Results from Tests with the Newracom NRC7394 Wifi HaLow SoC

2nd Wifi HaLow in Europe Workshop, ZHAW School of Engineering, Winterthur, Switzerland, 22 January 2025

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Outline

- Goals
- Overview of Wifi HaLow
- Regulatory Limitations (CH)
- Newracom NRC7394 Wifi HaLow SoC and Eval-Kit
- Transmit Power and Spectrum Measurements
- Duty-Cycle Measurements
- Sensitivity and Data-Rate Measurements
- Indoor Performance Measurements
- Outdoor Performance Measurements
- Next steps, Summary

Goals

- Test regulatory compliance and performance in lab
  - Transmit power
  - Duty-cycle
  - Sensitivity
  - Data-rate
- Characterize practical performance in typical indoor and outdoor environment

Overview of Wifi HaLow (IEEE 802.11ah)

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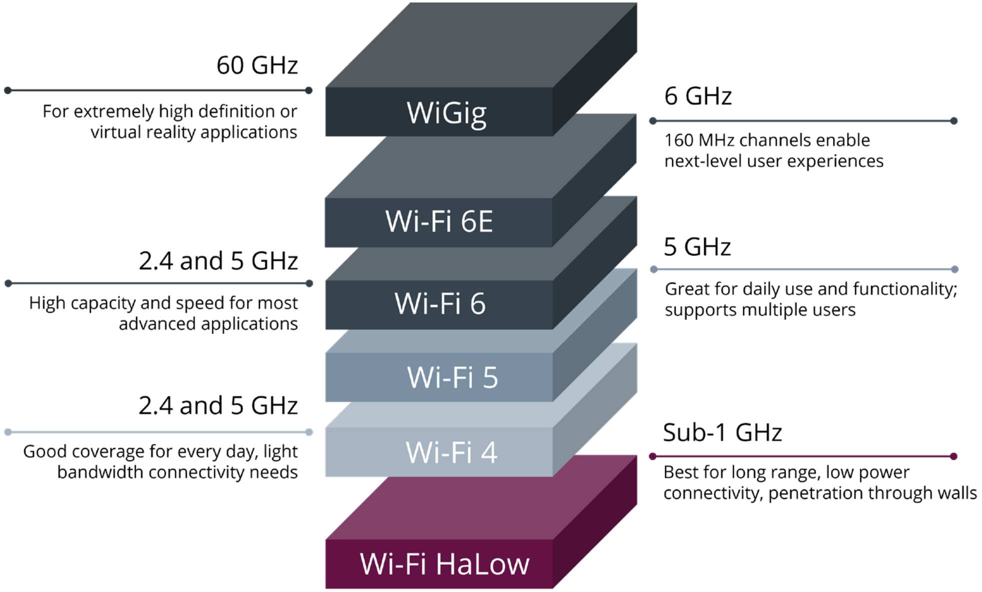
- Optimised for IoT applications
- Data-rate: 150 kbit/s to 78 Mbit/s
- Bandwidth: 1 MHz, 2 MHz, optional: 4 MHz, 8 MHz, 16 MHz in 868 MHz band (EU)
- Maximum of 8191 associated stations
- Energy saving enhancement functionalities
  - Target Wake Time (TWT), later included in Wifi 6 802.11ax
  - Restricted Access Window (RAW)
  - Traffic Indication Map (TIM) segmentation
- Sub-GHz band increases range
  - For same path-loss double distance at 863 MHz compared to 2.4 GHz (outdoor exponent-n model with n = 3)



Courtesy Wi-Fi Alliance

Sources:
S. Maudet et al, "Practical evaluation of Wi-Fi HaLow performance," in Internet of Things, Vol. 24, 2023, https://doi.org/10.1016/j.iot.2023.100957
Wi-Fi Alliance, https://www.wi-fi.org/discover-wi-fi/wi-fi-certified-halow

Regulatory Limitations (CH)

- Frequency-Spectrum regulatory framework:
  ITU (Global) → CEPT (Europe) → BAKOM (CH): Nationalen Frequenzzuweisungsplan (NaFZ)
- Relevant BAKOM Radio Interface Regulations (RIRs): RIR1003-11 (STA), RIR1003-12 (AP)

Parameter	Requirement
Frequency band	863 MHz…868 MHz
Bandwidth	0.6 MHz…1 MHz
Radiated Transmit Power P_{TX}	ERP: ≤ 14 dBm (≤ 25 mW), referred to dipole EIRP: ≤ 16.13 dBm, referred to omni-directional radiator
Duty cycle (1h observation window)	RIR1003-12 (AP): ≤ 10 %, polite spectrum access [1] RIR1003-11 (STA): ≤ 2.8 %, polite spectrum access [1]
Frequency planning assumptions	Conformance to EN 300 220-1 (industry standard)

[1] EN 300 220-1: Polite spectrum access = Listen Before Talk (LBT), alternatively additionally Adaptive Frequency Agility (AFA). The CSMA/CA algorithm of 802.11 systems provides the LBT functionality. Other RIRs for potential WiFi HaLow use require LBT **and** AFA functionality.

