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IEEE 802.19.3 Coexistence Recommendations for IEEE 802.11 and IEEE 802.15.4 Based Systems Operating in Sub-1 GHz Frequency Bands

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Abstract

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Abstract*—Internet of Things (IoT) applications are rapidly increasing. A broad range of low-power wide-area technologies have been developed in the Sub-1 GHz frequency bands to meet various application requirements. Massive IEEE 802.15.4g based systems have been deployed to provide low to moderate data rate capabilities. IEEE 802.11ah is designed to provide higher data rate capabilities than the data rates of IEEE 802.15.4g. In addition, other Sub-1 GHz band systems including LoRa and SigFox are also installed for applications with longer range communication need. There is considerable overlap in use cases targeted by these technologies. Due to the constrained spectrum allocation in the Sub-1 GHz frequency bands, these systems are likely to coexist. Therefore, the coexistence of heterogeneous Sub-1 GHz band wireless technologies becomes an issue to be addressed. Our measurements and simulations reveal significant interference among these systems. Previously the Sub-1 GHz band coexistence is not well addressed. Accordingly, IEEE New Standards Committee and Standard Board formed IEEE 802.19.3 Task Group in December 2018 to develop IEEE 802.19.3 standard for the coexistence of IEEE 802.11ah and IEEE 802.15.4g based systems to guide product deployment. IEEE 802.19.3 standard was published in April 2021. This article summarizes the Sub-1 GHz band systems, spectrum allocation, interference and noise measurements, coexistence issues and coexistence recommendations presented in IEEE 802.19.3. It aims to introduce IEEE 802.19.3 standard to readers outside of IEEE 802 standard body and to application developers to raise awareness of potential coexistence issues and available coexistence techniques for the better system deployment. In addition, this article presents performance evaluation of the coexistence methods recommended in IEEE 802.19.3.

***Index Terms*—Coexistence, spectrum sharing, interference, Sub-1 GHz frequency band, IEEE 802.19.3, IEEE 802.11ah, IEEE 802.15.4g, IoT.**

I. Introduction

As more and more intelligent devices connect to the Internet, the demand for Internet of Things (IoT) applications has been rapidly increasing. A broad range of Sub-1 GHz (S1G) frequency band low-power wide-area (LPWA) wireless communication technologies emerge to address requirements of diverse applications such as wireless smart utility networking (Wi-SUN), smart city, low-energy critical infrastructure monitoring and industrial automation.

IEEE 802.15.4g has been developed to provide low to moderate data rate capabilities. Massive 802.15.4g based devices have been deployed in the market. IEEE 802.11ah has been developed to provide higher data rate capabilities than the data rates of 802.15.4g. The Wi-Fi Alliance is promoting application of 802.11ah. In Japan, 802.11ah Promotion Council (AHPC) has been established to realize commercialization of 802.11ah products in the Japanese market. Typical communication range of 802.15.4g and 802.11ah is 1 km. LoRa, SigFox and IEEE 802.15.4w are technologies for low data rate capabilities with 15 km communication range. In addition, there are other S1G band technologies such as technologies specified in ETSI Technical Specification TS 103 357.

Due to the constrained spectrum allocation in the S1G band and use case overlapping, multiple heterogeneous wireless systems are likely to coexist. Even though there are low duty cycle regulations in the S1G band, interference can still be significant as the number of IoT devices increases. Therefore, ensuring harmonious coexistence of the S1G band wireless systems is clearly important. However, the coexistence of the S1G band wireless technologies had not been well studied. We have proposed prediction based transmission suspension [1], α-Fairness based ED-CCA [2], Q-Learning based CSMA/CA [2] and Q-Learning based restricted access window (RAW) scheduling [3] for 802.11ah. We have also proposed hybrid CSMA/CA [4] and active carrier sense (ACS) based CSMA/CA [5] for 802.15.4g. To the best of our knowledge, no other existing work addresses the coexistence of 802.11ah and 802.15.4g.

Generally, coexistence methods can be divided into active and passive mechanisms. Using an active coexistence mechanism, a transmitter tries to reduce its impact on others. A typical example is the use of carrier sense multiple access/collision avoidance (CSMA/CA). In contrast, a passive coexistence mechanism tries to reduce the impact of other systems on the desired signal. A typical example is the use of forward error correction (FEC) in addition to frequency hopping. IEEE 802.11ah, 802.15.4g and 802.15.4w provide both active coexistence mechanism, as they all offer CSMA/CA, and passive coexistence mechanism, as they all provide FEC. In contrast, LoRa and Sigfox only offer passive coexistence mechanism, the spreading factor by LoRa and multi-channel transmission by SigFox. More specifically, 802.11ah provides an energy detection clear channel assessment (ED-CCA) based CSMA/CA to coexist with other non-802.11 systems. Besides CSMA/CA, 802.15.4g specifies a multi-PHY management scheme using the common signaling mode (CSM) mechanism to facilitate inter-PHY coexistence, i.e., among devices using different 802.15.4g PHYs.

Using standard defined coexistence techniques, how well can these S1G band wireless technologies coexist? Our measurements and simulations show that there can be significant interference among different systems even while operating with a low duty cycle. To provide guidance and recommendations to achieve positive coexistence performance, IEEE New Standards Committee and Standard Board approved formation of IEEE 802.19.3 Task Group in December 2018 to develop an IEEE 802 standard for the coexistence of 802.11ah and 802.15.4g based systems to guide product deployment. Authors of this article led this standard development.

IEEE 802.19.3 standard [6] was published in April 2021. As a Recommended Practice, 802.19.3 aims to provide the best practices and recommendations for the coexistence of 802.11ah and 802.15.4g based systems. This article summarizes the S1G band systems, spectrum allocation, interference and noise measurements, coexistence issues and coexistence recommendations presented in 802.19.3. In addition, it presents performance evaluation of the recommended coexistence methods.

