Wi-Fi HaLow 802.11ah

Characterizing Wi-Fi HaLow for its use under Swiss Regulation

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by

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1

Introduction

Motivation

The increasing interest in 802.11ah, commonly known as WiFi HaLow, is driven by its potential to revolutionize wireless communication, particularly in the realm of the Internet of Things (IoT). Recent advancements and the availability of new modules on the market underscore the need for a deeper understanding of this technology. However, there has been limited focus on Swiss and broader European regulatory constraints, highlighting the importance of examining these aspects to ensure compliance and optimal performance. Additionally, understanding the inherent limitations of WiFi HaLow and rigorously testing and validating its capabilities are crucial steps in meeting the growing expectations of this promising technology.

Overview of Wi-Fi HaLow

WiFi HaLow, officially known as IEEE 802.11ah, was published in 2017 as a standard designed to enhance wireless communication for the Internet of Things (IoT). Operating in the sub-1 GHz band, WiFi HaLow enables medium to long-range, low-power communication, making it ideal for various IoT applications. Its innovative power-saving modes cater specifically to the needs of IoT devices, ensuring efficient energy use. Furthermore, WiFi HaLow supports standard WiFi security protocols, ensuring robust protection for data transmission. Remarkably, it can support up to 8191 devices per access point, significantly enhancing its scalability for large IoT networks.

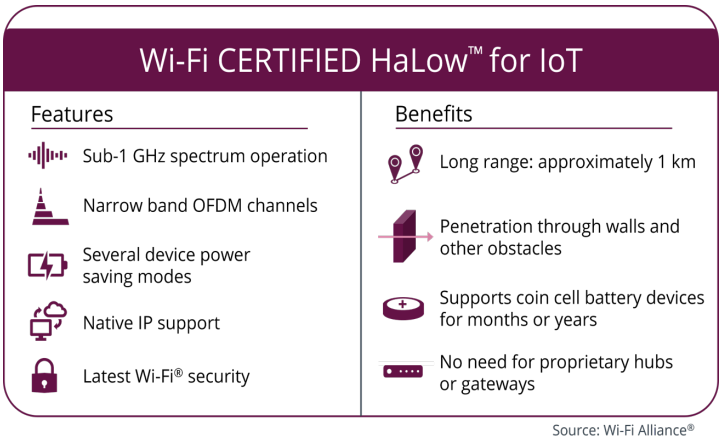


Figure 1.1: WiFi HaLow Features and Benefits

Operation in Sub-1GHz Frequency band

WiFi HaLow operates in the sub-1 GHz frequency band, which offers several advantages over the more commonly used 2.4 GHz and 5 GHz bands. One of the primary benefits is reduced congestion. The sub-1 GHz band is less crowded, leading to fewer interference issues and more stable connections.

Another significant advantage is the lower free space path loss associated with lower frequencies. This means that signals can travel further distances with less power loss, making WiFi HaLow particularly suitable for medium to long-range communication.

The allocated frequency for WiFi HaLow varies by region. In Europe, it operates within the 863-868 MHz range, while in the United States, the specific frequencies and channel bandwidths are more varied. For instance, the channel bandwidths are as follows:

- **Europe (CH/EU):** 1 MHz, 2 MHz
- **United States (US):** 1 MHz, 2 MHz, 4 MHz, 8 MHz, 16 MHz

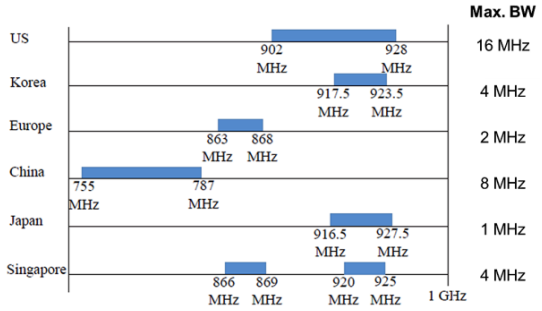


Figure 1.2: WiFi Halow spectrum allocation

Figure 1.3: Available channels bandwidth

Key features [10]:

- **Medium to long-range low-power communication:** Providing efficient communication over medium to long distances while maintaining low power consumption. This makes it ideal for IoT applications where devices need to operate for extended periods without frequent recharging or battery replacement.
- **Extended Range:** Reducing the operating frequency and channel bandwidth of a transmitted signal improves its reach. Lower frequencies, characterized by longer wavelengths, show less attenuation and can propagate over longer distances. Narrower channel bandwidths suffer from less interference and allow better signal propagation over extended ranges. Moreover, lower frequencies and narrower bandwidths are less susceptible to atmospheric absorption, ensuring signal integrity over longer distances.

  The sub-1 GHz narrowband signals utilized by Wi-Fi HaLow™ can propagate over ten times farther than the conventional 2.4 GHz and 5 GHz Wi-Fi® signals, enabling coverage of more than 100 times the area of traditional Wi-Fi networks. [1]

Distance (m)	900MHz free-space loss (dB)	2.4GHz free-space loss (dB)
10	72.2	81
100	92.5	101
1000	112.5	121

Figure 1.4: Indoor Path Loss [2]

[1] On January 23, 2024, Morse Micro set a record by performing a long-distance video call using Wi-Fi HaLow modules over a distance of more than 3 kilometres in San Francisco's Ocean Beach.

- **Low Power**: Wi-Fi HaLow incorporates advanced sleep and power management modes, enabling IoT devices to operate for extended periods, ranging from months to years.
  - **Target Wake Time (TWT)**: TWT allows devices to negotiate with the Access Point (AP) to sleep for longer durations than traditional Wi-Fi, with sleep periods customizable from seconds to months.
  - **Restricted Access Window (RAW)**: RAW serves as both a capacity planning tool and a power-saving mechanism. It allocates reserved slots for specific devices, reducing contention on the medium, minimizing collisions, and lowering power consumption associated with transmission retries.
  - **Extended BSS Max Idle**: This feature allows the AP to tolerate longer idle times from devices before disassociating them from the Basic Service Set (BSS). Devices are not required to remain awake to send keep-alive frames. Wi-Fi HaLow introduces a new scaling factor that extends idle STA tolerance for up to 5 years, enhancing power efficiency. [10]
- **Penetration**: Given that Wi-Fi HaLow operates at a lower frequency band than 2.4 GHz and 5 GHz Wi-Fi, it inherently has better penetration capabilities. The plot below shows the calculated attenuation rates of building materials.