Sources: BAKOM RIR1003-11 and RIR1003-12, ETSI EN 300 220-1; Saelens, M., Hoebeke, J., Shahid, A. et al., "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), https://doi.org/10.1186/s13638-019-1502-5

Newracom NRC7394 Wifi HaLow SoC

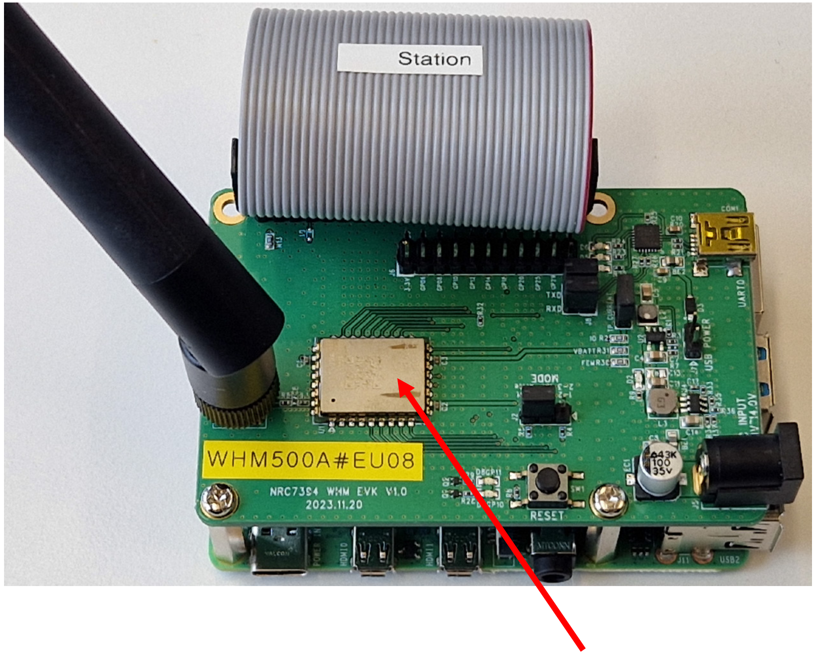
- Integrated SoC with
  - Baseband (MAC & PHY) of 802.11ah
  - Sub-GHz Radio, $P_{TX\,max} = 17$ dBm
  - Embedded Cortex-M3 ARM® processor
  - ADC/DAC (analog interface to external components) and other I/O interfaces

- 1, 2 and 4 MHz channel bandwidth, max. 15 Mbit/s

- The WHM500A module containing the NRC7394, Flash Memory and RF Filtering is CE certified

Setup of WHM500A Eval-Kits with NRC7394

- Eval-Kit: WHM500A-EVK-R (EU Frequency) with WHM500A module, operating in Host Mode with a Raspberry Pi
- Newracom Firmware Version: v1.2.1
- Configuration
  - Channel 36: 863.5 MHz, 1 MHz bandwidth
  - Region EU: Board Data File (BDF) ensures $P_{TX\ max}$ = 14 dBm according to Newracom
  - One Eval-Kit as AP and 1 as STA



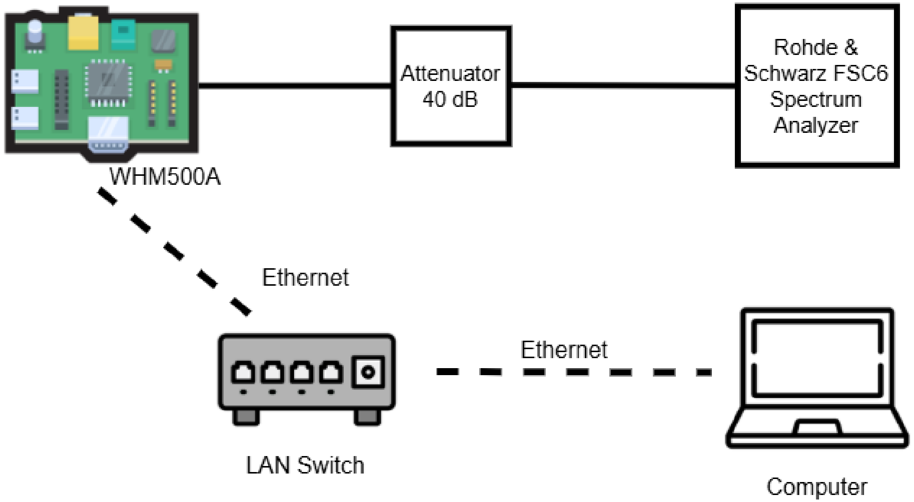
WHM500A Module

Basic configuration using scripts
For AP: ./start.py 1 0 EU
For STA: ./start.py 0 0 EU