The contributions of this article include: (1) Raise awareness of the S1G band wireless technology coexistence, (2) Present the S1G band coexistence behavior and issue, (3) Provide the S1G band coexistence recommendations, (4) Evaluate performance of the recommended coexistence methods, and (5) Introduce IEEE 802.19.3 standard to readers outside of the IEEE 802 standard body.

The rest of this article is organized as follows. Overview of the major S1G band technologies is given in Section II. Section III summarizes the S1G band spectrum allocation. We present the S1G band interference signal and noise measurements in Section IV. Section V describes interference causes and coexistence issues of the S1G band systems. The S1G band coexistence recommendations are provided in Section VI. Section VII presents performance evaluation of the recommended coexistence methods. We conclude this article in Section VIII.

II. Overview of S1G Band Systems

Many IoT applications require low bandwidth communications over moderate to long distances, while operating at low power. IEEE 802.11ah, 802.15.4g, 802.15.4w, LoRa and Sigfox are the major technologies that fulfill these requirements by using S1G frequency bands. A characteristic of licensed exempt operation around the world is that there can be many different radio systems operating in the same or overlapping frequency bands without coordination.

A. IEEE 802.11ah

IEEE 802.11ah is a wireless communication PHY and MAC layer standard that operates in the unlicensed S1G frequency bands. It defines an OFDM PHY with a minimum 1 MHz channel spacing. This makes it suitable for IoT applications. Frequency band allocation is region dependent, e.g., 902-928 MHz band in the United States and 863-868 MHz band in Europe. 915-928 MHz band has been identified for use in Japan. 802.11ah introduces several features such as RAW for spectrum efficiency and power efficiency. The RAW mechanism reduces contention by clustering stations into RAW groups and slots, only allowing the stations in one group to contend for the channel at any time slot. As such, it effectively combines CSMA/CA and TDMA into a dynamically adaptable MAC scheduler. Application categories for 802.11ah include smart city, smart building/home, smart power, hot spot, monitoring, industry and backhaul.

B. IEEE 802.15.4g

IEEE 802.15.4g was developed to address applications in a smart utility network (SUN) with modest data volume requirements, high tolerance to latency, and a requirement for ubiquitous and reliable delivery. 802.15.4g defines three new PHYs, SUN-FSK, SUN-OFDM and SUN-O-QPSK, to support principally outdoor IoT applications. It enables great flexibility in channelization for a wide variety of bands, with very narrow channel spacing. The flexibility of SUN-PHYs has made it a very popular network solution for IoT applications. The frequency band allocation is region dependent. Examples of S1G bands include the 902–928 MHz band in the United States, 169 MHz and 863–870 MHz bands in Europe and the 920–928 MHz band in Japan. In addition, IEEE 802.15.4x increases the maximum data rate of SUN-OFDM PHY from 800 kb/s to 2.4 Mb/s. Application categories for 802.15.4g include smart utility, smart city, smart building/home, monitoring and industry.

C. IEEE 802.15.4w

IEEE 802.15.4w defines an low-power wide-area networking (LPWAN) extension to the IEEE 802.15.4 low-energy critical infrastructure monitoring (LECIM) PHY layer. This extension is intended to cover network cell radii of typically 10 km to 15 km in rural areas and deep in-building penetration in urban areas. It uses the LECIM FSK PHY modulation schemes with extensions to lower data rates typically lower than 30 kb/s. It extends the frequency bands to additional S1G unlicensed and licensed frequency bands to cover the market demand. For improving robustness in channels with high levels of interference, 802.15.4w defines mechanisms for the fragmented transmission of FEC code-words as well as time and frequency patterns for the transmission of the fragments. The frequency band allocation is region dependent and supports most license-exempt S1G bands, e.g., 902–928 MHz band in the United States, 169 MHz and 863–870 MHz bands in Europe and 920–928 MHz band in Japan. Application categories for 802.15.4w include smart city, monitoring and manufacturing.

D. LoRa

LoRa is a proprietary PHY technology for long-range communication links. Details of the PHY are not disclosed. LoRa uses a modulation based on chirp spread spectrum (CSS). The Long Range Network protocol (LoRaWAN) defines the communication MAC protocol and system architecture for the network on top of the LoRa PHY layer. In contrast to the PHY, LoRaWAN is maintained by the LoRa Alliance and the specifications are the publicly available. LoRa typically operates in the license exempt frequency bands around 900 MHz. LoRa is designed to allow low-power devices to communicate with the Internet applications over long-range wireless connections. Application categories for LoRa include smart agriculture, smart city, industrial IoT, smart homes and buildings.

E. SigFox

SigFox is also a proprietary LPWA networking technology for long range IoT applications. It is based on a very low-rate BPSK modulation for the uplink and GFSK for the downlink. The bandwidth of the uplink channel is region dependent, e.g., 600 Hz in the United States and 100 Hz in Europe. The downlink channel is 1.5 kHz. The very low signal bandwidth enables long range communication that is comparable to 802.15.4w and LoRa. The frequency band allocation for SigFox is region dependent, e.g., 915 MHz in the United States, 868 MHz in Europe and 920 MHz in Japan. Application categories for SigFox include retail, smart city, monitoring and industry.

A feature summary of IEEE 802.11ah, IEEE 802.15.4g, IEEE 802.15.4w, LoRa and Sigfox is given in Table I.

III. S1G Band Spectrum Allocation

The spectrum allocation is constrained, especially in the S1G band, where spectrum allocation varies from country to country. The constrained spectrum allocation in some regions indicates the necessity of coexistence mechanisms. This section summarizes the spectrum allocation in the United States, Europe and Japan.