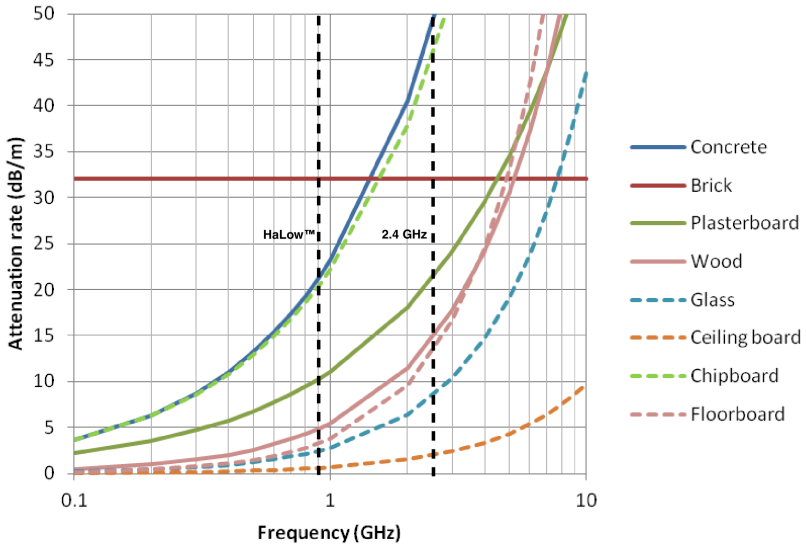


Figure 1.5: Calculated Attenuation rates of building materials [7]

- **Multi-STA Support**: Wi-Fi HaLow can support up to 8,191 devices from a single access point (AP), overperforming the network capacity of traditional Wi-Fi and other IoT protocols. This feature is significant for building dense, interconnected IoT ecosystems of the future.
- **Spectral efficiency:** Due to the congestion observed in the 2.4 GHz band traditionally used by Wi-Fi networks, the adoption of sub-megahertz bandwidth emerges as a good strategy to avoid undesired interference in saturated bands. This approach ensures optimal throughput and reliability, particularly for networks tasked with managing sporadic and low-volume data transmissions, as often encountered in IoT applications.
- **Robust security:** As part of the Wi-Fi family, this technology offers support for the most advanced Wi-Fi security: WPA3 and Wi-Fi Enhanced Open™.

Scope of the report

Despite the promising outlook presented above, it overlooks the constraints imposed by regional regulations. These limitations, as detailed in Section 3, include significant reductions in the maximum effective radiated power, allowing only a fraction of the power that commercial modules can transmit. Additionally, there are restrictions on the duty cycle, allowing the use of the channel for a limited time, and limitations on the channels used, prohibiting the use of wider band channels.

Such stringent constraints substantially alter the performance and capabilities of the network. Therefore, it is imperative to characterize the technology within these constraints to understand better its potential and the scenarios in which it could be utilized.

This report aims to display the capabilities of Wi-Fi HaLow technology while complying with European/Swiss regulations. It offers an overview of available modules, devices and chips in the market along with their characteristics, a comparison with other IoT wireless technologies, an analysis of the existing regulatory framework, and a portrayal of the technology's performance in real-world scenarios. Additionally, it explores the challenges and opportunities associated with implementing this technology, along with test cases and recommended deployment scenarios.

2

Comparing Wi-Fi HaLow with Leading IoT Protocols

The diverse and rich IoT landscape continues to expand at a rapid pace. As shown in the previous section, the number of IoT devices is increasing exponentially, and this trend is not expected to change in the foreseeable future. Wearables and home assistants are conquering the consumer market, enhancing personal convenience and connectivity. Simultaneously, major cities worldwide are embracing the development of digital twins and smart infrastructure, aiming to optimize urban planning, traffic management, and energy consumption. In the industrial sector, automation is advancing through the integration of IoT technologies, leading to more efficient production processes, predictive maintenance, and improved safety standards. Moreover, innovations in IoT are driving advancements in healthcare through remote monitoring and telemedicine. Agriculture is also experiencing a revolution with precision farming, while environmental monitoring is being enhanced to address climate change challenges.

This chapter explores the potential role of Wi-Fi HaLow within the diverse landscape of IoT technologies. It compares Wi-Fi HaLow to other Low-Power Wide-Area Network (LPWAN) and Personal Area Network (PAN) protocols, highlighting its **high throughput** and **medium/long-range** capabilities, bridging the gap between these two groups of technologies. Additionally, Wi-Fi HaLow offers very low power consumption, generally resulting in longer battery life.

LPWAN protocols

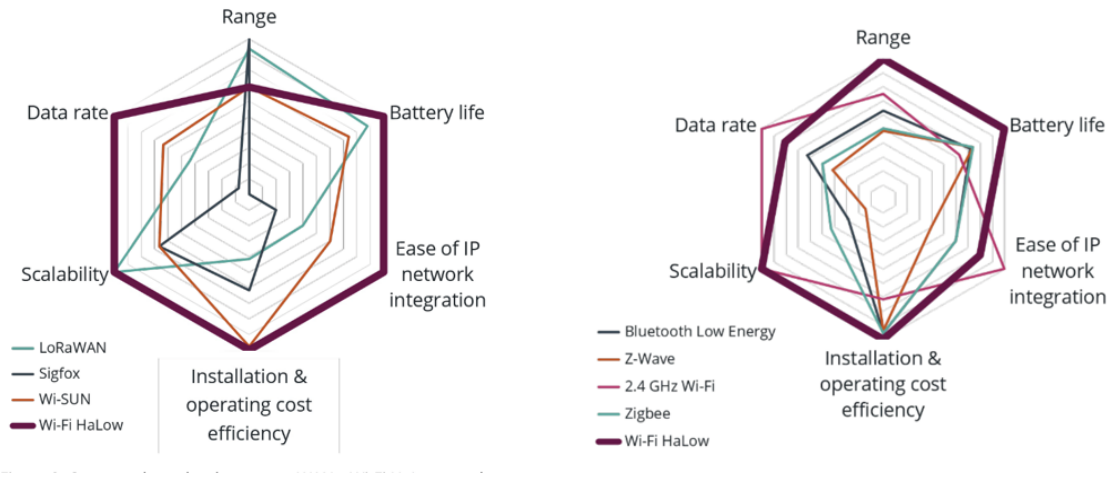
- **LoRa:** LoRaWAN, which stands for Long Range Wide Area Network, is engineered for low-power, long-distance communication. It operates on unlicensed radio frequency bands, such as EU868 (spanning 863–870/873 MHz in Europe), enabling devices to connect to the internet over vast distances, reaching up to 15 kilometers in rural areas and approximately 5 kilometers in urban environments. The data rate of LoRaWAN varies based on the spreading factor (SF) in use, ranging from 0.3 kbps to 27 kbps.
- **Sigfox:** Sigfox, a low-power wide-area network (LPWAN), operates on a proprietary network infrastructure, utilizing ultra-narrowband modulation. Sigfox operates on the 868-MHz frequency band, with the spectrum divided into 400 channels of 100 Hz. Each device can transmit up to 140 messages a day, with a payload size of 12 bytes, at a data rate of up to 100 bps. Sigfox claims that each access point can handle up to a million end devices, providing coverage areas of 30–50 km in rural regions and 3–10 km in urban areas.
- **DASH7:** Operating in operates in the sub-GHz ISM bands. DASH7 excels in urban and industrial network installations, connecting actuators and messaging applications (such as sensors, alarms, and states) with ranges extending up to 500 meters at a data rate of up to 167 kbit/s.
- **Mioty:** A low-power wide-area network (LPWAN) protocol, employs telegram splitting technology. This technique divides a data telegram into multiple sub-packets, which are then sent