Source: Newracom introduces next generation HaLow SoC - NRC7394

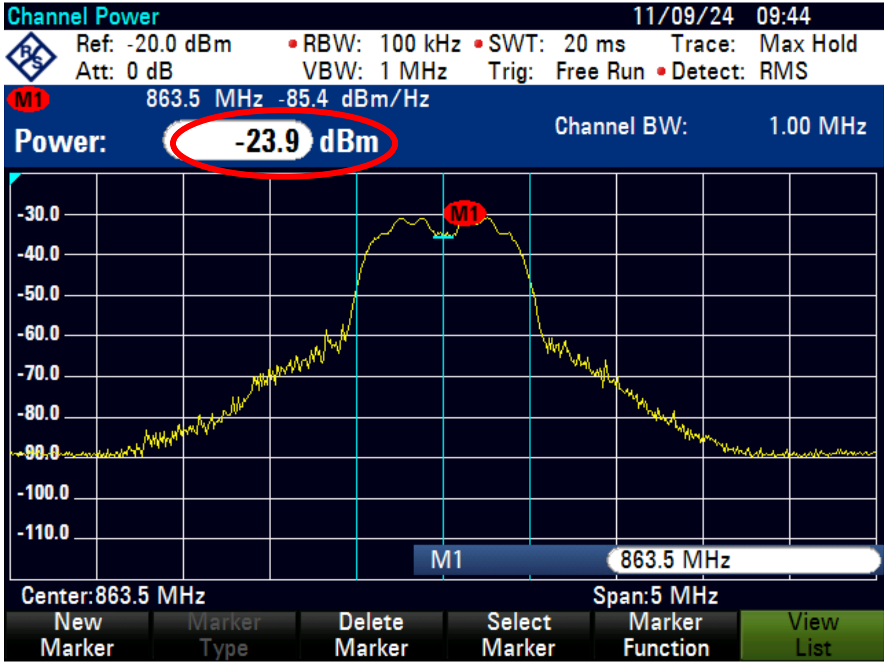
Transmit Power and Spectrum Measurements

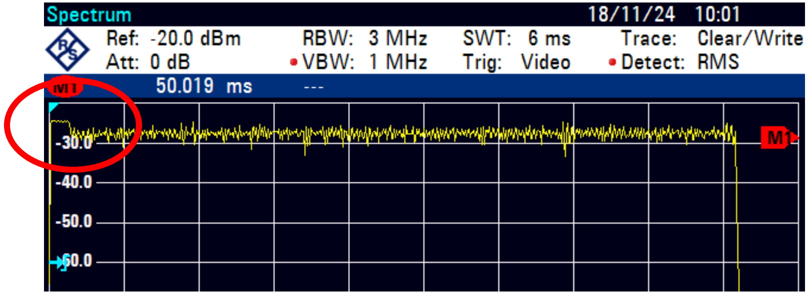
- AP sending beacon frames over coaxial cable to spectrum analyzer
- Measurement of power within channel bandwidth of 1 MHz (max. hold with RMS detector)



Transmit Power and Spectrum Measurements

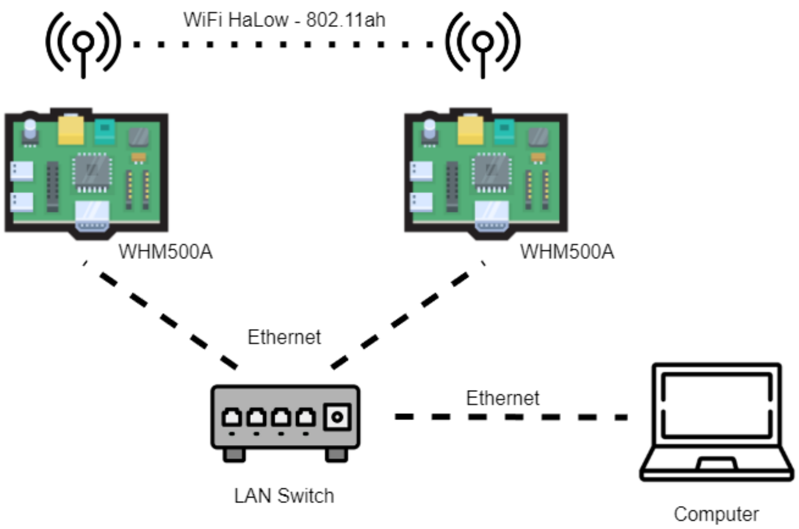
- Measured transmit power:
  $P_{TX\ meas}$ = -23.9 dBm + 40 dB = 16.1 dBm
- Just about fulfills the regulatory limit of 16.13 dBm EIRP when using antenna gain
  $G_{ant} = 0$ dBi
- Zero-span (time-domain) measurement: short power spike of 2…3 dB at the beginning of beacon frame observed (possibly Short Training Field with 3 dB boost) → increases $P_{TX\ meas}$





Duty-Cycle Measurements

- Duty cylce setting of D = 10 % (AP) and 2.8 % (STA) testet for data traffic and beacons
- For ease of measurement, observation intervall set to 1 s and 600 s (regulatory requirement 1 h)
- Data traffic generated with iPerf



Configuration of duty cycle using command line interface, times in µs for 600 s observation intervall
For AP (10 %): ./cli_app set duty on 600000000 60000000
For STA (2.8 %): ./cli_app set duty on 600000000 16800000

Duty-Cycle Measurements: Data traffic

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- Average throughput with 1 s intervall roughly in the range of 2.8 % (STA) / 10 % (AP) of throughput without limitation active → ok
- Within observation intervall, transmition at throughput without dity cycle limitation until around 2.8 % (STA) / 10 % (AP) of observation intervall, then zero throughput → ok

