Wi-Fi HaLow 802.11ah characterization under Swiss / EU regulations

Francesco Murande

&

Tony Raffoul

Ecole Polytechnique Fédérale de Lausanne

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- Francesco Murande Escobar
- MS EE, specialization IoT | EPFL
- BS EE | Politecnico di Torino

francesco.murandeescobar@epfl.ch

- Tony Raffoul
- BS Microengineering | EPFL

tony.raffoul@epfl.ch

Academic Advisor: Prof. Andreas Burg – TCL Lab
Supervisor: Herman Hüni – Ganstrich Energie AG

Motivation

- Increasing interest in 802.11ah.
- Availability of new modules on the market.
- Limited focus on Swiss/European regulatory constraints.
- Understanding technology limitations.
- Testing and validating expectations.

GOAL:

Comprehensive characterization of Wi-Fi HaLow capabilities in compliance with CH/EU regulatory requirements.

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Overview

Regulations

Market Availability

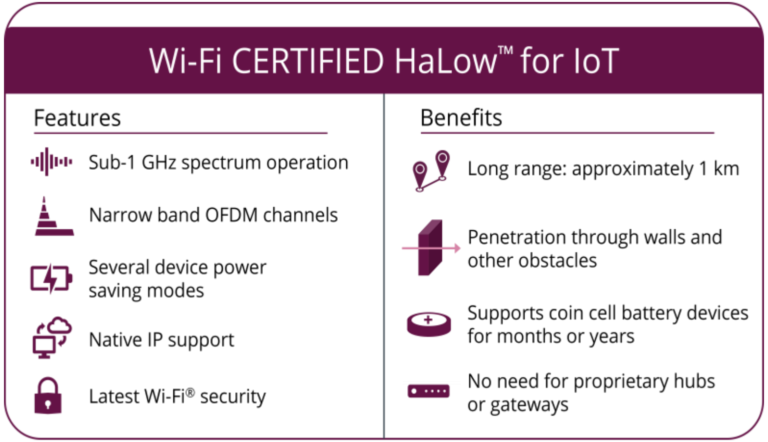
Characterization Setup

Results & Interpretations

Summary

WiFi HaLow

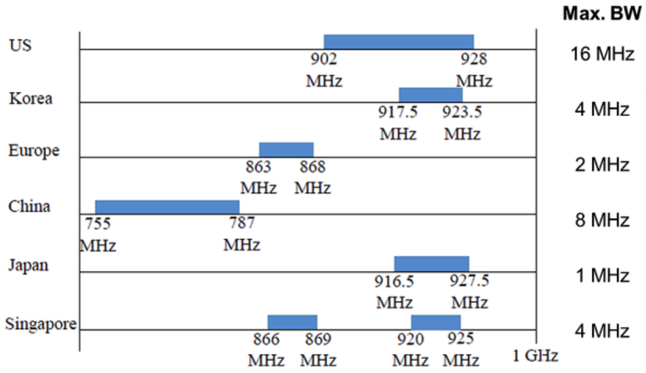
- Wi-Fi HaLow (IEEE 802.11ah) published in 2017.
- Operates in sub-1 GHz band.
- Enables medium to long-range low-power communication.
- Innovative power-saving modes for IoT needs.
- Supports standard Wi-Fi security.
- Up to 8191 devices per Access Point.



Source: Wi-Fi Alliance®

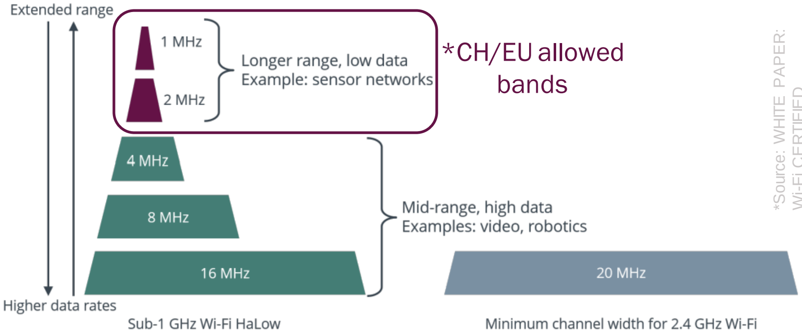
Operation in Sub-1GHz Frequency Band

- **Less congested** operation band than 2.4GHz and 5GHz.
- **Lower Free Space Path Loss** thanks to its lower frequency.
- Allocated Frequency: 863-868 MHz.
- Channels bandwidth:
  - **CH/EU:** 1, 2 [MHz]
  - **US**: 1, 2, 4, 8 ,16 [MHz]