A. United States

The S1G band spectrum allocation in the United States is specified by the FCC [7]. There are many frequency bands below 1 GHz in which radio frequency devices may operate as defined in the Code of Federal Regulations. General rules given in §15.209 prescribe very low power levels of 200 microvolts/meter (equivalent to less than -49 dBm) for incidental emissions. Higher power levels for fundamental emissions are allowed for specific bands. The 902 MHz to 928 MHz band is the only band that will support both 802.11 and 802.15.4 operations. The band used by systems covered in IEEE 802.19.3 is 902 MHz to 928 MHz, using the provisions of §15.247. Channel plans for this band are provided in both 802.11 and 802.15.4. Operation under this part requires either frequency hopping or a digital modulation.

Operation of 802.15.4 SUN-FSK is considered as frequency hopping systems to comply with this part. The requirements include a minimum channel spacing of 25 kHz and maximum allowed 20 dB bandwidth of the hopping channel of 500 kHz. The SUN-FSK PHY includes modes to meet these requirements with channel spacing of 200 kHz and 400 kHz defined for the band. Per channel duty cycle is limited: for 200 kHz channel spacing, the average time of occupancy on any frequency is limited to not greater than 0.4 seconds within a 20 second period, i.e., 2% duty cycle. For the 400 kHz channel spacing, the average time of occupancy on any frequency is limited to not greater than 0.4 seconds within a 10 second period, i.e., 4% duty cycle. Hopping systems have to use a pseudo-random sequence and the system designed so that all channels in a sequence are used equally on average over time.

Systems using 802.11ah are considered as digital modulation systems under this regulation. To be classified as using digital modulation techniques, the minimum 6 dB bandwidth is at least 500 kHz. The OFDM signal used by 802.11ah is considered as a digital modulation, and uses a minimum channel spacing of 1 MHz. Digital modulation systems are not required to employ frequency diversity, although use of hybrid systems that use both digital modulation and hopping are allowed.

B. Europe

The S1G band spectrum allocation for Europe is specified in Annex B and Annex C of ETSI EN 300 220-2 [8]. Table II lists the most relevant operational bands that are Europe wide harmonized according to Annex B. Operational bands listed in Annex C are not Europe wide harmonized and define additional frequencies between 870 MHz and 920 MHz. Additional spectrum allocations, e.g., for 802.11ah, are already defined in CEPT ERC Recommendation 70-03 [9], and will be included in the upcoming version of ETSI EN 300 220-2. Many European states have already adopted the use of 802.11ah in the frequency range 863–868 MHz. The frequency regulation defines a bandwidth between 600 kHz and 1 MHz, a maximum transmit power of 25 mW, and a duty cycle of 2.8% for end devices and 10% for an AP.

The latest version of ETSI EN 300 220-2 allows the use of polite spectrum access instead of a classical duty cycle restriction. The polite spectrum access is a precise definition of CCA and timing parameters, e.g., a maximum transmit duration of 1 second for a single transmission. The maximum duty cycle is given by 2.7% per 200 kHz portion of spectrum usage. The duty cycle can be significantly increased if a narrow-band system uses frequency hopping. A system with a bandwidth of less than 200 kHz hopping in the 600 kHz wide band M could therefore reach a duty cycle of 8.1%. This means a significant extension compared to the classical 1% duty cycle.

C. Japan

Japanese standards ARIB STD-T106 [10], ARIB STD-T107 [11] and ARIB STD-T108 [12] specify the S1G band spectrum allocation in 920 MHz band for IoT devices based on radio type and transmission power. These standards regulate the spectrum for different use cases. ARIB STD-T106 specifies the regulation for RFID equipment that uses the frequency range between 916.7 MHz and 920.9 MHz. The target system is the high power passive tag system. The interrogators typically transmit powers of 1 W or more in order to supply the passive transponders using the radiated electromagnetic field. ARIB STD-T107 specifies the regulation for RFID equipment that uses the frequency range between 916.7 MHz and 923.5 MHz to identify passive transponders. However, in contrast to the previous standard this standard only specifies medium to low

TABLE I: Sub-1 GHz Frequency Band Technology Feature Summary

Technology	PHY Modulation	Channel Width	PHY Data Rate	Typical TX Range	Max TX Power	Channel Access
IEEE 802.11ah	OFDM	1/2/4/8/16 MHz	150 kb/s–346 Mb/s	1 km	1000 mW	CSMA/TDMA
IEEE 802.15.4g	SUN-FSK/SUN-OFDM/ SUN-O-QPSK	200/400/600/800/ 1200 kHz	6.25 kb/s–2.4 Mb/s	1 km	1000 mW	CSMA/TDMA/ ALOHA
IEEE 802.15.4w	GMSK	2.3–19 kHz	600 b/s–9 kb/s	15 km	1000 mW	ALOHA/TDMA
LoRa	CSS/FSK	125/250/500 kHz	300 b/s–5.5 kb/s	15 km	1000 mW	ALOHA/TDMA
SigFox	BPSK/QFSK	0.1/0.6/1.5 kHz	100 b/s–600 b/s	15 km	1000 mW	ALOHA

TABLE II: Europe Wide Harmonized Sub-1 GHz Spectrum Allocation According to ETSI EN 300 220-2