Configuration	Throughput STA → AP (Duty Cycle *D* = 2.8 %)	Throughput AP → STA (Duty Cycle *D* = 10 %)
Duty cycle limitation inactive	1.82 Mbit/s	1.95 Mbit/s
Duty Cycle limitation active, observation Interval 1 s	41.7 kBit/s (2.3 % of 1.82 Mbit/s)	123 kBit/s (6.3 % of 1.95 Mbit/s)
Duty Cycle limitation active, observation Interval 600 s	1.82 Mbit/s for 20s (3.3 % of time), then 0 for 580s	1.95 Mbit/s for 55s (9.2 % of time), then 0 for 545s

Duty-Cycle Measurements: Beacon Frames (AP)

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- Beacon frame transmission from Wireshark recording (second Eval-Kit is sniffer)
  - 135 Bytes every 1 s, 65 bytes every 100 ms inbetween (short beacon interval = 100 ms)
  - MCS 10 with short Guard-Interval of 0.4 µs (170 kbit/s)

No.	Time	Source	Destination	Protocol	Length	Info
1	0.000000000	SeongjiI_f1:fa:82 (…		802.11	135	S1G Beacon, Flags=....R...C, SSID=halow_demo
2	0.099017709	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
3	0.201347174	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
4	0.303803230	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
5	0.406164250	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
6	0.508576307	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
7	0.610928494	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
8	0.713368623	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
9	0.815773270	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
10	0.918164084	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
11	1.023885896	SeongjiI_f1:fa:82 (…		802.11	135	S1G Beacon, Flags=....R...C, SSID=halow_demo
12	1.122959435	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
13	1.225340379	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
14	1.327868468	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
15	1.430171248	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
16	1.532543784	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
17	1.635002153	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
18	1.737310041	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
19	1.839716539	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC
20	1.942140258	SeongjiI_f1:fa:82 (…		802.11	65	S1G Beacon, Flags=....R.FTC

Duty-Cycle Measurements: Beacon Frames (AP)

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- Theoretical duty cylce usage (occupancy) due to beacons, including 560 µs preamble duration: $D_{BF} = \frac{N_{bits/s}}{R_{bit}} + T_{preamble/s} = (135 + 65 \cdot 9) \cdot \frac{8}{170 \cdot 10^3} + 10 \cdot 560 \cdot 10^{-6} = 0.0395$ → 3.95 % out of 10 % available duty cyle used by beacon frames when short beacon interval = 100 ms
- According to Newracom beacon frames count towards the duty cycle, how is it implemented?
  - With observation window 600 s, *Remain tx duration* is set to 45.1 s instead of expected 60.0 s
  - *Remain tx duration* reduces by less than 1 s during 600 s of beacon frame transmission instead of expected 23.69 s reduction → beacon frames do not seem to be included in *Remain tx duration*
  - Unclear if the 15 s reserve is meant to cover beacon transmission, as this would only correspont to $\frac{15}{600} = 0.025$ → 2.5 % duty cyle usage

```
pi@raspberrypi:~/nrc_pkg/script $ ./cli_app show duty
Duty cycle                          : on
Duty window                         : 600000000
Tx duration                         : 60000000
Remain tx duration                  : 45124328
Duty margin                         : 0
OK
```

Observation window: 600 s
Total TX duration: 60 s
Remaining TX duration: 45.1 s

Source: IEEE Standard for Information technology--Telecommunications and information exchange between systems - Local and metropolitan area networks--Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Sub 1 GHz License Exempt Operation," 5 May 2017, https://doi.org/10.1109/IEEESTD.2017.7920364

Sensitivity and Data-Rate Measurements

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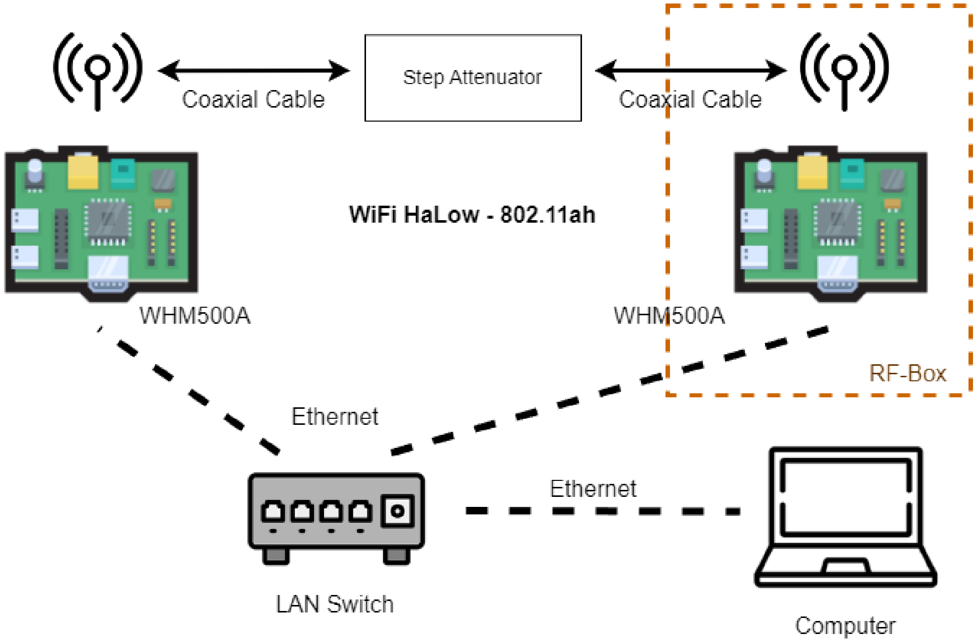
- AP and STN connected via coaxial cable and step attenuator
- One device in shielded RF box for additional attenuation
- Data traffic generated with iPerf
- Duty-Cycle limitation not active
- Maximum receiver sensitivity configured manually according to information from Newracom, otherwise sensitivity limited to around -87 dBm
  - "The transceiver estimates the interference level during initialization and adjusts it RX sensitivity accordingly"
  - "By issuing the command 'modem rxgain 85', you're forcing the transceivers to operate in 'interference free' RX mode, which allows the reception of lower energy signals"