WiFi HaLow operation bands

*Source: https://www.eenewseurope.com/en/ieee-802-11ah-wi-fi-below-1-ghz/

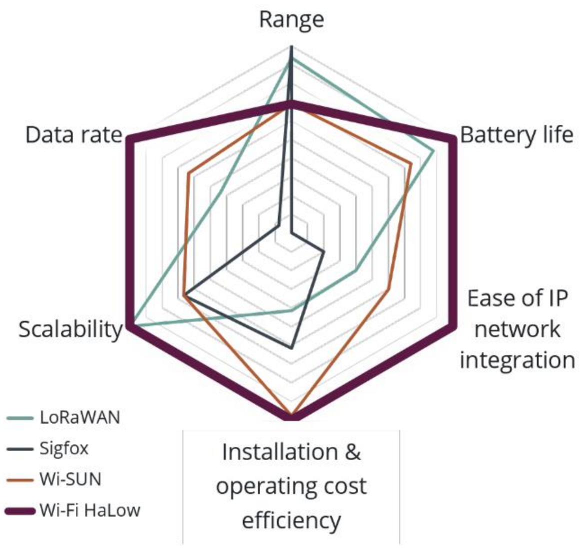


WiFi Halow channel bandwidths

*Source: WHITE PAPER: Wi-Fi CERTIFIED HaLow™ Technology Overview

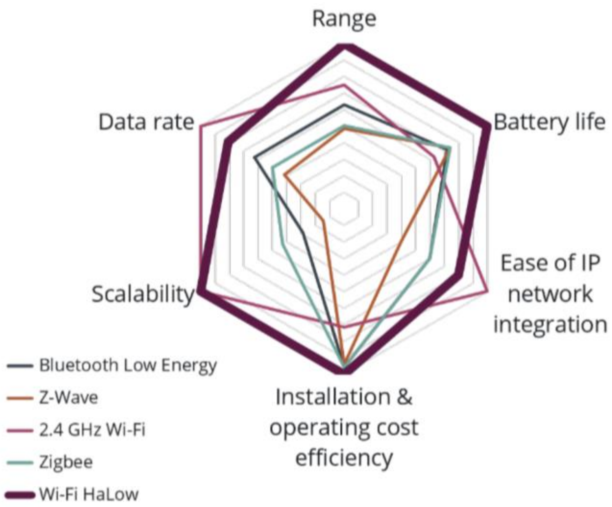
Technology Comparison

Comparison of HaLow to LPWAN technologies



- **Higher Data Rate** and **Battery life** than LPWAN IoT

Comparison of HaLow to PAN technologies

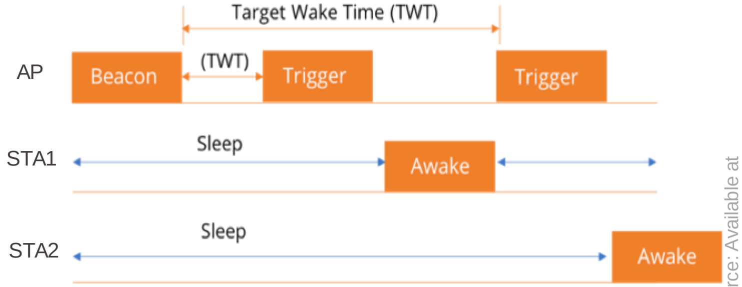


- **Higher Range** and **Battery life** than PAN

*Source: WiFi Alliance WiFi HaLow white paper

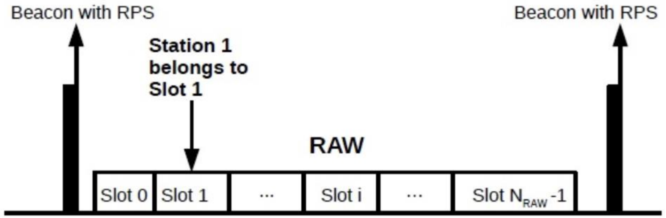
MAC Features

- **RAW** (Restricted Access Window): subset of clients transfer data, while others are forced to sleep.
- **Not-TIM (Traffic Indication Map)** modes: devices do not have to stay awake to actively monitor the beacon frames.
- **TWT** (Target Wake Time): client device enter a very low power sleep state, until the target wake time arrives.
- Shorter MAC headers.



Target Wake Time Mechanism

*Source: Available at https://blogs.arubanetworks.com/solutions/three-ways-802-11ax-makes-wi-fi-better/

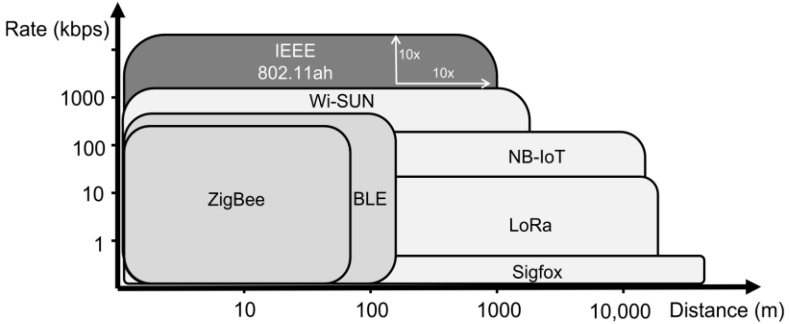


Restricted Access Window Mechanism

*Source: Soares, S.M.; Carvalho, M.M. "Throughput Analytical Modeling of IEEE 802.11ah Wireless Networks."

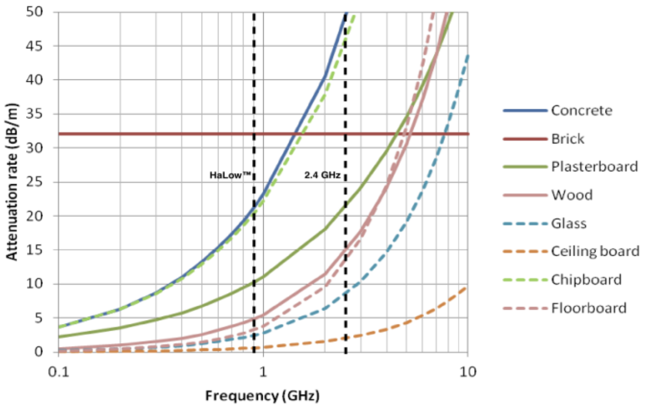
Filling the gap between PAN and LPWAN

- **Extended range** compared to PAN / LAN.
- **Higher bitrate** than LPWAN.
- Good **signal penetration** through walls and obstacles.



Range-Rate comparison of existing LPWAN technologies

*Source: Wi-Fi HaLow for the Internet of Things: An up-to-date survey on IEEE 802.11ah research, Journal of Network and Computer Applications, Volume 182, 2021.



Attenuation rates of building materials.

*Source: Richard Rudd et al. "Building Materials and Propagation: Final Report". In: Ofcom 2604/BMEM/R/3/2.0 (Sept. 2014).

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Regulations (ECC & BAKOM)

- European and Swiss regulations are aligned.
- Polite spectrum access:
  - Listen Before Talk (LBT) + Adaptive Frequency Agility (AFA).
  - **Wider bands : 4MHz is not allowed;** unable to do AFA.