Name:Frequency Range	Max TX Power	Max Bandwidth	Usage Restriction
D: 169.4000 MHz to 169.4875 MHz	500 mW	50 kHz	$\leq$ 1% duty cycle, $\leq$ 10% duty cycle for metering devices
H: 433.050 MHz to 434.790 MHz	10 mW	Whole band	$\leq$ 10% duty cycle
J: 433.050 MHz to 434.790 MHz	10 mW	25 kHz	
K: 863 MHz to 865 MHz	25mW	Whole band	$<$ 0.1% duty cycle or polite spectrum access
L: 865 MHz to 868 MHz	25mW	Whole band	$<$ 1% duty cycle or polite spectrum access
M: 868.000 MHz to 868.600 MHz	25mW	Whole band	$<$ 1% duty cycle or polite spectrum access
N: 868.700 MHz to 869.200 MHz	25mW	Whole band	$<$ 0.1% duty cycle or polite spectrum access
O: 869.400 MHz to 869.650 MHz	500 mW	Whole band	$<$ 10% duty cycle or polite spectrum access
P: 869.700 MHz to 870.000 MHz	5 mW	Whole band	
Q: 869.700 MHz to 870.000 MHz	25 mW	Whole band	$<$ 1% duty cycle or polite spectrum access

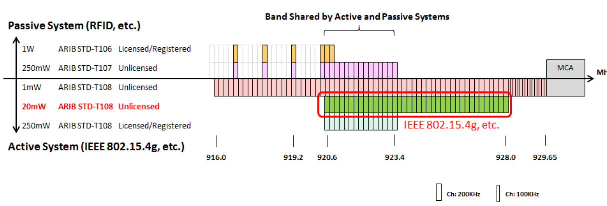

Fig. 1: 920 MHz Band Channel Plan in Japan

output powers. ARIB STD-T108 specifies two systems, land mobile stations and specified low-power radio stations. Land mobile stations use the frequency range between 920.5 MHz and 923.5 MHz, and a maximum transmit power of 250 mW. Specified low-power radio stations use the frequency range between 915.9 MHz and 929.7 MHz with a maximum transmit power of 20 mW. For both systems, a radio channel consists of up to five consecutive 200 kHz unit channels. The channels are defined by their center frequencies in steps of 200 kHz.

In addition, ARIB STD-T108 also defines operational rules for coexistence by two different categories based on carrier sense (CS) duration: short CS stations using a carrier sense time of 128 μs and long CS stations using carrier sense time of at least 5 ms. Short CS stations are intended to be energy efficient, typically powered by batteries, achieved by means of short data communication. Total transmission time per arbitrary one hour per short CS station may be 720 seconds or less while the sum of transmission time per arbitrary one hour per radio channel is limited to 360 seconds or less, i.e., 20% per station duty cycle and 10% per channel duty cycle. IEEE 802.15.4g operates as a short CS station.

Figure 1 summarizes channel plans for 920 MHz band radio equipment according to ARIB STD-T106, ARIB STD-T107, and ARIB STD-T108. It can be seen that 923.5 $\sim$ 928.1 MHz (4.6 MHz bandwidth) is the only reasonable unlicensed frequency band for 802.15.4g and 802.11ah applications.

IV. S1G Band Interference Signal and Noise Measurement

To demonstrate real environment interference signal and radio noise to IEEE 802.11ah and IEEE 802.15.4g systems in the S1G bands, extensive measurements have been conducted at different places in Japan and Europe. Significant levels of interference signals from mobile network stations have been observed. A numerous number of LoRa signals are also observed, especially in residential areas. SigFox signals are not often present, but when they are present they last for several seconds. In addition, some machinery can emit powerful radio noise, which can also have serious impact on both 802.11ah and 802.15.4g systems.

A. 920 MHz Band Measurements in Japan

The measurements over the 920 MHz band have been conducted by using a real-time spectrum analyzer. The spectrum utilization was measured at several places including railway stations, university campuses, a large exhibition center, a football stadium and buildings. The interference signal and radio noise measurements are presented in Yano et al [13]. These measurements raise the following concerns:

- Cellular signals can cause non-negligible interference due to their out-band emission.
- Several wireless communication systems including 802.11ah, 802.15.4g and some non-standard based communication systems will share the 920 MHz band. They have different transmission patterns such as spectral mask shape and duty cycle as shown in Figure 2, where the measurements were conducted at a large exhibition center during the R&D exhibition of wireless communication technologies.
- Several types of machinery at railway station emit radio noise as shown in Figure 3 that may radiate sufficient energy to impact wireless communication systems.

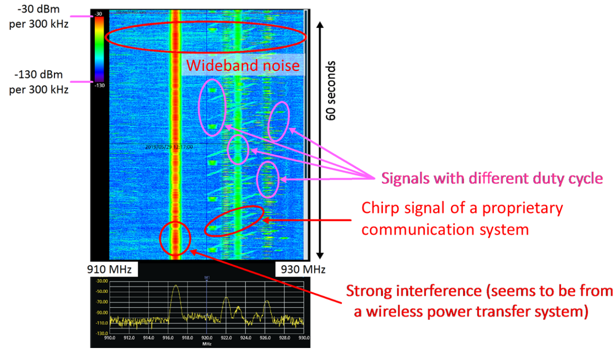

Fig. 2: Spectrum Utilization Measurement at Exhibition Center

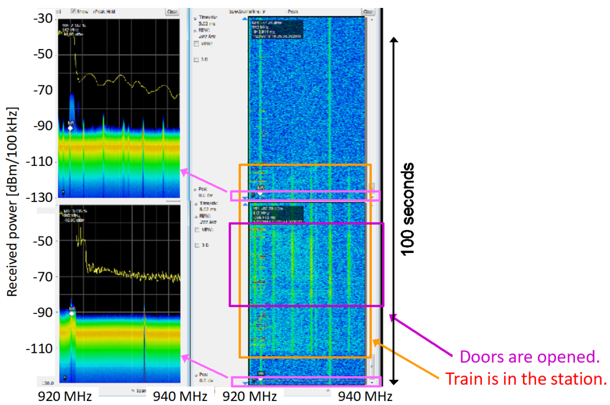

Fig. 3: Spectrum Utilization Measurement at Railway Station

These interference signal and radio noise can have significant impact on the performance of IEEE 802.11ah and IEEE 802.15.4g systems.