Configuration of maximum rx sensitivity on UART0 of NRC7394 EVK: modem rxgain 85

Sensitivity and Data-Rate Measurements

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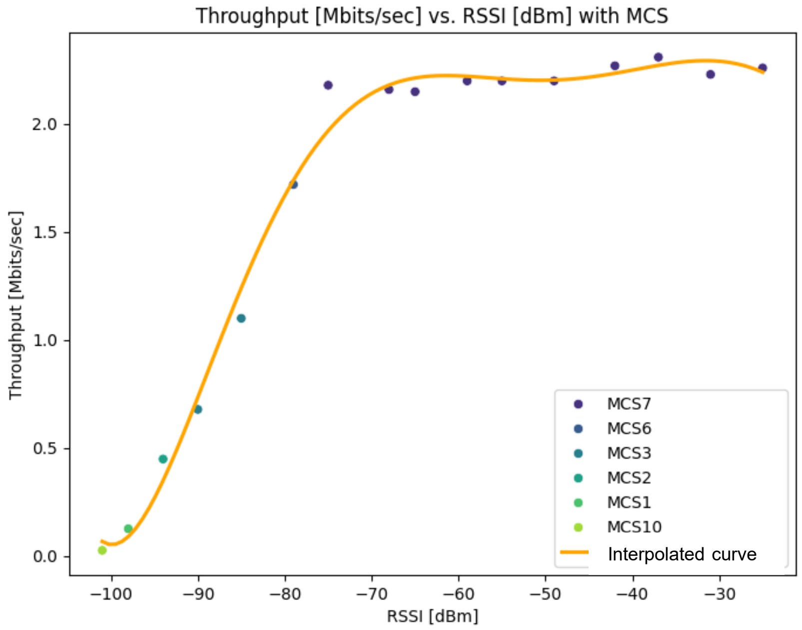
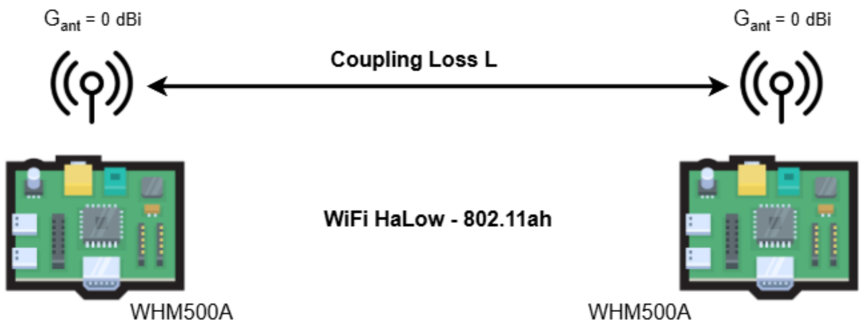


- MCS increases from MCS10 ("lowest") to MCS7 ("highest") with increasing RSSI
- Maximum throughput at MCS7: 2.3 Mbit/s (theoretical value at MCS7 3.0 Mbit/s [1]) → ok including protocol overhead and acknowledgments
- Minimum receive sensitivity $P_{RX\ min}$ = -101 dBm (similar to other studies [2,3]) → ok

[1] Newracom, "NRC7394 Datasheet", Ver 1.3, Jan 22, 2024
[2] S. Maudet et al, "Practical evaluation of Wi-Fi HaLow performance," in Internet of Things, Vol. 24, 2023, https://doi.org/10.1016/j.iot.2023.100957
[3] F. Escobar, T. Raffoul, "Wi-Fi HaLow 802.11ah, Characterizing Wi-Fi HaLow for its use under Swiss Regulation", EPFL BSc Project, July 2024

Sensitivity and Data-Rate Measurements

- Comparison of maximum calculated coupling *L* loss between TX and RX for different technologies and resulting range



Technology	Maximum coupling loss $L = P_{TX\ max} - P_{RX\ min}$	[3] Calculated Outdoor Range *r* non line-of-sight
802.11ax (2.4 GHz-band, 20 MHz BW)	$20 - (-85) = 105\ dB$ [1]	358 m
802.11ah (868 MHz-band, 1 MHz BW)	$14 - (-101) = 115\ dB$	1'541 m
LoRa (868 MHz-band, 125 kHz BW)	$14 - (-138) = 152\ dB$ [2]	26'363 m