after applying error-correcting codes, following a partly predefined time and frequency pattern. This approach ensures robust transmission, resistant to interference and packet collisions. Operating in the 868 MHz band, license-free in Europe, Mioty requires a bandwidth of 200 kHz for two channels. Its operating range varies from a few kilometers in urban areas to over 10 km in rural settings.

- **NB-IoT:** Narrowband IoT (NB-IoT) is a radio technology explicitly designed for the Internet of Things (IoT). It leverages existing mobile networks, offering extended battery life. The NB-IoT bands selected for Europe include B3 (1800 MHz), B8 (900 MHz), and B20 (800 MHz).

WAN protocols

- **Bluetooth Low Energy (BLE):** Designed for short-range communication with low power consumption, BLE offers a range of up to 100 meters and a data rate of up to 2 Mbps. It operates in the 2.4 GHz band.
- **Z-Wave:** Z-Wave is specifically designed for home automation and control. It offers a range of up to 100 meters and a data rate of up to 100 kbps. One of its greatest advantages is its robust mesh networking and interoperability among certified devices.
- **2.4G Wi-Fi:** Originally developed as a general-purpose wireless networking technology for various applications, including internet access, Wi-Fi 2.4GHz has a typical range of tens of meters. Depending on the standard, it can achieve very high data rates, up to 300 Mbps with 802.11n.
- **Zigbee:** Zigbee is intended for low-power, low-data-rate wireless communication in personal area networks. It typically supports a range of up to 100 meters (328 feet) and a maximum data rate of 250 kbps, operating in the 2.4 GHz band.



(a) Comparison of WiFi HaLow to LPWAN technologies

(b) Comparison of WiFi HaLow to PAN technologies

Figure 2.1: Comparison of WiFi HaLow to different technologies [4]

In this scenario, WiFi Halow shines for its high data rate even at a long-range, in addition to its low power consumption, robustness and security characteristics mentioned in the introduction.

Filling the gap between PAN and LPWAN

In the IoT market, Wi-Fi HaLow occupies a unique niche that other technologies have yet to fill, specifically in the medium-range, high-to-medium data rate segment. This technology is significant for IoT applications requiring higher throughput than conventional LPWAN protocols while still needing a long range. Additionally, it serves IoT applications that need throughput close to traditional PAN networks but must maintain very low power consumption as a constraint.

3

Regulatory Framework

In this chapter, we will explain the main regulatory bodies in Europe, the restrictions that WiFi HaLow technology must comply with to operate in license-free frequency bands, and how these limitations redefine the capabilities discussed in previous chapters.

Relevant regulatory bodies

Several European and Swiss authorities provide guidelines and coordinate the activities of national regulatory authorities (NRAs) for communications, including spectrum management. These authorities are:

- **European Commission (EC):** The EC provides extensive guidelines and policies for spectrum management and telecommunications across the EU.
- **European Conference of Postal and Telecommunications Administrations (CEPT):** Within CEPT, the Electronic Communications Committee (ECC) develops policies and regulations for electronic communications, including spectrum management.
- **BAKOM:** known in English as the Federal Office of Communications (OFCOM), is the national regulatory authority responsible for communications in Switzerland. BAKOM plays a significant role in spectrum management within its borders and cooperates closely with European and international bodies on telecommunications and spectrum issues.

Although BAKOM operates independently from EU institutions, its work in spectrum management is generally aligned with broader European objectives through its participation in CEPT and other international forums.

Regulated Parameters

Both regulatory bodies BAKOM and CEPT are aligned in the following parameters:

- **Spectrum Allocation:** WiFi HaLow working band span from 863 MHz to 868 MHZ.
- **Transmission Power:** The maximum Effective Radiated Power (ERP) is 25 mW or 14 dBm
- **Channel Access:** A Polite Spectrum Access or Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is required.
- **Duty Cycle:** In compliance with a Polite Spectrum Access is 2.8% for the STAtions and 10% for the Access Points (AP).

Channel Bandwidth

The channel bandwidth remains unclear to us. The Swiss National Frequency Allocation Plan and Specific Assignments 2024 reference the Radio Interface Regulation for Switzerland and the Principality of Liechtenstein, as outlined in documents RIR1003-11 and RIR1003-12. These documents specify that for transmissions in these frequencies, the channel bandwidth should be greater than

600 kHz and smaller than 1 MHz, in alignment with the European ERC Recommendation 70-03 from the CPT. However, in the BAKOM WLAN FACTSHEET [3], of March 2023 Wi-Fi HaLow is listed with 2 channels of 2 MHz and 5 channels of 1 MHz

Duty Cycle

Each frequency band imposes constraints on the maximum allowable transmission time for devices. These restrictions are delineated in the form of a duty cycle that can be variable depending on the possibility to perform polite spectrum access through control protocols like AFA (Adaptive Frequency Agility) or LBT (Listen Before Talk).

The duty cycle is expressed as the ratio of the accumulated transmission time within an observation period. The default duration of this observation period is 1 hour.

$$\mathrm{DC}_{\mathrm{max}} = \frac{T_{\mathrm{on}}}{T_{\mathrm{obs}}}$$

The duty cycle places no restrictions on how transmissions are distributed over time. It does not distinguish between evenly spaced transmission times and instances where transmission time is concentrated at the beginning of the observation period, with the remaining time left idle. The only requirement is adherence to the maximum duty cycle ratio. Therefore, devices are permitted to transmit using burst traffic. However, it is crucial to ensure that such bursts do not coincide within the same observation period.