B. 868 MHz Band Measurements in Europe

Robert [14] presents 868 MHz band measurements in Europe from 863 MHz to 870 MHz using a sampling rate of 10 MHz.

Figure 4 shows the short-range devices (SRD) band measurements using the base station at the Nuremberg Trade-Fair Center, which is surrounded by residential and industrial areas. The different operational bands ranging from K to P/Q are indicated in the figure. The narrow band between N and O is not assigned to SRD applications. The measurements show the typical use of the SRD frequency bands.

The frequency bands K and L are assigned to 802.11ah in Europe. Figure 4 shows many almost constant carriers over the complete measurement time. These carriers originate from UHF RFID. The maximum transmit power for RFID is 2 W. In contrast, the maximum transmit power of 802.11ah is limited to 25 mW. Hence, even distant RFID readers can lead to significant interference levels in bands K and L.

The frequency band O is typically used for downlink signals in LPWAN. It allows a maximum transmit power of 500 mW and a duty cycle of 10%. Hence, Sigfox and many LoRa networks use this frequency band. It is clearly visible in Figure 4 that the band is very narrow and the channel load is high. As systems like LoRa and Sigfox will typically not use CCA, a high collision probability can be expected. The typical

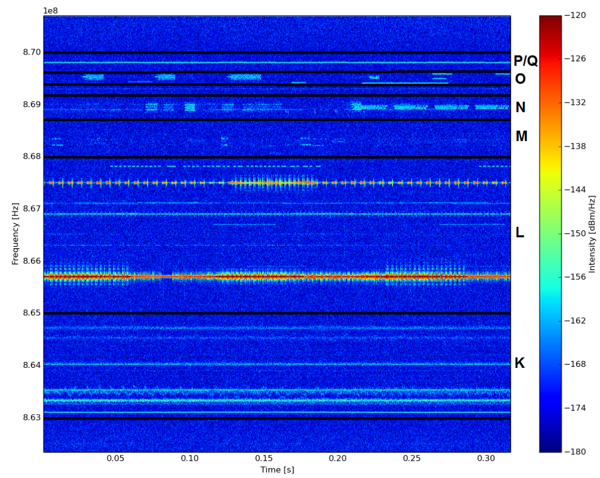

Fig. 4: 863–870 MHz SRD Band Measurement

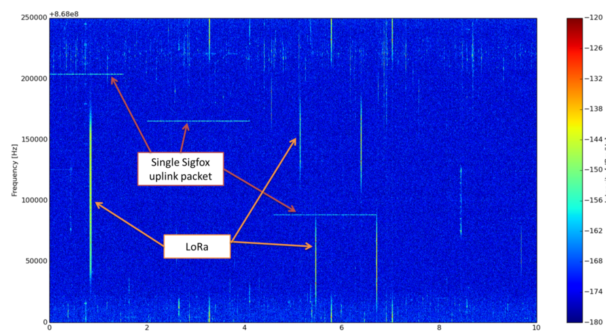

Fig. 5: 868–868.25 MHz Band Measurement

frequency bands for most 802.15.4 based SRD applications are bands M and N. These frequency bands seem almost unused.

Figure 5 shows a detailed view of the lower half of band M (868–868.25 MHz) measured at the Nuremberg Trade-Fair Center, but a few minutes after the measurements shown in Figure 4. Due to the lower sampling rate, the system was able to capture a continuous stream, from which a 10 second measurement duration is shown. Band M is typically used as the uplink for LPWAN systems, as it offers a duty cycle of 1% if CSMA/CA is not used (e.g., LoRa, Sigfox). The band is used by a variety of systems, most of them with short transmit times of a few ms and a bandwidth of up to 100 kHz. LPWAN systems are also present. The arrows mark a single Sigfox packet, which consists of three narrow-band transmissions, each lasting 2 seconds. In addition, multiple LoRa packets are present, some of them marked by arrows.

In summary, all frequency bands are heavily used. IEEE 802.11ah and IEEE 802.15.4g systems will need to coexist with strong narrow-band RFID signals. The high-power band O is highly occupied by the downlink of different LPWAN systems. Finally, the frequency bands M and N are also highly occupied by systems with typical short transmit bursts and LPWAN systems.

V. Interference Causes and Coexistence Issues of IEEE 802.11ah and IEEE 802.15.4g

To explore coexistence behavior among the S1G band systems, we take the coexistence of IEEE 802.11ah and IEEE 802.15.4g as study case.

A. Interference Causes Between 802.11ah and 802.15.4g

The protocol differences between 802.11ah and 802.15.4g result in different coexistence behavior.

1) Higher 802.11ah ED Threshold Can Cause 802.15.4g Packet Collision: The 802.11ah ED threshold is -75 dBm in a 1 MHz channel. The 802.15.4g ED threshold ranges from -100 dBm to -72 dBm depending on PHY mode of operation. The higher ED threshold of 802.11ah can cause 802.11ah frame transmission collision with 802.15.4g frame transmission. If the detected energy level of an 802.15.4g frame transmission is above 802.15.4g receiver sensitivity and below 802.11ah ED threshold, the energy level is high enough for 802.15.4g device to successfully decode the frame. However, the detected 802.15.4g frame transmission is disregarded by 802.11ah ED-CCA. In this case, an 802.11ah frame transmission collides with the ongoing 802.15.4g frame transmission.

2) Faster 802.11ah Backoff Can Interfere with 802.15.4g Transmission Process: The 802.11ah backoff process is much faster than 802.15.4g backoff process due to the smaller time parameters, e.g., 52 μs time slot, less than 40 μs CCA time and less than 5 μs turnaround time. As a result, 802.11ah devices can interfere with 802.15.4g transmission process. For example, with 50 ksymbol/s symbol rate, 802.15.4g turnaround time is 240 μs that is long enough for an 802.11ah device to complete a backoff procedure with 4 or less time slots and start packet transmission, which may interfere with 802.15.4g data packet transmission. In addition, the 802.15.4g acknowledgement (ACK) waiting time could be up to 1600 μs that is long enough for an 802.11ah device to complete a backoff procedure with 30 or less time slots and start packet transmission, which may interfere with 802.15.4g ACK packet transmission.

