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Executive Summary

This document comprises a detailed description of the hardware solution adopted for building the Wireless Network Backbone (WNB) of the SCADA system that is being developed within the project PANTHEON. The document is organized as follows: i) first the hardware components are described, then ii) the software components are described, and finally iii) an experimental validation on the field of the WNB performance is discussed.

Table of Content

Abbreviations and Acronyms

ROS	Robot Operating System
WNB	Wireless Network Backbone
DB	Data Base
FIFO	First In First Out
UGV	Unmanned Ground Vehicle
AGV	Unmanned Aerial Vehicle
PoE	Power on Ethernet
MIMO	Multiple-Input and Multiple-Output
LAN	Local Area Network
WLAN	Wireless Local Area Network
WAN	Wide Area Network
DHCP	Dynamic Host Configuration Protocol
CPE	Customer Premise Equipment
AP	Access Point
PtP	Point-to-Point
RTT	Round-Trip Time
SFTP	SSH File Transfer Protocol
SSH	Secure SHell

1 Wireless Network Backbone

1.1 Overview

The Wireless Network Backbone (WNB) is the infrastructure responsible for interconnecting the elements of the SCADA system. All the components, from the central unit (local server on the field) housing the Data Base (DB) to the single robots moving in the field, are interconnected through to the WNB. The architecture of WNB is made up by two different components: a set of mesh antennas and two long-distance antennas. The former is required to create a mesh network on the field, so that UGVs and UAVs can operate in the field itself, while the latter are necessary to connect the central unit, stored in a remote warehouse, to the mesh network (which is instead in the field).

For the sake of easy hardware and software integration, it was decided to rely on commercial Wi-Fi solutions based on the 802.11 standard, at either 2.4GHz or 5.0GHz.

A schematic of this architecture can be appreciated in Figure 1.

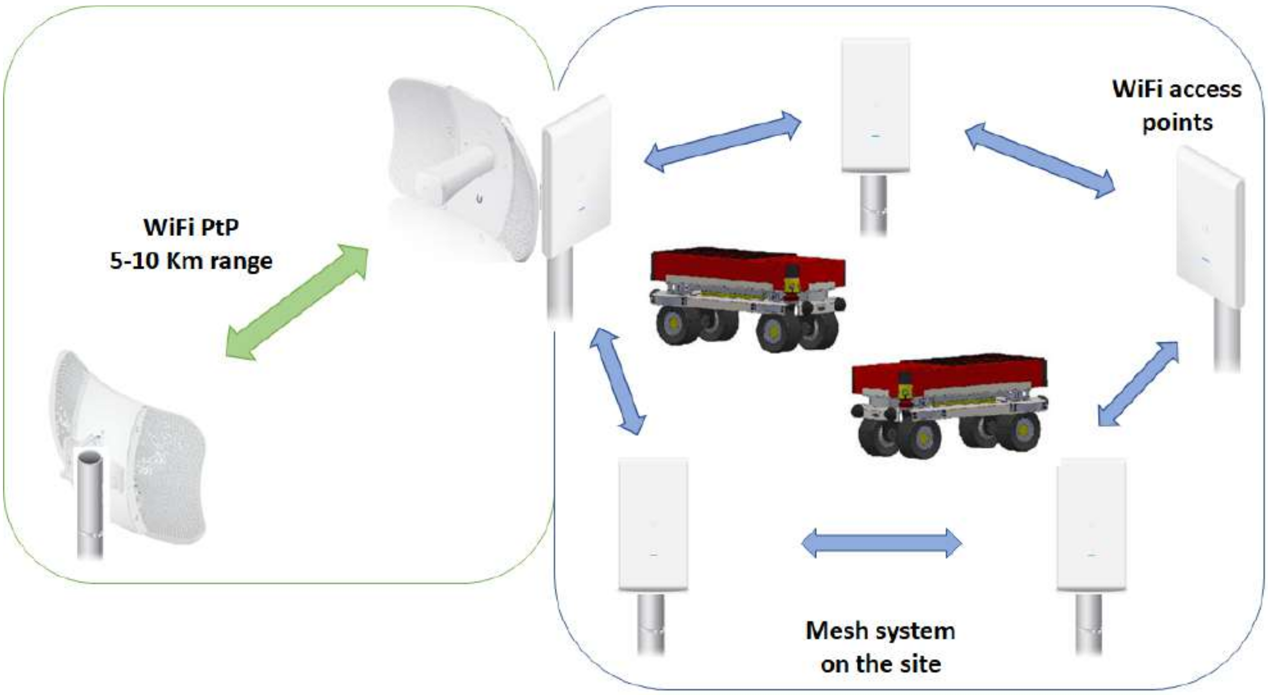

Figure 1 - Overview of the WNB Architecture

1.2 Architecture

The proposed architecture is based on Ubiquity commercial products. This choice is supported by the fact that Ubiquity products result to be widely used for providing connectivity, well tested and a community is actively contributing for customized solutions. The WNB deployed within the PANTHEON experimental field consists of:

- 2 AIRMAX antennas (LiteBeam AC GEN2);
- 5 UNIFI antennas (AC MESH PRO);
- 1 router (IR615-S-EN000-WLAN).

1.2.1 Antennas

The two Airmax are long-range point-to-point antennas which can be deployed to build point-to-multipoint networks based on the airMAX ac protocol, a TDMA (Time Division Multiple Access) protocol purposely design to enhance performance for outdoor applications.

All the Unifi devices are instead conventional Wi-Fi access point (typically 100m range, up to 300Mbps), which can be conveniently accessed even with a mobile phone, a useful feature for experiments and debugging purposes.

The mesh established between Unifi antennas is necessary to cover all the desired area and is made by a total of 5 devices that are enough for the WBN.

A detailed description of the hardware components will be provided in the sequel.

1.2.2 Wiring and Placements

Compared to the network overview provided in the Deliverable D2.1 “Requirements, Specifications and Benchmark”, a different network configuration has been adopted. In particular, as depicted in Figure 1, the long-range antenna Airmax2 (located on the roof of the warehouse) is now wired connected through an Ethernet cable to the central unit (located in a remote warehouse) and oriented toward the long-range antenna Airmax1, which is instead placed in the field where the router is also located. As a matter of fact, the re-location of the router into the field turned out to be a better solution as it allows to create a connection from the control room to the mesh network deployed in the field. An additional benefit is related to the fact that with this configuration a possible temporary failure of the point-to-point, or long-range, connection between the central unit and the mesh network does not prevent the usability of the unmanned vehicles on the field by relying only on the Mesh network.

Regarding the mesh network, the Unifi antenna Mesh A is wired connected to the long-range antenna Airmax1 (located in the field) through to an ethernet cable and to the router, utilizing another ethernet cable. Any other Unifi antenna is wireless connected, i.e. through an uplink-downlink radio connection as specified by the Unifi protocol, detailed in the next sections, in order to create a mesh network. In this way the signal is re-broadcasted through a desired network topology pre-configured from a Unifi Controller, a configuration software described later, permitting the connection between all devices in the field.

As depicted in Figure 2, next to the antenna Mesh C, there is located a weather station which is responsible, together with the (Long Range) LoRa sensor network, to collect agrometeorological data of various nature. More details are given in Section 1.3.

Figure 2 - Wireless Network Backbone Deployment

1.2.3 Mounting devices

The following images depict respectively an Unifi Mesh Antenna mounted in the field (Figure 3) and the Airmax1, together with the Mesh A, arranged also in the field (Figure 4). As it is possible to see from these images, the couple Airmax-Mesh are the only wired connected parts of the field, since there is a power source inside the small tower of Figure 4 while all the other Unifi Mesh Antennas, like the one in Figure 3, are powered through a solar panel that can be appreciated in the same Figure.

All the mounting parts for both solutions are included with Ubiquity products. For further details on how to mount the devices, it is possible to read the full online documentation for both Airmax and Unifi.

Figure 3 - Unifi Mesh antenna

Figure 4 - Airmax1 + Mesh A antennas

To bring power to the Mesh, the network includes also 4 *power boxes,* one for each antenna, whose components are showed in Figure 5. The content of these boxes is composed by:

- 12V 9Ah Sealed Lead Acid Battery
- 300W Inverter
- 48V PoE Adapter

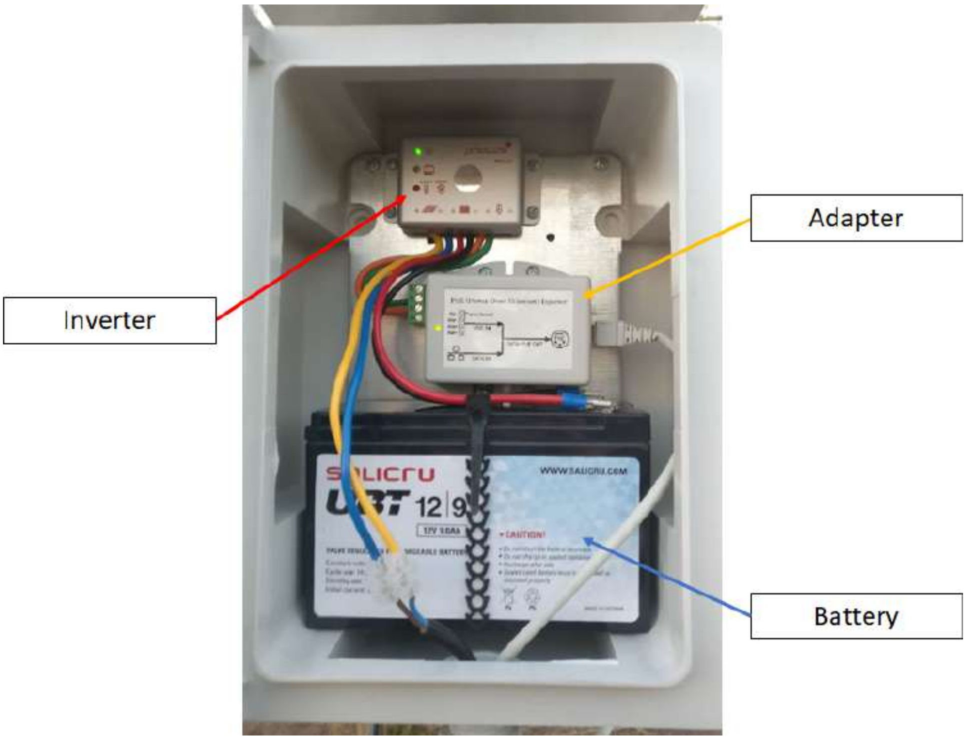

Figure 5 - Internal view of a power box

Apart from those inside the boxes, the system includes 4 additional spare batteries for continuous operation, and 4 chargers for the batteries. The wiring of battery-inverter-charger has been done with power connectors and faston terminals, to have the flexibility at using different chargers and batteries.

All the Mesh antennas' solar panel (except for the A, which is wired connected to a power source) are able to re-charge the batteries through to the inverter. More specifics about these solar panels will be given in the Section 2.4.

1.2.3.1 Quick-Start

In the following, the procedure to set up first the Mesh antennas and then the Airmax antennas is provided. The steps for connecting the Mesh are recursive and should be done for each antenna of this type.

First, connect the Ethernet cable to the Mesh antenna. This single cable just connected will contain supply (SoE) and, in the case of Airmax antennas, also data. The next step is to connect the adapter to the other end of the ethernet cable, as can be seen in Figure 5 (where it is also possible to see the cable going out from the box toward the Mesh antenna). Then, the last step is to connect the Inverter with both the battery and the solar panel.