Loosened Restrictions thanks to Polite Spectrum Access

WiFi HaLow distinguishes itself from protocols like LoRaWAN and SigFox, which lack Clear Channel Assessment (CCA) capabilities and thus do not support Polite Spectrum Access. WiFi HaLow's ability to use Polite Spectrum Access allows it to utilize 10% of the duty cycle for Access Points (AP) and 2.8% for STA's. Polite spectrum access involves two key aspects: Listen Before Talk (LBT) & Adaptive Frequency Agility (AFA).

LBT requires a device to check if the medium is already in use through a Clear Channel Assessment (CCA) check before transmitting. If the medium is occupied, the device must either wait for a random backoff interval or switch frequencies before attempting to transmit again, as defined by AFA. [8]

Power Considerations

In addition to the duty cycle restrictions, there is also a limit on the transmission power that is expressed in milliwatt (mW) or decibel-milliwatt (dBm).

The power values are defined here as Effective Radiated Power (ERP) values; the power that must be given to a reference halfwave dipole antenna to get the same electrical field strength as the actual device at the same distance in the direction of the antenna gain. Another often-used definition is Effective Isotropic Radiated Power (EIRP); the power that must be given to a reference isotropic antenna to get the same electrical field strength as the actual device at the same distance.

For WiFi HaLow, the EU and Swiss restrictions impose a **maximum transmission power of 25 mW or 14 dBm**. [3]

4

Chipsets, Modules & Commercial Devices

Since the WiFi HaLow protocol was published in 2017, various companies have entered the market with different chips, modules, and commercial devices. The following table shows the available chips in the market, the modules these chips can be found in, and some commercial devices that require minimal configuration and expertise to operate.

Chipset	Modules	Devices
Morse Micro MM6108	SX-SDMAH (Silex) MM610X-001 (Asia RF) AHST6108D (ALFA) FGH100M (QUECTEL)	Morse Micro MM6108-EKH03 ARFHL-WHM BLE (Asia RF) AP-100AH (SILEX)
Newracom NRC7292	AHMC7292S (ALFA) RYW729x (REYAX) SX-NEWAH (SILEX)	NRC7292 EVK AHPI7292S Halow-U, Tube-AH
Newracom NRC7394	MYNA NK1-EU8DI-Q (TECKHNE) AHST7394S (ALFA)	NRC7394 EVK
Taixin TXW8301	TX-AH-R900PNR-860M	STK-AIR700

Table 4.1: Chipsets, their corresponding modules, and devices

Notably, among the listed modules, only **FGH100M (QUECTEL)**, **MYNA NK1-EU8DI-Q (TECKHNE)** and **TX-AH-R900PNR-860M** seem to hold a **CE certification**.

Considerations for Selecting Wi-Fi HaLow Modules

In line with the project's scope, the first consideration when selecting Wi-Fi HaLow modules was their compatibility with the European unlicensed band (863-868 MHz). Additionally, an evaluation kit was needed to characterize the module's behaviour under various conditions, such as using different bandwidth channels, employing a fixed Modulation and Coding Scheme (MCS), or utilizing the rate control algorithm to adapt the MCS to testing conditions.

Considering the ease of setup and the degree of freedom that offered Newracom Software Development kit we selected the AHPI7292S HAT in combination with a Raspberry Pi 4.

5

Research Methodology

Characterization Setup

WiFi HaLow Module

The ALFA HAT 7292S module, featuring the Newracom NRC7292 chip, was selected for its availability and robust performance. This module has been widely used in multiple studies[1], underscoring its reliability and effectiveness in WiFi HaLow research. Both ALFA and Newracom offer extensive documentation on the use of the modules, which was instrumental in setting up our experiments. The provided guidelines ensured that we could efficiently configure and optimize the module's performance.

We were able to configure several parameters of the MAC and PHY layers, including the specific channel used for communication, the bandwidth settings applicable to our experiments, and the transmission power (TX Power) delivered to the antenna. This capability is crucial for ensuring functioning under regulatory constraints.

Antenna

We use a generic omnidirectional antenna for this range of frequencies with a max gain inferior to 3 dB. Specifically, we used `ANT-8/9-IPW1-SMA` from TE technologies.[1]

Control device

We connect the ALFA HAT modules to a Raspberry Pi 4.

Two modules were used to simulate a one-to-one connection: one module was configured as an Access Point (AP) and the second as a Station (STA). This setup allowed us to accurately test and

[1]Sebastien Maudet et Al from Nantes University, have used this device in multiple characterization studies.

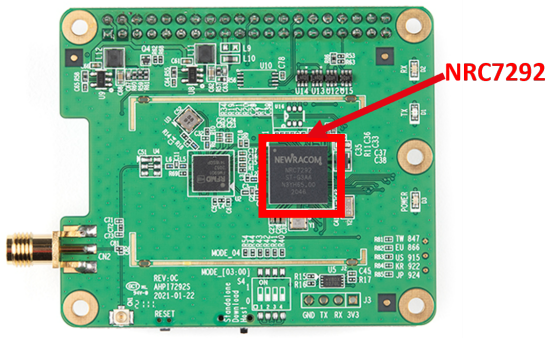


Figure 5.1: ALFA HAT 7292S

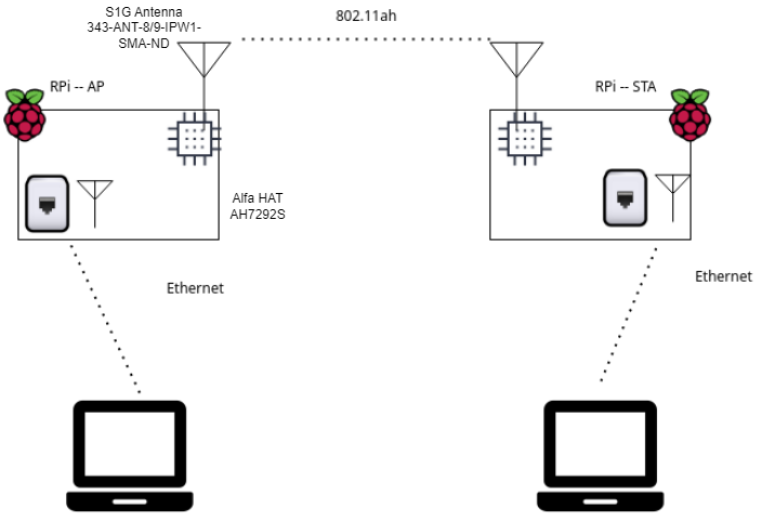


Figure 5.2: Network Topology

evaluate the performance of WiFi HaLow under controlled conditions.

