Measurement Study of IEEE 802.11ah Sub-1 GHz Wireless Channel Performance

Stefan Aust
Strategic Technologies Development Group, Incubation Division
NEC Communication Systems, Ltd.
Kawasaki, Kanagawa 211-8666, Japan
aust.st@nec.com

2024 IEEE 21st Consumer Communications & Networking Conference (CCNC) | 979-8-3503-0457-2/24/$31.00 ©2024 IEEE | DOI: 10.1109/CCNC51664.2024.10454693

***Abstract*—The IEEE 802.11ah WLAN Study Group had their kickoff meeting in 2011 to amend the IEEE 802.11 wireless standard by adding license exempt sub-1 GHz frequencies, which are available in different areas around the world. In this paper, a first version of a commercially available and certified IEEE 802.11ah system is tested and analyzed. The performance study includes the measurement of data transmissions in regionally available sub-1 GHz channels, which are in compliance with Japanese regulators for indoor and long-range outdoor deployments. The wireless measurements include different channel widths (1 to 4 MHz) and multiple sending rates (up to 10 Mbps). Test results indicated that significant data transmission limitations exist, which will be removed in a later release. The long-range performance was analyzed and up to 3 km transmission range was found plausible. The tested 802.11ah model is an interesting candidate for dense network deployments and future research.**

***Index Terms*—IEEE 802.11ah WLAN, Wi-Fi HaLow, sub-1 GHz, 920 MHz, M2M, IoT, channel bandwidth**

I. Introduction

The IEEE 802.11ah standard was completed in 2016 [1] and was titled by the Wi-Fi Alliance as Wi-Fi HaLow (trademark) [2]. National regulators soon started considering the harmonization of use cases which are different for each location. Hence, each national regulator had their own frequency spectrum compliance program defined. In Japan the Association of Radio Industries and Businesses (ARIB) is in charge of the national frequency spectrum so that sub-1 GHz and low-power wide-range IoT communication systems can coexist, e.g., passive systems vs active systems [3]. The duty cycle is an important technique to mitigate selfish use of the spectrum by dominant systems [4]. A different approach is to reduce the sending power of the access points (APs) and the stations (STAs). The device under test (DUT) in this study is limited in its features, and only a single antenna configuration is supported. The DUT has a maximum wireless coverage range of 3 km and supports 10 mW sending power [5]. Because the DUT is new to the Japanese market, only a limited number of sub-1 GHz channels are available for testing. Available channel bandwidths (BW) include 1, 2, and 4 MHz for data transmission, with specific long-range wireless coverage at 4 MHz BW and modulation and coding scheme (MCS) between 0 and 7.

II. Device Under Test (DUT)

The IEEE 802.11ah AP in this study is a compact wireless unit (126 mm x 75 mm x 24 mm), with 1 single antenna port for 920 MHz signal transmission, and 1 single LAN port (RJ-45 connector) for network access [6], [7]. The LAN port provides 100 Mbps (100Base-TX) and makes it simple to integrate the AP into any IP-based network, such as home, office, or logistic centers. The antenna port allows the attachment of an 920 MHz external antenna. Multi-antenna transmission is not supported by the DUT. The DUT is equipped with a micro-server allowing the AP to be configured from a terminal, i.e., laptop or PC. The micro-server provides the settings for login, security, network masks, channel selection, channel bandwidth, sending power, and duty cycle. The server also reports when an active STA is associated with the AP by indicating its IP-address, name, and connection status. The settings for the duty cycle are variable, however the DUT, in the current firmware version 4.10, only allows the setting of 60 s with 1/10 duty cycling. Thus, for wireless testing, the tests were executed within 5s to avoid any duty cycle operation during testing. AP sending power was selected as default (100%), equal to 10 mW.

The AP provides management settings, such as automatic channel selection. If selected, channels cannot be modified; thus, switching off the automatic channel selection enables a manual configuration of the target sub-1 GHz frequency band. These are for 1 MHz BW: 921, 923, 924, 925, 926, and 927 MHz carrier frequency; for 2 MHz BW: 923.5, 924.5, 925.5, and 926.5 MHz carrier frequency; for 4 MHz BW: 924.5, and 925.5 MHz carrier frequency. The STA simply associates via the antenna to the AP and connection is established. In contrast to the AP's micro-server settings, the STA settings are somewhat different in a way that no wireless channel can be selected. The AP controls the wireless connections to all STAs within the wireless coverage. Research about the DUT concluded that the wireless driver used in the AP and STA has strong similarities to the Newracom 7292 driver, also referred to *NRC7292* [8]. This driver supports channel widths at 1, 2, and 4 MHz with optional short guard interval (SGI), with data transmissions from 150 kbps up to 15 Mbps and rates between MCS0-MCS7, MCS10 (1 MHz only).

