A Multi-Tenant SDN Architecture for Network Deployment Using a Wi-Fi HaLow-based IEEE 802.11s Mesh

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***Abstract*—This paper presents a new application of the IEEE 802.11ah standard, commonly called Wi-Fi HaLow, for the configuration of networks through Software-Defined Networking (SDN). The proposed architecture aims to leverage the flexibility of SDN to configure and monitor network equipment in a dedicated autonomous Wi-Fi HaLow network using an IEEE 802.11s mesh topology. In this way, this technology and topology increase the control range of the network, thus providing better redundancy of the network while being able to provide enough speed for several current use cases, including real-time IoT solutions where the data volume is higher. The system uses a multi-tenant architecture with Wi-Fi HaLow devices and permits the dynamic configuration of several production networks through a single separated configuration network. The prototype of the proposed architecture and mesh connection tests were implemented using devices with the Newracom 7292 chipset. The prototype was employed for functional tests, while mesh connection tests were conducted to evaluate range and bitrate. The results show that the network is capable of efficiently handling low-to-moderate data traffic at a distance as large as 1.1 km in an indoor environment, showing great flexibility and long-range connectivity through mesh networking.**

***Index Terms*—Wi-Fi HaLow, IEEE 802.11ah, SDN, IEEE 802.11s, mesh, multi-tenant, network configuration.**

I. Introduction

The advent of Software-Defined Networking (SDN) has enabled configuring, managing and programming networks remotely. In this architectural configuration, the control plane is physically separated from the data plane. Consequently, it is of particular interest to study the different technologies that can be used in the control plane.

In light of the aforementioned considerations, we propose the utilisation of Wi-Fi HaLow, a technology that operates in unlicensed sub-GHz bands. This technology is theoretically capable of achieving throughputs between 150 kbps and 86.7 Mbps [1] within a radius of 1 Km. This technology enables the connection of 8191 stations (STA) per access point (AP) [2], thereby facilitating Internet Protocol (IP) communication.

This article proposes an architecture based on the concept of SDN to allow network devices to be configured programmatically and centrally via an autonomous network, which is separate from the production network. This results in a physical separation between the data plane and control plane. The architecture presented in this study employs a Wi-Fi HaLow-based IEEE 802.11s mesh. This approach allows for configuring a large number of devices over long ranges while providing enhanced security and redundancy. The control plane has a dedicated physical network, ensuring that a failure in the production network does not affect the control network. This separation guarantees the security and reliability of the configuration process. Furthermore, this approach facilitates the configuration and monitoring of large, poorly structured networks or those requiring highly dynamic configurations, whether wired or wireless.

This work makes the following contributions:

- **New Application of IEEE 802.11ah**: Introduces a new application of the IEEE 802.11ah standard (Wi-Fi HaLow) by using the concept of SDN to configure network devices via an independent network based on Wi-Fi HaLow.
- **Infrastructure Improvement**: Leverages an IEEE 802.11s-based mesh network infrastructure to enhance the flexibility and range of the Wi-Fi HaLow solution.
- **Multi-Tenant Architecture**: By proposing a multi-tenant architecture using Wi-Fi HaLow devices, the approach enables the dynamic configuration of multiple production networks through a single, dedicated configuration network.
- **Mesh tests**: Range and bitrate tests of mesh connections using Wi-Fi HaLow were conducted in an urban scenario.

The document is organised as follows: Section II introduces the main concepts used in developing the solution: Wi-Fi HaLow, Software-Defined Networking, and IEEE 802.11s. Section III reviews related work pertinent to the proposed architecture. Sections IV and V detail the proposed architecture and the solution built upon it, respectively. In Section VI, the range and bitrate of outdoor connections in mesh mode were evaluated and the results presented . Finally, Section VII summarises the conclusions drawn from this work and suggests directions for future research.

II. Background

A. Wi-Fi HaLow

The IEEE 802.11ah standard, also known as Wi-Fi HaLow [3], was officially launched in 2016 [4]. It operates in unlicensed frequency bands below 1 GHz, which enables long-

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distance signal propagation and offers excellent transmission and diffraction rates through obstacles [3]. This technology's primary features include high data throughput, ranging from 150 kbps to 86.7 Mbps [1], and high energy efficiency, with a 500 mAh battery capable of operating for up to 3.15 years [5]. It can also connect up to 8191 STAs per AP within a 1 km coverage radius [2].