Important Note: check carefully the powering since Unifi antennas need to be attached to 48V PoE while Airmax ones require 24V PoE. Power Box should have two different PoE devices with different voltages so one must take into account this remark.

Repeat this procedure for all the Mesh antennas present in the network. Once all the devices are connected, power on them using the ON/OFF switch that is installed outside the Power Box.

Remark: remember to switch it off and, eventually, disconnect the battery-inverter connector to save battery after usage.

Connect then the antenna Airmax 2 to local network at the Central Unit (local server) using the two ports of PoE device (this device is supposed to be connected to the power grid using the standard power connector).

Make sure that antenna Airmax 1 is also connected (wired) to Unifi first uplink (Mesh A of Figure 4). Both PoE ports of the Adapter in the power box should be connected in this case.

At this point, the Unifi Mesh should have been automatically established, providing a single Wi-Fi network.

For monitoring and configuring the devices of the network, the *AirOs* and *Unifi Controller* applications, which are tools provided directly by Ubiquity, have been used. These applications also provide good ways of monitoring the performances of the network (bandwidth, quality of the signal, etc.) for debugging purposes.

1.2.3.2 Troubleshooting

In the following, a collocation of advices concerning the configuration of the Mesh Network is shown, if the *adoption process* needs to be done. The *adoption process* consists in adding a new Mesh antenna to the network. When the Unifi Controller software is launched, in the page “Devices” the new Mesh should appear as *Pending Approval* (*Wireless*) and it should be possible to click on *Adopt* button.

The whole procedure results so to be:

- Make sure that the devices share the same subnet
- To do so, follow this process:
    1. Configure master router with desired IP range
    2. Connect 1st antenna to router (wired)
    3. Open Unifi Controller software
    4. Adopt first device (should be adopted with an IP in the same subnet)
    5. Connect another device to router (wired)
    6. Adopt it
    7. Repeat with all devices
    8. In section “site”, make sure that *Wireless uplink* and *failover* options are enabled
    9. After this process, remove wires. The wireless uplink should be automatically stablished.

1.3 LoRa Network

Even though the LoRa network is not properly part of the WNB it is worth to mention it. It is a digital wireless data communication technology which is responsible for sensing, management and monitoring of weather conditions.

It is made by three main components:

- Sensors (or nodes) which are scattered in the field;
- A weather station next to Mesh C of Figure 2;
- A raspberry 3B+ placed together with Mesh A and Airmax 1 of Figure 2.

The nodes (Figure 6), which are scattered in the field and inserted in the soil at two different depths (15cm and 40cm respectively), are responsible for monitoring of soil properties (such as soil moisture and soil temperature).

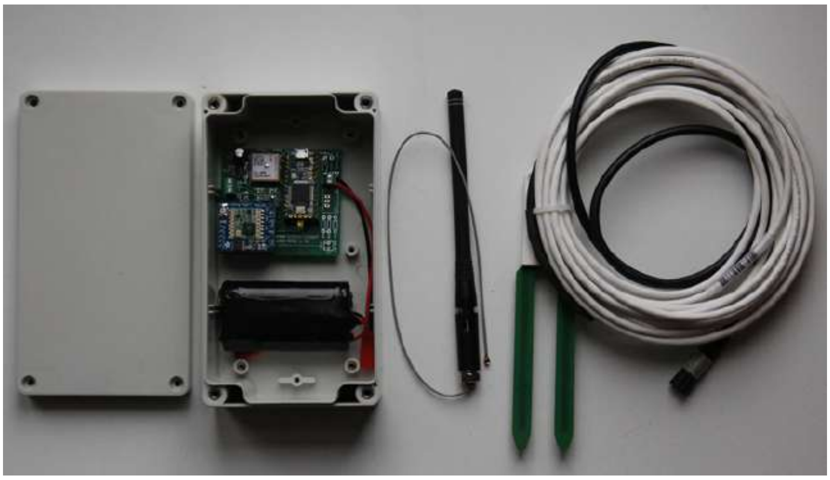

Figure 6 - Sensor of the LoRa network

The weather station (Figure 7) is responsible for monitoring the weather conditions, such as air humidity, air temperature, air pressure and rainfall.

Figure 7 - Weather Station

The raspberry 3B+ (Figure 8) is responsible for bridging the IoT agrometeorological monitoring network whose communication is based on the LoRa technology with the ROS network whose communication is based on standard TCP/IP over WiFi.

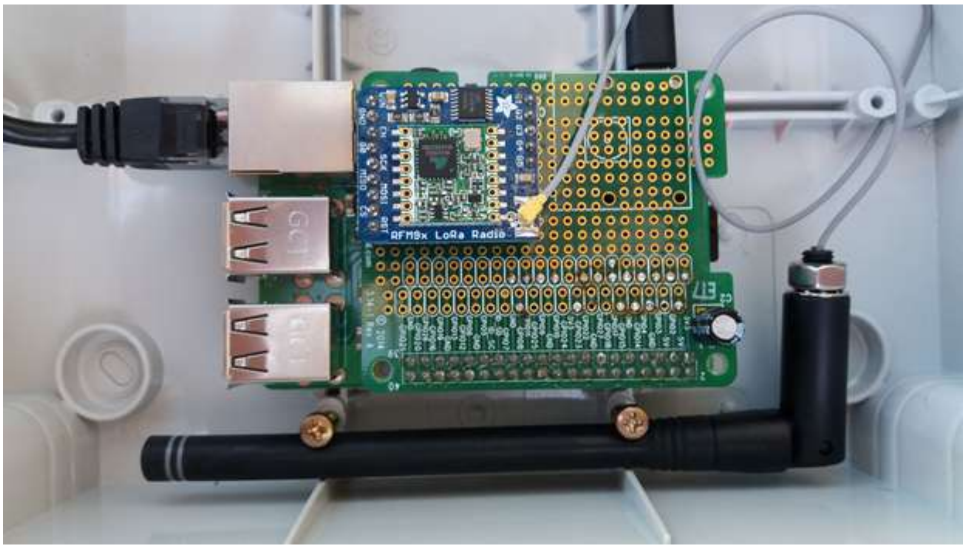

Figure 8 – Raspberry 3B+

The working principle can be summarized as follows:

1. Data (both coming from soil and weather) are collected by the weather station and from the LoRa nodes.
2. Data are sent to the raspberry that store them and manage them by a queue system.
3. By following a Fist-In-First-Out (FIFO) order, data is converted to be shared within the ROS network by using the the Wi-Fi interface.
4. In particular, the data is sent over the Mesh network by exploiting the TCP/IP protocol in order to be received and stored by the Central Unit. This is achieved by using the long-range point-to-point connection between the Airmax 1 and the Airmax 2.

2 Hardware Components

2.1 Mesh Pro

The Unifi AC MESH PRO is an access point wireless dual-band 802.11 AC 3x3 MIMO produced by Ubiquiti Networks Inc., with two Gigabit Ethernet port and an integrated omni-directional antenna.

The first port, or *main port*, is a Gigabit PoE port used to connect the power and should be connected to the LAN and DHCP server. Even though it is possible to provide power in three different ways, it was used the PoE *Adapter* provided directly with the Mesh Pro. The second port is of the same type but is used just for bridging. It is also present a reset button to perform two functions for the UniFi AP: restart and restore to default settings (if held more than 5 seconds).

Figure 9 - Unifi Mesh Pro antenna

To summarize, the main features of the Unifi AC MESH PRO are:

- Power Supply: 48V,0.5A PoE Gigabit Adapter
- Max. Power Consumption: 9W
- Max. Transmission Power: 22 dBm at both 2.4 GHz and 5 GHz
- Throughput Speed:
  - 2.4 GHz: 450 Mbps
  - 5 GHz: 1300 Mbps
- Range: 183 m
- Antenna gain: 8 dBi
- Operating Temperature: from -40°C to 70°C
- Operating Humidity: 5-95% Noncondensing

The Mesh device supports an off-site management given by UniFi Controller.

2.2 Airmax

The Airmax LiteBeam AC GEN2 is an ultra-lightweight airMAX ac CPE device produced by Ubiquity Networks Inc., that can provide 23 dBi of gain for long-distance connectivity and which uses a directional antenna pattern (through to two side reflectors) for improved noise immunity and to provide directional outdoor coverage. The *Adapter* is included also with this antenna and is used to bring both data and power supply (PoE).

Figure 10 - Airmax antenna

To summarize, the main features of the Airmax LiteBeam AC GEN2 are:

- Antenna gain: 23 dBi
- Max. Power Output: 25 dBm
- Max. Power Consumption: 7W
- Power Supply: 24V, 0.3A PoE Gigabit Adapter
- Operating Temperature: from -40°C to 70°C
- Operating Humidity: 5-95% Noncondensing
- Operating Frequency: 5150-5875 MHz
- Management Radio: 2412-2472 MHz

2.3 Industrial Router

The IR615-S-EN00-WLAN is an industrial router produced by the InHand Networks designed to withstand high processing temperatures (-20°C ÷ 70°C), which supports Ethernet and Wi-Fi connections. This router is ideal for large-scale Internet of things (IoT) applications including the SCADA architecture which is begin developed within the PANTHEON project.

Figure 11 - Industrial Router used for the deployed WNB

The full documentation can be found here.

The main specifics of this router are:

- Network: LAN (Ethernet) and WLAN (optional)
- WLAN: Speed 300 Mbps, Distance 100m
- Power Supply: DC 9-26V
- Power Consumption: 150-320 mA (operating)
- Operating Temperature: -20-70°C
- Operating Humidity: 5-95% Nonconsending

This router results very reliable since it reconnects automatically when a link failure is detected and is also present a hardware watchdog for auto-recovery.

As it is possible to see in Figure 11 there are present led indicators for POWER, STATUS, WARN, ERROR, Wi-Fi, SIM and three levels for cellular signal strength.

The InRouter615-S-EN00-WLAN utilizes also remote management such as a CLI, a web interface and InHand Device Manager Cloud platform for batch configuration and monitoring.

2.4 Solar Panel Power Supply

Other than the batteries stored in the power boxes, one solar panel is provided for each antenna of the WNB. The choice fell on the MF-20W produced by GREEN POWER as solar panel for the project.

Figure 12 - Solar Panel mounted with Meshes antennas

The specifics for this photovoltaic cell are:

- Max Power: 20W
- Voltage at Max. Power: 17.49 V
- Current at Max. Power: 1.14 A
- Short circuit current: 1.22 A
- Body Dimensions: 505x353x28 mm
- Gross Weight: 5.63 Kg

The solar charge controller (the one called inverter in Figure 5) is the model ECO10 produced by Phocos. This controller is equipped with 3 LEDs to display the operating status: charging status, battery status and the load output status. It is also present a low voltage disconnection function to protect the battery against a deep discharge that switches off the load output if the battery voltage drops below the threshold (11.0 V). It manages also the overvoltage situation with a threshold of 15.5 V.

