On the Resilience and Coexistence of IEEE 802.11ah Sub-1 GHz WLAN

Stefan Aust
Strategic Technologies Development Group, Incubation Division
NEC Communication Systems, Ltd.
Kawasaki, Kanagawa 211-8666, Japan
stefanaust@ieee.org

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***Abstract*—Sub-1 GHz wireless local area networks (WLANs) have gained significant interest in the wireless community due to their long-range coverage and high penetration of obstacles at low frequencies. This study summarizes the transmission performance results of IEEE 802.11ah sub-1 GHz WLAN modules, operating in the license exempt 920 MHz channel bands, which are readily available. Transmission performance was analyzed and system settings for optimal quality of experience (QoE) configuration were identified, which are of importance for long-range remote control and teleoperation use cases. Further, spectrum measurements were conducted to identify any coexistence issues caused by legacy sub-1 GHz wireless sensor devices. Measurement findings were discussed and directions on future IEEE 802.11ah WLAN research were presented.**

***Index Terms*—IEEE 802.11ah WLAN, Wi-Fi HaLow, sub-1G Hz, QoE, jammer, wireless coexistence**

I. Introduction

The IEEE 802.11ah wireless LAN (WLAN) standard activities started in 2011 when topics of Internet-of-Things (IoT) and Machine-to-Machine (M2M) gained significant attention in the wireless community [1]. Use cases include smart grid, IoT, massive M2M communication, in areas such as home, office, industry, health, vehicles, and logistics, operating in the sub-1 GHz frequency band. Recently, due to the activities in the field of wide-area wireless networks and Tactile Internet (TI), other use cases, such as remote control and teleoperation, are areas of interest related to IEEE 802.11ah systems [2], [3]. In these systems, user expectations with high quality assurance for data transmission of sensor data, audio and video, are of importance; thus, teleoperation requires an optimal quality of experience (QoE) performance, even in wireless systems, such as IEEE 802.11ah WLANs (named by the Wi-Fi Alliance as *Wi-Fi HaLow* [4]). When IEEE 802.11ah and other sub-1 GHz devices are operating in the license exempt sub-1 GHz band, coexistence becomes a challenging task. Previous deployed sub-1 GHz sensors in logistics and container terminals have their own implemented wireless coexistence strategies, such as energy detection (ED) of wireless signals emitted by other wireless sensors [5]. In contrast, IEEE 802.11ah uses carrier sense multiple access - collision avoidance (CSMA-CA) to mitigate data transmission errors. Additionally, IEEE 802.11ah and other sub-1 GHz sensors have different data rate performance. Sub-1 GHz sensor devices provide low to moderate data rate, whereas IEEE 802.11ah WLAN provides higher data rates, while operating in the same frequency bands. Hence, field tests are needed to identify the operation of IEEE 802.11ah modules, while in the presence of other sub-1 GHz wireless sensors. This study has two objectives, which are finding first the system settings for optimal QoE operation, and second any coexistence issues, which would become relevant for the system performance of the measured modules.

II. Related Work

The IEEE 802.19.3-2021 standard in [6] addresses the concerns regarding the coexistence of IEEE 802.11ah and other sub-1 GHz devices, such as IEEE 802.15.4g, operating in the sub-1 GHz frequency bands. It includes recommendations, a guidance, and best practices for coexistence in the license exempt sub-1 GHz frequency band. Coexistence mechanisms and related issues are included, addressing IEEE 802.11ah WLAN, IEEE 802.15.4g and other low power wide area networks (LPWANs), e.g., IEEE 802.15.4w, LoRaWAN (Long Range Wide Area Network), and Sigfox. A simulation study in [6] has shown that IEEE 802.11ah performs at high levels of data transmission, while in the presence of other sub-1 GHz systems. However, challenges occurred for IEEE 802.11ah systems, when the network topology was changed to a higher number of wireless nodes, indicating that wireless coexistence, carrier sense (CS), and other medium access control (MAC) related network optimization needs further investigation.

The authors in [7] reported on the resilience requirements for the TI when using wireless multipath. To improve the resilience, an adaptive forward error correction (FEC) and network coding method was applied to wireless signal paths to mitigate latency issues. Simulation results included Long Term Evolution (LTE) and Wi-Fi, showing an error reduction of up to 10% for optimal path allocation.

The authors in [8] reported about their findings on QoE and quality of decision (QoD) in wireless communication for digital twins and remote robotic operations. Addressed challenges included the compression of multimedia streams for machine decision-making based on quality of decision (machines) and the enhancement of multimedia streams for human perception based on QoE (humans).