Due to these characteristics, IEEE 802.11ah has been standardised for IoT applications that require low cost, low power consumption, and long-range communication [3]. To achieve these capabilities, modifications were made to the physical layer (PHY) and the medium access control layer (MAC) compared to previous Wi-Fi standards [3].

Channel bandwidths are based on a tenfold down-clocked version of the IEEE 802.11ac standard modes [4]. By reducing the clock frequency, the operating frequency is lowered without changing system parameters [3]. Channels with bandwidths of 1, 2, 4, 8, and 16 MHz are supported, and devices must support 1 and 2 MHz to comply with IEEE 802.11ah [4]. In terms of channels, wider bandwidth offers higher data throughput but shorter range, and vice versa [5].

B. Software-Defined Networking

SDN specifies the physical separation between the control plane and data plane, which are managed logically, centrally, and programmatically [6]. Management external to the devices, along with abstract representation of network infrastructure, allows for quicker provisioning, management, and programming during configuration and operation [7].

The SDN architecture consists of three layers: the application layer (where the application plane is located), the control layer (where the control plane is located), and the infrastructure layer (where the data plane is located). These layers communicate via northbound and southbound Application Programming Interface (API) [8], [9].

C. IEEE 802.11s

The IEEE 802.11s standard is an appendix to the IEEE 802.11 standard. It was developed by the Task Group S starting in 2004 to extend WLAN range, enabling low-cost data transfer networks with wide coverage using unlicensed bands. Unlike many other Wireless Mesh Networks (WMN), which use the IP layer for multi-hop communication and are not inherently dependent on wireless technology, the 802.11s-based multi-hop operates at the MAC layer. This allows native support for layer 2 traffic and transparent operation at higher layers.

In this type of network, a STA can detect another STA through active scanning (sending a probe frame) or passive scanning (observing a beacon frame). A beacon or probe frame contains the mesh ID, enabling STAs to identify nearby devices that could belong to the mesh and establish a connection using the Mesh Peer Link Management protocol.

Typically, a mesh network using this standard comprises mesh points (MP). Some of these devices also serve as mesh point portals (MPP) to ensure connectivity to other networks or the Internet. Additionally, specific mesh points can function as mesh APs (MAP), allowing non-mesh STAs to connect to the mesh network.

In terms of security, this standard employs the Simultaneous Authentication of Equals (SAE) algorithm, which provides each pair of connected mesh STAs with a Pairwise Master Key (PMK) to encrypt their frames. Authentication between each link is independent, and all broadcast traffic reaches all authenticated STAs [10].

III. Related Work

After extensive research, no studies have been found that propose the use of SDN with Wi-Fi HaLow for network configuration. However, several works are relevant due to correlations in some parameters, as shown in Table I, with the architecture proposed in this work. The following parameters are compared and represented in the table using these abbreviations: Communication Technology (CT); Long Range (LR); Mesh Topology (M); Multi-Protocol (MP); IP Connectivity (IP); Network Configuration (NC); Flow Control (FC); Network Monitoring (NM); SDN Solution (SDNS); Multi-Tenant (MT); Logical Separation (LS) and Physical Separation (PS) between the configuration and production networks.

In [11], a Wi-SUN Smart Grid is used as the backhaul for a LoRaWAN network. In [12], an SDN-based architecture controls the data plane traffic of 6LoWPAN wireless sensor networks. References [13], [14] describe an SDN Wi-Fi framework designed for versatile management using virtual-AP abstraction and per-client control for dense Wi-Fi networks, like residential ones. In [15], an SDN-based architecture manages traffic flows in heterogeneous home networks. In [16], OpenSDWN is presented as a prototype based on an SDN/NFV architecture, providing flexible and fine-grained management of Wi-Fi networks. Reference [17] introduces Odin, an SDN-based solution for managing Wi-Fi networks, offering novel abstractions for various network services. In [18], an SDN-based solution for enterprise WLANs is proposed to enable flexible policy control in access, mobility, and interference management. In [19], CADWAN is introduced as a control architecture for dense Wi-Fi networks that complements IEEE 802.11 developments by offering flexibility, scalability, and extendibility. Reference [20] proposes an SDN approach using multi-interface routers with backhaul, access, and provisioning modules for joint access-backhaul and multi-tenant capabilities. Finally, [21] explores how SDN can be applied to wireless IoT edge networks, proposing an architecture integrating LoRa with SDN.