Figure 13 - Controller (or Inverter) of the power boxes

The fully documentation of the controller is available at this link, while an overview of the main specifics is given in the next:

- Max. Charge current: 10 A
- Max. Load current: 10 A
- Overvoltage protection: 15.5 V
- Discharge protection (cut-off): 11.0 V
- Reconnect level: 12.8 V
- Undervoltage protection: 10.5 V
- Max. PV panel voltage: 30V
- Max. Battery voltage: 30 V
- Self-consumption: <5 mA
- Operating temperature: from -40 °C to 60 °C
- Battery type: Lead acid (GEL, AGM, flooded)

3 Software Components

The management of WBN requires different software components to supervisor and control the devices described above, e.g. check status of connectivity, check alignment of antennas, configure parameters.

3.1 UniFi Controller

The UniFi devices are bundled with the UniFi Controller software, which allows managing the UniFi network by resorting to a web browser. After having installed this software on a Linux machine and having configured a basic network, e.g. "PANTHEON_WIFI", it is possible to access this platform by using the IP of this machine (port 8443) as URL, after logging in with the UniFi administrator account. Currently, this machine is a laptop that can be persistently present or not in the experimental field. Note that, if this specific machine is not connected to the WBN, it is not possible to change the network settings or check if any component does operate properly. However, the network can operate even without the presence of this controller.

3.1.1 Sites Manager

The UniFi Controller can manage multiple UniFi networks, which are called sites. Each site has its own configurations, maps, statistics, guest portals, and site administrator accounts. The multiple sites are logically separated. Specifically, the site of Pantheon is named "PANTHEON" and provides a 2.4GHz Wi-Fi network.

The status of each site is represented on the Sites Overview, where are displayed the following parameters:

- Name – the name of the site;
- Alerts – the number of pending alerts;
- WAN – WAN connection status;
- LAN – the wired network connection status;
  - Active – the number of active wired devices;
  - Inactive – the number of inactive wired devices;
  - Pending – the number of wired devices pending adoption;
- WLAN – the wireless network connection status;
  - Active – the number of active wireless devices;
  - Inactive – the number of inactive wireless devices;
  - Pending – the number of wireless devices pending adoption;
- Users – the number of wired users and the number of wireless users;
- Guests – the number of wired guests and the number of wireless guests.

On this panel it is possible to configure and manage more other useful features.

After setting a site, the UniFi software consists of six primary pages that compose the Navigation Bar which is always displayed at the left side of the web browser:

- Dashboard
- Statistics
- Map
- Devices
- Clients
- Insights

The Dashboard screen displayed in Figure 14 provides a visual representation of status of the network. Basic information is provided for each node, e. g. Latency, Throughput.

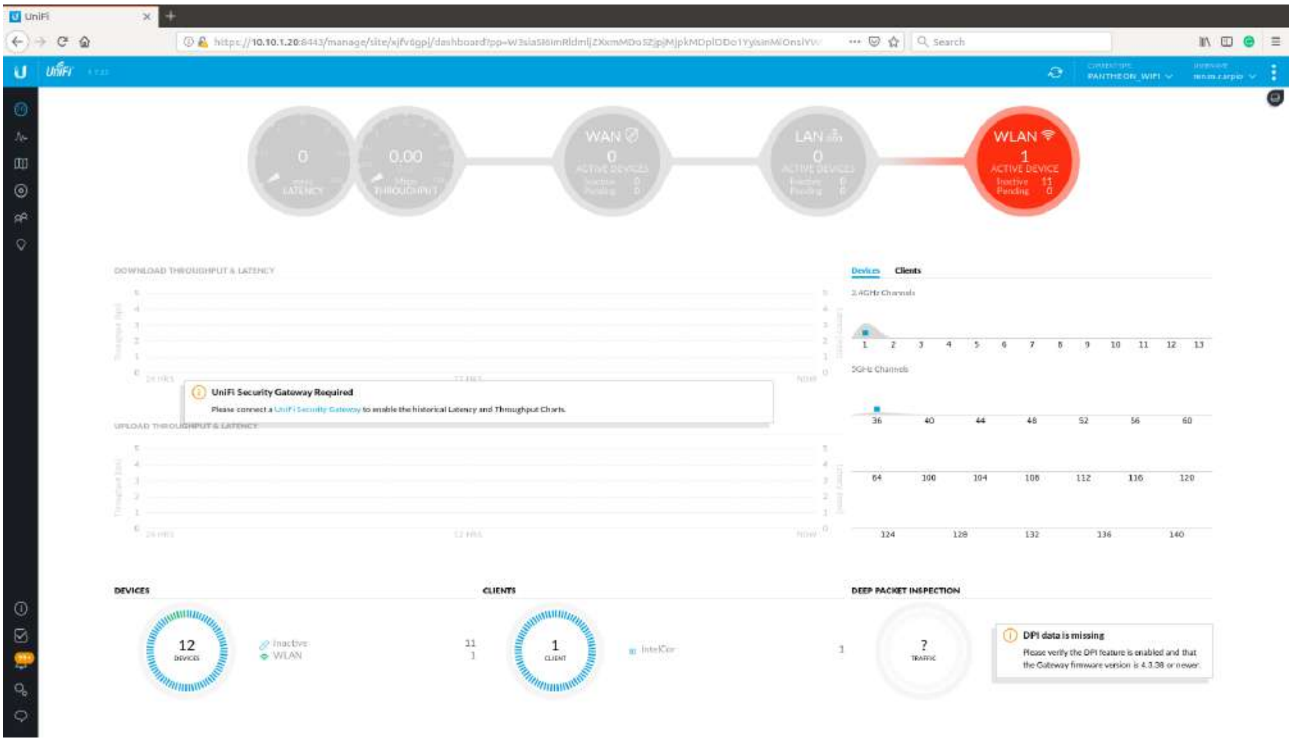

Figure 14 - UniFi Dashboard

The Statistics screen displayed in Figure 15 provides a visual representation of the clients connected to the network and the actual traffic on the network.

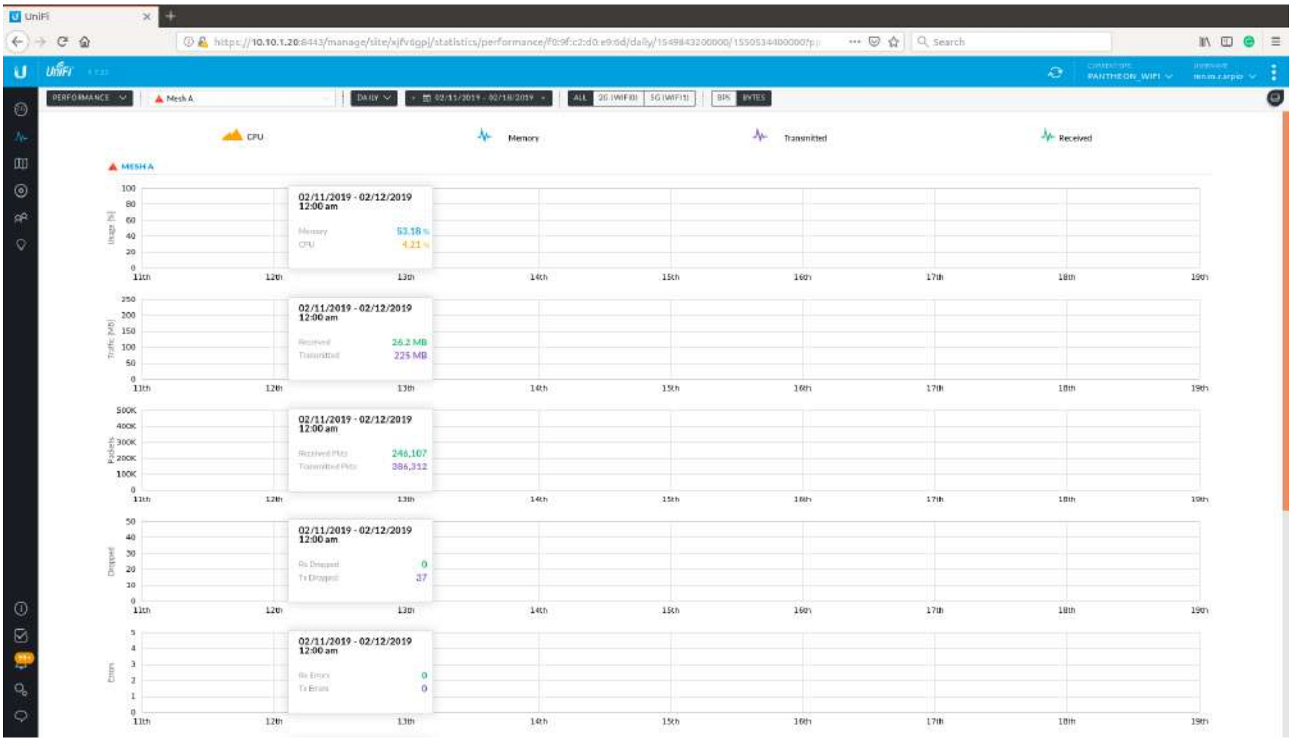

Figure 15 - UniFi Statistics

The Map screen depicted in Figure 16 allows to upload custom map images of desired location for a visual representation of the UniFi network, in our case our experimental field. It is also possible to enable the view of the system network topology. After having launched the UniFi Controller application, a default map could be displayed. The map scale is shown in the legend at the bottom of the map.

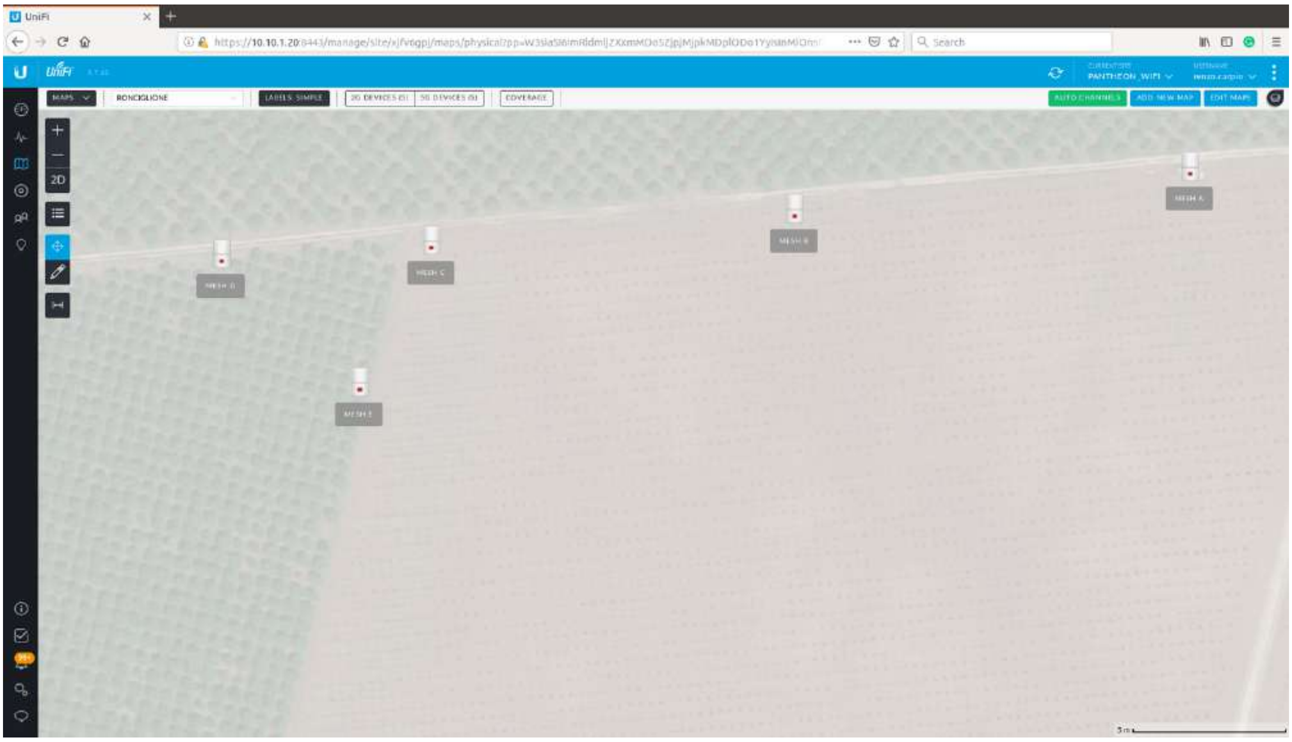

Figure 16 - UniFi Map

The Devices screen given in Figure 17 displays a list of UniFi devices discovered by the UniFi Controller.

