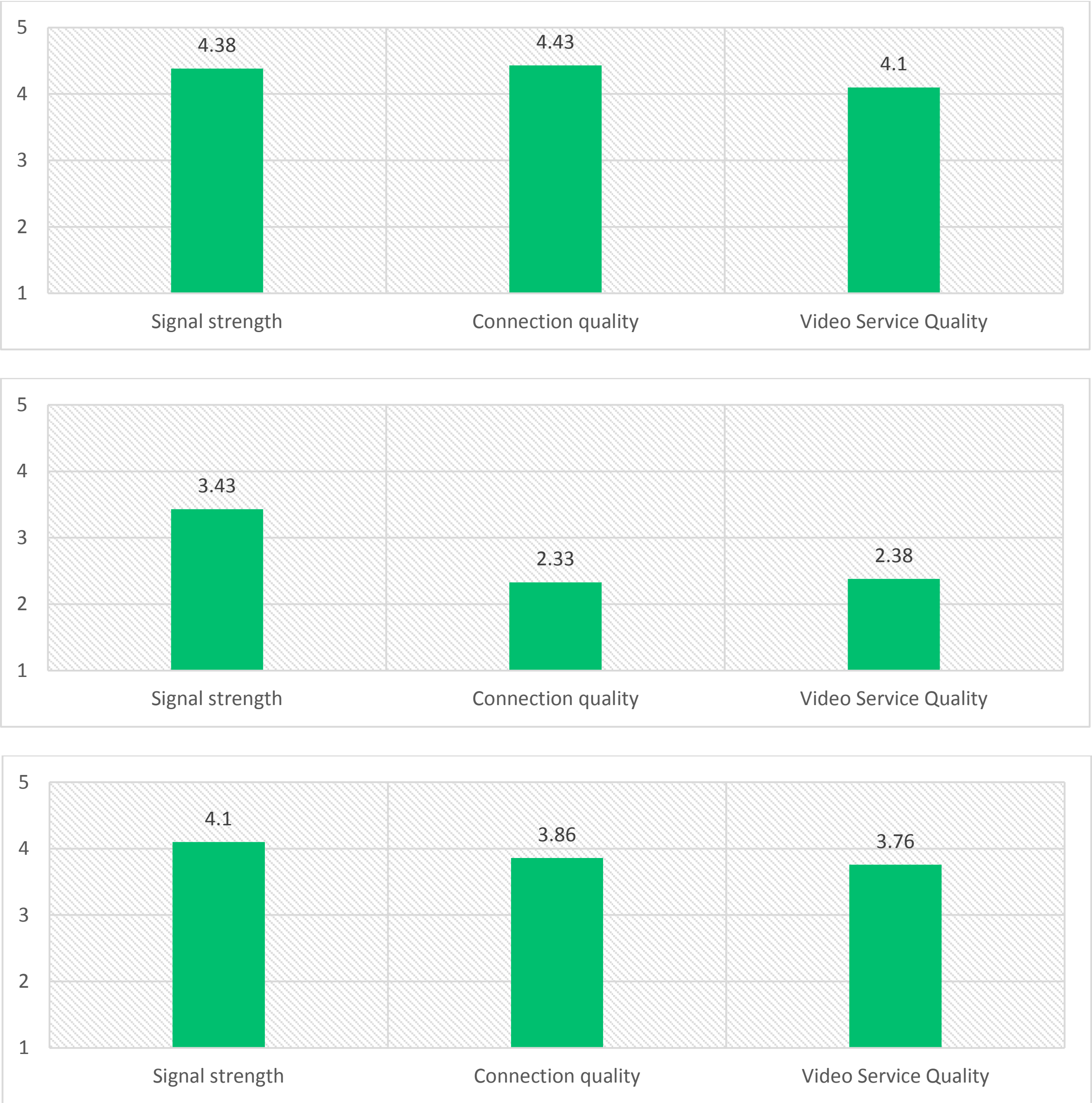
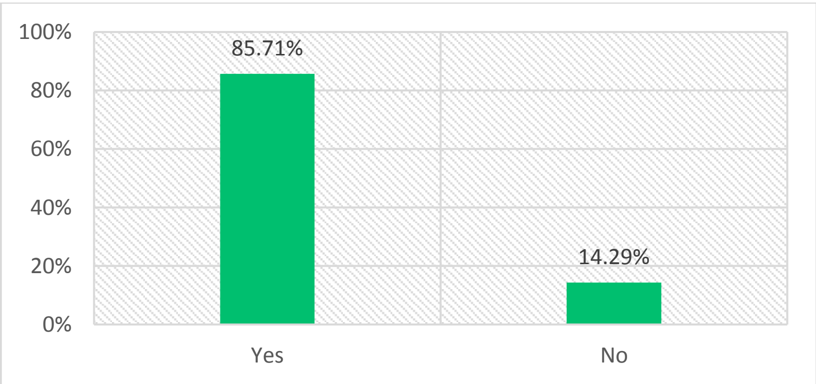