3) Lower 802.15.4g PHY Data Rate Can Delay 802.11ah Packet Transmission: 802.11ah CSMA/CA performs CCA in each backoff time slot. The backoff procedure can proceed only if the channel is determined to be idle. During 802.11ah backoff suspension, 802.15.4g devices may start transmission. The lower PHY data rate of 802.15.4g means that an 802.15.4g packet transmission can take more time relative to the 802.11ah packet transmission duration, and therefore can cause longer delay for 802.11ah packet transmission.

4) Wider 802.11ah Channel Can Interfere with Multiple 802.15.4g Systems: 802.11ah channel is wider than 802.15.4g channel. Therefore, an 802.11ah system can interfere with multiple 802.15.4g systems.

B. 802.11ah and 802.15.4g Coexistence Issues To Be Addressed

Extensive coexistence simulations of 802.11ah and 802.15.4g have been conducted in Guo et al [1], [15], [16], [17], [18], [19], [20], Liu et al [2], and Nagai et al [4], [5], [21]. We present simulation results in Table III to show coexistence behavior of 802.11ah and 802.15.4g networks using standard defined coexistence mechanisms, i.e., to show how coexisting 802.11ah and 802.15.4g networks affect each other. The detailed simulation profiles are specified in Nagai et al [22], where 1 MHz channel and 300 kb/s PHY data rate for 802.11ah and 400 kHz channel and 100 kb/s PHY data rate for 802.15.4g are used.

TABLE III: Coexistence Performance of 802.11ah and 802.15.4g Using Standard Defined Coexistence Mechanisms

Network Offered Load [kb/s]		Packet Delivery Rate [%]		Average Packet Latency [ms]	
802.11ah	802.15.4g	802.11ah	802.15.4g	802.11ah	802.15.4g
20	20	100	98.1	9.9	22.3
40	20	100	94.0	16.7	26.9
60	20	100	84.7	45.4	34.6
80	20	99.9	67.9	145.3	39.2
100	20	99.7	49.1	169.1	44.2
20	30	100	94.2	12.1	26.4
40	30	100	86.6	23.7	32.3
60	30	100	71.4	101.2	38.7
80	30	99.8	54.6	175.8	42.4
100	30	99.4	35.7	189.8	48.2

In the simulations, 802.11ah and 802.15.4g nodes are deployed in an area with diameter of 200 meters and density of 500/km^2, 15 nodes for each of 802.11ah and 802.15.4g networks. The payload for both 802.11ah and 802.15.4g frames is 100 bytes. Considering higher data rate of 802.11ah, we simulated five network load scenarios, 20/40/60/80/100 kb/s. On the other hand, since 802.15.4g data rate is lower, we simulated two network load cases, 20/30 kb/s. The network load is uniformly distributed among 15 nodes. The highest duty cycle for 802.11ah node is 2.2% and for 802.15.4g node is 2%. The network traffic is generated according to a Poisson distribution.

Table III shows packet delivery rate (PDR) and packet latency (PL) of 802.11ah and 802.15.4g networks over different network load scenarios. For the PDR, it can be seen that 802.11ah PDR is nearly 100%, which indicates that 802.15.4g traffic has slight impact on 802.11ah PDR. However, 802.15.4g PDR decreases significantly as 802.11ah network load increases from 20 kb/s to 100 kb/s, e.g., 58.5% drop for the case of 30 kb/s 802.15.4g network load. This reveals that the transmission of 802.15.4g packet can be greatly suppressed by 802.11ah traffic. With respect to the PL, 802.15.4g PL increases about 22 ms with 80 kb/s increase in 802.11ah network load from 20 kb/s to 100 kb/s. However, 802.11ah PL increases much more than 802.15.4g PL does, e.g., 55.8 ms increase with only 10 kb/s increase in 802.15.4g network load from 20 kb/s to 30 kb/s for the case of 60 kb/s 802.11ah network load. This means that the transmission of 802.11ah packet can be considerably delayed by 802.15.4g traffic.

In summary, 802.11ah system and 802.15.4g system can interfere with each other. The interference can be serious even if both systems operate at low duty cycles. 802.11ah traffic can significantly degrade 802.15.4g PDR. 802.15.4g traffic can considerably prolong 802.11ah PL. Therefore, the coexistence technologies mainly need to address 802.15.4g PDR and 802.11ah PL.

VI. Coexistence Recommendations for IEEE 802.11ah and IEEE 802.15.4g

Many factors can affect coexistence behavior of the S1G band wireless systems. These factors can be divided into two categories: protocol factors such as ED threshold and network factors such as network load. Even though application developers may not be able to control protocol factors, they can manage network factors. Most importantly, application developers can apply appropriate coexistence methods to improve system performance. Therefore, this section provides coexistence recommendations for 802.11ah and 802.15.4g systems. The coexistence of 802.11ah and 802.15.4w can be seen in Robert [23]. The coexistence of wireless systems involved LoRa and SigFox needs further study.

A. Coordinated coexistence method recommendations

Coordinated coexistence assumes availability of a device that can coordinate the coexistence. The coordinated coexistence methods can be categorized into centralized coexistence, where a full function coordinator controls coexistence, and cooperated coexistence, where a limited function coordinator assists coexistence. Table IV summarizes the recommendations for centralized and cooperated coexistence methods.