Research work related to the IEEE 802.11ah WLAN physical layer (PHY) and MAC has been reported in [9] and [10], respectively. The PHY implementation results (MATLAB, m-files) are available for download, including additional work related to IEEE 802.11af. The research on the IEEE 802.11ah MAC has shown that many challenges still exist as to this day, including the negative impact of hidden terminals, which was solved with dynamic address allocation so some extent. However, centralized node management, dynamic reconfiguration, and support of large-scale networks, as for IoT and M2M, remaining largely unsolved.

Impacts of ready to send/clear to send (RTS/CTS) jamming attacks on IEEE 802.11ah MAC, based on simulations, have been reported in [11]. The authors concluded that beside the large number of IEEE 802.11ah MAC features, vulnerabilities related to RTS/CTS attacks still exist, resulting in serious network damage. To conclude the related work, no research work has addressed the data transmission performance and QoE of readily available IEEE 802.11ah WLAN hardware, while in the presence of a sub-1 GHz jammer; therefore, this study was conducted.

III. DEVICE UNDER TEST (DUT)

A. IEEE 802.11ah WLAN (The DUT)

This study utilizes IEEE 802.11ah commercially available WLAN modules (in Japan) as device under test (DUT) [12], [13]. The PHY and MAC of IEEE 802.11ah was designed for wireless operation in the sub-1 GHz bands, which are available in different locations, including U.S., South Korea, Japan, Europe, China, Australia, and other regions. Examples of utilized regional channels are 902-928 MHz in the U.S., 921-928 MHz in Japan, and 863-868 MHz in Europe [14], [15]. The PHY's minimum channel width is defined at 1 MHz and uses 56 orthogonal frequency division multiplexing (OFDM) subcarriers with 4 pilot tones and a modulation and coding scheme (MCS) up to 256-quadrature amplitude modulation (QAM). Region specific long-range data rates (150 kbps up to 86 Mbps), a supported number of spatial streams, max. Tx-power, and channel widths are listed in [6]. The DUT, size 126 mm x 75 mm x 24 mm, supports up to 1 Mbps, 10 dBm Tx-power (one spatial stream), MCS 0-7 and 10, 921-928 MHz carrier frequencies, 1, 2, and 4 MHz channel width in compliance with the Japanese regulators. The standard MAC supports up to 8191 associated stations (STAs) per access point (AP), with 4-level scalability and grouping features for efficient STA management [6]. The DUT in this study supports up to 10 STAs (675 STAs in a licensed version). Other IEEE 802.11ah features include restricted access window (RAW) and sub-channel selective transmission (SST) for coexistence in large networks, which are not supported by the DUT. As for Japan, the ARIB defines the coexistence rules for 2 different types i) for low-power stations with a CS time of 128 μs, and ii) for stations with a CS time of at least 5 ms [5]. The required duty cycle in the 920 MHz band is 10%, that is 360 s transmission time per arbitrary one hour per radio channel. The DUT is shown in Fig. 1, with sub-1 GHz antenna, LED indicator, LAN port (100 Base-TX), and (external) power connector.

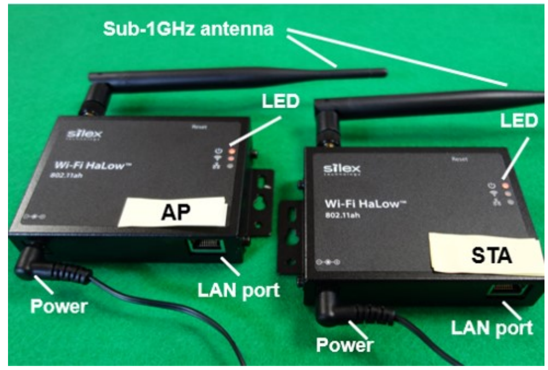

Fig. 1. IEEE 802.11ah DUT with access point (AP) and station (STA).

B. 920 MHz wireless sensors (The jammer)

As a jammer device, two 920 MHz wireless legacy sensor modules (NEC H001-000013-005, manufactured in 2014), size 39.5 mm x 20 mm x 3.9 mm, with 3.0 V and max. 44 mA (sending data) were configured [16], [17]. The module's PHY is a Gaussian Frequency Shift Keying (GFSK) with a proprietary transmission protocol (ARIB STD-T108 compliant), 9.6 kbps data rate at 20 mW, 920.7 MHz-923.3 MHz (14 ch., 200 kHz channel width), with CS at 5 ms. The long-range transmission performance is 400 m at 20 mW. The modules are shown in Fig. 2, with interface board, sensor module, antenna, battery, RS232C interface (UART), and terminator.