Figure 23: Charts of the answers to question 1 for tests 1-4 (top to bottom)

Question 2: Did you experience any lags\delays while connected to "wi5community"



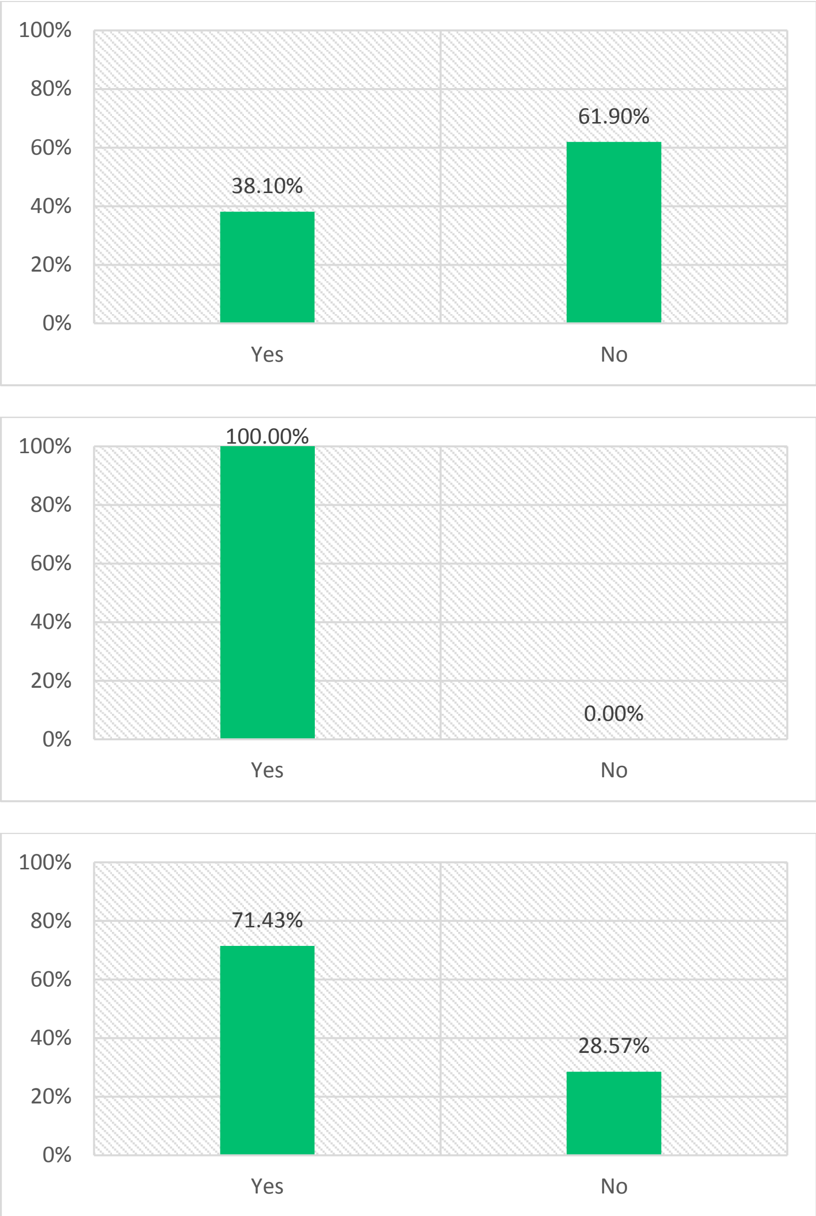
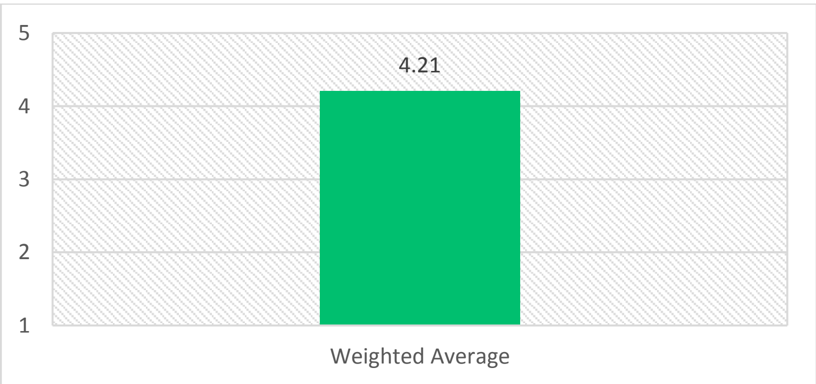