Software packages

- `NRC_SW_1.3.4_2022_04_18` preconfigured image [6]
- `iperf3`

Metrics Collected

Newracom provided various configuration and testing tools to evaluate and implement their evaluation kit. We utilized these tools to run `iperf3` commands for data rate tests. Using Newracom's Command Line Interface (CLI) app, we were able to configure and evaluate metrics such as transmit power, bandwidth (1 or 2 MHz), and collect SNR and RSSI values. Additionally, the CLI app allowed us to view the network configuration.

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We ran more than 300 tests considering all scenarios. The data collected was then processed through a Python script and organized for visualization. The script and related resources are available in the referenced GitHub repository.[9]

Commands Used:

- **Data Rate Test**:

  ```
  iperf3 -c 192.168.200.1 -u -b 0 -t 45
  ```

  `-c`: client mode, specifies the IP address of the server.
  `-u`: uses UDP.
  `-b`: sets target bitrate, `0` indicates the maximum possible.
  `-t`: length of the transmission in seconds.

- **Collecting RSSI and SNR Values**:

```
./cli_app show signal start 1 20
```

This command shows the current RSSI and SNR values of the signal for a duration of 20 seconds, with an interval of 1 second between each measurement.

- **Getting Current Configuration**:

```
./cli_app show config
```

This command provides the current state of the network. We collected the MCS value that was set up by the rate control algorithm.

Description of the Testing Environment

Coaxial Reference

To simulate an interference-free environment, we connected the devices using coaxial cables coupled with attenuators. By controlling the transmit (TX) power of the modules, we were able to manage the RSSI signal. To cover a range of RSSI values, we varied the attenuation levels (-50, -60, -70 dB) and swept through TX power values from 0 to 20 dBm for each level of attenuation. This approach allowed us to characterize the capabilities of the modules and facilitated comparison with future results.

Indoor Environment

In the indoor environment, we aimed to test the module's capability to penetrate walls and floors at varying distances. We conducted tests in various scenarios across different buildings. With a fixed AP position and a moving STA, we collected network metrics. We tested in four buildings: in the first building, we experimented in different rooms on the same floor (cf. Fig 5.2); in the other buildings, we tested across different floors to maintain a consistent distance increment for each floor.

Point	Distance (m)
A	0
B	10
C	20
D	30
E	40

Table 5.1: Distance between points Scenario 1

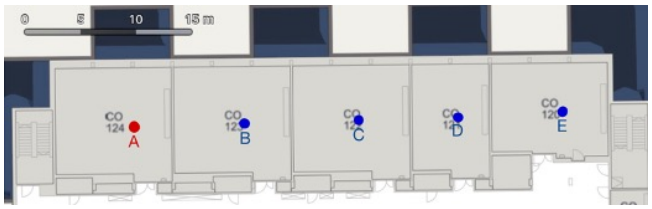


Figure 5.3: Indoor Testing scenario 1

The subsequent testing scenarios were performed in multi-floor buildings. We kept the AP on a fixed floor and ran iperf tests at each measuring point, tracking the distance and the number of floors penetrated.

Floor	Distance (m)
1st	4
2nd	8
3rd	16
4th	20

Table 5.2: Distance between different floors

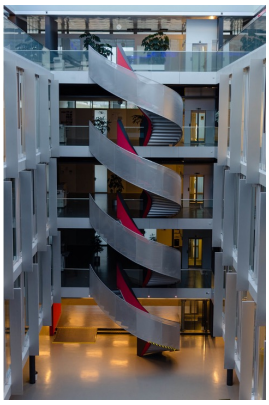


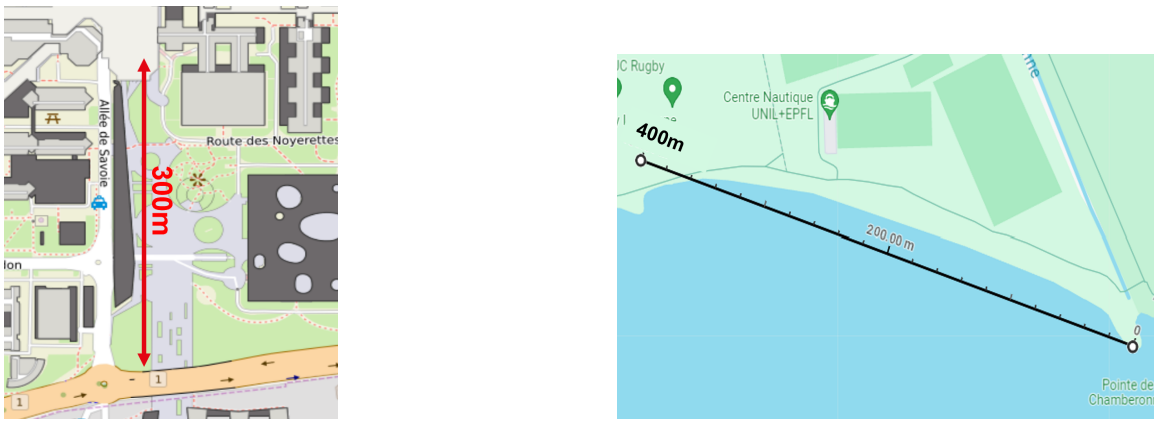
Figure 5.4: Indoor Testing scenario 2

(a) Atrium **(b)** BM **(c)** Vortex

Figure 5.5: Other buildings where indoor test were performed

Outdoor Environment

The goal of the outdoor measurements was to determine the maximum range of our modules, testing the coverage capabilities of WiFi HaLow. We initially conducted tests on the EPFL campus, utilizing a 300-meter Line of Sight (LoS) outdoor environment. Following these tests, we moved to Lac Léman to achieve a wider unobstructed LoS over a longer distance. This relocation also helped us rule out any potential interference that might have affected the measurements taken on the campus.



(a) EPFL Campus Map **(b)** Lac Léman

Figure 5.6: Outdoor scenarios considered

6

Experiment Results

Power Measurements

Before starting the actual experiments, we aimed to ensure that our devices were compliant with the Swiss power regulations, which set a limit of 25mW (14 dBm). We used a spectrum analyzer, following the setup shown in Figure 6.1, to measure the output power of the device. A 50dB attenuator was included in the setup to prevent saturating the spectrum analyzer.