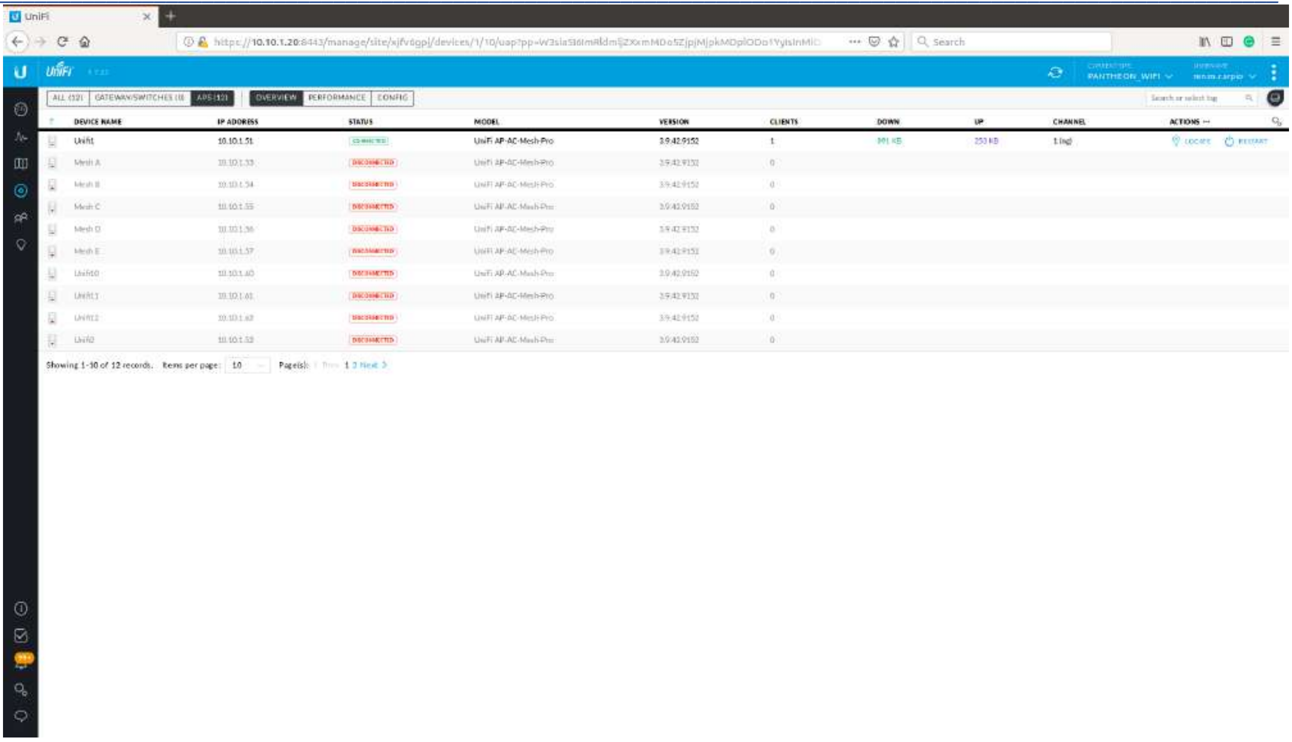

Figure 17 - UniFi Devices

The Clients screen of Figure 18 displays a list of network clients.

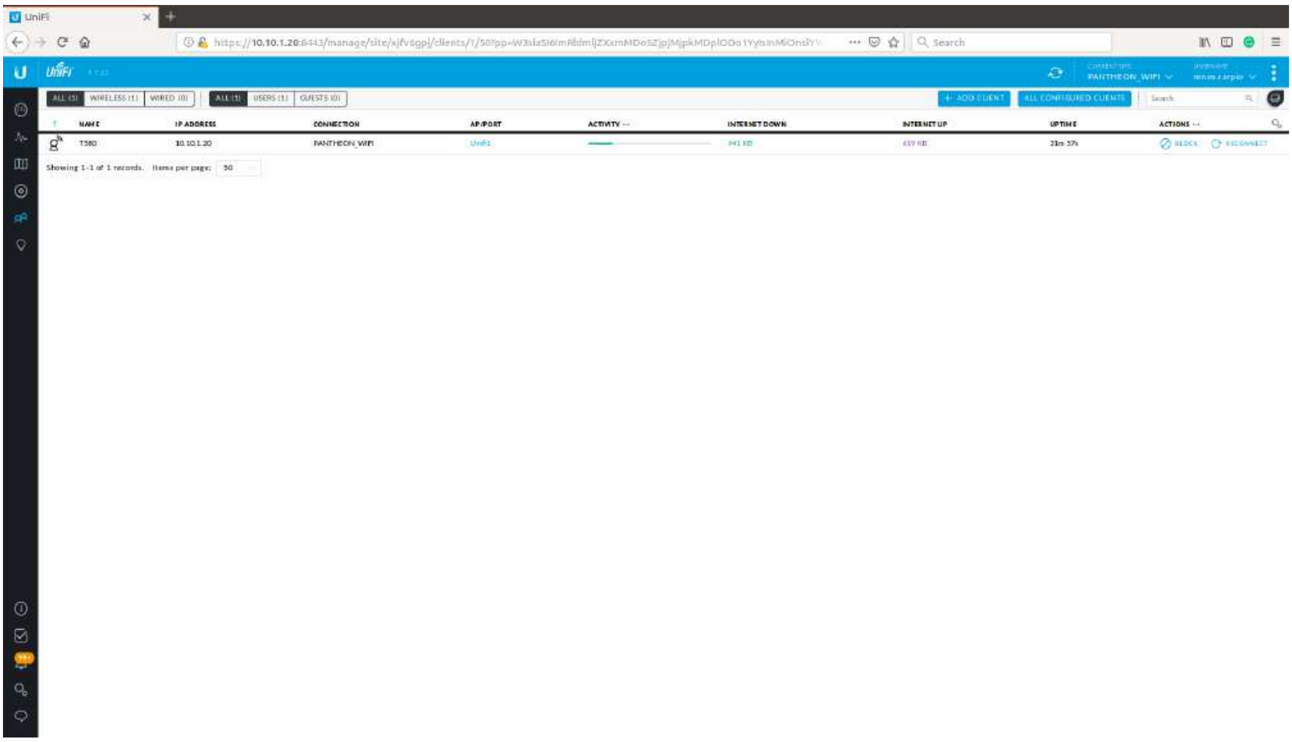

Figure 18 - UniFi Clients

The screen given Figure 19 shows the Insights page, displays different kinds of status information, e.g. Neighboring Access Point.

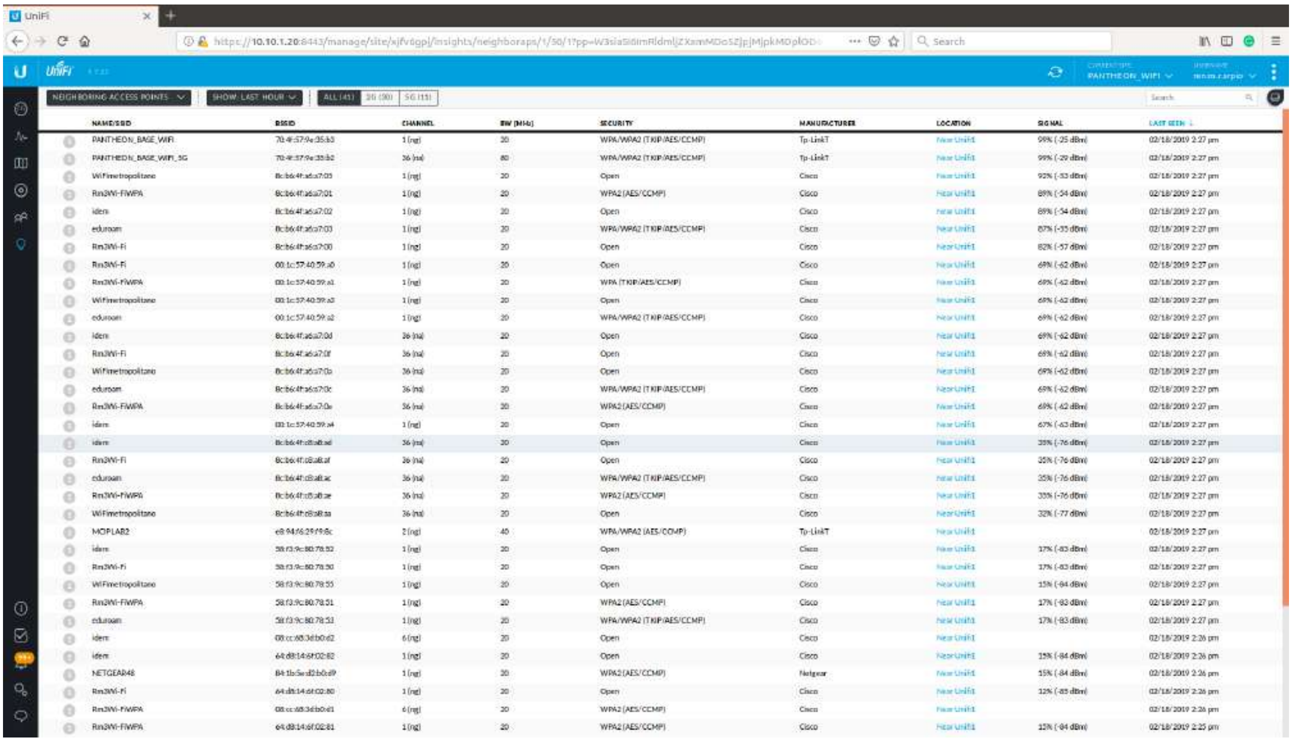

Figure 19 - UniFi Insights

3.1.2 Wireless Uplink

The UniFi Controller also supports wireless connection between UniFi devices by resorting to the concept of Wireless Uplink, which means that the connection among Mesh antennas is still a wireless connection, but it uses radio protocol to communicate instead of the Wi-Fi one. The working concepts is based on a “tree” structure whose root is called Base Station. As shown in Figure 20, when two antennas are connected, there is a “parent” which is the Uplink and a “child” which is the Downlink. This set-up allows to extend Wi-Fi coverage to inaccessible or no power areas, e.g. agricultural fields, since it is always possible to add new children, i.e., Mesh Antennas, to the tree. However, it should be noticed that the addition of new antennas implies an overall reduction of the network bandwidth each time the depth of the tree is increased. Any desired configuration and settings could be changed directly from UniFi Controller.