Figure 24: Charts of the answers to questions 2 for tests 1-4 (top to bottom)

Question 3: How disturbing\serious were the lags\delays that you experienced?



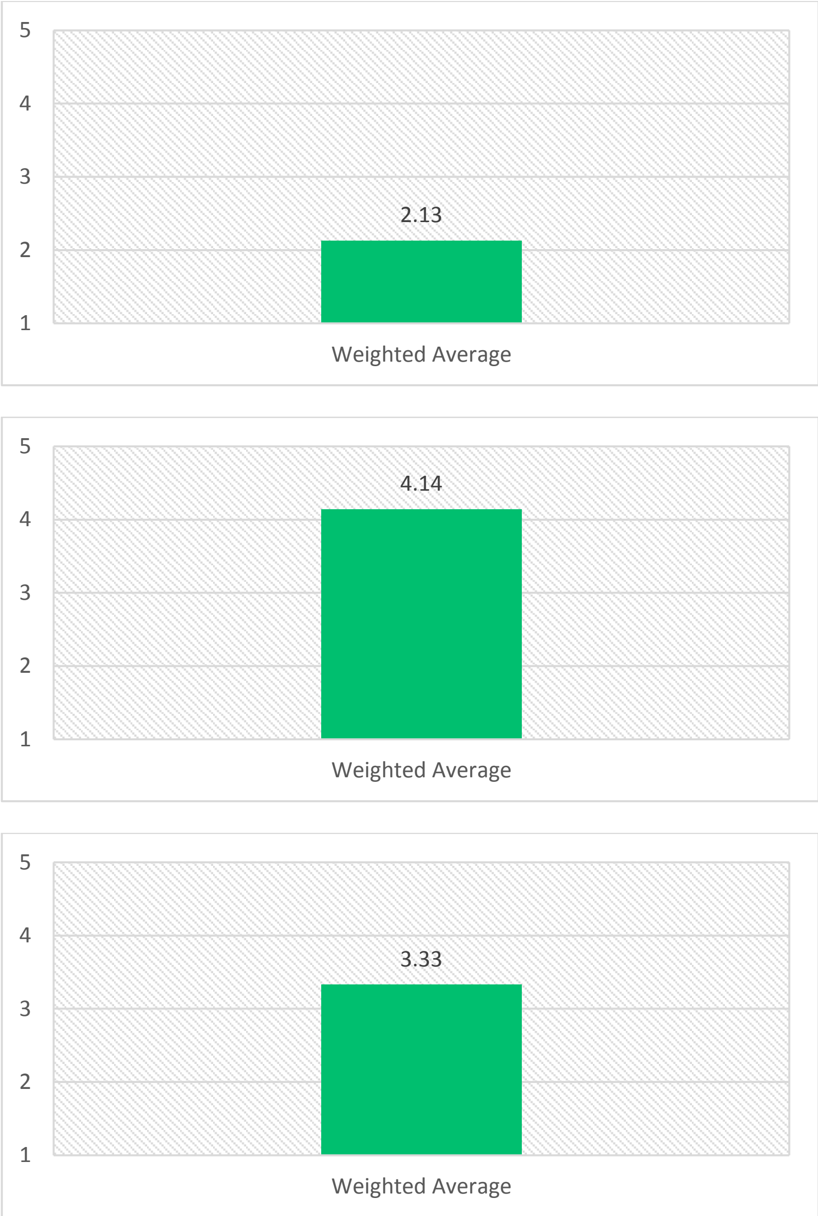


Figure 25: Charts of the answers to questions 3 for tests 1-4 (top to bottom)

Question 4: Did you experience any disconnection while connected to wi5community"? (Completely Disconnect and Service Stop for long time?)