Parameter	Values
Frequency band	863-868 MHz
Transmit power	Max. 25 mW e.r.p | 14dbm
Channel Access	Polite Spectrum Access
Duty cycle max	2.8% (STA), 10% (AP)
Bandwidth	>600 kHz ≤ 1MHz

Available at:
- BAKOM WLAN FACTSHEET
- Swiss National Frequency Allocation Planand Specific Assignments
- Switzerland and the Principality of Liechtenstein Radio Interface Regulation: RIR1003-11, RIR1003-12
- ERC Recommendation 70-03, CEPT, ECC

Regulations (ECC & BAKOM)

- It seems to be a mismatch in channel-bandwidth restrictions:
  - BAKOM: lists 5 available channels of 1 MHZ and 2 of 2 MHz.
  - Radio Interface Regulation, CEPT: set an upper bound of 1MHz for the occupied bandwidth.

- BAKOM WLAN FACTSHEET

Standard	Frequency range (GHz)	Number of channels	Bandwidth (MHz)
IEEE 802.11ah (HaLow)	863 - 868 MHz	5 (1 MHz) 2 (2 MHz)	1 2

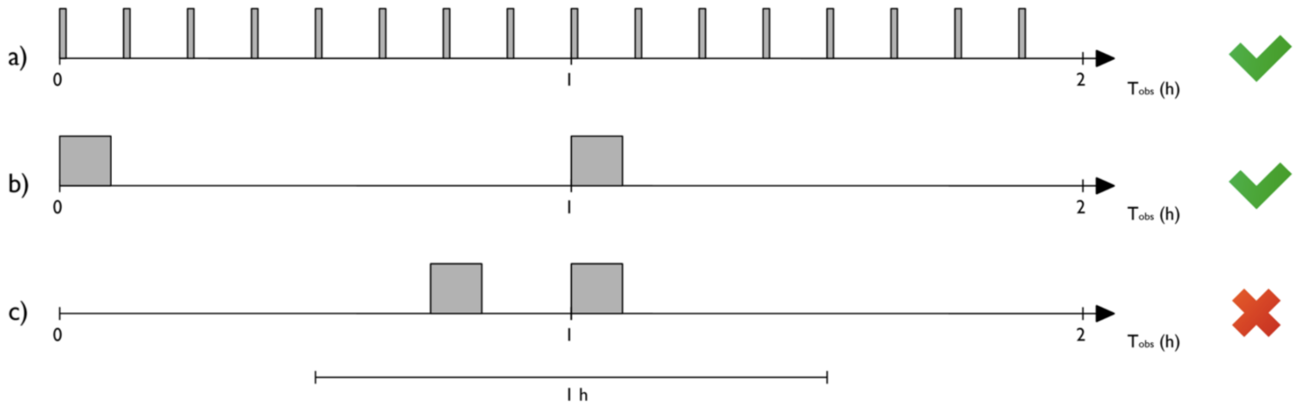
- Switzerland and the Principality of Liechtenstein Radio Interface Regulation: RIR1003-11, RIR1003-12

Nr	Parameter 2)	Description
5	Modulation / Occupied bandwidth	- / min. 600 kHz, max. 1 MHz.

- ERC Recommendation 70-03, CEPT, ECC

Frequency Band		Power / Magnetic Field	Spectrum access and mitigation requirements	Modulation / maximum occupied bandwidth
a1	863-868 MHz	25 mW e.r.p.	≤ 10% duty cycle for network access point and polite spectrum access. ≤ 2.8% duty cycle otherwise and polite spectrum acces	> 600 kHz ≤ 1 MHz

How is the duty cycle measured?



Transmission time spreading

*Source: Impact of EU duty cycle and transmission power limitations for sub-GHz LPWAN SRDs: an overview and future challenges. J Wireless Com Network 2019, 219 (2019).

Default observation period : 1h

a. Evenly distributed.

b. Single burst.

c. Not conform to the duty cycle regulations.

$$DC_{max} = \frac{\sum T_{on}}{T_{obs}}$$

NEWRACOM

Morse Micro

TEKHNĒ

QUECTEL

silex technology

AsiaRF

ALFA NETWORK

REYAX TECHNOLOGY CORPORATION, LTD

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Market Availability

- Increasing interest in this technology:
  - New devices continuously entering the market.
  - Academic community actively testing and verifying the capabilities of this protocol.

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

- Among the listed modules, only **FGH100M (QUECTEL) , MYNA NK1-EU8DI-Q (TECKHNE)** and **TX-AH-R900PNR-860M** seems to have a **CE certification.**