[1] $P_{RX\ min}$ relative to measured value for 802.11ah considering larger min. bandwidth of 802.11ax (20 MHz) and different lowest MCS index of 801.11ax (BPSK ½)
[2] ZHAW ISC, WCOM2 Lecture Slides, Chapter 8: Applications of Chirp-Spread- Spectrum (CSS) Modulation
[3] Exponent-n model with n = 3, d_0 = 100m, shadowing,margin X = 8.25 dB, Antenna gains G_{ant} = 0 dBi

Indoor and Outdoor Performance Measurements: General Setup

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- Measurement of throughput with iPerf, logging of MCS and RSSI
- Maximum receiver sensitivity configured manually: *modem rxgain 85*
- Duty-Cycle limitation not considered
- No attempt to move the antennas to maximise throughput due to multipath-propagation made
- Omni-Directional Antennas with Gain G_{ant} = 3 dBi used
- Environments
  - Indoor across multiple offices on the same floor
  - Indoor across multiple floors at the same position
  - Outdoors urban street environment with partial line-of-sight

Indoor Performance Measurements: Same Floor

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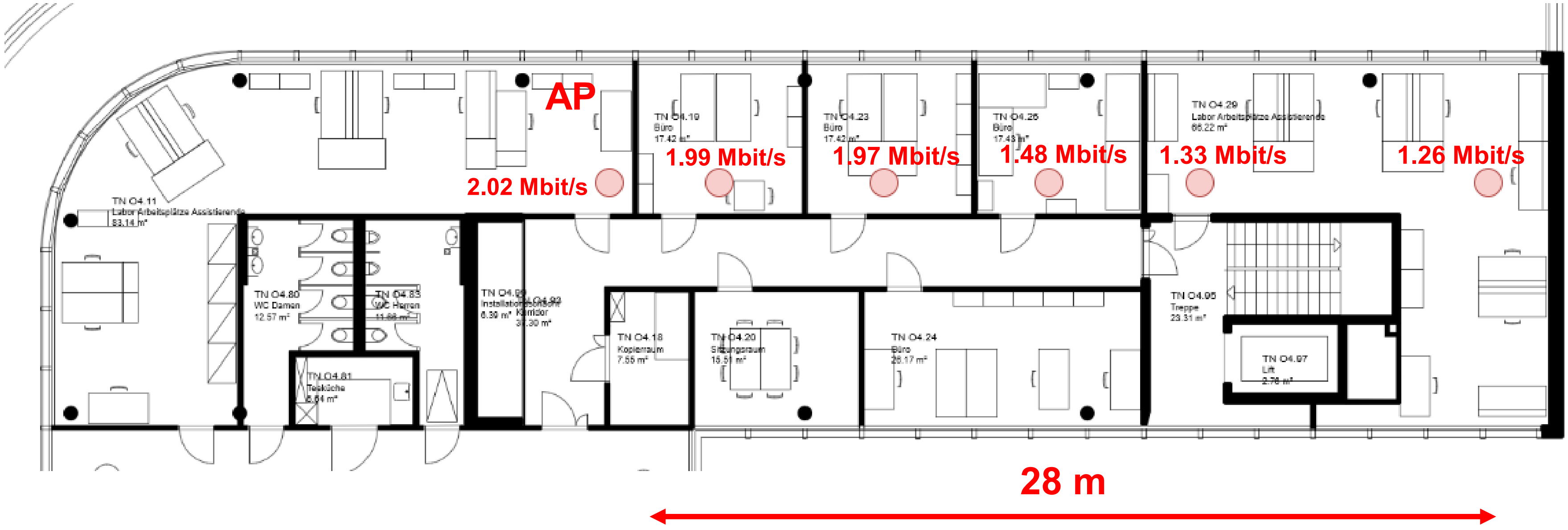
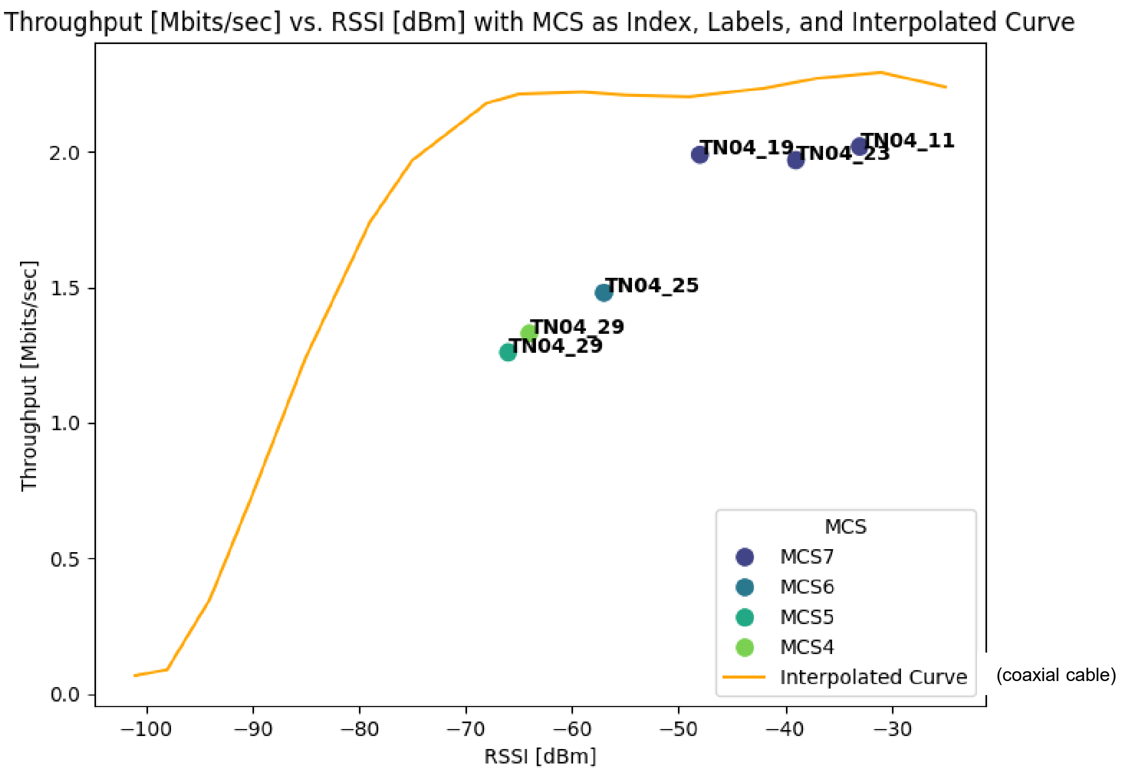
Floor plan with throughputs, 4th floor ZHAW building TN, Winterthur