B. Distributed coexistence method recommendations

Distributed coexistence assumes that a coexistence coordinator is not available. Therefore, 802.11ah and 802.15.4g networks need to perform distributed coexistence. Table V summarizes the recommendations for distributed coexistence methods.

C. Network Load Recommendation

The network load can have major impact on coexistence performance. Even for a standalone network, the network performance may degrade as the network load increases. Therefore, application developers are recommended to follow the duty cycle regulated by the government, e.g., Japan requires that an active radio device cannot have a duty cycle greater than 10% in the S1G bands and Europe even requires 1% of duty cycle for some S1G bands. Furthermore, application developers should consider the possibility of the coexistence and apply appropriate coexistence methods.

D. Network Size Recommendation

The network size can also affect coexistence performance. Application developers have opportunity to determine the network size based on cost consideration for the best performance. Taking 802.11ah and 802.15.4g networks for example:

- If the network load is low for both 802.11ah and 802.15.4g networks, the network size has little impact on coexistence performance. Application developers should deploy fewer devices for cost optimization.
- If the network load for 802.11ah network is high and the network load for 802.15.4g network is low, application developers should deploy fewer 802.11ah devices, especially for latency critical applications.
- If the network load for 802.11ah network is low and the network load for 802.15.4g network is high, application developers should deploy more 802.15.4g devices, especially for reliability critical applications.
- High network load for both 802.11ah and 802.15.4g networks is not recommended.

In IEEE 802.19.3 standard, network load that is lower than or equal to 30 kb/s is referred to as "low" and network load that is higher than 30 kb/s is referred to as "high". In addition, network size that is smaller than or equal to 80 nodes is referred to as "small" and network size that is more than 80 nodes is referred to as "large".

E. Frame Size Recommendation

Improved coexistence performance for 802.11ah and 802.15.4g networks can be achieved by adjusting frame size of each network according to the network conditions as shown in Table VI, where performance priorities are 802.15.4g packet delivery rate and 802.11ah packet latency. For 802.15.4g packet latency and 802.11ah packet delivery rate, the medium frame size is recommend for both networks. In IEEE 802.19.3 standard, a frame with payload smaller than 80 bytes is referred to as "small", a frame with payload in between 80 bytes and 120 bytes is referred to as "medium", and a frame with payload greater than 120 bytes is referred to as "large".

F. Backoff Parameter Recommendation

Both 802.11ah and 802.15.4g apply exponential backoff mechanism in which backoff window size is doubled after each unsuccessful transmission attempt of the same frame. Table VII summarizes backoff parameter recommendations. For 802.11ah contention window (CW), the CW_{min} is referred to as the "small CW" and the CW_{max} is referred to as the "large CW". For 802.15.4g, $macMinBE$ = 2, $macMaxBE$ = 4, and $macMaxCSMABackoffs$ = 3 are referred to as the "small backoff parameters"; $macMinBE$ = 2, $macMaxBE$ = 5, and $macMaxCSMABackoffs$ = 4 are referred to as the "medium backoff parameters"; and $macMinBE$ = 2, $macMaxBE$ = 6 and $macMaxCSMABackoffs$ = 5 are referred to as the "large backoff parameters". In addition, we conducted further simulations after the publication of IEEE 802.19.3 standard to make superior recommendations in Table VII for the scenarios where IEEE 802.19.3 standard does not recommend specific coexistence methods in its Table 12.

G. Frequency Hopping Recommendations

Frequency hopping summarized in Rolfe [24] and [25] is a coexistence method in which all devices perform channel hopping according to hopping sequences. Frequency hopping is a popular technique to improve reliability by mitigating interference impact and adapting to the environment in licensed exempt spectrum, especially for narrow-band systems where a large number of channels can be available. Frequency hopping is commonly used with 802.15.4 SUN-FSK. Frequency hopping is recommended when a large number of channels are available and regulatory requirements are met.

TABLE IV: Recommendations for Centralized and Cooperated Coexistence Methods

Coexistence method	**Recommendation to apply the method**
Centralized channel switching	This method should be applied when the coordinator can locate channels with less interference.
Centralized 802.11ah RAW and 802.15.4g superframe construction	This method should be applied when the coordinator coordinates coexistence of 802.11ah network and beacon enabled 802.15.4g network.
Centralized 802.11ah beamforming	This method should be applied when the coordinator has information about geometric placement of 802.11ah devices and 802.15.4g devices.
Centralized transmission power setting	This method should be applied when the coordinator coordinates coexistence of 802.11ah and 802.15.4g networks with certain data patterns and/or geometric device placement.
Cooperated channel switching	This method should be applied when the network manager can locate a channel with less interference.
Cooperated 802.11ah RAW and 802.15.4g superframe construction	This method should be applied if 802.15.4g network is beacon enabled and load information of both 802.11ah and 802.15.4g networks is available.
Cooperated 802.11ah beamforming	This method should be applied when the relative position of nodes is known or predictable and not aligned closely in space.
Cooperated transmission power setting	This method should be applied when received signal condition information is available per link, link adaptation capability is available in devices, and link information can be shared between transmitter and receiver.
Cooperated α-Fairness based ED-CCA [2]	This method should be applied when 802.11ah devices are aware of coexistence of 802.15.4g devices and the coordinator can provide network performance metrics such as data packet delivery rate.
Cooperated Q-Learning based CSMA/CA [2]	This method should be applied when 802.11ah devices are aware of coexistence of 802.15.4g devices and the coordinator can provide information to configure Q-Learning rewards.