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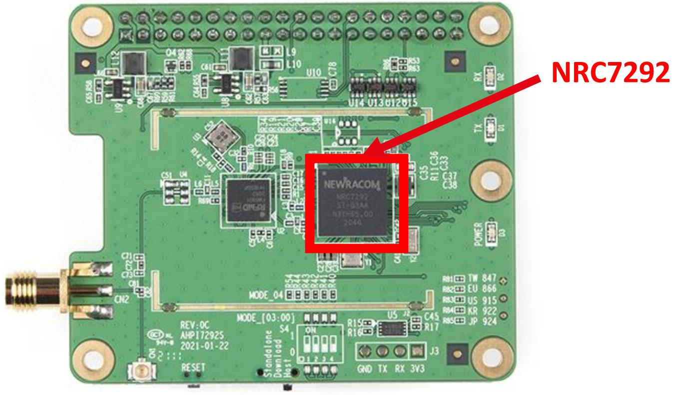
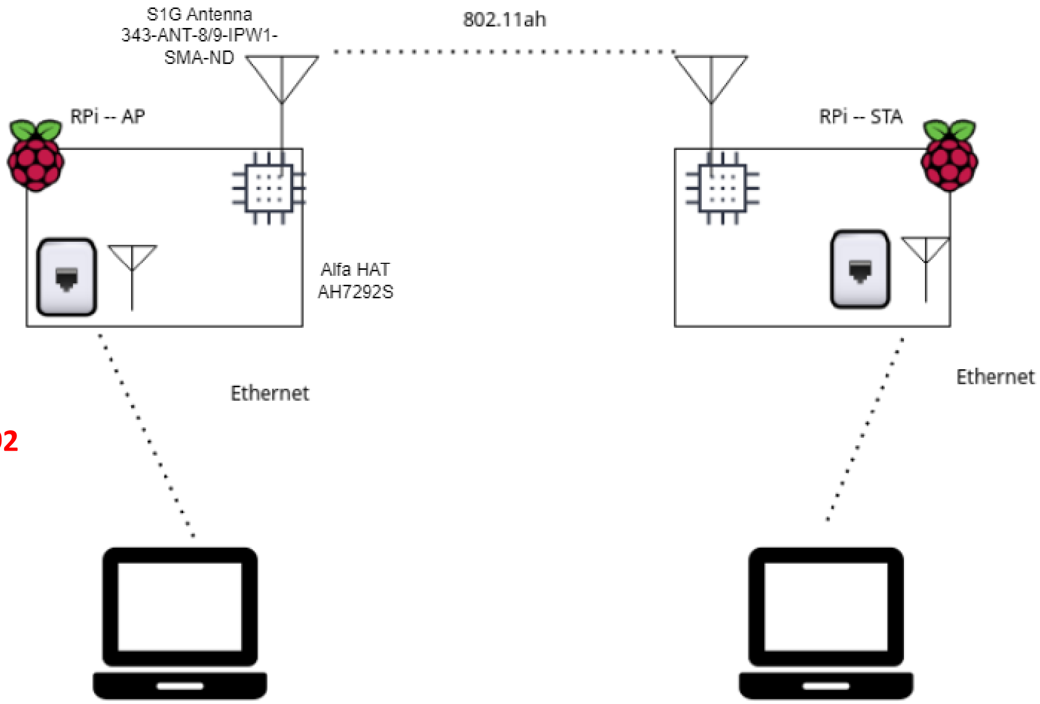
Experimental Setup

Raspberry 4



ALFA HAT AH7292S



Metrics Collected

- **Data Rate**, through **iperf3** test with UDP.
  - `iperf3 -c 192.168.200.1 -u -b 0 -t 30`

- **RSSI** and SNR values through **CLI_APP** provided by vendor NRC.

- **MCS** used by rate control algorithm through **CLI app.**

- Used Software packages:
  - *CLI app version 2.10
  - *NRC_SW_1.3.4_2022_04_18

Metrics Collected – Data Example

```
=========================================================
     Newracom Command Line Application (2.10)
=========================================================
NRC> show signal start 1 12
OK
NRC> Mac Addr : 00:c0:ca:b4:65:38       rssi: -91       snr: 16

Mac Addr : 00:c0:ca:b4:65:38    rssi: -91       snr: 16

Mac Addr : 00:c0:ca:b4:65:38    rssi: -91       snr: 15

Mac Addr : 00:c0:ca:b4:65:38    rssi: -92       snr: 15
```

iperf3 –c 192.168.200.1 –u –b 0 –t 30

```
*** iperf3 Test ***
Connecting to host 192.168.200.1, port 5201
[  5] local 192.168.200.23 port 50396 connected to 192.168.200.1 port 5201
[ ID] Interval           Transfer     Bitrate         Total Datagrams
[  5]   0.00-1.00   sec   184 KBytes  1.51 Mbits/sec  130
[  5]   1.00-2.00   sec   113 KBytes   927 Kbits/sec  80
[  5]   2.00-3.00   sec  99.0 KBytes   811 Kbits/sec  70
[  5]   3.00-4.00   sec   113 KBytes   927 Kbits/sec  80

[  5]  23.00-24.00  sec   113 KBytes   927 Kbits/sec  80
[  5]  24.00-25.00  sec   127 KBytes  1.04 Mbits/sec  90
[  5]  25.00-26.00  sec   141 KBytes  1.16 Mbits/sec  100
[  5]  26.00-27.00  sec   127 KBytes  1.04 Mbits/sec  90
[  5]  27.00-28.00  sec   127 KBytes  1.04 Mbits/sec  90
[  5]  28.00-29.00  sec   141 KBytes  1.16 Mbits/sec  100
[  5]  29.00-30.00  sec   127 KBytes  1.04 Mbits/sec  90
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate         Jitter    Lost/Total Datagrams
[  5]   0.00-30.00  sec  3.87 MBytes  1.08 Mbits/sec  0.000 ms  0/2800 (0%)  sender
[  5]   0.00-30.57  sec  3.87 MBytes  1.06 Mbits/sec  15.184 ms  0/2800 (0%)  receiver
```

```
----------------------------------------------------
[MAC Configuration]
Device Mode                      : STA
MAC Address                      : 00:c0:ca:b4:65:2e
Country                          : DE
Bandwidth                        : 1M
Frequency                        : 8635
MAC80211_freq                    : 5180
Rate Control                     : ON
 -MCS                            : 4
 -bw                             : 1 Mhz (NRC Auto)
Guard Interval                   : LONG
Security                         : OFF
RTS                              : OFF
RTS threshold                    : 0
Format                           : S1G
Preamble type                    : 1M
Promiscuous Mode                 : OFF
color                            : 0x0
Auto CFO Cal                     : OFF
BSSID                            : 00:c0:ca:b4:65:38
AID                              : 1

[PHY Configuration]
TX_Gain                          : 14
RX_Gain                          : 82

Tx Power                         : 14
----------------------------------------------------
```

Scenarios Considered

Coaxial

- Controlled environment, limited to no interference.
- Sweeping through different transmission power levels with varying attenuation values.
- Benchmarking values for device capabilities.

Indoor

- NLoS measurement
- Characterizing wall/floor breaking capabilities, robustness of signal .
- Tested in 5 different buildings.