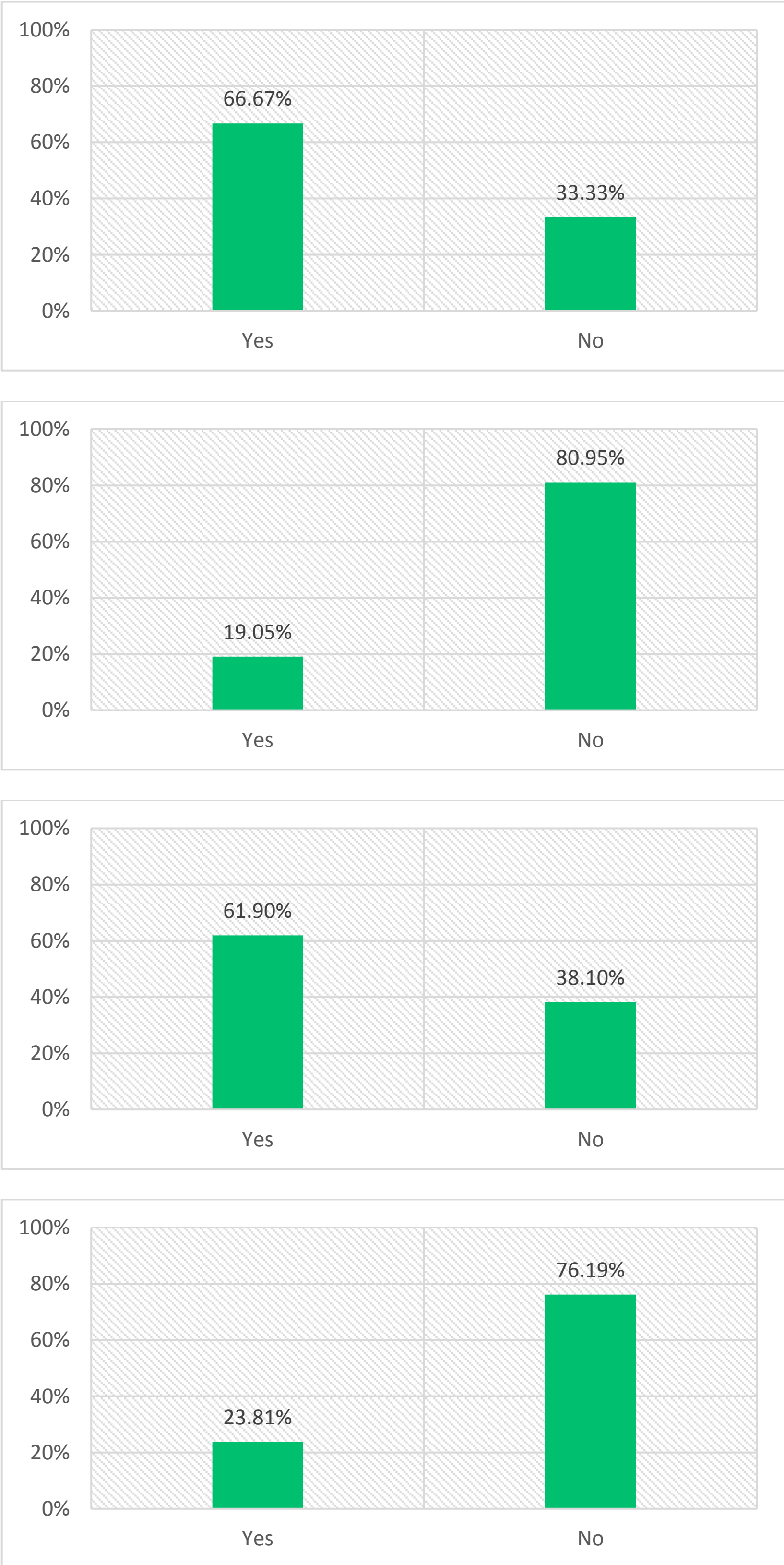


Figure 26: Charts of the answers to questions 4 for tests 1-4 (top to bottom)

Question 5**:** How disturbing\serious were the disconnections that you experienced?

Figure 27: Charts of the answers to questions 5 for tests 1-4 (top to bottom)

From an initial overview of the results we can see that the user experience is better in the second test compared to the first one and it is also better in the fourth test compared to the third one. Now we will compare the tests taking into account each question separately.

In the results of question 1 it is clear that the first test holds the worse results as was expected since each STA remains connected to AP1 through all the path. We see also that the second test is the best since each STA is moving to the closest AP and there is no other traffic in the system. In the third test we have bad results as expected due to the extra traffic in the system. The users noticed that the signal to the STA was better than in the first test, but the experience regarding the service was similar most likely due to the congestion. In the fourth test we observed better results than in the third one. Moreover, we observed slightly better experience in the second test over the fourth one because the algorithm in the fourth test is also performing load balancing.

From question 2 we see that most of the users experienced some kind of lag and delay but tests 2 and 4 performed better than 1 and 3. To draw a further conclusion we needed to see the third question to compare how serious were those delays in the different tests.