We conducted tests with both 1 MHz and 2 MHz bandwidths. The station was directly connected to the spectrum analyzer, and as the devices were placed close to each other, the antenna socket of the station was able to detect the AP even without any antenna attached.

While saturating the connection with an `iperf` test, we used the max hold function on the spectrum analyzer to measure the power output of the device. According to the spectrum analyzer power measurements, the output power never surpassed the 14 dBm limit.

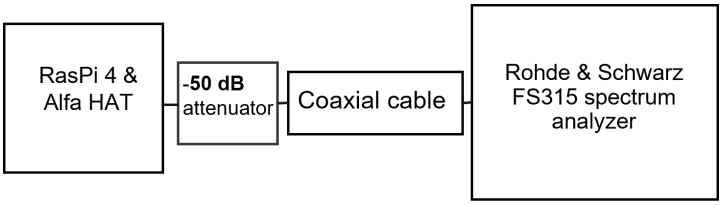


Figure 6.1: Setup for measuring the output power of the device

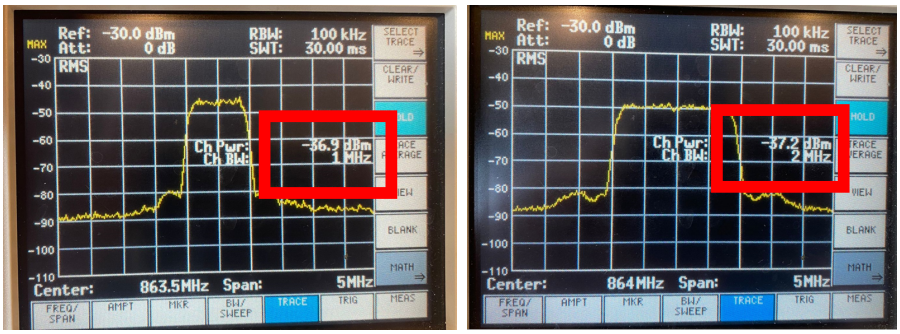


Figure 6.2: 1 MHz (right) and 2MHz (left) max hold measurements

Coaxial Results

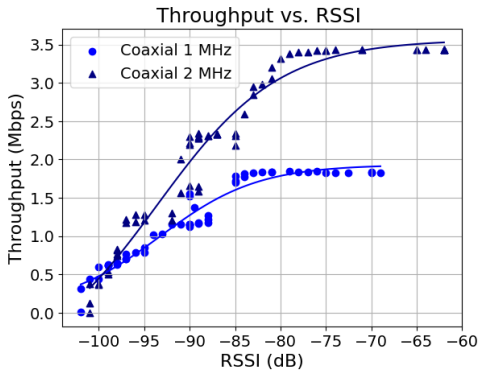
The goal of these tests was to characterize the module capabilities in an interference-free environment. After running the tests described in Section 5, we collected the results for throughput against the RSSI, as shown in Figure 6.3.

The maximum achievable speeds were:

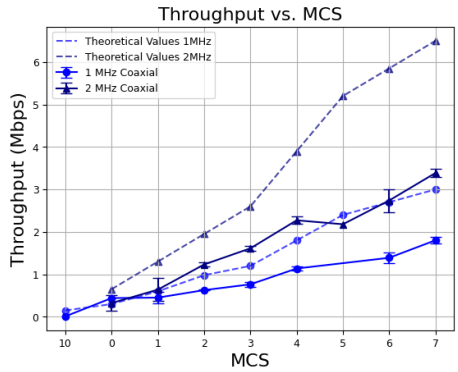
- **1 MHz channel:** 1.85 Mbps
- **2 MHz channel:** 3.43 Mbps

Additionally, we graphed the throughput versus MCS (Modulation and Coding Scheme) along with the sensitivity curve from the IEEE 802.11 paper [5].

When compared to the theoretical values, we observed that we were able to achieve only about 50 to 60% of the theoretical maximum throughput. We speculate that the difference between the maximum throughput and our measured UDP throughput could be due to the MAC header overhead and guard intervals used by the UDP protocol.



(a) Throughput vs. RSSI coaxial results



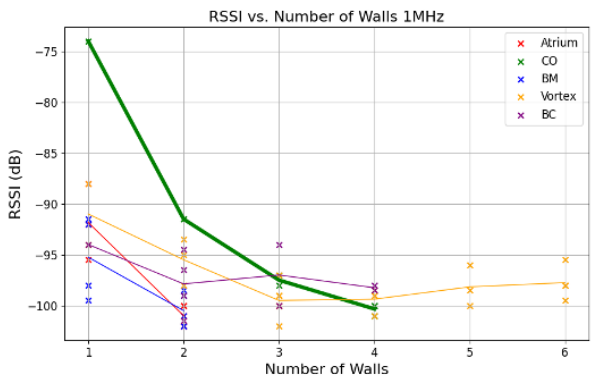
(b) UDP Throughput and Theoretical Maximum Throughput vs MCS

Figure 6.3: Coaxial Results

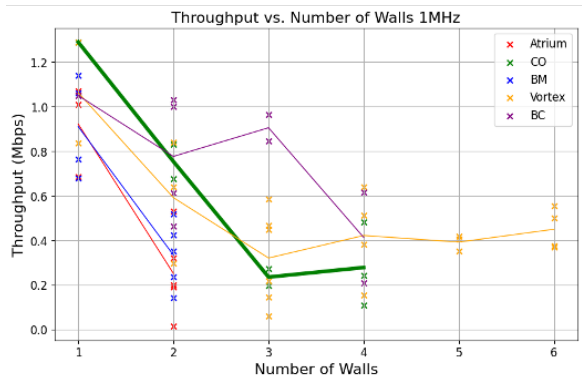
Indoor Scenario

Same floor Results

The aim of testing in this first scenario was to evaluate performance under consistent conditions: one wall and a distance of 10 meters for each testing point. This setup could provide insights into the signal's ability to penetrate walls and its propagation characteristics indoors.