Two modules operate as sender (Tx) and receiver (Rx), while the sender is connected via RS232C to a host PC (channel selection, CS settings, start/stop data traffic), the receiver is configured with a terminator so it can respond as an independent sensor. Tx and Rx communication is self-configured during the Rx-scanning period. Tab. I presents the system parameter of the DUT and the jammer.

The objective is to test how IEEE 802.11ah behaves in the presence of the wireless jammer. There may be correlated events, such as packet loss, which will be then analyzed.

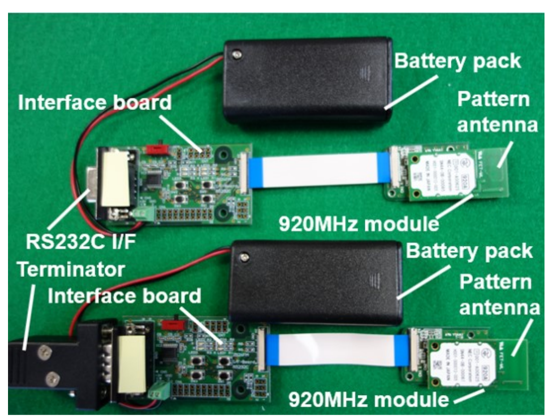

Fig. 2. 920 MHz legacy sensor modules configured as a sub-1 GHz jammer.

TABLE I
SYSTEM PARAMETER SETTINGS OF THE DUT AND THE JAMMER

Parameter settings	DUT (IEEE 802.11ah)	Jammer (920 MHz sensors)
Transmission	OFDM	Proprietary
Modulation	MCS[b] 0-7, 10	GFSK
f_c [MHz]	921	921
Channel width [MHz]	1	0.2
Tx-power[a] [mW]	10	20
Rx-sensitivity [dBm]	-98 (1/2 BPSK)	-92
Carrier sense (CS)	CSMA/CA	ED
Packet size [Byte (B)]	200-800	200
Target bitrate	0.1-0.6 Mbps	9.6 kbps
Wireless range [m]	<3000	<400

[a]Device default settings.
[b]BPSK, QPSK, QAM (16, 64).

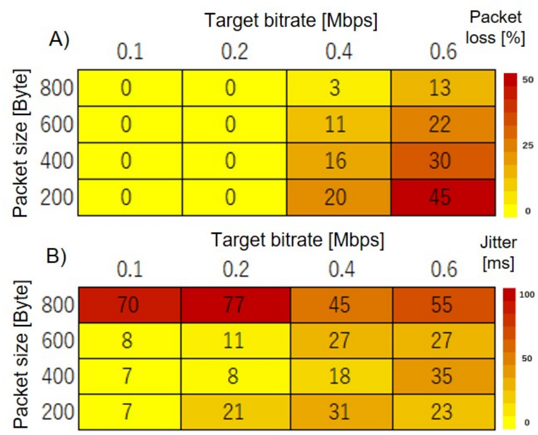

Fig. 4. Heatmap of DUT's A) measured packet loss and B) jitter performance for different target bitrates and packet sizes.

IV. RESILIENCE TESTING (DUT ONLY)

A. DUT performance testing

The objective of this study is to test the resilience of IEEE 802.11ah systems. Only recently, resilience has become a topic of interest, due to long-range wide-area use cases, with ultra-low delay and jitter performance, e.g., for remote control, remote steering and teleoperation. In [6], it is defined that coexistence mechanisms are applied to improve resilience and reliability in a shared environment, at the same time, and overlapping frequency bands. However, teleoperation requires a higher level of resilience (operating regimes with minimal impact from *stressors*, such as packet loss and jitter to reduce user's frustration and anxiety when they occur frequently), which prioritizes the user's experience, or so-called QoE. This study focuses on the user-centric QoE metrics *packet loss* and *jitter* when IEEE 802.11ah is utilized, e.g., in teleoperation systems. The DUT configuration is shown in Fig. 3.

Previous test studies of the DUT have been reported in [18], indicating a constant transmission performance over all available channels (921-927 MHz) and all available channel widths (1, 2, and 4 MHz). The max. data transmission rate of the DUT was identified at 1Mbps, due to the fact that no aggregation is available in the primary version (future wireless driver updates may enable higher data rates). In this study, the variations in UDP packet size (200, 400, 600, 800 B) and target bitrate (0.1, 0.2, 0.4, 0.6 Mbps) and their influence of packet loss and jitter were tested. The tests were conducted with a constant data packet flow, using iPerf3 [19], as outlined in [18]. The results of the measurements are shown in Fig. 4.