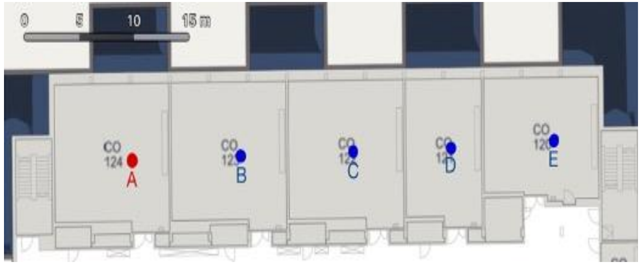
Outdoor

- LoS measurements
- Range test

*236 tests were conducted

Indoor Scenarios

- CO



- BM

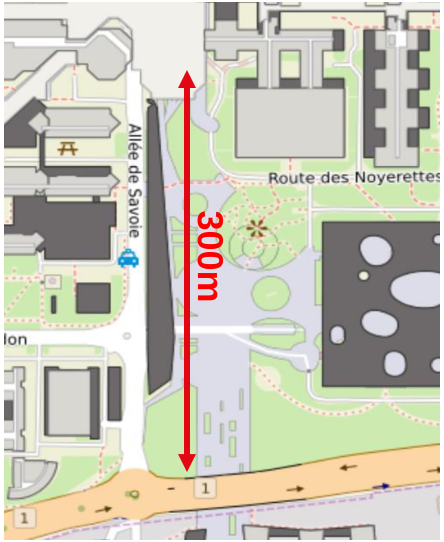
- BC

- Vortex

- Atrium

Outdoor Scenarios

- EPFL Campus



- Lac Léman

*Source: https://plan.epfl.ch/ , https://www.google.com/maps/@46.5176701,6.5841045,343m/

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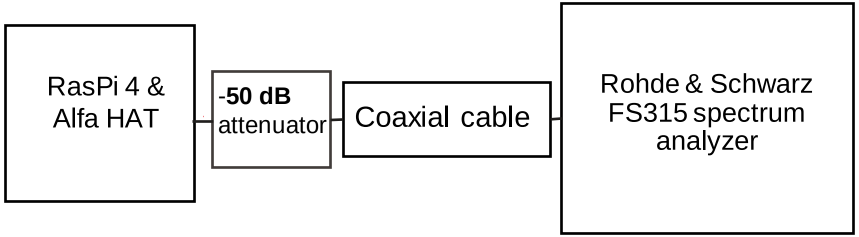
Power & Spectrum Measurements



Block Diagram of the measurement environment

≈ -37 + **50** = 13dBm

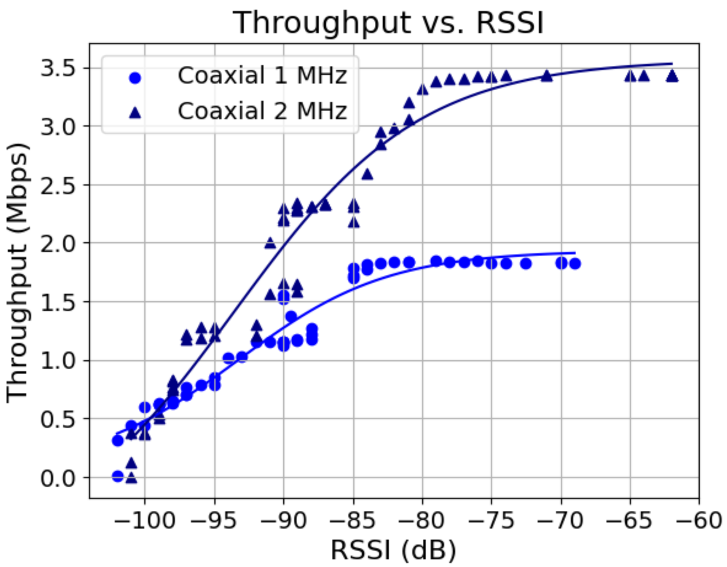
1 MHz channel power measurement

2 MHz channel power measurement

- Attenuators used to avoid spectrum analyzer saturation.
- Considering the 50dB attenuator,
  max hold peak output power delivered by module is about **13-14 dBm.**
- Devices respect 25mW – 14dBm power regulations.

Coaxial Results

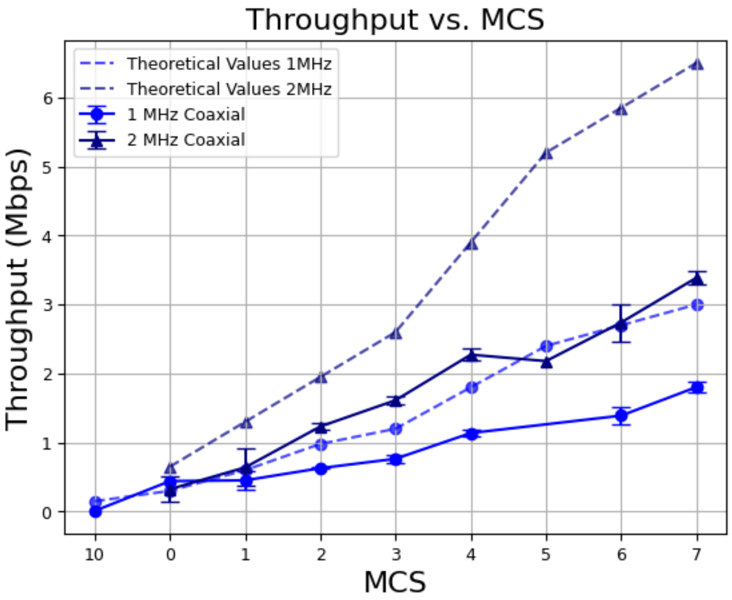
- Module throughput in controlled setting.