Examining Table I, the proposed architecture in this work stands out from the others due to its: long-range communication, use of mesh topology, ability to configure and monitor network devices via multiple protocols, architecture supporting multi-tenancy, and logical and physical separation between production and configuration networks.

TABLE I: Comparative Analysis between Related Works and the Proposed Architecture

Work	**CT**	**LR**	**M**	**MP**	**IP**	**NC**	**FC**	**NM**	**SDNS**	**MT**	**LS**	**PS**
[11]	Wi-SUN & LoRaWAN	✓	✓	✓				✓				
[12]	6LoWPAN	✓			✓		✓		✓			
[13], [14]	Wi-Fi				✓	✓			✓	✓		
[15]	Ethernet, Wi-Fi, and Power-line			✓	✓		✓	✓	✓			
[16]	Wi-Fi				✓	✓	✓		✓			
[17]	Wi-Fi				✓	✓	✓	✓	✓			
[18]	Wi-Fi				✓	✓	✓		✓			
[19]	Wi-Fi (focus on IEEE 802.11ax)				✓	✓			✓			
[20]	Wi-Fi				✓	✓			✓	✓	✓	
[21]	LoRa	✓					✓		✓			
Proposed Architecture	Wi-Fi HaLow	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓

Other works have suggested uses for Wi-Fi HaLow. In [22]–[24], this technology is proposed for disaster scenarios involving collapsed structures, with simulations conducted on signal propagation in such conditions. Reference [25] proposes using IEEE 802.11ah-based networks for medical emergencies lacking adequate network infrastructure.

As this work includes a practical evaluation of IEEE 802.11ah's performance and functionality, it is also worth mentioning [26], which evaluates throughput, round-trip time, RSSI, and communication range between an AP and a STA in indoor and outdoor scenarios, using similar hardware to this work.

IV. Proposed Architecture

This work proposes a network architecture that allows the configuration of various network devices using the SDN concept through an autonomous network based on Wi-Fi HaLow and a mesh topology. This network can operate in multi-tenant mode, meaning that it can configure multiple autonomous local networks via a single configuration network.

Figure 1 shows the proposed network architecture in a scenario where three separate networks can be configured remotely through a single Wi-Fi HaLow configuration network.

The configuration network should be connected to the Internet and host a server with the services and resources required to implement the SDN concept. To facilitate configuration, address allocation within the network must be handled dynamically by a Dynamic Host Configuration Protocol (DHCP) server. Configuration devices should communicate using Wi-Fi HaLow interfaces with 802.11s mesh protocol support, and may have different roles within the network: MPP or MP. Devices configured as MPPs act as Internet gateways to the HaLow mesh network and must be connected by cable to the internal network router. Devices set up as MPs should configure other Wi-Fi HaLow devices via the 802.11ah interface and network devices via cable or 2.4 GHz Wi-Fi. Within the configuration network, all devices should be configurable through a web interface provided by an internal server.

The SDN architecture must follow the standard outlined in subsection II-B. Its implementation should enable configuration and monitoring of the devices themselves and network devices, such as routers, switches, and firewalls. It must allow integrating modules to communicate with devices regardless of brand or protocol used, ensuring all configurations are performed according to the network administrator's requirements.

V. Developed solution

Following the architecture described in Section IV, we present the developed SDN solution and the supporting network infrastructure. Additionally, we outline the procedure for configuring network devices.

A. Conceptual network architecture

Given how the SDN application and controller are implemented, as explained in Subsection V-B, the configuration network can be deployed in various ways. For a general understanding of how the solution functions, we selected a mesh network architecture tested and shown in Figure 2.