III. DUT testing setup

A. DUT limitations

The testing limitations were as follows:

- The DUT modules can only be used in Japan due to the regulatory spectrum compliance.
- The DUT modules have a limited access of parameter settings, e.g., limited selection of available frequencies. Signal power can be tuned from 100% down to 5%, where 100% equals 10 dBm (10 mW) and is configured in units of percentage.
- According to ARIB, the duty cycle is 360 s/h. Because the duty cycle limits the wireless performance, the default settings were applied, which is 60 s resulting in a 6 s active sending window (1/10). Measurements where conducted within 5s and whenever the duty cycle went active, testing was stopped and resumed after few seconds (the wireless driver restarted the internal duty cycle timer).

B. DUT configuration

The DUT testing setup is presented in Fig. 1, indicating the AP's and STA's indoor configuration, with a 5 m distance. Because the DUT is certified for unlicensed use, no specific environment (shielded room, anechoic chamber) was needed. The AP used a self-configured IP address which was 169.254.218.90/16, port 5201. The STA used an IP-address (assigned by the AP) which was 169.254.20.35/16, port 56592, connected to the AP via port 5201, see Fig. 1. For the testing iperf3, version 3.1.3 (latest stable version), for Windows 64bit, was used [10]. UDP data traffic was applied with 1 stream (200 Byte blocks, variable target bitrate), and continuous streaming for 5s to avoid active duty cycling. AP as well as STA were connected via LAN cable to separate host PCs (Windows 10). AP's configuration settings were visible at the host PC's web-browser, IP:169.254.111.100, and the STA's settings were visible at IP:169.254.111.111 at the client host. A 3rd host PC (Windows 10) was configured as a wireless spectrum monitor, consisting of a USB software defined radio (SDR) dongle [11] and the free open-source software spectrum monitor HDSDR [12]. The dongle has a frequency range of 100 kHz-1.75 GHz. The HDSDR uses the dongle to monitor the signal power over time (waterfall). The spectrum monitor is useful to verify that no other 920 MHz terminals are in the vicinity and to observe the DUT's transmitted signals.

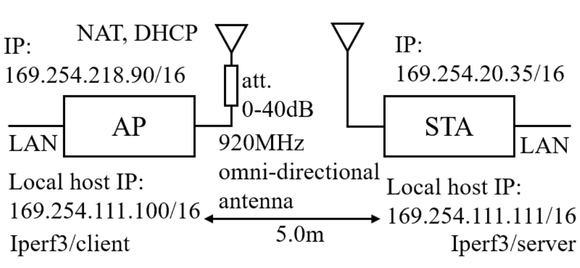

Fig. 1. DUT test configuration with attenuation for long-range tests.

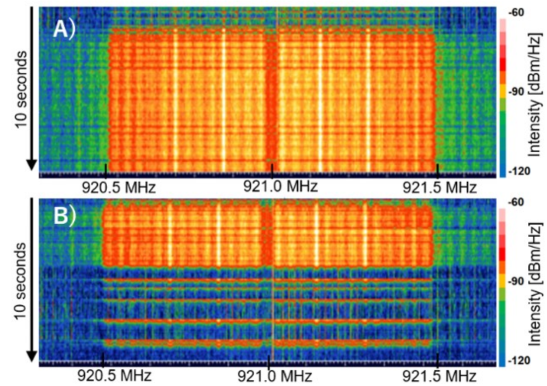

Fig. 2. DUT spectrum, 1 Mbps target bitrate, fc=921 MHz, 1 MHz BW, A) no duty cycle, B) with duty cycle (x-axis: freq. [kHz], y-axis: time[s]).

IV. Observations and Findings

The general operation of the AP/STA communication is presented in Fig. 2, A). It shows the spectral characteristic of the 1 Mbps target bitrate data transmission with iperf3 over 5s in the 921 MHz band. The pilot signals (white lines) of the OFDM PHY signal can be observed clearly. Next, Fig. 2, B) presents the same configuration. However, during this test, the wireless driver (NRC7292) activated the duty cycle operation, triggered by its internal timer settings, causing increased packet loss and jitter, due to alternating (start/stop) the data transmission over an extended time period. Observed time intervals of the duty cycle in Fig. 2, B) are approximately between 300-500 ms.