- Throughput increases with RSSI values.
- Max value for bandwidth:
  - 1MHz : 1.85 Mbps
  - 2MHz : 3.43 Mbps

Coaxial Results – Comparing to Theory

- Comparing throughput to the standard (Std 802.11-2016) theoretical values



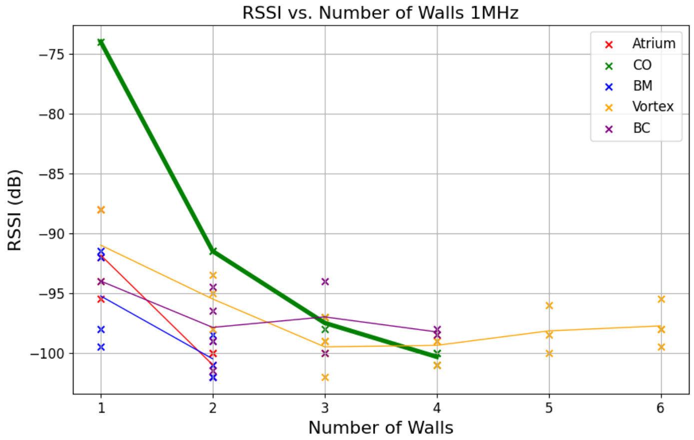
BW	MCS	Modulation	*Theoretical Data Rate (Mbps)	Actual Data Rate (Mbps)	Actual vs. Theoretical Data Rate %
1	7	64-QAM	3.00	1.85	61
2	7	64-QAM	6.50	3.43	52

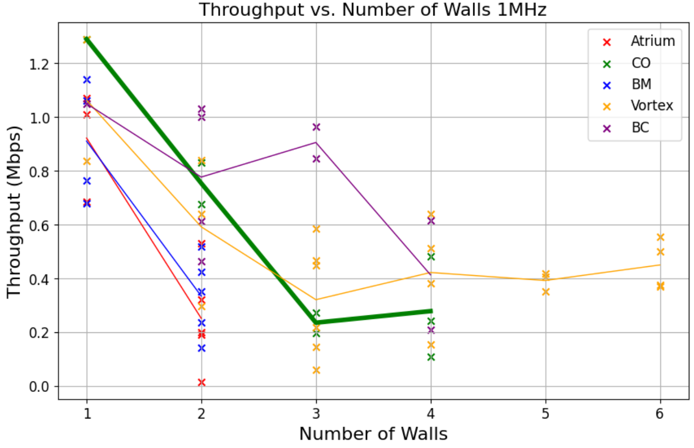
*IEEE Std 802.11ah-2016 (Amendment to IEEE Std 802.11-2016, as amended by IEEE Std 802.11ai-2016);

- Difference between max throughput and UDP throughput could be due to MAC headers, guard intervals…
- Other characterization studies yielded similar results**

**Kane, Luke. An Experimental Field Comparison of Wi-Fi HaLow and LoRa for the Smart Grid, Table 5

Indoor Results – Same Floor Results



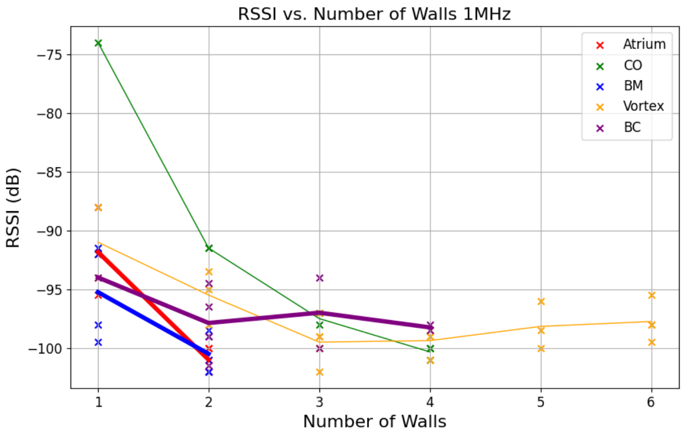


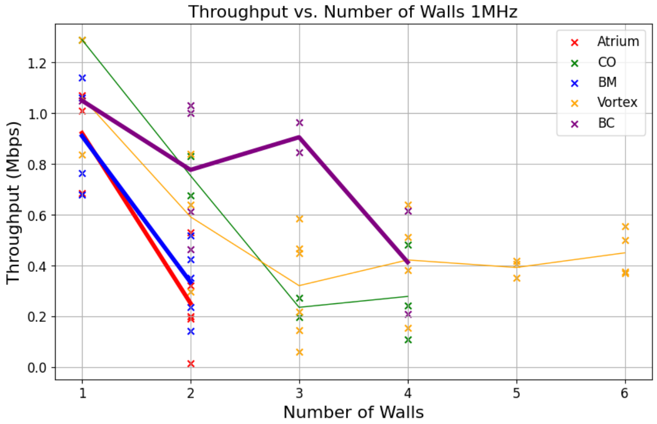
CO

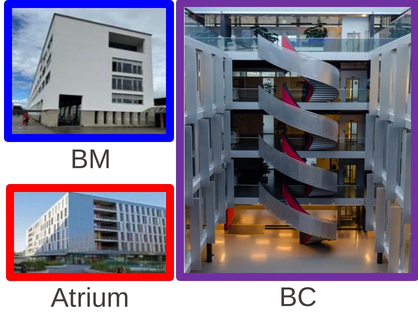
Evaluating the performance with a consistent change: 1 wall and 10m.