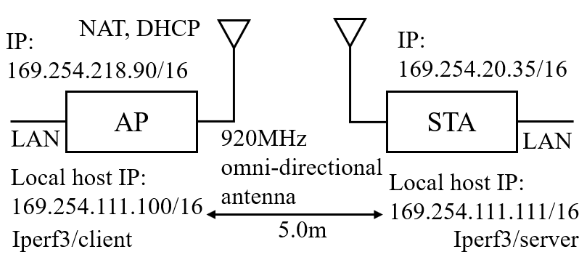

Fig. 3. DUT configuration with IEEE 802.11ah WLAN AP and STA.

In Fig. 4, subfigure A) shows the measured packet loss [%] between the AP and STA, for different packet sizes and target bitrates. No packet loss was observed at low bitrates (0.1 and 0.2 Mbps) and for all measured packet sizes. Packet loss increased at higher bitrates (0.4 and 0.6 Mbps), indicating a higher packet loss (45%) for smaller packet size (200 B). This is due to the fact that a smaller packet size increases the sending rate at higher bitrates; thus, resulting in increased packet loss rate.

In Fig. 4, subfigure B) presents the measured jitter [ms] for different packet sizes and target bitrates. The results indicate that a lower packet size (200-600 B) and lower target bitrate is optimal for low jitter (7-21 ms). Otherwise, a significant increase in jitter (>70 ms) can be observed for 800 B packet size, even at low target bitrates (0.1-0.2 Mbps). To achieve higher accuracy, dedicated network monitoring tools are suggested for future studies.

It can be concluded, that there must be a regime for low target bitrates, to keep the packet loss at zero. Additionally, another regime can be found for low packet sizes and target bitrates, to keep the jitter below 20ms. To further evaluate these findings and to consider the influence on QoE performance, the methods in [20] were applied.

B. Resilience and QoE

To calculate the QoE in terms of packet loss and jitter, based on the DUT's measurements presented in Fig. 4, the following equations have been applied from [20], for the packet loss as reported in Section IV-A:

$$QoE_1 = 3.5e^{-120\,PLR} + 0.5e^{-400\,PLR} + 1\,, \tag{1}$$

with PLR as packet loss ratio, and for jitter [ms], as:

$$QoE_{2a} = 3.56e^{-0.02\,jitter} + 0.35e^{-0.65\,jitter} + 1\,. \tag{2}$$

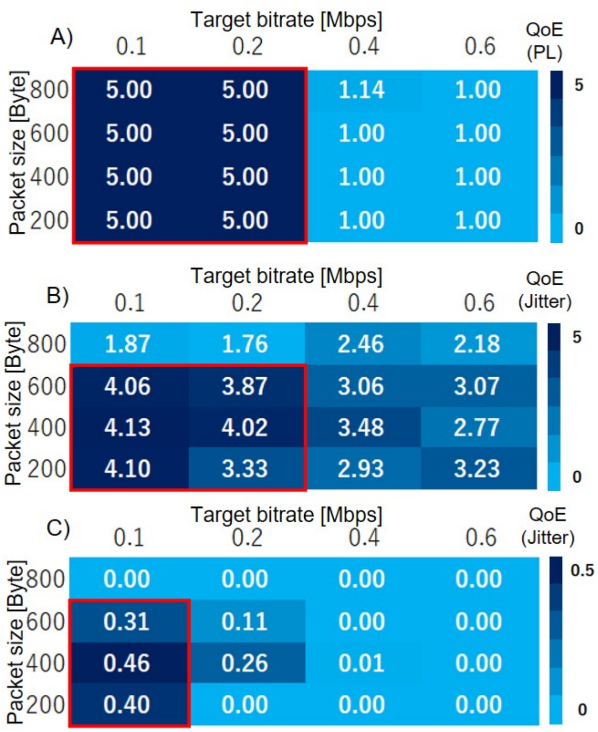

Fig. 5. DUT's QoE performance with A) packet loss (PL) (QoE_1), and B) jitter (QoE_{2a}), C) (QoE_{2b}). Red lines indicate areas of best performing QoE.