- Measured throughput with 4 partition walls over 28 m distance: 1.26 Mbit/s

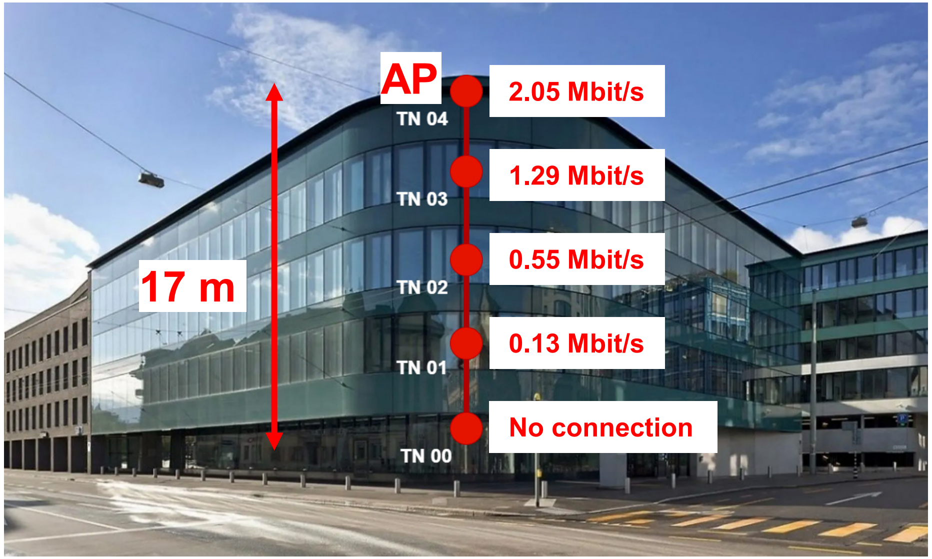
Indoor Performance Measurements: Same Floor



- RSSI and throughput reduce with larger number of separating walls between AP and STA
  - Exception: Room TNO4_23 has larger RSSI than TNO4_19, despite larger distance to AP
    → Likely multipath-propagation impact
- Larger RSSI required for given throughput than with coaxial cable test → External Interference?