From question 3 we see that in the first and third tests we have the most serious delays. Again as in question 1 we see that the fewer delays happen in the second test. Note that the weighted average illustrated in Figure 25 is the arithmetic mean of all the scores obtained from the answers to question 3, which range from 1 (very low) to 5 (very serious). It is important to note here that this is the average of the answers only from those who answered positively in question 2, and the rest of the users did not answer question 3.

From question 4 we see that most disconnections happen in the first test. From the rest, the best tests were second and fourth.

Question 5 did not show anything extra beyond question 4. As above, the weighted average shown in Figure 27 is the arithmetic mean of all the scores obtained from the answers to question 5, which range from 1 (very low) to 5 (very serious). Again we have to note that the weighted average of the chart is the average of the answers only from those who answered positively in question 4, and the rest of the users did not answer question 5.

Tables 15 and 16 show the results of question 6 in questionnaires 2 and 4.

Question 6: How do you compare the Wi-5 system in the first and second tests?

Table 15: Results from question 6 questionnaire 2

	1st better	2nd better	On both tests it was the same
Signal Strength	0.00%	100.00%	0.00%
Connection Quality	0.00%	100.00%	0.00%
Video Service Quality	0.00%	95.24%	4.76%

Question 6: How do you compare the Wi-5 system in tests 3 and 4?