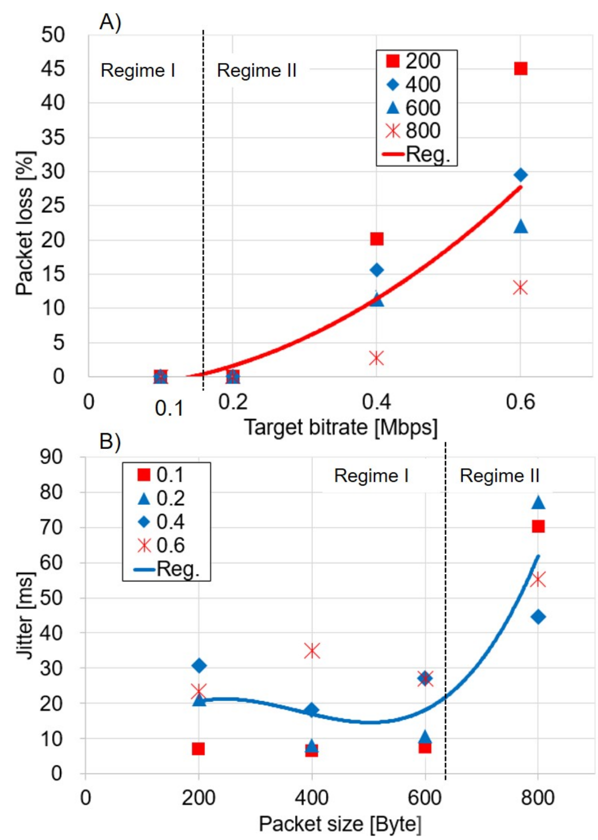

Fig. 6. QoE performance regime identification for packet loss and jitter.

Following the example in [20], for the jitter, a more rigorous model can be applied as:

$$QoE_{2b} = 11.62e^{-3.386\,jitter} + 4.408e^{-0.3477\,jitter}. \quad (3)$$

Equation (1), (2), and (3) transform the measured DUT performance into QoE values, which are highly effective to find operational regimes of preferred QoE performance. Transformation results are shown in Fig. 5.

In Fig. 5, A) the QoE in regards to measured packet loss (PL) is shown based on (1), for different packet sizes (200, 400, 600, 800 B) and target bitrates (0.1, 0.2, 0.4, 0.6 Mbps). Two regimes can be observed, for all packet sizes, in which the QoE value of 5.0 indicates best QoE (depicted with the red lined box), whereas the remaining QoE values are at/around 1.0. Any packet loss in the system is highly punished by (1); thus, resulting in these 2 regimes, indicating best QoE performance for low target bitrates (0.1, 0.2 Mbps). Higher target bitrates would result in packet loss and thus, a significant drop in QoE performance is the result, see Fig. 5, A).

In Fig. 5, B) QoE performance related to the measured jitter is shown, as reported in IV-A, based on (2). Again, a high QoE value, around 4 to 5, indicates best performing QoE (red lined box), while lower QoE values indicate a loss in QoE performance. Only for low/medium packet size (200, 400, 600 B) and low target bitrates (0.1, 0.2 Mbps) high QoE values can be observed. However, if the packet size increases (800 B) a significant drop in QoE performance can be observed, which is due to the measured jitter. Additionally, if the target bitrate is high (0.4, 0.6 Mbps), the QoE performance is reduced, due to the increased jitter from the measurement results.

Finally, the QoE performance can be further analyzed with a more rigorous model, based on (3), that is more sensitive to the jitter performance. Results are shown in Fig. 5, C). Here, only low target bitrates (0.1 Mbps) in combination with low packet sizes (200, 400, 600 B) result in optimal QoE performance (red lined box), whereas other combinations are punished by (3) with zero; thus, an approximation of the best QoE regime can be found.

C. Optimal QoE performance regimes

To conclude the QoE findings in IV-B, further analysis based on the measurements in IV-A is conducted, namely to identify the max. packet size and transmission rate to adjust the DUT for a best performing QoE, following (3).

In Fig. 6, A), the performance of the packet loss is depicted for different packet lengths (200, 400, 600, 800 B) and different target bitrates (0.1, 0.2, 0.4, 0.6 Mbps). The regression line shows the transition of the packet loss when the target bitrate is increased. Following the model in (1), which highly punishes any packet loss, a zero packet loss is preferred; thus, suggesting a max. target bitrate at 150 kbps, as shown in Fig. 6, A), implying a regime with high QoE when the packet loss is zero (Regime I), or low QoE in the presence of any packet loss (Regime II), when the approximations from IV-B are applied.

In Fig. 6, B), the jitter performance is depicted at different target bitrates (0.1, 0.2, 0.4, 0.6 Mbps) and packet sizes (200, 400, 600, 800 B), as reported in IV-A.

The regression line shows the transition of the jitter performance when the packet size is increased from 600 to 800 B. A 20 ms jitter cut-off leads to a max. packet size of 620 B; thus, implying a regime with high QoE (Regime I) and low QoE (Regime II).

The best guaranteed DUT's QoE performance is achieved with a max. packet length at 620 B and a max. 150 kbps bitrate. Any increase of the stressor's values would result in QoE performance loss; thus, a user would experience a quality loss due to transmission errors in the communication system.