In the following, a brief description of Wireless Uplink components is provided:

- Base Station - Access point with a wired data connection that is configured to relay data to and from Mesh APs (Downlink AP).
- Mesh APs - Access point without wired data connection, that functions as a normal wired AP would by sending/receiving client data wirelessly to/from the base station, or an intermediate AP by use of the wireless uplink feature (the second option is only supported with UniFi Mesh product line as intermediate AP). Is sometimes also called “island” AP.
- Multi-hop Wireless Uplink - A deployment that uses a base station but has more than one level of wireless uplink with intermediate APs relaying data to and from the base station. When usingmultiple levels of APs, the uplink tiers can be referred to by root (base station), first hop, second hop, etc.

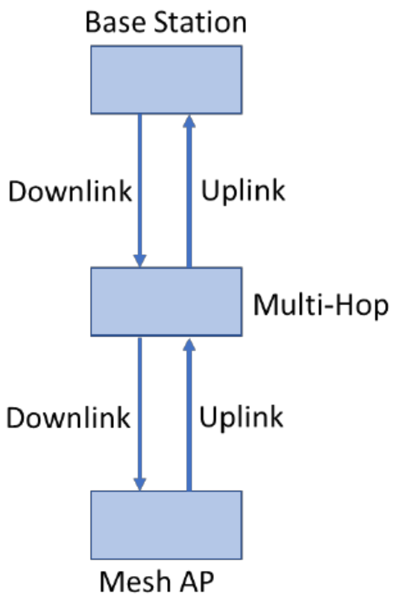

Figure 20 - Up/Downlink working concept

The Mesh network deployed in the experimental field is currently composed as follows. In particular, by taking Figure 2 as a reference, the Mesh Antenna A, which is placed near to the cabin of power grid, and which is directly wired connected to the industrial router, is the Base Station (root). Instead, the Mesh Antennas B and C are two Multi-hop Wireless Uplink since they are connected in cascade to the Base Station. Furthermore, the Mesh Antennas D and E, which are leaves of the tree, are labeled as Mesh Aps. Figure 21 provides a topological representation of such a tree structure.

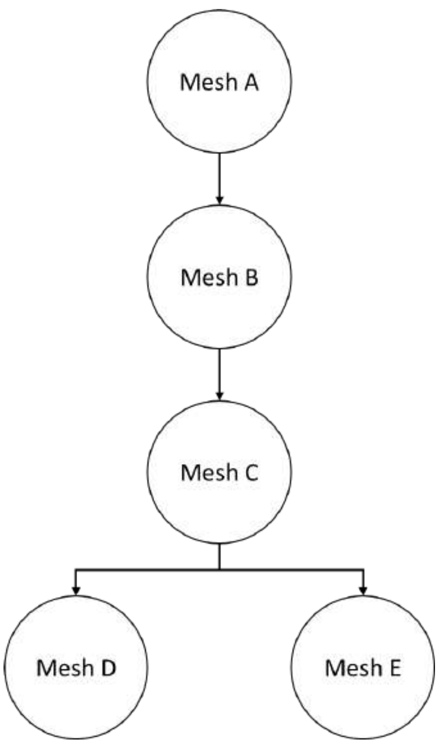

Figure 21 - Topological Map

3.2 AirOS 8

The Ubiquiti airMAX ac products work with a specific operating system called AirOS, which provides a built-in easy management interface through a web browser. Specifically, this build-in system offers the following wireless features:

- Access Point PtMP airMAX Mixed Mode
- airMAX ac Protocol Support
- Long-Range Point-to-Point (PtP) Link Mode
- Selectable Channel Width: 10/20/30/40/50/60/80 MHz
- (channel selection varies by product model)
- Automatic Channel Selection
- Transmit Power Control: Automatic/Manual
- Automatic Distance Selection (ACK Timing)
- Strongest WPA2 security

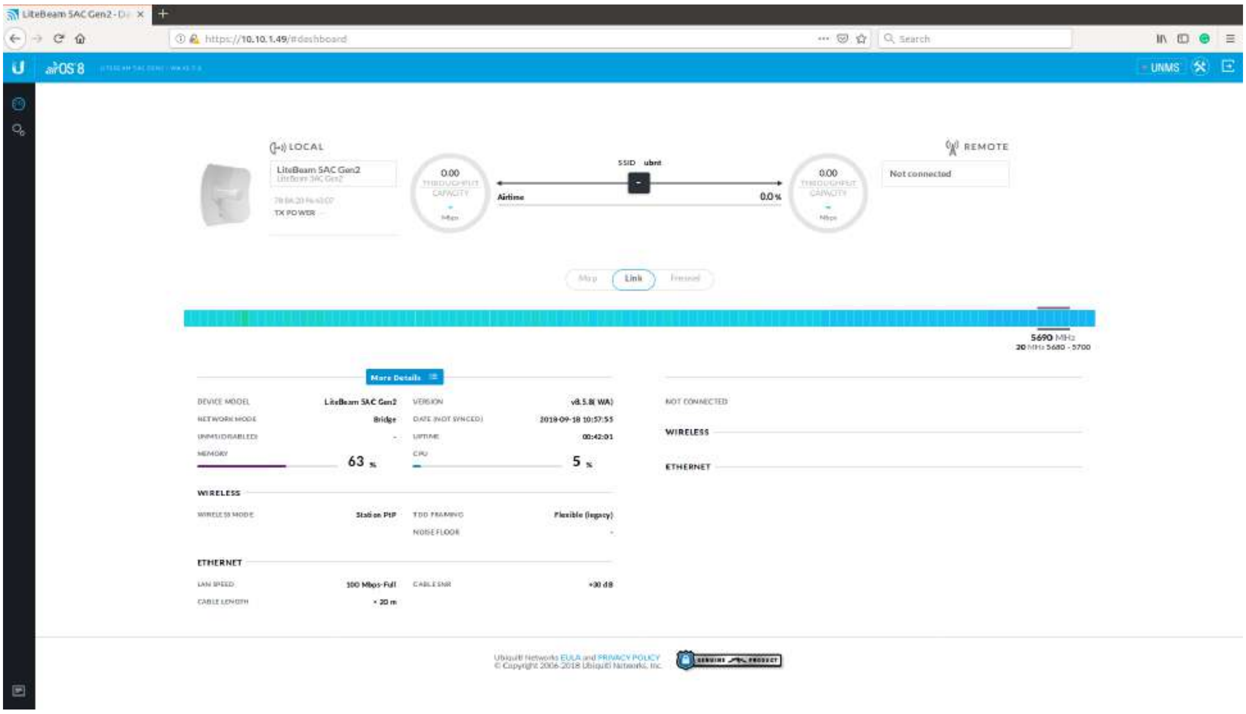

Figure 22 - AirOs8 Dashboard

The Dashboard page (Figure 22) provides a summary of the link status information, current values of the basic configuration settings (depending on the operating mode), network settings and information, and traffic statistics.

The Wireless tab contains everything needed to set up the wireless part of the link, including the wireless mode, SSID, channel and frequency, output power, data rates, and wireless security.

The Network tab allows to configure bridge or routing functionality and IP settings.

The Services page configures system management services: Ping Watchdog, SNMP, servers (web, SSH, Telnet), NTP, DDNS, system log, and device discovery.

The System page contains administrative options. This page enables the administrator to reboot the device, reset it to factory defaults, upload new firmware, back up or update the configuration, and configure the administrator account.

The AirMagic page displays the airMagic tool. Briefly, by using a dedicated co-processor, airOS 8 collects network-wide RF metrics to make real-time scheduling decisions. airMagic provides system-based spectrum analysis and recommends the top three channels based on spectral efficiency, capacity, and remote/local RF environment reporting.

3.2.1 Tools and alignment

The interface of AirOS also provides other tools and information, e.g. Alignment, Ping, Traceroute, Speed Test. Using the Antenna Align Tool, the network administrator could check the signal level and try to fix it moving manually the antennas. Figure 23 shows this tool with the relative panel.

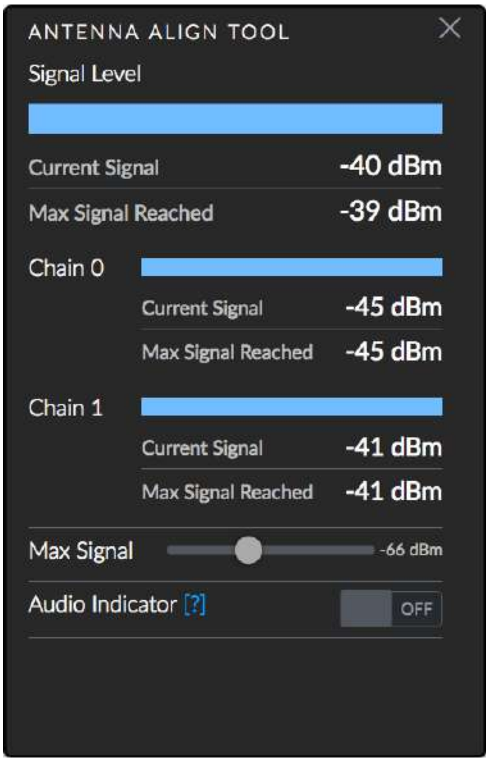

Figure 23 – Antenna Align Tool

After setting the optimal parameters, checking the signal level between two network devices and by assuming the alignment of the two antennas has been done successfully, a second antenna will appear on the right-hand side of the Dashboard, as shown in Figure 24.

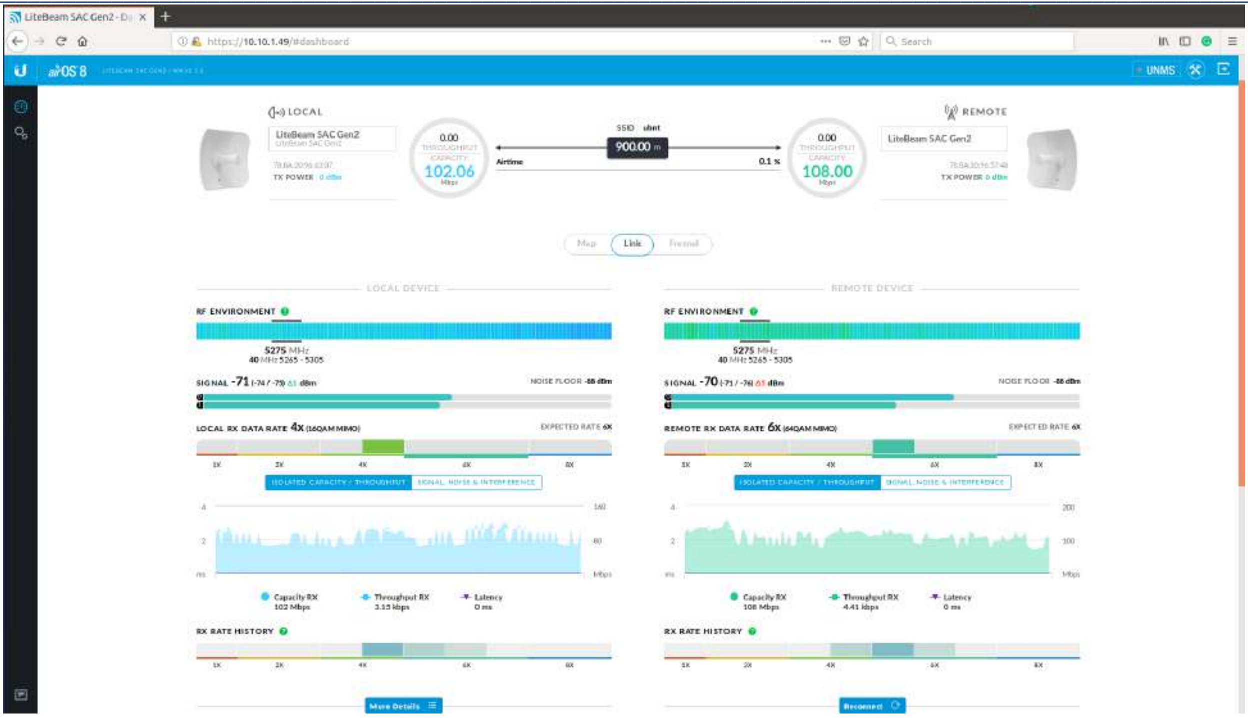

Figure 24 - AirOs 8 Dashboard Throughput

4 Experimental Validation

Several experiments have been carried out to evaluate the performances and the reliability of the WNB deployment. In particular, several indicators can be considered such as: i) RTT, ii) Latency, iii) Packet Loss, iv) Throughout, iv) Bandwidth and ROS rate. The following Sections are devoted to show in details such network indexes.