- Max range: **40m, 4 concrete walls.**
- **RSSI decreased significantly after the first wall,** then decreased at smaller rates.
- Throughput decreases almost consistently based on the RSSI and the corresponding MCS.
- At **border line condition an stable transmission of 250 kbps** was performed

Indoor Results – Inter Floor Results

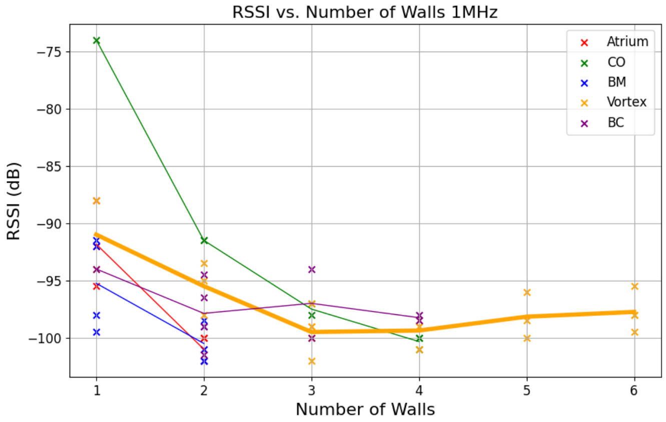


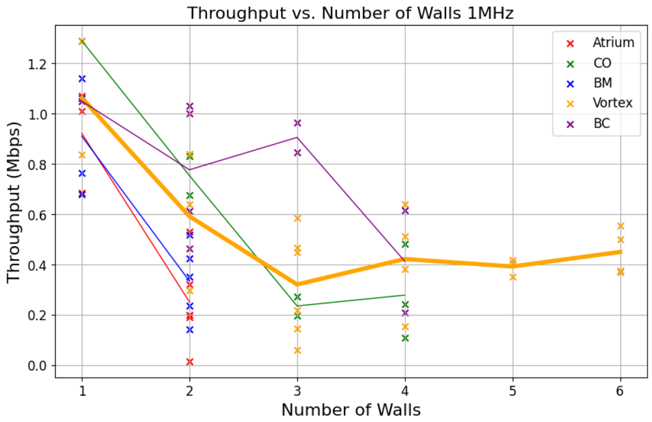




- We adjusted the antenna position while monitoring the RSSI to get the **best possible signal.**
- Worse Signal propagation in comparison with the same floor scenario **(CO).**
- Hard to go beyond 2 floors.
- **BC** shows an open interior with **thinner floors** that could benefit **reflections explaining the good results**.

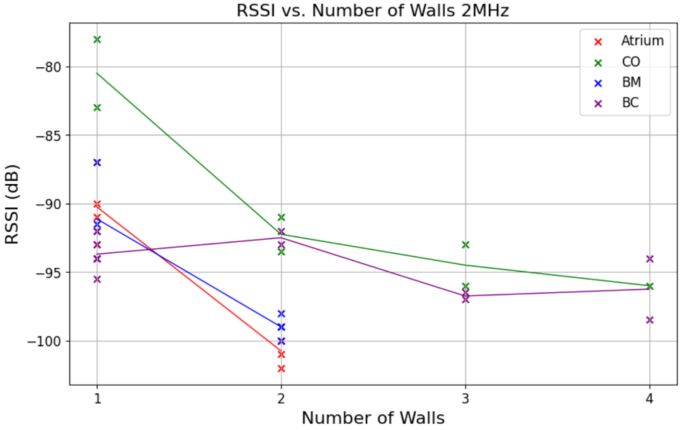
Indoor Results - Potential Outlier

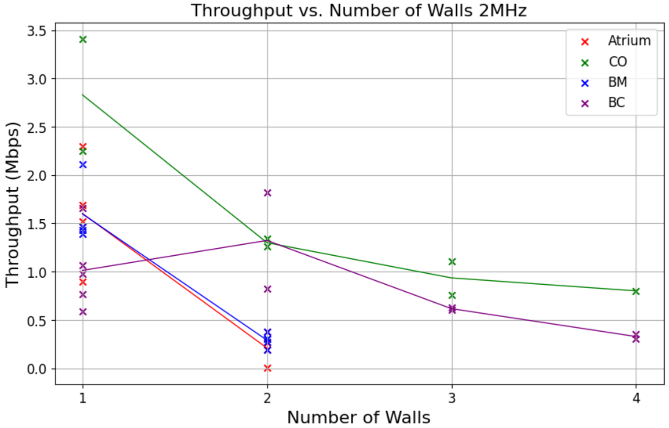




- Signal propagation possibly dominated by horizontal reflections

Indoor Results – 2MHz

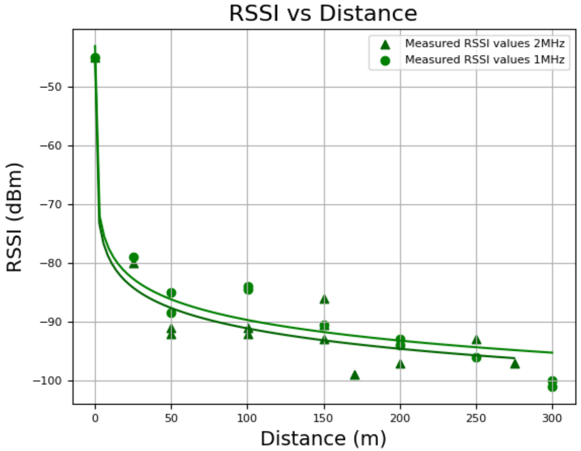


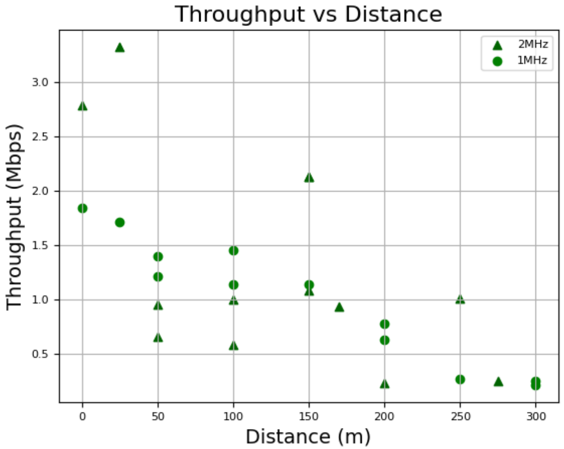


- **2MHz channels** has similar propagation than 1 MHz ones and **offer almost 2x throughput**
- In every building, breached **at least 2 walls/floors.**
- Signal degradation depends on building type.
- Multipath fading could have affected measurement quality.