(a) RSSI as a function of the number of walls in an indoor environment



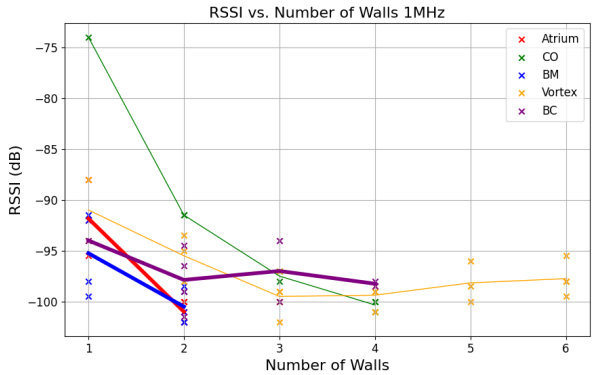
(b) Throughput as a function of the number of walls in an indoor environment

Figure 6.4: Characterization of 1 MHz channel bandwidth performance in indoor (CO) environments

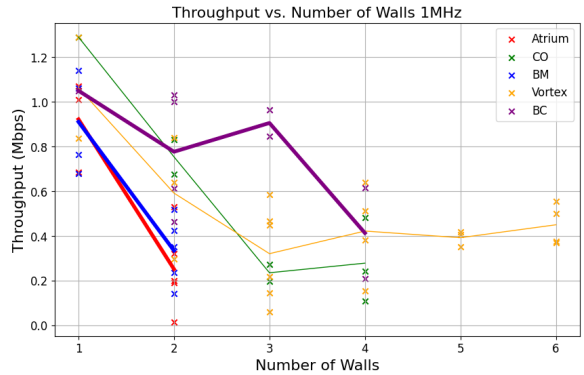
The green line stops at four walls because we could not extend the measurement further, indicating that our maximum range in this building was approximately 44 meters, with the signal penetrating four walls. At that point, we obtained varying throughputs at three slightly different measurement points: 108 kbps, 243 kbps, and 483 kbps.
These different measurements were taken to mitigate multipath fading, demonstrating the significant improvement between a 'bad point' and a 'good point'.

Inter-floor Results

With this second category of scenarios, we wanted to test the capability of the module to penetrate a more difficult and also common obstacle like floors.



(a) RSSI as a function of the number of walls in an indoor environment



(b) Throughput as a function of the number of walls in an indoor environment

Figure 6.5: Characterization of 1 MHz channel bandwidth performance in interfloor environments

It is observed that in the older buildings (BM and Atrium), signal propagation is worse, potentially due to thicker floors, heating ducts, and other unknown factors. In these buildings (Red and Blue lines), the signal could not penetrate beyond two floors.

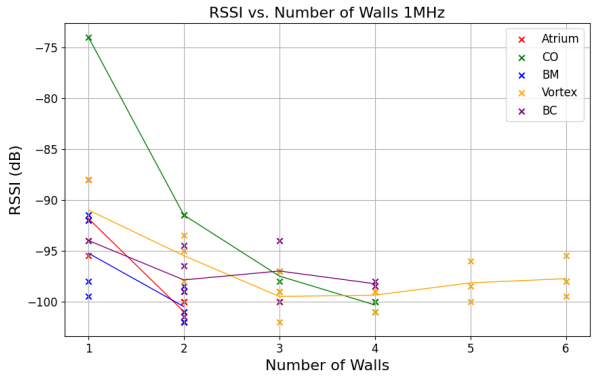
An interesting behavior is shown by the BM building (Violet line), where the module was able to penetrate four floors with minimal signal loss, achieving throughputs of 210 kbps and 616 kbps. This behaviour could be explained by a convenient horizontal reflection of the signal due to its open interior or differences in floor thickness and materials.

Potential Outlier

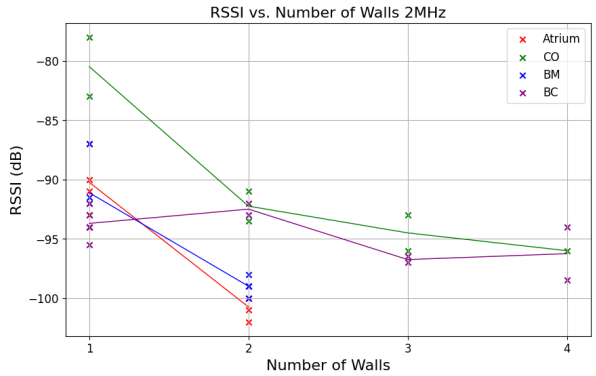
Among the buildings described in the previous plots, the yellow line draws particular attention as it penetrates six floors. It is noteworthy to mention that this building is a recently constructed student hall featuring an open internal patio and outside corridors surrounding its outer perimeter. This special geometry may facilitate reflections, enabling transmission even under challenging conditions such as penetrating six floors.

1MHz - 2MHz Comparison

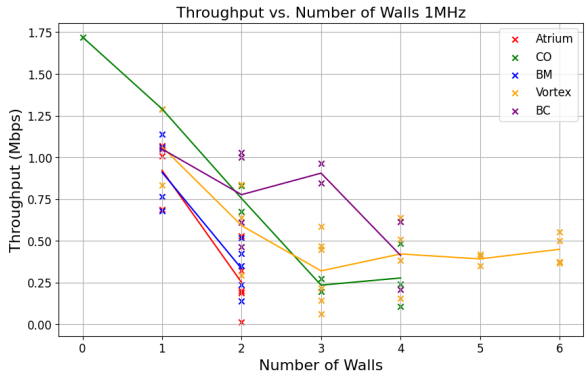
To characterize the performance of the technology under regulatory constraints we performed measurements using the two available bandwidths. We expected better signal propagation in the narrower channel, however, the results show a similar propagation and breaking wall capability for both channel bandwidths.



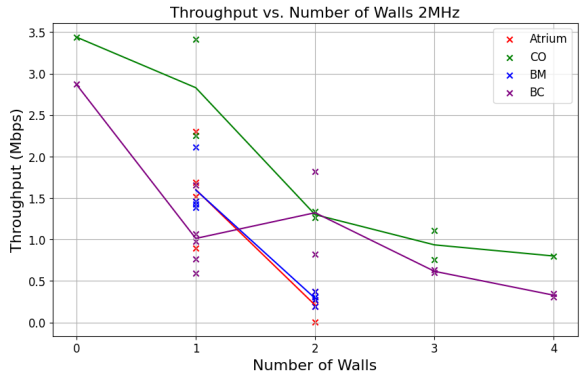
(a) RSSI as a function of the number of walls in an indoor environment, 1MHz channel bandwidth



(b) RSSI as a function of the number of walls in an indoor environment, 2MHz channel bandwidth



(a) Throughput as a function of the number of walls in an indoor environment, 1MHz channel bandwidth