A Mikrotik hAP ac2 router separates the configuration network from the rest of the network, enabling NAT-based Internet access. This router also functions as a DHCP server, providing IP addresses to configuration network devices. It connects to the SDN server and a HaLow Wi-Fi device, which serves as the entry point to the mesh network (MPP). The mesh network comprises three Raspberry Pi 3B equipped with AHMB7292S [27] and AHPI7292S [28] Wi-Fi HaLow interfaces. These interfaces work similarly but differ in format: one is a Raspberry Pi Hardware Attached on Top (HAT), and the other a MikroBUS module. They are based on the Newracom 7292 chipset [29], which supports global Wi-Fi HaLow frequencies and channels with 1, 2, and 4 MHz bandwidths. In addition, the limited availability of 802.11ah-compliant devices on the market, and the fact that it is sometimes incompatible with frequencies authorised in Europe, meant that this equipment was ultimately chosen.

The HaLow Wi-Fi devices connect through an IEEE 802.11s mesh network, where one device acts as an MPP and the MP1 and MP2 devices act as MPs. The MPs allow configuration of other network devices via cable.

B. SDN solution

The developed SDN solution enables the configuration and monitoring of HaLow Wi-Fi devices in accordance with the standard architectural presented in Subsection II-B.

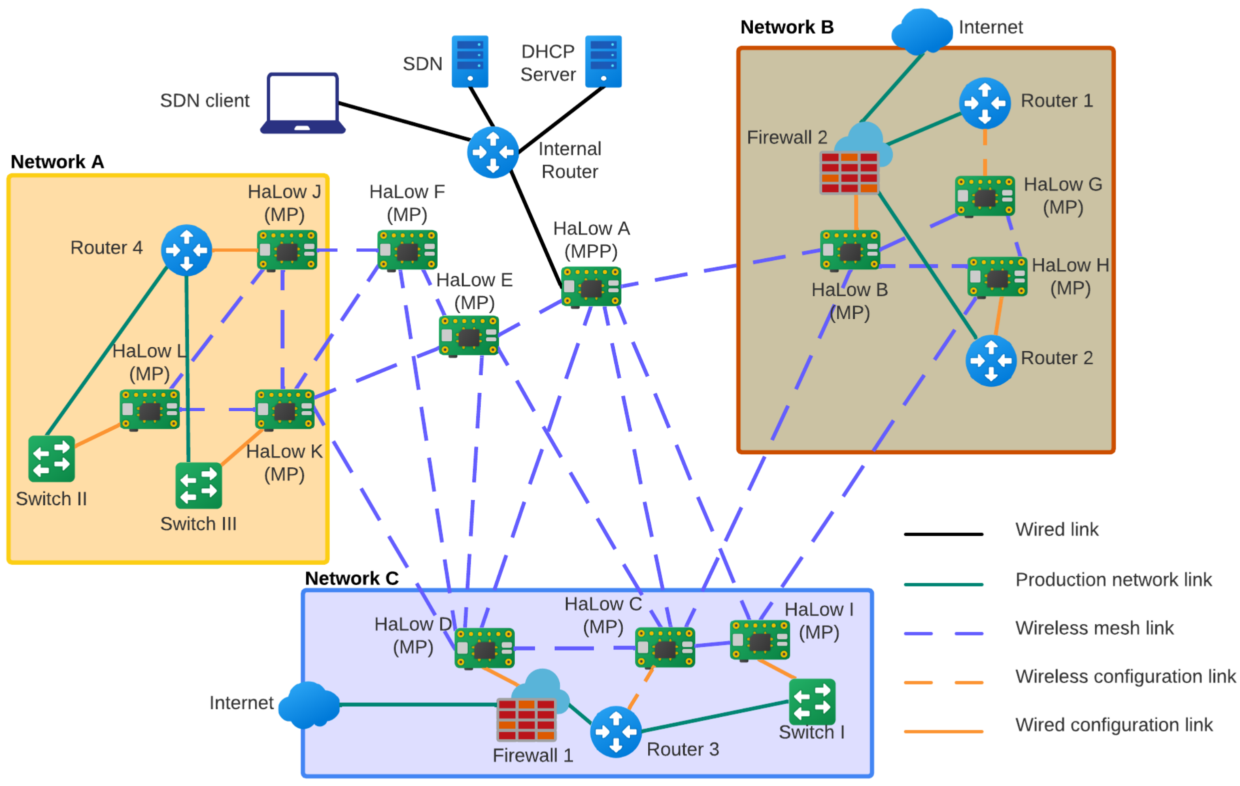

Fig. 1: Multi-tenant network architecture

In the data plane and infrastructure layer, HaLow Wi-Fi devices provide a REpresentational State Transfer (REST) API as the Southbound API. In the control plane, a Laravel "Backend" application offers a REST API that serves as the Northbound API. Finally, a Vue.js-based frontend application sits at the application layer, as shown in Figure 3.