V. Coexistence Testing (DUT and jammer)

A. Challenges regarding wireless coexistence

The second objective in this study is to identify as to which degree coexistence issues exist when the DUT and other sub-1 GHz systems share the same frequency, while transmitting data concurrently. Coexistence is defined in [6] as the ability of multiple systems (with different rule sets) to perform tasks in a given shared environment, at the same time, at the same frequency. Further, [6] gives an overview of the available coexistence methods which are classified in i) active and ii) passive coexistence techniques. Active coexistence is when some wireless systems perform CS to mitigate transmission failures, e.g., CSMA/CA or ED. However, almost all wireless systems apply a passive coexistence strategy, such as forward error correction (FEC) and/or frequency hopping (FH). Both, the DUT and the jammer, provide CS and FEC.

B. Sub-1 GHz coexistence testing

The DUT/jammer configuration is shown in Fig. 7. The DUT operates at the constant wireless channel (921 MHz) with 1 MHz channel width. Default settings were applied with no changes on CS or transmit power.

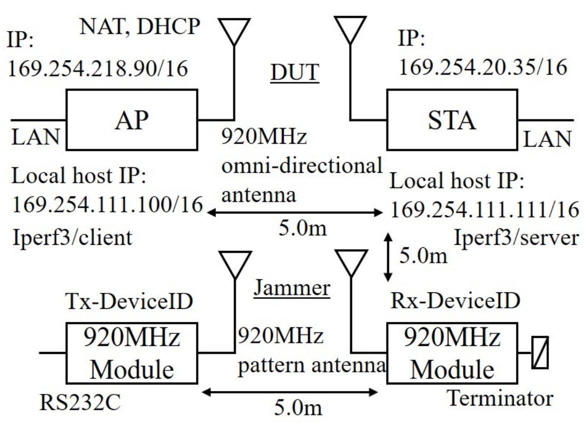

Fig. 7. Wireless DUT/jammer configuration.

During the DUT's testing, it was the objective to avoid any active duty cycle operation, triggered by the DUT's wireless driver. Otherwise, an active duty cycle operation may have caused measurement artifacts during the tests. Additionally, the jammer was configured, consisting of two 920 MHz wireless modules, operating with default settings, at the DUT's wireless channel (f_c=921 MHz), see Tab. I.

Additionally, a wireless spectrum monitor was configured, consisting of a software defined radio (SDR) USB dongle [21] and an open-source spectrum monitoring tool HDSDR [22]. Details of the spectrum monitor configuration are given in [18]. The wireless spectrum monitor is helpful to observe the PHY/MAC behavior of the DUT and the jammer. The assumption is that either the DUT, the jammer, or both may show changes in their data transmission, while in the presence of each other, which can be observed from changes in their spectrum characteristics.

C. Sub-1 GHz coexistence observations (optimal QoE)

Spectrum observations of the coexistence between the DUT and the jammer are shown in Fig. 8. In Fig. 8, A) the start of the DUT data transmission (iperf3, packet size 200 B, target bitrate 0.2 Mbps) can be observed, at i) the carrier frequency f_c=921 MHz, with 1 MHz channel width. The IEEE 802.11ah pilot signals can be clearly noticed (white lines).

Shortly after, ii) the jammer's data transmission was activated. A higher sending power intensity of the jammer can be observed, indicating a stronger narrow-band (200 KHz) signal of the jammer, compared to the DUT. While the DUT and the jammer were transmitting data concurrently, no data loss occurred, despite the overlapping signals. However, the DUT changes the sending power in the presence of the jammer.

Next, to identify any effect of signal collision beside the carrier frequency, the jammer's channel was modified, so that the signal was present in a higher area of the DUT frequency band. The modified jammers's channel data transmission is shown in Fig. 8, B), with i) DUT's f_c=921 MHz, and ii) the jammers f_c=921.2 MHz. Again, despite the signal collision in the higher band of the DUT, no packet loss was observed.

Finally, to conclude on the effect of signal collision, the DUT data transmission i) was started at f_c=921 MHz, while the jammers's channel frequency ii) was increased to f_c=921.4 MHz. This signal constellation has not resulted in any packet loss at either the DUT or the jammer.

Additionally, the spectrum observations in Fig. 8, A), B), and C) show, that there were no significant changes in duty cycle or CS operation by the DUT, despite the presence of the signal from the jammer. The same is true for the jammer, which does not show significant changes in transmission performance or signal detection. Note, that a thorough analysis of the CS performance (CS detected, lost packets, error rate, etc.) of the DUT was not possible at this moment, due to the lack of deep packet inspection, e.g., promiscuous mode operation in combination with a packet monitoring tool.