Outdoor Results

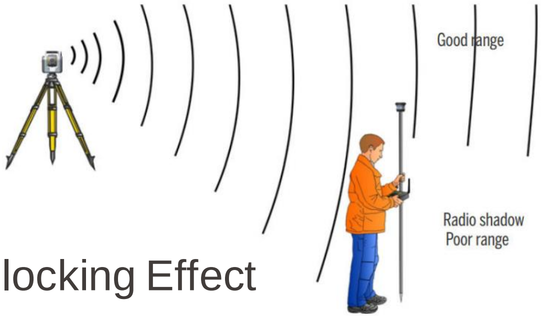
- **Max distance :**
  - Stable connection: **300m**
  - Unstable connection: **400 meters** (RSSI = -103dB to low to perform any test).
- **Throughput** at borderline condition: **250 kbps**
- Small differences in propagation between the two channel-widths.



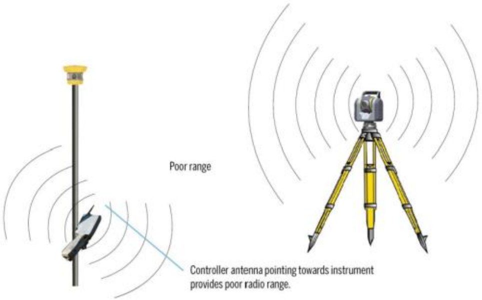


Outdoor Results – Potential Causes

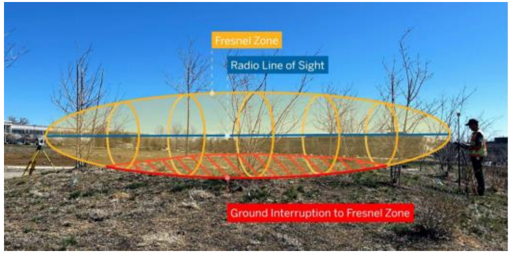
Why didn't we get any further ?



- Body Blocking Effect



- Antenna Angle



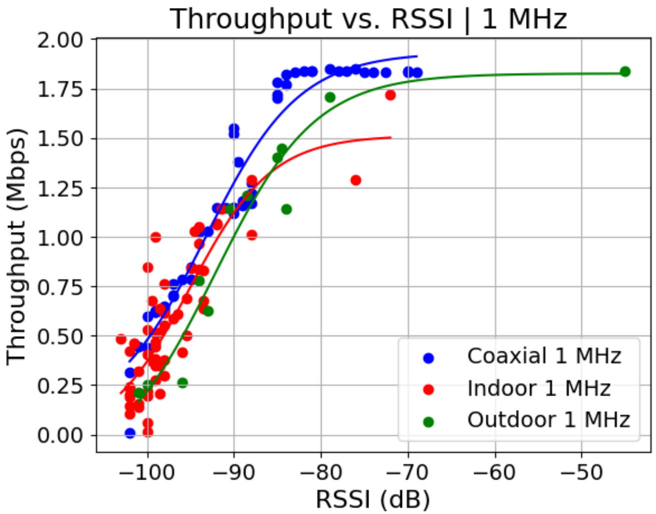
- Fresnel Zone

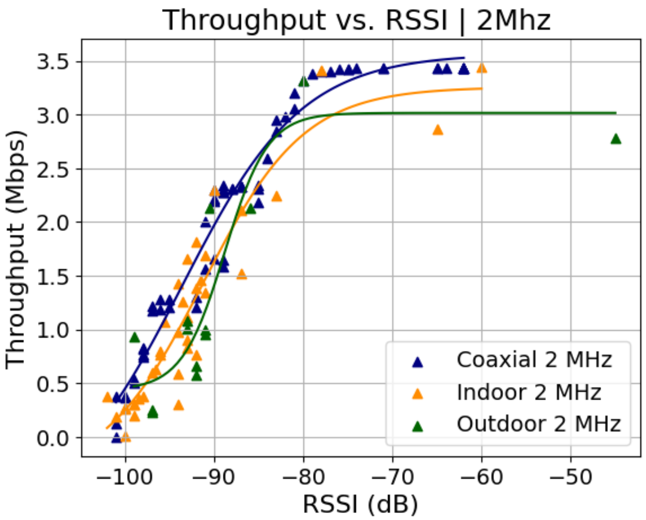
Module Limitation?

*Source: White Paper Wi-Fi HaLow Radio Technology with Trimble SX12 & EM130

Comparing with Coaxial

- Evaluating consistency across coaxial, indoor and outdoor measurements





- Indoor and Outdoor results matches coaxial/controlled environment results.
- Throughput vs RSSI trend remains consistent in all scenarios.
- Higher RSSI needed for 2 MHz, tradeoff for higher throughput.

O U T L I N E

Summary

- In **compliance with the Swiss Regulations** WiFi HaLow showed:
  - **Robust Performance:** In challenging scenarios, Wi-Fi HaLow demonstrated its ability to penetrate through tough obstacles, including **at least two walls or floors** in any building, **reaching distances of tens of meters**.
  - **Stable Data Rates:** Despite challenging conditions, Wi-Fi HaLow allowed connections from **250 kbps in borderline conditions, up to 3.5 Mbps in best case scenarios**.

- We believe reliable **transmission in outdoor scenarios may still be achievable.**
  - During our tests, **we did not surpass 400 meters**. This limitation may have been due to imprecise antenna positioning or interference in the measurement zone.
  - Andreas Speiss **reached 1.4 km** under conditions compliant with the regulations. Available at https://www.youtube.com/watch?v=rj9GZQtFs8k&t=863s

WiFi on LoRaWAN bands (HaLow) offers good penetration and long range (802.11ah)

EPFL

Wi-Fi HaLow 802.11ah characterization under Swiss / EU regulations

Francesco Murande

&

Tony Raffoul

5th June 2024

Ecole Polytechnique Fédérale de Lausanne

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