4.1 RTT, Latency and Packet Loss

In general, several indicators can be considered for evaluating the performance of a network, such as RTT, latency and packet loss.

RTT: The round-trip time (RTT) is the length of time it takes for a signal to be sent plus the length of time it takes for an acknowledgement of that signal to be received (i.e. coming back of the data), so:

$$RTT = T_{tx} + 2T_p$$

where T_{tx} is the transmission time and T_p the propagation time.

Latency: The latency is the network delay for getting a packet from point A to B, and the RTT is how long it takes a transmission to get from A to B and a response from B to A. Thus, it is not required to analyze both.

Packet Loss: Packet loss occurs when one or more packets of data travelling across a computer network fail to reach their destination, basically this parameter represents how reliable a network is.

In order to carry out an analysis of the RTT and packet loss under realistic working conditions, the WNB deployed in the experimental field was monitored while performing a typical ROS-based application involving interactions among different nodes, thus generating traffic over the network.

In the following, the results of the experiments carried out on Field 16 and Field 18 (see Figure 25), i.e. the fields selected for the experimental activities of the project as detailed in the Deliverable D2.1 "Requirements, Specifications and Benchmark", are proposed.

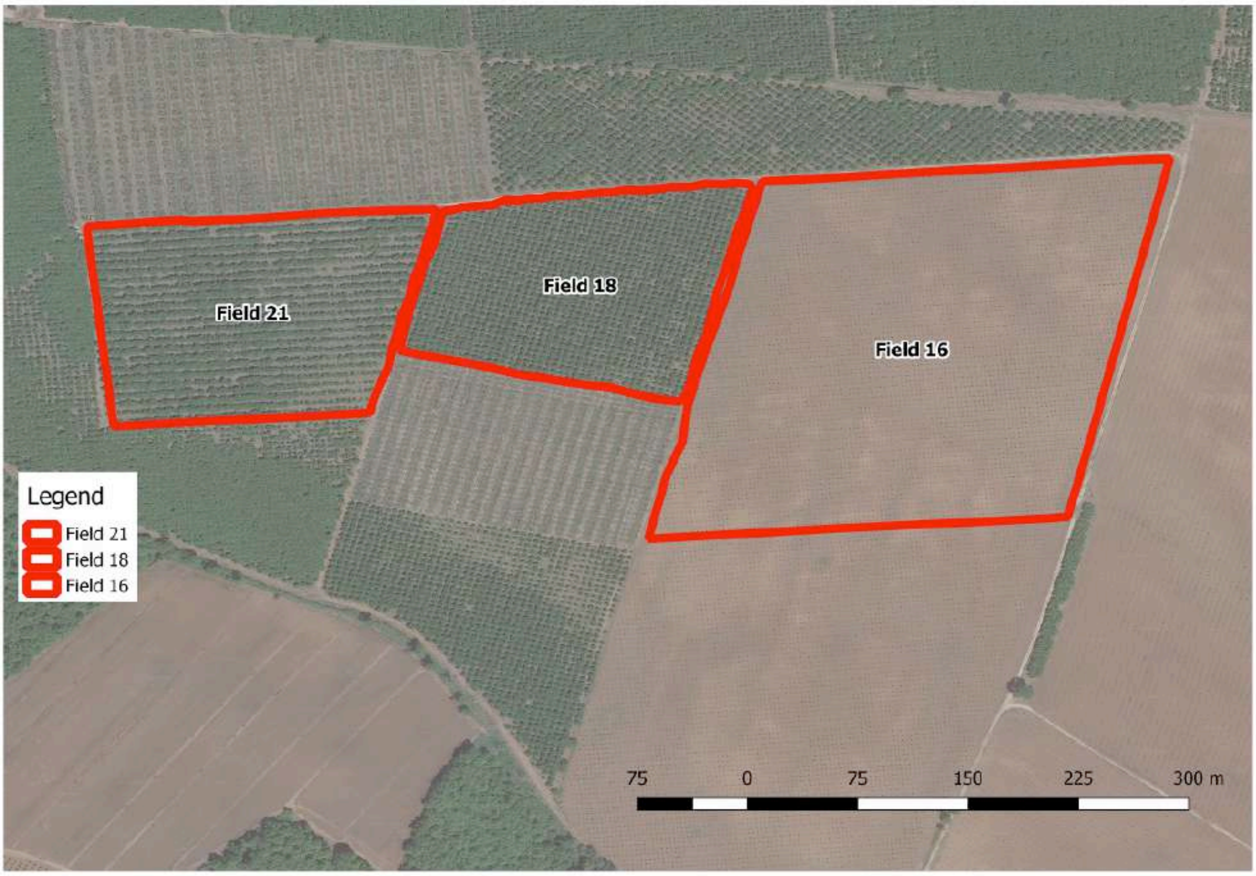

Figure 25 - Selected fields for the PANTHEON project

In particular, for the experimental validation, three different laptops (Linux-based) have been involved and located as described in Figure 26:

- The laptop "Master" which was moving inside the field to evaluate the coverage of the WNB.
- The laptop "Host 1" which was deployed near the antenna Mesh A to check only the behavior of the Multi-hop Wireless network.
- The laptop "Host 2" which was deployed inside the Warehouse to check the behavior of the entire network.

Figure 26 – Laptops location during RTT experimental test. The polygon describes the area where the "Master" was allowed to move

Table 1 and Table 2 show minimum, average, maximum and standard deviation (Std dev) of RTT for the experiments carried out respectively on Field 16 and Field 18.

From	To	Min	Average	Max	Std dev
Master	Host 1	3.790	11.787	135.968	13.475
Master	Host 2	3.607	9.995	176.496	12.756
Host 1	Master	3.736	15.650	396.651	35.331
Host 1	Host 2	2.503	6.877	112.166	10.965
Host 2	Master	3.459	9.459	127.225	9.454
Host 2	Host 1	2.404	6.563	111.968	10.762

Table 1 - RTT on Field 16

From	To	Min	Average	Max	Std dev
Master	Host 1	4.404	16.083	394.527	28.077
Master	Host 2	4.479	15.337	1882.720	69.309
Host 1	Master	4.658	16.085	472.122	24.236
Host 1	Host 2	2.544	7.074	152.176	12.652
Host 2	Master	4.382	15.525	1805.394	71.411
Host 2	Host 1	2.496	6.998	150.196	12.048

Table 2 - RTT on Field 18

Table 3 and Table 4 show respectively transmitted packets, received packets, packet loss and the total time to accomplish the whole transmission.

From	To	Packets transmitted	Packets received	Packet loss	Time(ms)
Master	Host 1	685	683	0%	684983
Master	Host 2	684	684	0%	683950
Host 1	Master	691	690	0%	691139
Host 1	Host 2	667	667	0%	681947
Host 2	Master	679	677	0%	679149
Host 2	Host 1	680	679	0%	680173

Table 3 - Packet loss on Field 16

From	To	Packets transmitted	Packets received	Packet loss	Time(ms)
Master	Host 1	865	860	0%	865293
Master	Host 2	865	864	0%	865202
Host 1	Master	744	744	0%	744247
Host 1	Host 2	848	845	0%	867286
Host 2	Master	730	724	0%	730328
Host 2	Host 1	730	730	0%	730221

Table 4 - Packet loss on Field 18

According to the collected data and by looking at the results proposed in the above Tables, the following considerations can be drawn:

- The deployed WNB is a reliable network as the packet loss is less than 1%;
- The long-range point-to-point communication is a very reliable communication link;
- The Multi-hop Wireless network can represent (sometimes) the bottleneck of the network.

4.2 Throughput

The network throughput is defined as the rate of successful message delivery over a communication channel. It is usually measured in bit per second (bit/s) or in data packets per second (p/s). In this case the throughput has been measured using FileZilla, which uses Secure File Transfer Protocol (SFTP).

Two experiments have been conducted to evaluate the network throughput using three laptops, as shown in Figure 27. In particular the first experimental test, which involved the “Host 1” laptop and the “Host 2” laptop, was focused on the evaluation of the long-range point-to-point communication channel, while the second experimental test, which involved instead the “Host 1” laptop and the “Master” laptop, was focused on the evaluation of the multi-hop Mesh network.

Figure 27 - Position of laptops during Throughput experimental validation

Figure 28 shows the first experimental test where the laptop “Host 1” acted as SFTP server and the laptop “Host 2” acted as SFTP client. In particular, it can be noticed that this segment of network has very good performances, indeed the download speed was stably about 3.2 MB/s on FileZilla GUI with a throughput of 27.4 Mbps on AirOs 8.