Next, a DUT/jamming configuration was configured to observe any changes in both systems, while forced to operate

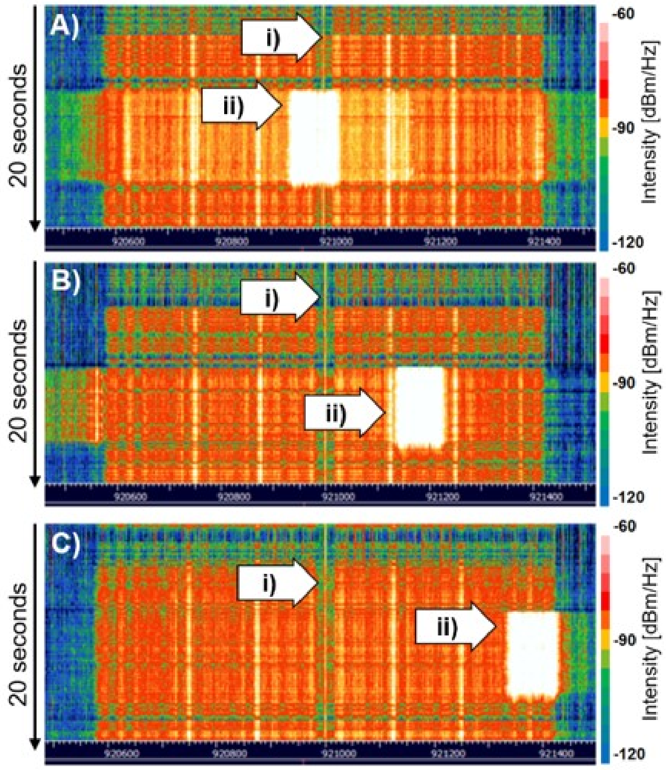

Fig. 8. DUT's transmission at i) f_c=921 Mhz, ii) jamming A) f_c=921 MHz, B) f_c=921.2 MHz, and C) f_c=921.4 MHz (x-axis: freq. [kHz], y-axis: time[s]).

within the same frequency band at the same time. In Fig. 9 i) the jammer's data transmission was activated with an offset f_c=921.2 MHz from ii) the carrier frequency of the DUT f_c=921 MHz. The jammer's signal was active each time for 2 s, with short pause intervals. The three narrow-band jammer's spectrum signals (200 kHz) can be observed in Fig. 9. Next, ii) the DUT signal was started, and shortly after, iii) the next jamming sequence was started, as shown in the spectrum image. Again, despite the forced signal collision, no data loss was observed at the DUT or the jammer. It can be concluded that the passive coexistence mechanisms in both systems, the DUT and the jammer, operate without transmission loss, while in the presence of a jamming signal. Additionally, as observed from Fig. 9, a DUT's activated duty cycle operation could have been present; however, a clear indicator from the DUT's wireless driver was not available.

D. Sub-1 GHz coexistence observations (non-optimal QoE)

To force the DUT/jammer configuration to increase the packet loss (no stressors were found in the optimal QoE regime), the jammer was added, while the DUT was configured with a high bit rate (1 Mbps) and large packet size (800 B), which is a non-optimal QoE regime with high packet loss and jitter. The DUT was sending data traffic for 50 s, while the jammer was active for 10 s, during the DUT's data transmission. Results are presented in Fig. 10.

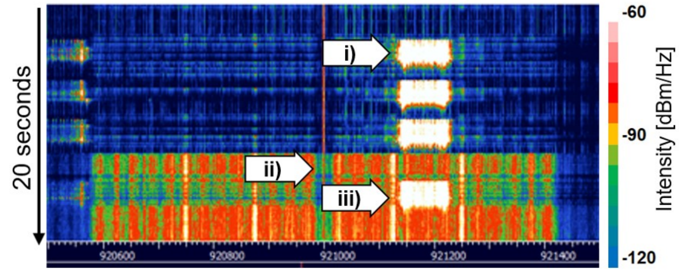

Fig. 9. Jammer i) at f_c=921.2 MHz, during ii) DUT's transmission f_c=921 MHz, with iii) signal collisions (x-axis: freq. [kHz], y-axis: time[s]).

In this scenario the observed (median) jitter (>120 ms) in Fig. 10, A) and packet loss (>45%) in Fig. 10, B) performance is present with/without jammer; thus, concluding that the jammer does not add any significant packet loss or jitter. The overall conclusion is that the duty cycle function has shown an adverse effect on the transmission performance compared to possible coexistence issues. Even in the presence of collided signals, both systems, IEEE 802.11ah and 920 MHz sensors, do operate without significant performance loss; thus, indicating a resilient PHY and MAC. This is due to the fact that the 920 MHz signal is a narrow-band (200 kHz) signal with high intensity, compared to the wide-band (1 MHz) signal of IEEE 802.11ah. A thorough packet analysis will be part of future studies.