The spectrum monitoring has shown different PHY operations for 1, 2, and 4 MHz. In the case of 2 MHz BW, there is a lower band, and a higher band. Fig. 3 shows the carrier frequency f_c=924.5 MHz, 2 MHz BW constellation when the STA connects to the AP. First, AP and STA utilize the lower band, as shown in Fig. 3, A), i). This lower band is used for transmitting management frames between the AP and STA. After the initial negotiation, the lower band and the higher band are utilized for data transmission, as shown in Fig. 3, A), ii). The same spectrum characteristics were observed at f_c=926.5 MHz, 2 MHz BW as shown in Fig. 3, B) i) and ii).

When using the 4 MHz BW configuration, there are 2

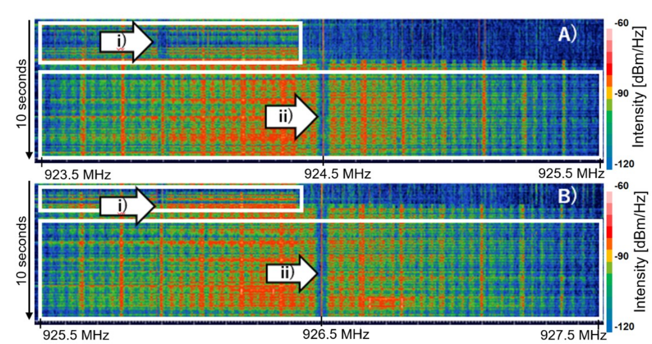

Fig. 3. AP/STA handshakes A) fc=924.5 MHz, B) fc=926.5 MHz, 2 MHz BW.

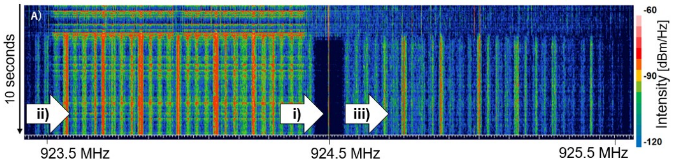

Fig. 4. Spectrum with ii) high utilization and iii) low utilization.

channel bands higher than f_c and 2 bands lower than f_c, see the middle-bands in Fig. 4, i) at f_c=924.5 MHz. The spectral observation concluded that the higher bands are less used, Fig. 4, ii) compared to the lower bands, Fig. 4, iii). An explanation for this finding is that the implementation of the wireless driver prioritizes the sending of management frames as well as data frames in the lower bands, resulting in an elevated sending probability compared to the higher bands.

Next, the spectral image of the 4 MHz transmission has shown a different spectral pattern compared to 1 MHz BW and 2 MHz BW (compare Fig. 2, Fig. 3, and Fig. 4). However, this spectral observation is due to the fact that the wireless driver reduces the subcarrier power at the band edges to suppress out-of-band emissions, especially for the 4 MHz band, which would have a longer reach. Hence, the observed differences in the spectral images.

Next, sporadic, but visible energy bursts outside the active channels were observed, see Fig. 5 , i) at fc=926 MHz, 1 MHz BW. However, since the testing was not conducted in a controlled environment, indoor reflections may have caused such events. Additionally, SDR imperfections are known for producing internal signals showing up as spectral events [11].

V. Long-range Observations and Discussion

A transmitting antenna located in free space (in the absence of multi-path propagation), follows the *Friis transmission* [13]:

$$\frac{P_{rx}}{P_{tx}} = G_{tx}G_{rx}\left(\frac{\lambda}{4\pi d}\right)^2, \tag{1}$$

with P_{tx} and P_{rx} as the transmitted and received power in [dB], respectively. G_{tx} and G_{rx} are the antenna gains in [dBi] at the transmitter and the receiver, λ as the wavelength [Hz], and d as the distance [m]. The basic path loss PL_{ref} between isotropic antennas over d in [km] is given by [14]:

$$PL_{ref}(dB) = 32.44 + 20\log_{10} f_{MHz} + 20\log_{10} d_{km}. \tag{2}$$

To estimate the long-range path loss characteristics, PL_{ref} is calculated at f_c=921 MHz. The model in (2) is used to judge the DUT long-range performance. Following (2), an applied attenuation of 20 dB at the AP's antenna, see. Fig. 1, equals a 1 km distance path loss between AP and STA (subtracting near-pathloss at 100 m with 72 dB to judge the long-range path loss characteristics). With 40 dB attenuation, a significant increased jitter was observed, see Fig. 6, at fc=924.5 MHz, 4 MHz BW. It was also accompanied by increased packet loss at 40 dB attenuation, see Fig. 7. More than 40 dB attenuation resulted in link disruptions. The conclusion is that the DUT supports 1 km distance and beyond, because even at 40 dB attenuation a link measurement was possible. However, since the antenna were at near distance (5 m), antenna gains should be considered (6 dBi) as indicated in (1). Following (2), a 30 dB path loss would equal 3 km distance, which is claimed as the long-range performance of the DUT in [5].