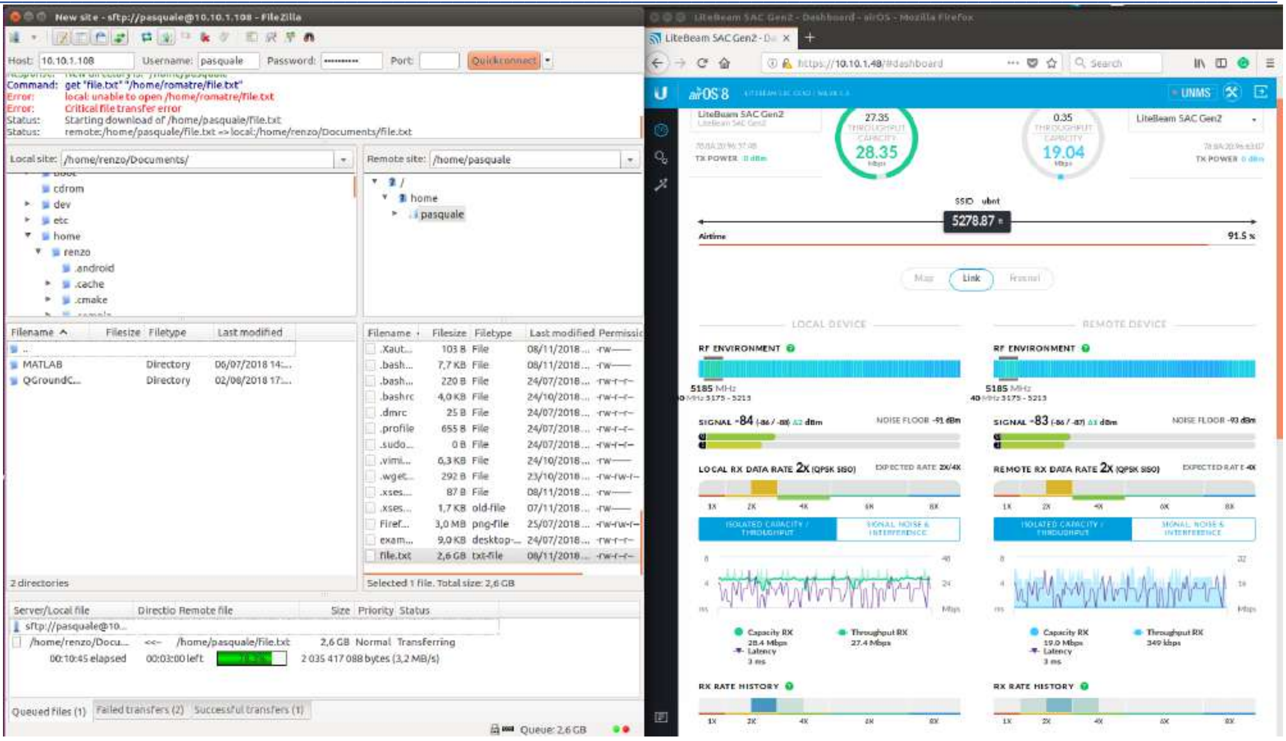

Figure 28 - Throughput from Host 1 to Host 2

Figure 29 shows the second experimental test where the laptop “Master” acted as SFTP server and the laptop “Host 2” acted as SFTP client. In particular, it can be noticed that the bottleneck, in term of throughput, is the Multi-Hop Wireless Network, indeed the download speed was 137.9 KB/s on FileZilla GUI, and RTT/latency quite high. This indicates that the traffic over the Mesh network should be reduced to the strict necessary in order to guarantee overall good performances. As a matter of fact, this indication will be taken into account when designing the ROS architecture and in particular this will be considered to decide whether a multi-master paradigm should be considered in ROS.

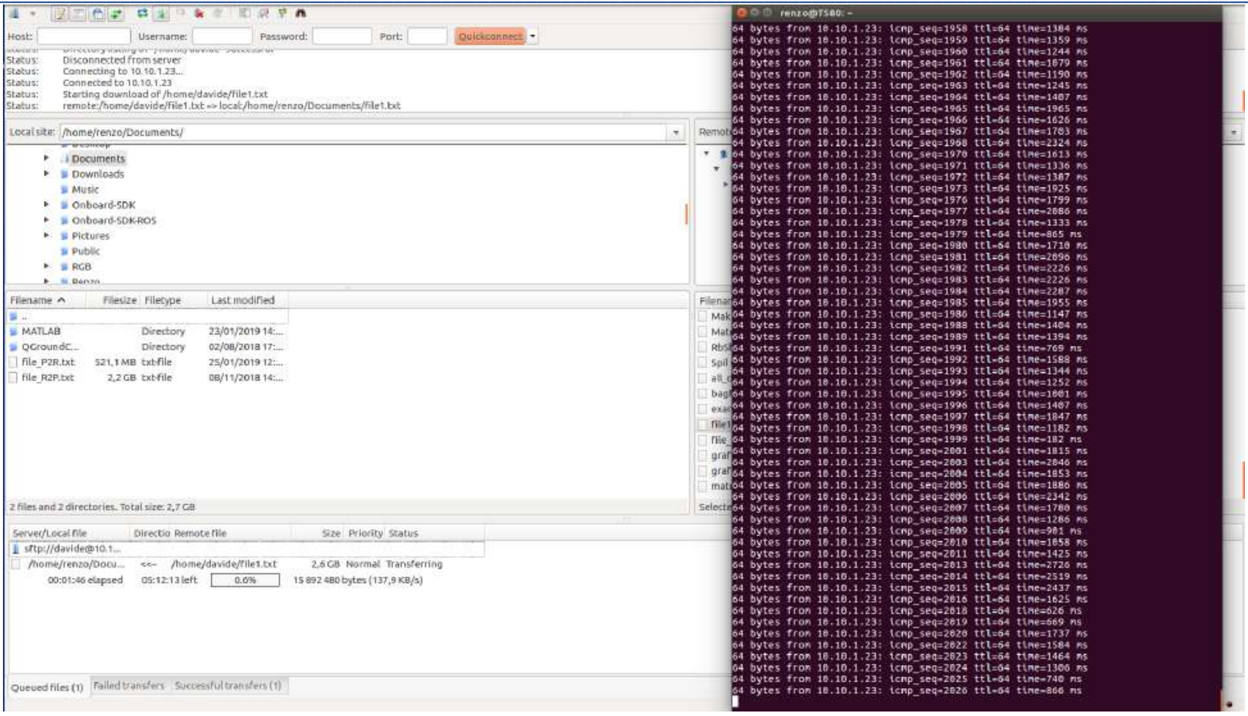

Figure 29 - Throughput from Master to Host 2

4.3 ROS Performance Validation –Bandwidth and Rate

In order to evaluate the operation of the Multi-hop Wireless and long-range point-to-point connection under a realistic scenario, a basic behavior of a robotic platform moving in the field has been simulated through the laptops by resorting to the ROS environment. Briefly, this has been achieved by generating a typical ROS data flow as the one that would be required to have a robotic platform moving within the field. In particular, the list of ROS topic involved in the experiments with relative message, structure, type and rate associate to get a reference for all data on the network is given in the following:

- /fix
    - Rate: 20Hz
    - Type: sensor_msgs/NavSatFix
        - uint8 COVARIANCE_TYPE_UNKNOWN=0
        - uint8 COVARIANCE_TYPE_APPROXIMATED=1
        - uint8 COVARIANCE_TYPE_DIAGONAL_KNOWN=2
        - uint8 COVARIANCE_TYPE_KNOWN=3
        - std_msgs/Header header
            - uint32 seq
            - time stamp
            - string frame_id
        - sensor_msgs/NavSatStatus status
            - int8 STATUS_NO_FIX=-1
            - int8 STATUS_FIX=0
            - int8 STATUS_SBAS_FIX=1
            - int8 STATUS_GBAS_FIX=2
            - uint16 SERVICE_GPS=1
            - uint16 SERVICE_GLONASS=2

                - uint16 SERVICE_COMPASS=4
                - uint16 SERVICE_GALILEO=8
                - int8 status
                - uint16 service
            - float64 latitude
            - float64 longitude
            - float64 altitude
            - float64[9] position_covariance
            - uint8 position_covariance_type
- /gps
    - Rate: 20Hz
    - Type: nav_msgs/Odometry
        - std_msgs/Header header
            - uint32 seq
            - time stamp
            - string frame_id
        - string child_frame_id
        - geometry_msgs/PoseWithCovariance pose
            - geometry_msgs/Pose pose
                - geometry_msgs/Point position
                    - float64 x
                    - float64 y
                    - float64 z
                - geometry_msgs/Quaternion orientation
                    - float64 x
                    - float64 y
                    - float64 z
                    - float64 w
            - float64[36] covariance
        - geometry_msgs/TwistWithCovariance twist
            - geometry_msgs/Twist twist
                - geometry_msgs/Vector3 linear
                    - float64 x
                    - float64 y
                    - float64 z
                - geometry_msgs/Vector3 angular
                    - float64 x
                    - float64 y
                    - float64 z
            - float64[36] covariance
- /cmd_vel
    - Rate: 20Hz
    - Type: geometry_msgs/Twist
        - geometry_msgs/Vector3 linear
            - float64 x
            - float64 y
            - float64 z
        - geometry_msgs/Vector3 angular
            - float64 x

            - float64 y
            - float64 z
- /tf
    - Rate: 11Hz
    - Type: tf2_msgs/TFMessage
        - geometry_msgs/TransformStamped[] transforms
        - std_msgs/Header header
            - uint32 seq
            - time stamp
            - string frame_id
        - string child_frame_id
        - geometry_msgs/Transform transform
            - geometry_msgs/Vector3 translation
                - float64 x
                - float64 y
                - float64 z
            - geometry_msgs/Quaternion rotation
                - float64 x
                - float64 y
                - float64 z
                - float64 w
- /diagnostics
    - Rate: 1Hz
    - Type: diagnostic_msgs/DiagnosticArray
        - std_msgs/Header header
            - uint32 seq
            - time stamp
            - string frame_id
        - diagnostic_msgs/DiagnosticStatus[] status
            - byte OK=0
            - byte WARN=1
            - byte ERROR=2
            - byte STALE=3
            - byte level
            - string name
            - string message
            - string hardware_id
            - diagnostic_msgs/KeyValue[] values
                - string key
                - string value
- /tcptime_ref
    - Rate: 20Hz
    - Type: sensor_msgs/TimeReference
        - std_msgs/Header header
            - uint32 seq
            - time stamp
            - string frame_id
        - time time_ref
        - string source

As mentioned before, the above topics represent a subset of the topics that could be active during basic operations of the robots. In particular, the /fix topic is produced by the RTK-DGPS node, and it represents the main data to validate the quality of the GPS coverage within the experimental field. The /gps topic contains Odometry messages generated from /fix topic. The /cmd_vel is a virtual velocity for a robot produced by an emulator. The /tf topic maintains the relationship between coordinate frames in a tree structure, and in this case is composed by two different set of messages that are published at 10Hz and 1Hz. The /diagnostics and /tcptime_ref are auxiliary topics used by the ROS package mapviz which have been considered only to generate additional traffic to the network (in order to consider a sort of worst-case scenario).

Sub-section 4.3.1 and 4.3.2 show the obtained results for the experiments concerning the network coverage of the Field 16 and Field 18. It should be noticed that as a byproduct the collected data also allows to verify the quality of the RTK-DGPS localization the robots are equipped with, as a bad network coverage would result in a shortage of RTK-DGPS correction messages due to packet loss, thus leading to a bad reconstruction of the path “walked” by the robots.

The experiments focused on a comparison between the bandwidth and the rate of ROS messages received by three different machines deployed in the field as shown in Figure 30. The different laptops were used for the experiments:

- The laptop “Master” which was moving within the field in order to mimic the behavior of a ground robot;
- The laptop “Host 1”, which was deployed near the Mesh Antenna A, was dedicated to check the behavior of the Multi-hop Wireless network;
- The laptop “Host 2”, which was deployed inside the Warehouse, was dedicated to check the behavior of the entire network.

It should be noticed that the laptop “Master” had several active ROS nodes while moving. In particular, among the others a localization node was active which is capable of producing odometric information by integrating the data coming from the GPS antenna with the RTK-DGPS correction messages which were sent over the WNB by a base-station.

Figure 30 - Laptops location during ROS experiments. The polygon describes the area where the “Master” was allowed to move

4.3.1 ROS experiments on Field 16

Figure 31 shows the path covered by the laptop “Master” during its motion within the Field 16, where data has been generated from the topic /fix. It should be noticed that in this case the data was produced and consumed directly by the “Master”, thus no traffic was generated over the WNB, since the Linux IPC architecture was used instead. For this reason, in this case, no packet loss is experienced and thus the data collected from the “Master” can be used as a reference for the experiment.