1) Data plane and infrastructure layer: The data plane and infrastructure layer has a REST API that was developed for simple, remote configuration of HaLow devices and integration into the SDN solution. The Laravel framework is used, running on an Nginx server with MariaDB database.

Each HaLow device uses a Raspberry Pi OS base image (32-bit) with pre-installed HaLow interface drivers and software, as well as the REST API, which is ready to run.

The API supports the following tasks:

- Display device characteristics and status;
- Show HaLow interface configuration and status;
- Start or stop HaLow interface operation (which can be set to start by default);
- Remove startup HaLow configuration;
- Stop the execution of the HaLow configuration;
- User login and logout;
- Display and set transmission power;
- Restart and shut down the device.

2) Control plane and control layer: In the control plane and control layer, a Laravel "Backend" was developed to send Hypertext Transfer Protocol (HTTP) requests to each HaLow device's REST API. The application could be easily modified to interact with other network device APIs. The application uses PHP: Hypertext Preprocessor (PHP) version 8.1 and MySQL database.

This "Backend" provides a REST API, enabling interaction between the control plane and the application plane. This interaction enables the following:

- Return the list of all HaLow devices;
- Register new HaLow devices;
- Displays, edits, and removes HaLow device records;
- Shows the HaLow devices available on the network and whether or not they have active configurations;
- Provides user login and logout;
- Invokes all HaLow device API endpoints;
- Lists all available endpoints.

3) Application plane and application layer: In the application plane and application layer, a Vue.js-based "Frontend" was developed to communicate with the "Backend" via a graphical web interface. Network administrators can use this interface to centrally change settings and monitor one or more devices.

C. Device configuration procedure

Configuration of the HaLow device is achieved through a graphical web interface. First, the device should be checked for registration in the SDN controller. If unregistered, it must