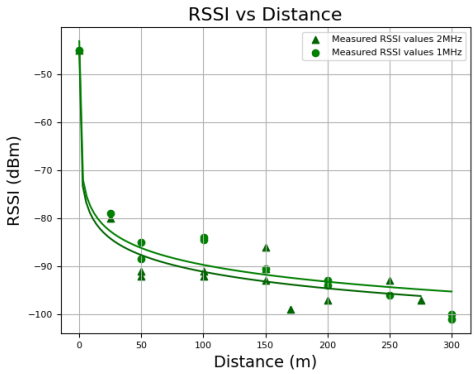


(b) Throughput as a function of the number of walls in an indoor environment, 2MHz channel bandwidth

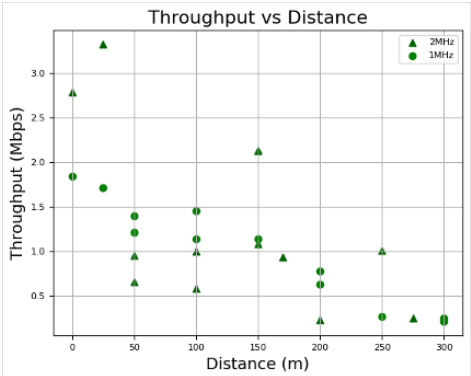
The plots show a very similar signal propagation across both bandwidths. However, it is evident that the 2MHz band consistently delivers higher throughput compared to the narrower band.

Outdoor Scenario

In the Outdoor scenario, the goal was to verify the maximum range in a LoS condition. Again, the differences between the two channels were subtle.



(a) RSSI-Distance, LoS, 1-2 MHz



(b) Throughput-Distance, LoS, 1-2 MHz

The maximum distance achieved was 300 meters with a stable connection. At 400 meters, although a connection between the Access Point (AP) and the Station (STA) was established, it was too weak to conduct any tests effectively.

At the borderline point, we obtained a throughput of 251 kbps using the 2MHz channel and 250 kbps using the 1MHz channel. The minimum measured Received Signal Strength Indication (RSSI) was -103 dBm.

Potential causes for the limited coverage observed are discussed in the Challenges section below. Other studies have shown connections for distances up to 1 km.

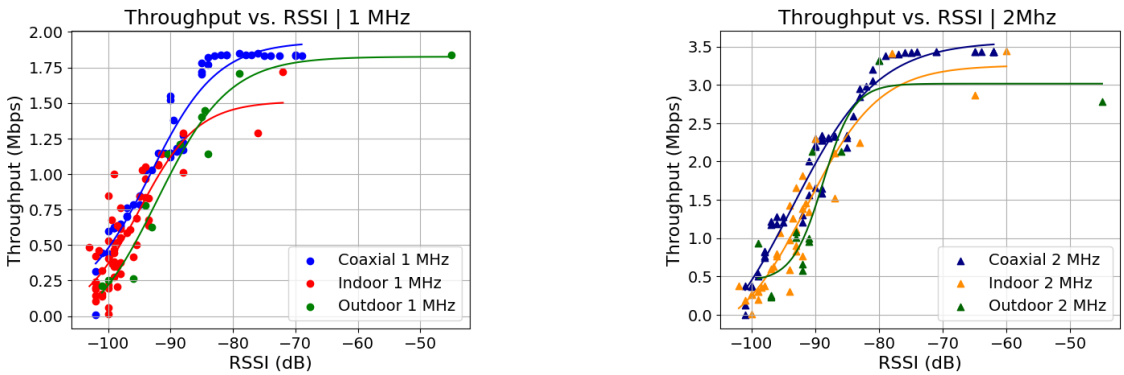
As seen in the graphs, there is a clear relationship between RSSI and distance: as the distance increases, the signal strength decreases. On the other hand, the throughput shows a less stable decreasing trend. This could be attributed to the robustness of the rate control algorithm against small movements or its ability to stabilize and maintain a good connection.

Consistency among results

This section aims to demonstrate that all our results align with our initial characterization using the coaxial network. From the graph in Figure 6.10, we can observe that the indoor and outdoor results correspond closely to the coaxial ones.

There is a clear trend across all results: as the RSSI increases, the throughput also increases.

It is also evident that for the 2 MHz channel, a higher RSSI is required to stabilize the connection. This is a trade-off for achieving a higher data rate. We observed that the throughput reaches a plateau around 90 dB for the 1 MHz channel and around 85 dB for the 2 MHz channel.



(a) All 1 MHz measurements

(b) Al 2 MHz measurements

Figure 6.9: Troughput vs RSSI in all scenarios considered

Identification of challenges encountered during testing

- **Antenna Angle:** One of the primary challenges during testing involves the precise positioning of antennas. Variations in antenna angle can significantly impact signal strength and reception quality, requiring careful adjustment and calibration. However, we lacked the necessary tools to perform this process effectively. Even when aiming to maintain a steady antenna position to achieve a high Received Signal Strength Indication (RSSI), this was not always achievable.
- **Fresnel Zone interruption:** The Fresnel Zone interruption occurs when obstacles disrupt the radio waves' propagation path, leading to signal attenuation or distortion. Due to limitations in finding sufficiently elevated positions for antenna placement, an interruption of the Fresnel Zone is plausible.
- **Water Wave phenomena:** Surface waves can cause fluctuations in signal strength and introduce noise, impacting the performance of wireless systems. Reflection, refraction, diffraction, and interference are common issues arising from the conductive nature of water and its dynamic surface. These kinds of phenomena should be taken into account when analyzing the outdoor results.
- **Body Blocking Effect:** When a person stands between the transmitter and receiver, it can obstruct the signal, leading to signal degradation or complete loss. While this wasn't problematic in Line-of-Sight (LoS) scenarios, in indoor environments, it was difficult to ensure free paths

between the Access Point (AP) and the Station (STA). Consequently, additional attenuation due to this phenomenon must be considered in such settings.

7

Conclusion

In conclusion, our characterization of Wi-Fi HaLow's performance under Swiss regulations underscores its impressive penetration capabilities, reliably going through multiple obstacles like walls or floors, even penetrating two floors within any building. Furthermore, its consistent data rates across various conditions attest to its reliability, even in challenging scenarios.
While our outdoor testing fell short of surpassing a transmission distance of 400 meters, we acknowledge potential influencing factors such as antenna placement or interference within the testing environment.
To summarize, Wi-Fi HaLow's capabilities are redefined in terms of distance and throughput due to regulatory constraints. Nonetheless, its potential for delivering high data rates over extended distances is still valid.

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