Figure 31 - Path on the Field 16 recorded by Master

In addition, Figure 32 and Figure 33 show the same path covered by the laptop “Master” during the motion within the Field 16, but in this case the data was produced by the topic /fix on the “Master” while it was consumed by the “Host 1” and the “Host 2”. It should be noticed that even though there were a few points where messages were not received, overall the packet lost could be considered negligible. Moreover, it should also be mentioned that in a real case, where a robot would move within the field, both the producer (/fix) and consumer (some ROS nodes) would be on the same machine, thus minimizing any risk of packet loss and any risk of bad reconstruction of the path “walked” by the robots.

Figure 32 - Path on the Field 16 recorded by Host 1

Figure 33 - Path on the Field 16 recorded by Host 2

Bandwidth

As far as the bandwidth of the ROS messages is concerned, the outcome of the experiments is shown in the following tables. Specifically, the Average value was calculated on a number of samples equal to the Window value, and since the size of ROS messages does not change over time, the Mean, Min and Max value result to be always the same. In particular, Table 5 shows the reference of the bandwidth as computed by the "Master" where the data is both produced and consumed (with no packet lost since all packets are local to the same machine). Table 6 and Table 7 allows to evaluate the actual behavior of network as the indicators are computed from packets which have been actually transmitted over the network and the bandwidth has been recorded from "Host 1" and "Host 2". In this regard it can be noticed that the obtained results are consistent with the reference values shown in Table 5.

Machine	Topic	Average	Mean	Min	Max	Window
Master	/fix	2.5KB/s	0.12KB	0.12KB	0.12KB	100
Master	/gps	14.64KB/s	0.72KB	0.72KB	0.72KB	100
Master	/cmd_vel	967.31B/s	48.00B	48.00B	48.00B	100
Master	/tf	1.00KB/s	0.09KB	0.09KB	0.10KB	100
Master	/diagnostics	189.23B/s	188.00	188.00B	188.00	100
Master	/tcptime_ref	928.94B/s	46.00B	46.00B	46.00B	100

Table 5 - Bandwidth of Master on Field 16

Machine	Topic	Average	Mean	Min	Max	Window
Host 1	/fix	2.5KB/s	0.12KB	0.12KB	0.12KB	100
Host 1	/gps	14.52KB/s	0.72KB	0.72KB	0.72KB	100
Host 1	/cmd_vel	965.18B/s	48.00B	48.00B	48.00B	100
Host 1	/tf	1.00KB/s	0.09KB	0.09KB	0.10KB	100
Host 1	/diagnostics	189.19B/s	188.00	188.00B	188.00	100
Host 1	/tcptime_ref	924.52B/s	46.00B	46.00B	46.00B	100

Table 6 - Bandwidth of Host 1 on Field 16

Machine	Topic	Average	Mean	Min	Max	Window
Host 2	/fix	2.5KB/s	0.12KB	0.12KB	0.12KB	100
Host 2	/gps	14.63KB/s	0.72KB	0.72KB	0.72KB	100
Host 2	/cmd_vel	966.59B/s	48.00B	48.00B	48.00B	100
Host 2	/tf	1.00KB/s	0.09KB	0.09KB	0.10KB	100
Host 2	/diagnostics	188.32B/s	188.00	188.00B	188.00	100
Host 2	/tcptime_ref	923.16B/s	46.00B	46.00B	46.00B	100

Table 7 - Bandwidth of Host 2 on Field 16

Rate of ROS messages

Regarding the rate of ROS messages, the outcome of the experiments is shown in the following tables. Similar to the previous experiment, Average value still depends on the Window samples. Min, Max values indicated the minimum and maximum time required to receive the next message and Std dev indicated the related standard deviation. Table 8 shows the reference of real rate where it should be noticed that the Min value of the topic /tf is too small. This can be explained by the overlap of the 10Hz messages and the 1Hz messages, which are published on the same topic and this fact renders this measurement inaccurate. Table 9 and Table 10 show the effective behavior of the network in term of the rate of ROS messages as again in this case the indicators are computed from packets which have been actually transmitted over the network. In particular, these tables highlight that the ROS rate recorded from "Host 1" and "Host 2" are consistent with the reference values shown in Table 8.

Machine	Topic	Average	Min	Max	Std dev	Window
Master	/fix	19.999	0.041s	0.060s	0.00333s	500
Master	/gps	19.999	0.042s	0.062s	0.00324s	500
Master	/cmd_vel	19.999	0.048s	0.052s	0.00058s	500
Master	/tf	10.992	0.001s	0.101s	0.02548s	516
Master	/diagnostics	0.998	1.000s	1.003s	0.00042s	100
Master	/tcptime_ref	20.000	0.040s	0.061s	0.00343s	500

Table 8 - Rate of Master on Field 16

Machine	Topic	Average	Min	Max	Std dev	Window
Host 1	/fix	19.999	0.000s	0.888s	0.04166s	500
Host 1	/gps	19.999	0.000s	0.086s	0.01656s	501
Host 1	/cmd_vel	19.999	0.026s	0.068s	0.00377s	500
Host 1	/tf	10.991	0.000s	0.328s	0.03426s	509
Host 1	/diagnostics	0.998	0.983s	1.020s	0.00448s	100
Host 1	/tcptime_ref	19.998	0.028s	0.072s	0.00584s	500

Table 9 - Rate of Host 1 on Field 16

Machine	Topic	Average	Min	Max	Std dev	Window
Host 2	/fix	19.991	0.030s	0.070s	0.00499s	500
Host 2	/gps	19.979	0.000s	0.096s	0.01701s	500
Host 2	/cmd_vel	19.999	0.000s	0.494s	0.03326s	500
Host 2	/tf	10.989	0.000s	0.212s	0.02370s	506
Host 2	/diagnostics	0.998	0.874s	1.130s	0.01854s	100
Host 2	/tcptime_ref	19.997	0.032s	0.074s	0.00555s	500

Table 10 - Rate of Host 2 on Field 16

4.3.2 ROS experiments on Field 18

In this section, similarly to Section 4.3.1, the outcome of the experiments carried out within the Field 18 is reported.

In particular, Figure 34 shows the path covered by the laptop “Master” during its motion within the Field 18, where data has been generated from the topic /fix. It should be noticed that also this case the data was produced and consumed directly by the “Master”, thus no traffic was generated over the WNB, since the Linux IPC architecture was used instead. For this reason, in this case no packet loss is experienced and thus the data collected from the “Master” can be used as a reference for the experiment.

Figure 34 - Path on the Field 18 recorded by Master

Figure 35 and Figure 36 show the same path covered by the laptop "Master" during the motion within the Field 18, but as for the previous experiment in this case the data was produced by the topic /fix on the "Master" while it was consumed respectively by the "Host 1" and the "Host 2".

Figure 35 - Path on the Field 18 recorded by Host 1

Figure 36 - Path on the Field 18 recorded by Host 2

Bandwidth

Table 11 shows the reference of bandwidth. Table 12 and Table 13 show instead the effective behavior of network in term of bandwidth. As for the previous experimental test on Field 16, these tables highlight that the bandwidth recorded from "Host 1" and "Host 2" is consistent with the reference value shown in Table 11 also for the experiment carried out within Field 18.

Machine	Topic	Average	Mean	Min	Max	Window
Master	/fix	2.52KB/s	0.12KB	0.12KB	0.12KB	100
Master	/gps	14.57KB/s	0.72KB	0.72KB	0.72KB	100
Master	/cmd_vel	964.81B/s	48.00B	48.00B	48.00B	100
Master	/tf	1.01KB/s	0.09KB	0.09KB	0.10KB	100
Master	/diagnostics	189.30B/s	188.00	188.00B	188.00	100
Master	/tcptime_ref	928.06B/s	46.00B	46.00B	46.00B	100

Table 11 - Bandwidth of Master on Field 18

Machine	Topic	Average	Mean	Min	Max	Window
Host 1	/fix	2.51KB/s	0.12KB	0.12KB	0.12KB	100
Host 1	/gps	14.56KB/s	0.72KB	0.72KB	0.72KB	100
Host 1	/cmd_vel	962.52B/s	48.00B	48.00B	48.00B	100
Host 1	/tf	998.21B/s	90.72B	90.00KB	98.00B	100
Host 1	/diagnostics	188.59B/s	188.00	188.00B	188.00	100
Host 1	/tcptime_ref	922.48B/s	46.00B	46.00B	46.00B	100

Table 12 - Bandwidth of Host 1 on Field 18

Machine	Topic	Average	Mean	Min	Max	Window
Host 2	/fix	2.52KB/s	0.12KB	0.12KB	0.12KB	100

Host 2	/gps	14.55KB/s	0.72KB	0.72KB	0.72KB	100
Host 2	/cmd_vel	964.94B/s	48.00B	48.00B	48.00B	100
Host 2	/tf	1.01KB/s	0.09KB	0.09KB	0.10KB	100
Host 2	/diagnostics	187.80B/s	188.00	188.00B	188.00	100
Host 2	/tcptime_ref	926.12B/s	46.00B	46.00B	46.00B	100

Table 13 - Bandwidth of Host 2 on Field 18

Rate of ROS messages

Table 14 shows the reference of rate. Table 15 and Table 16 show the effective behavior of network in term of rate. As for the previous experimental test on Field 16, these tables highlight that the ROS rate recorded from "Host 1" and "Host 2" are consistent with the reference value shown in Table 14 also for the experiment carried out within Field 18.

Machine	Topic	Average	Min	Max	Std dev	Window
Master	/fix	19.999	0.040s	0.061s	0.00335s	500
Master	/gps	20.001	0.042s	0.063s	0.00303s	500
Master	/cmd_vel	20.001	0.048s	0.052s	0.00060s	500
Master	/tf	10.992	0.000s	0.102s	0.02402s	516
Master	/diagnostics	0.998	1.001s	1.003s	0.00046s	100
Master	/tcptime_ref	19.999	0.040s	0.061s	0.00340s	500

Table 14 - Rate of Master on Field 18

Machine	Topic	Average	Min	Max	Std dev	Window
Host 1	/fix	19.999	0.000s	0.233s	0.01077s	501
Host 1	/gps	19.988	0.000s	0.104s	0.01694s	500
Host 1	/cmd_vel	19.997	0.026s	0.095s	0.00479s	500
Host 1	/tf	10.992	0.000s	0.125s	0.02659s	506
Host 1	/diagnostics	0.998	0.796s	1.240s	0.03234s	100
Host 1	/tcptime_ref	19.998	0.024s	0.086s	0.00670s	500

Table 15 - Rate of Host 1 on Field 18

Machine	Topic	Average	Min	Max	Std dev	Window
Host 2	/fix	19.999	0.000s	0.239s	0.01288s	500
Host 2	/gps	20.001	0.000s	0.086s	0.01743s	500
Host 2	/cmd_vel	20.001	0.048s	0.172s	0.01459s	500
Host 2	/tf	10.990	0.000s	0.132s	0.02598s	506
Host 2	/diagnostics	0.998	0.983s	1.019s	0.00448s	100
Host 2	/tcptime_ref	19.998	0.000s	1.892s	0.09162s	500

Table 16 - Rate of Host 2 on Field 18