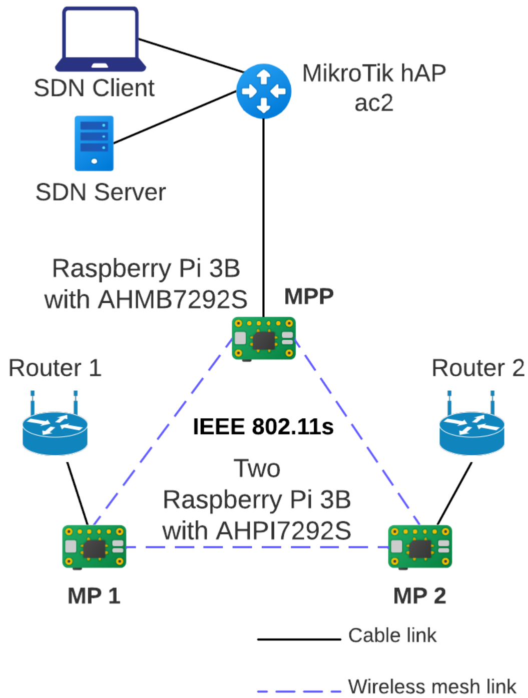

Fig. 2: Conceptual network architecture

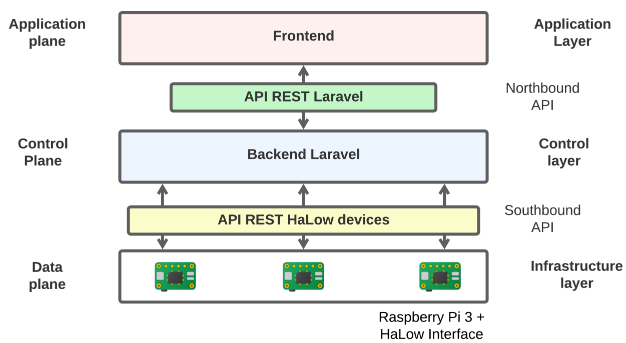

Fig. 3: Architecture of developed SDN solution

be registered and selected for configuration. The configuration mode (MPP or MP) is then selected, and if MPP is chosen, a static address is assigned within the configuration network's address space. The region, country, Service Set Identifier (SSID), and frequency for the HaLow mesh network are specified, and the option to start this configuration by default when the device powers on is set. If this is enabled, the device can also be powered off after submitting the new configuration, which is useful if configuring a device for later use. The security type for the HaLow mesh network is then defined, either open or WPA3-SAE. If WPA3-SAE is chosen, a password must be entered. After setting these parameters, the configuration can be submitted.

To apply the configuration, the device must have the base image installed and be connected to the network in one of the following ways:

- Via cable to the internal router of the configuration network;
- Via cable to an MP device;
- If configured as an MP, the device can be reconfigured.

VI. Wi-Fi HaLow range evaluation in mesh mode

To understand the range achievable in a mesh connection between two devices under different configurations, connections were established in an urban scenario at distances of 51, 166, 664, 978, and 1140 metres. These distances were chosen to ensure line-of-sight visibility.

For these tests, two Raspberry Pi 3B units equipped with AHPI7292S hats and antennas centered at 868 MHz (7 dBi gain) were used. The OS image was provided by Alfa Network, with "nrc7292_sw_pkg" version 1.3.4 installed, with no significant modifications made, with the exception of the procedure to activate mesh connectivity.

Transmission power was set to 20 dB on both devices, and channels 867.5 MHz (1 MHz), 913 MHz (2 MHz), and 914 MHz (4 MHz) were used. IP addresses were dynamically assigned via DHCP.

Despite efforts, no device could be associated with the 2 MHz and 4 MHz channels at any of the distances tested. This limitation may be related to the version of "nrc7292_sw_pkg" used in testing (version 1.3.4) or interface limitations.

Additionally, the download and upload bitrates over a period of 10 seconds were evaluated, using the "iperf3" utility, in all scenarios where a connection could be established. Download bitrate values ranged from 0.76 to 1.31 Mbits/sec. Upload bitrate values ranged from 0.66 to 1.51 Mbits/sec.

A review of the results obtained in these tests reveals a relatively high range, which makes this technology especially promising for implementing the proposed architectural framework in Section IV in an urban setting. Furthermore, the high bitrate values indicate that it is feasible to configure and monitor network devices, and to extrapolate its applicability beyond this scenario to scenarios that require a high volume of data, such as video streaming.

VII. Conclusion and future work

This work proposed, implemented, and tested an SDN architecture enabling network device configuration through an independent network based on IEEE 802.11ah and IEEE 802.11s. A prototype was developed to validate and test the architecture.

A literature review was conducted on Wi-Fi HaLow, SDN, IEEE 802.11s, SDN solutions for wireless networks, proposed applications for Wi-Fi HaLow, and performance testing of IEEE 802.11ah with real devices.

Experiments were conducted to assess the range and bitrate of Wi-Fi HaLow connections in mesh mode within an urban environment, at different distances. The results demonstrated the viability of this technology for developing an urban scenario solution based on the proposed architecture. Furthermore, these results highlight potential applications, especially in IoT scenarios requiring real-time or delayed transport of larger data (e.g., video, images, and sound), which cannot be handled by other medium and long-range technologies like LoRa, ZigBee, and Wi-SUN due to their transfer rates. Moreover, the IP-based nature of this technology simplifies the implementation of different communication protocols without the need for interoperability mechanisms, enabling heterogeneous networks combining Wi-Fi HaLow, Wi-Fi (2.4 or 5 GHz), and Ethernet.

Future work should include testing other versions of "nrc7292_sw_pkg" to determine if mesh network connectivity issues are due to software/firmware implementation problems, a specific limitation of the IEEE 802.11ah protocol, or the devices used. It would also be valuable to test the solution with more devices to verify the theoretical potential of connecting up to 8191 STAs per AP. Additionally, developing new SDN modules to enable the configuration of different types and brands of network equipment would be worthwhile.

Overall, the proposed architecture achieves its intended purpose, considering the results obtained during testing and the developed solution.

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