Table 16: Results from question 6 questionnaire 4

	3rd better	4th better	On both tests it was the same
Signal Strength	14.29%	76.19%	9.52%
Connection Quality	14.29%	80.95%	4.76%
Video Service Quality	4.76%	80.95%	14.29%

From the results of the tables above we can clearly see the users think that the second test was better than the first and the fourth was better than the third. This demonstrates that the goal of each mode in the Smart AP Selection was achieved. It therefore depends on the administrator of the potentially deployed Wi-5 System to decide which mode to use depending on the expected traffic from the STAs in the system.

5 Conclusion

In this final section we recap the observations, comments and conclusions from the field trials results. We also present the conclusions oriented towards the Smart AP selection and Channel Assignment applications and their different modes that were used in our tests. For every part, we will provide some suggestions and technical feedback that could be used to further improve the next versions of the Wi-5 System.

From our overall assessment of Wi-5 we conclude that in general the system is functional and the applications running on top of the Wi-5 Controller are working and provide significant improvements to the issues they are trying to solve. On the other hand, the Wi-5 System is clearly still in the prototype phase and it has limitations in terms of its operation and performance.

The most obvious practical drawback of this prototype system is the inability to work well with many devices. In many cases a device is not able to associate with the Wi-Fi at all. In other cases even if a device is able to associate to the system, it may need to attempt many times in order to connect successfully and also it may get disconnected all of a sudden. We believe that this is the main area on which a further implementation of the system should focus as a high priority should always be given to the robustness of the system. While there will always be some devices that need some configuration changes in order to operate, we have to ensure that the majority of the devices will connect and that they should have consistent behaviour, which at the moment is not the case.

Regarding the Smart AP Selection, we performed several tests both in a controlled environment and involving the users. Here we have used the RSSI, Fittingness Factor (FF), and Balancer modes. In the trials we tried to judge the Smart AP Selection as the application which makes the decision on the handoff of an STA from one AP to another, rather than the performance of the handoff itself. The Smart AP Selection in the FF mode has been validated and an interesting output in terms of scanning time has been provided. Specifically, we illustrated the importance of the scanning time considered to compute the achievable throughput used as an input for the Smart AP Selection based on the FF. For the Smart AP Selection in the RSSI mode, based on observations and QoS and QoE measurements, we found it offers a significant improvement against the sticky client problem where there is no movement of the LVAP and the STA remains connected to one AP until it loses connection. In addition, the Smart AP Selection in the Balancer mode offers improvements against the RSSI mode in the cases of congestion in a particular AP.

Under simplified conditions with only one STA moving, we show that the problem in some cases was not in the decision itself but in the procedure of the handoff. After trying the system with demanding services we observed a better handoff with less disruption in the cases where all APs belonged to the same channel against the case where the APs were in different channels. The problem identified was with the physical change of the channel in the STA in order to communicate with the LVAP in the new AP. This action is therefore considered as a bottleneck in the handoff procedure. Future improvements here could take this into account based on the device and service requirements and try to work around it until handset design is improved. The problem is obvious in limited cases when the service is very demanding and when the APs have different channels. In a step forward, the application should take into account the service used by an STA and perform a handoff between APs with different channels in cases where the service is not very demanding, e.g. browsing and file downloading.

For most of the Channel Assignment trials we used the SOHO scenario with 4 APs. Initially we ran the application and discovered some minor issues with the calculation of the interference impact but those flaws were quickly corrected. Most of the attention in the trials was then given to test the performance of the application in its internal interference mode. That was more feasible here since the SOHO scenario was setup in a real office where the external interference was not controlled and we could not make any valid comparison between the tests. The Channel Assignment application generally worked well and it assigned a good combination of channels in terms of the achieved throughput and spectral efficiency from the possible combinations. However, further testing and refinements are needed to also address external interference, which might affect the channel assignment results in more congested environments.

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