Indoor Performance Measurements: Different Floors

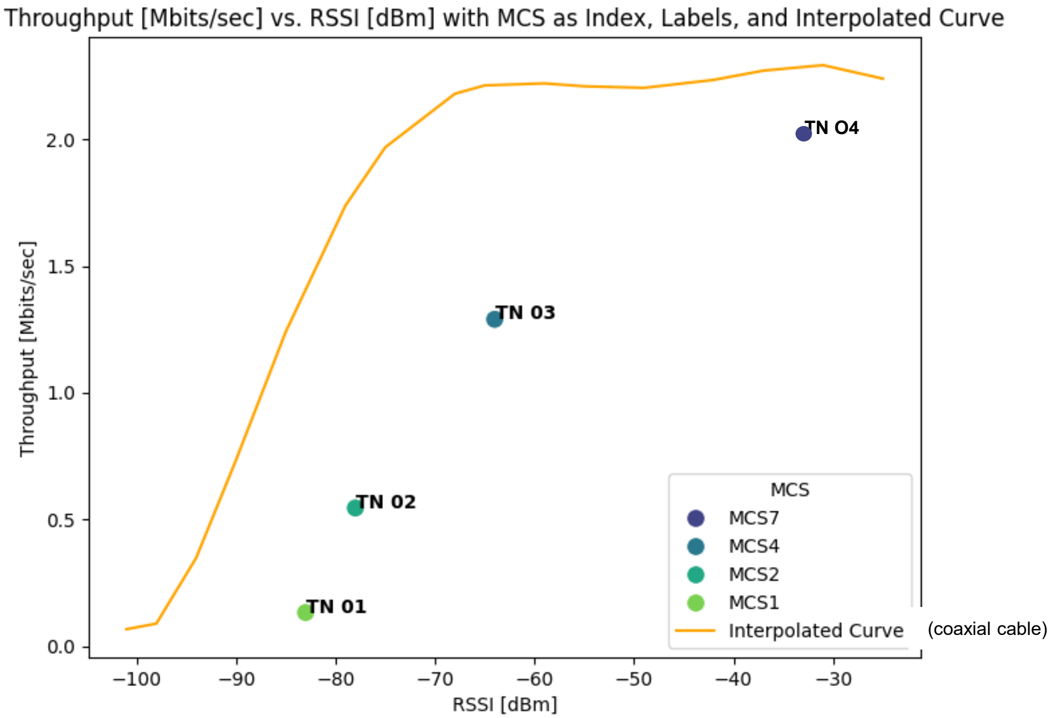
Building layout with throughputs, ZHAW building TN, Winterthur



- Measured throughput across 3 reinforced concrete floors: 0.13 Mbit/s
- No connection across 4 floors → 2 APs may be sufficient in this mid-sized office building

Source: ZHAW ISC

Indoor Performance Measurements: Different Floors



- RSSI and throughput reduce with larger number of separating floors between AP and STA
- Larger RSSI required for given throughput than with coaxial cable test → External Interference?

Outdoor Performance Measurements

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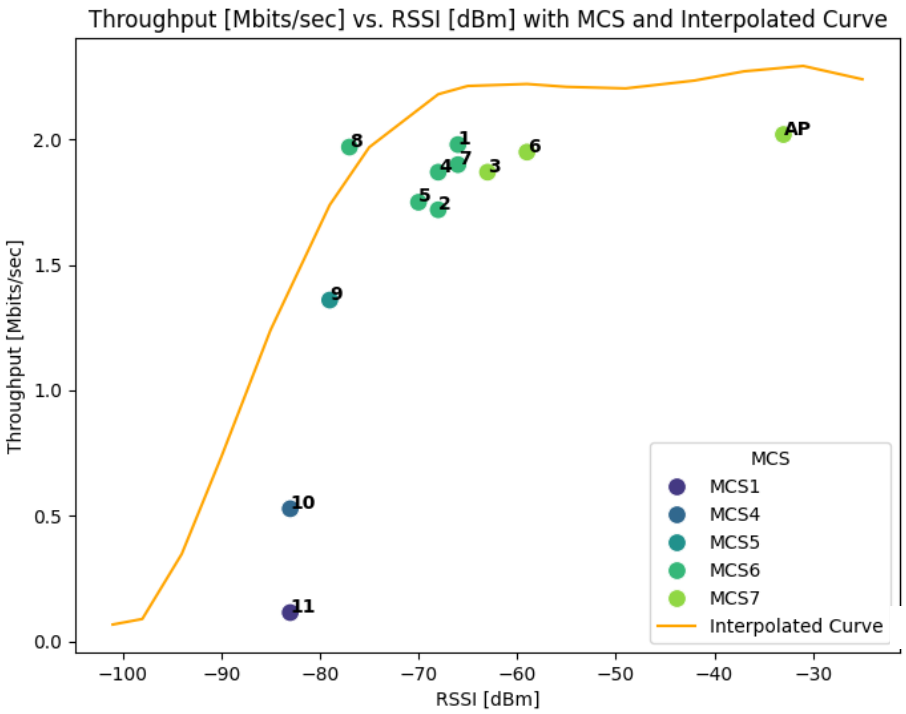
Map with throughputs, Technikumstrasse, Winterthur, partial line-of-sight

- Measured throughput at 230 m distance: 0.11 Mbit/s
- No connection for larger distances

Source: swisstopo

Outdoor Performance Measurements



(coaxial cable)

- Reasonable agreement with with coaxial cable test

Next Steps

- Can WiFi HaLow be used in low-power IoT Applications? Is it competitive?
- Indoor coverage test in other building (ZHAW TE building Winterthur)

Next Steps

- Planned: Performance comparison between HaLow, mioty, and LoRa regarding
  - range
  - packet error rate
  - power consumption
  - data rate
  - etc.

- Paper Release planned in 2025

Summary

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- Throughput limited to ≈ 2.3 Mbit/s due to regulatory bandwidth restriction of 1 MHz
- The beacon frames use up a large proportion of the 10 % regulatory duty-cycle allowance
- Transmit power of NRC7394 may exceed regulatory limit of 14 dBm ERP when antenna gain $G_{ant} > 0\ dBi$
- Higher coupling loss and lower frequency-band results in larger coverage range compared to standard Wifi
- For indoor coverage 1 AP every 2..3 floors in mid-sized office building may be sufficient
- For outdoor coverage 1 AP may cover a small campus (range ≈ 200 m with partial line-of-sight)

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