VI. Discussion

In [6] it was reported that IEEE 802.11ah transmissions have an impact on the jammers (IEEE 802.15.4g device) packet delivery rate, by lowering the jammers packet delivery and increasing IEEE 802.11ah traffic delivery (findings were based on a simulated network). However, the findings in this study have shown that both, the DUT as well as the jammer, continuously transmit their data (iperf3 traffic) and without any observed reduction in packet delivery rate, packet loss or jitter, in a real wireless network setup. Note, that a thorough packet inspection (error rates) is part of future studies.

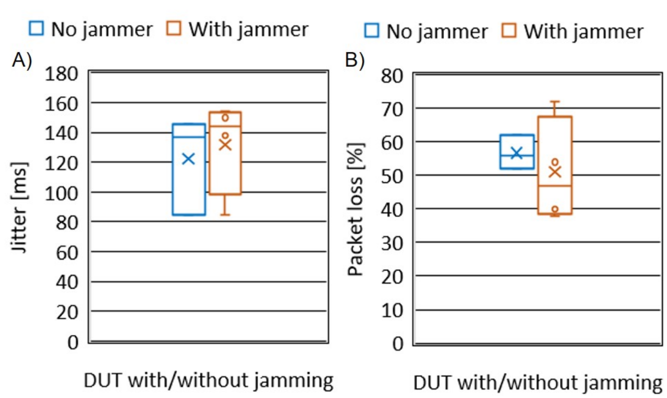

Fig. 10. DUT/jammer tests with forced packet loss (with/without jammer).

Additionally, it was found in [6] that IEEE 802.11ah delivers near 100% of sent data. This study confirms that the DUT is delivering at a high packet delivery rate, while in the presence of the jammer. The spectral observations have shown none or minimal response of the DUT when the jammer started its data transmission. The conclusion is that the DUT provides an efficient passive coexistence scheme, in which FEC would correct any transmission errors, while in the presence of the jammer. Stressors (increased packet loss and jitter) due to duty cycle operations are of higher importance, compared to active/passive coexistence methods. Note, that an active coexistence operation could still be activated in the presence of the jammer, which is hard to observe from the spectrum signals. It would be preferable, if the DUT's wireless driver would have an indicator, such as state of duty-cycle operation, CS detected, etc. More research is needed, e.g., with a higher number of STAs and different PHY/MAC feature settings. Finally, it was stated in [6], that the coexistence methods for both, "... IEEE 802.11ah and iEEE 802.15.4g do not work well in some scenarios.". To conclude the findings, the DUT's data transmission is resilient in the jammer's presence. The same is true for the jammer's data transmission, while in the presence of the DUT.

Finally, it should be noted, that the DUT's performance is highly affected by its duty cycle mechanism (but also significantly by its data rate limitations, i.e., < 1 Mbps, that resulted in non-ideal jitter performance). Measurements in this study were somewhat influenced when the duty cycle becomes active (identifiable/non-identifiable). However, a negative impact due to an active duty cycle was avoided. This is true for the measurements, conducted in IV-A, which have demonstrated an optimal method to approximate the DUT's QoE configuration, that is highly preferable for long-range remote control with high quality experience.

VII. Conclusion

This study presented measurement results of IEEE 802.11ah wireless local area network (WLAN) modules, which are readily available. While basic IEEE 802.11ah WLAN channel measurement results have been reported in a previous study, this paper presents new results, targeting the quality of experience (QoE) performance and optimal device under test (DUT) settings. Although, the DUT in its current form has significant limitations (data rate transmission is < 1 Mbps), optimal QoE was identified, e.g., for resilient teleoperation. This is of importance when IEEE 802.11ah WLAN is used for remote control with demanding requirements (mitigation of stressors, such as packet loss and jitter). Further, spectrum measurements of the DUT demonstrated that data transmission remains unaffected, while in the presence of a (narrow-band) sub-1 GHz jammer.

Future research should examine the transmission performance of IEEE 802.11ah WLAN devices with data rates, that are in the range of the standardized PHY/MAC operation, e.g., > 1 Mbps. This would include multi-stream/multi-antenna PHY/MAC support, with advanced MAC operation for large number of WLAN stations (STAs), while connected to a single WLAN access point (AP). Next, outdoor long-range measurements are of interest to discover the coverage range of IEEE 802.11ah WLANs. Finally, IEEE 802.11ah's coexistence performance and duty cycle operation remain challenging topics which require further investigations.

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