Finally, it was found that the data transmission in all measurements could not achieve higher sending rates than 1 Mpbs (1, 2, and 4 MHz BW) before the packet loss increased up to 20% for UDP traffic, see Fig. 8. The measured jitter performance remained low at 8 ms, 6 ms, and under 6 ms for 1, 2, and 4 MHz BW, respectively. This observation is shown in Fig. 8 A), B), C) for all possible channels. Additionally, the increased packet loss, starting at 0.8 Mpbs, can be observed in Fig. 8 D), E), F). Hence, there must be a limitation somewhere in the system, because the NRC7292 driver is specified to support up to 15 Mbps [8], [9]. The wireless driver has disabled aggregated data streams in the current DUT version, which will be removed in future driver updates.

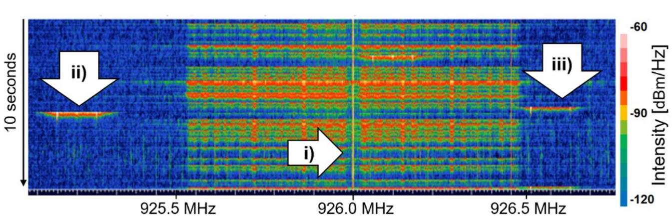

Fig. 5. Sporadic energy bursts ii) in the lower and iii) higher band.

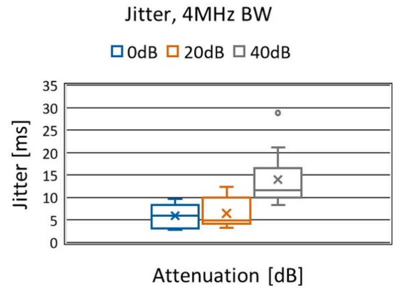

Fig. 6. Long-range performance with 3-fold increased jitter at 40 dB (att.).

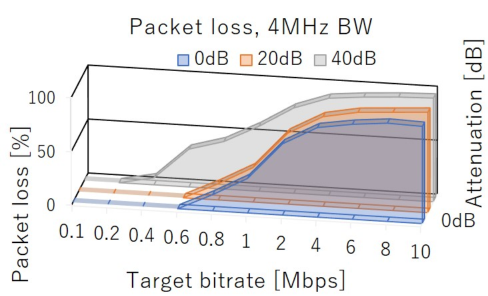

Fig. 7. Long-range performance, with packet loss at 400 kbps (40 dB att.).

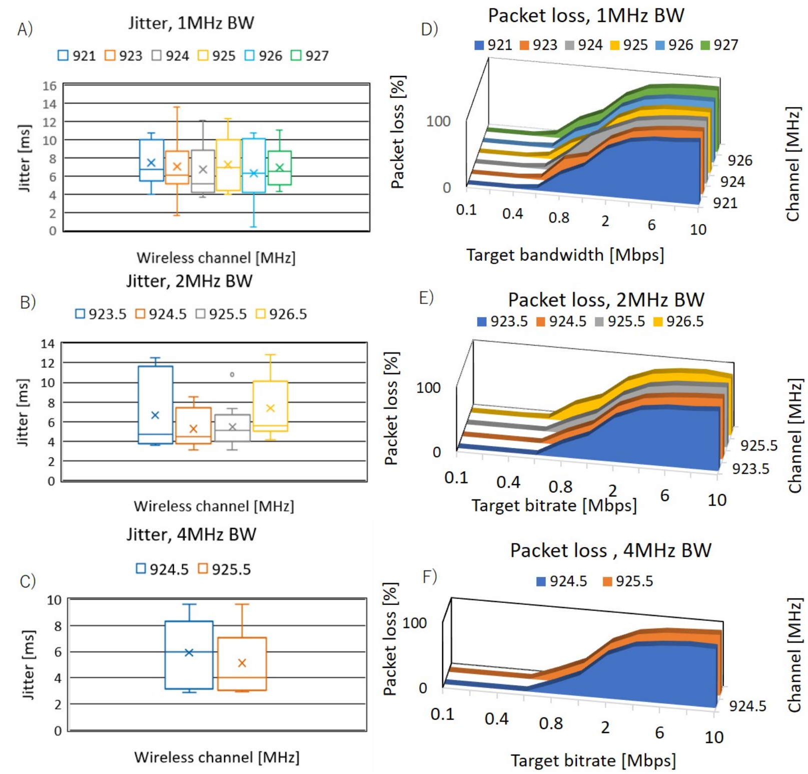

Fig. 8. DUT measurement results of 1, 2, and 4 MHz BW. A), B), C) showing jitter [ms], D), E), and F) showing packet loss [%].

Conclusions

A first version of a commercially available and certified sub-1 GHz IEEE 802.11ah module, operating in the Japanese frequency bands between 921-927 MHz, was tested and analyzed. Basic physical (PHY) and media access control (MAC) functions were tested (modulation, channel settings, and duty cycle). Different channel bandwidth settings were measured at 1, 2, and 4 MHz, indicating a throughput performance at 1 Mbps. Inactive data aggregation in the device under test (DUT) has been identified as a cause for the limitation. Next, a long-range measurement was conducted (indoor, with attenuators). It was found that the DUT supported a setup in which 1-3 km long-range coverage is plausible. Next, spectrum observations have reveiled an uneven use of the transmission channels and as a cause, DUT characteristics were discussed. DUT limitations include single antenna, sending power (10 mW), and a progressive duty cycle, causing increased packet loss and jitter. The DUT sending rate is limited at 1 Mpbs, although the wireless driver is designed to achieve up to 15 Mbps, indicating significant performance gains in future wireless driver releases.

Acknowledgment

The authors would like to thank Silex Technology, Kyoto and NICT, Japan.
In memory of Shusaku Shimada (Yokogawa Electric, Japan).

References

[1] IEEE Standard for information technology - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Amendment 2: Sub 1 GHz, IEEE Computer Society, 2016.
[2] Wi-Fi certified HaLow, long range, low power Wi-Fi for IoT, https://www.wi-fi.org/discover-wi-fi/wi-fi-certified-halow, last access: 3/20/23.
[3] ARIB STD-T108, 1.4, 920 MHz-Band Telemeter, Telecontrol and Data Transmission Radio Equipment, ARIB Standard, Association of Radio Industries and Businesses, 4/23/21, https://www.arib.or.jp/kikaku/kikaku_tushin/desc/std-t108.html, last access: 3/25/23.
[4] S. Aust, R.V. Prasad, I.G. Niemegeers, "Outdoor long-range WLANs: A lesson for IEEE 802.11ah," IEEE Commun. Surv. Tutorials 17 (3), pp. 1761-1775, 2015.
[5] Silex Technology, "First Commercial 802.11ah (HaLow) Wireless Access Point AP-100AH-Easily Deploy your First 802.11ah Infrastructure Network,", AP-100AH Product Brochure, 2023.
[6] IEEE 802.11ah wireless access point, AP-100AH, User's Manual (in Japanese), www.silex.jp, last access: March 20th, 2023.
[7] S. Aust, "On the resilience and coexistence of IEEE 802.11ah sub-1 GHz WLAN," 13th Int. Workshop on Resilient Network Design and Modeling (RNDM), 2023.
[8] Gateworks, GW16146 802.11ah HaLow Mini-PCIe Radio Module, Silex SX-NEWAH module, Newracom NRC7292, 2023.
[9] NRC7292 Evaluation Kit User Guide (S1G Channel) - Ultra-low power & Long-range Wi-Fi, https://github.com/newracom/nrc7292_sw_pkg/issues/28, last access: Feb. 10th, 2023.
[10] iPerf - The ultimate speed test tool for TCP, UDP and SCTP, https://iperf.fr/iperf-download.php, last access: Feb. 1st, 2023.
[11] NESDR RTL-SDR dongle (100 kHz-1.75 GHz), https://www.nooelec.com/store/sdr/sdr-receivers/nesdr.html, last access: Feb. 1st, 2023
[12] High Definition Software Defined Radio (HDSDR), https://www.hdsdr.de, last access: Feb. 10th, 2023.
[13] L. Barclay, Propagation of Radiowaves - 2nd Edition, The Institution of Electrical Engineers (IEE), 2003.
[14] D. Parsons, The Mobile Radio Propagation Channel, Pentech Press limited, London 1992.