TABLE V: Recommendations for Distributed Coexistence Methods

Coexistence method	**Recommendation to apply the method**
Distributed transmission time delay	This method should be applied when an 802.11ah/802.15.4g device is aware of transmission of 802.15.4g/802.11ah devices.
α–Fairness based ED-CCA [2]	This method should be applied when an 802.11ah device is aware of coexistence of 802.15.4g devices and the detected energy level is between 802.15.4g receiver sensitivity and 802.11ah ED threshold.
Q-Learning based CSMA/CA [2]	This method should be applied when an 802.11ah device is aware of the coexistence of 802.15.4g devices and its backoff counter reaches zero with idle channel status.
Prediction based transmission suspension [1]	This method should be applied when an 802.11ah device is aware of the coexistence of 802.15.4g devices.
Hybrid CSMA/CA [4]	This method should be applied when an 802.15.4g device is aware of significant interference on its channel.
Q-Learning based 802.11ah RAW scheduling [3]	This method should be applied when 802.11ah AP is aware of the coexistence of the beacon enabled 802.15.4g networks.
ACS-based CSMA/CA [5]	This method should be applied when an 802.15.4g device is aware of significant interference on its channel.

TABLE VI: Summary of Frame Size Recommendations

Network Scenario			Performance Priority	Frame Size Recommendation	
Network Size	Offered Network Load				
	802.11ah	802.15.4g		802.11ah	802.15.4g
Small	High	Low	802.15.4g Packet Delivery Rate	Medium	Large
			802.11ah Packet Latency		Small
Small	Low	High	802.15.4g Packet Delivery Rate	Medium	Large
			802.11ah Packet Latency		Large
Large	High	Low	802.15.4g Packet Delivery Rate	Medium	Large
			802.11ah Packet Latency		Small
Large	Low	High	802.15.4g Packet Delivery Rate	Medium	Large
			802.11ah Packet Latency		Medium

VII. Performance Evaluation of Recommended Coexistence Methods

We evaluated the recommended coexistence methods by comparing their performance with the performance of the standard defined coexistence mechanisms on two main coexistence issues described in Section V, i.e., 802.15.4g PDR and 802.11ah PL. Simulation results show that the recommended coexistence methods improve 802.15.4g PDR. However, they extend 802.11ah PL in the most of network load scenarios because of more 802.15.4g packet transmissions. Both 802.15.4g PDR and 802.11ah PL are simultaneously improved in the lowest network load case.

A. Packet Delivery Rate

Table VIII shows effect of the recommended coexistence methods on PDR in different network load scenarios. It can be seen that when the total network load is not close to the network capacity (Cases A to D and G to I), the recommended coexistence methods improve 802.15.4g PDR without degrading 802.11ah PDR by enhancing channel access efficiency to

TABLE VII: Summary of Backoff Parameter Recommendations

Network Scenario			Performance Priority	Backoff Parameter Recommendation	
Network Size	Offered Network Load				
	802.11ah	802.15.4g		802.11ah CW	802.15.4g Backoff Parameters
Small	High	Low	802.15.4g Packet Delivery Rate	Standard	Large
			802.11ah Packet Latency		Small
			802.15.4g Packet Latency		Standard
			802.11ah Packet Delivery Rate		Standard
Small	Low	High	802.15.4g Packet Delivery Rate	Standard	Large
			802.11ah Packet Latency		Large
			802.15.4g Packet Latency		Small
			802.11ah Packet Delivery Rate		Standard
Large	High	Low	IEEE 802.15.4g Packet Delivery Rate	Small	Large
			802.11ah Packet Latency		Large
			802.15.4g Packet Latency		Standard
			802.11ah Packet Delivery Rate		Standard
Large	Low	High	802.15.4g Packet Delivery Rate	Small	Large
			802.11ah Packet Latency		Large
			802.15.4g Packet Latency		Small
			802.11ah Packet Delivery Rate		Standard

increase 802.15.4g transmission opportunity. However, when the total network load is close to the network capacity (Cases E to F and K to L), the recommended coexistence methods improve 802.15.4g PDR at the expense of 802.11ah PDR since the improvement is saturated.

The recommended coexistence methods for 802.11ah and 802.15.4g have very different effect. The 802.11ah coexistence methods are active and therefore, can achieve more improvement on 802.15.4g PDR at the expense of 802.11ah PDR. As a result, 802.11ah PDR degrades considerably as total network load approaches to the network capacity. On the other hand, 802.15.4g coexistence methods are passive and aim to improve 802.15.4g PDR without suppressing 802.11ah transmission. Therefore, 802.15.4g PDR is improved by achieving more efficient spectrum sharing. Accordingly, these methods improve 802.15.4g PDR without significantly affecting 802.11ah PDR, but the improvement is less.

B. Data Packet Latency

Table IX shows effect of the recommended coexistence methods on PL in different network load scenarios. The 802.11ah PL can be significantly increased by the 802.11ah coexistence methods since these methods suppress 802.11ah transmission for 802.15.4g transmission. The 802.15.4g coexistence methods can moderately increase 802.11ah PL because the increased 802.15.4g transmissions can further delay 802.11ah transmissions. On the other hand, 802.15.4g PL increases slightly over the 802.15.4g coexistence methods due to more 802.15.4g transmissions. However, the 802.11ah coexistence methods can reduce 802.15.4g PL.

VIII. Conclusions

Various Sub-1 GHz frequency band low-power wide-area wireless communication technologies have been developed to address a diverse set of IoT applications. Based on characteristics of each technology, the expected use cases vary. However, there is considerable overlap in use cases and thus these heterogeneous technologies are likely to coexist. As a result, the interference becomes an issue to be addressed. In fact, the significant interference and strong noise have been observed in Sub-1 GHz frequency bands via measurements and simulations. The importance of Sub-1 GHz band coexistence has been fully recognized. IEEE 802.19.3 Task Group was formed to develop IEEE 802.19.3 standard for Sub-1 GHz frequency band coexistence. This article aims to introduce IEEE 802.19.3 standard to readers outside of IEEE 802 standard body and to industry to raise awareness of potential coexistence issues and available coexistence mechanisms for the better system deployment. It takes IEEE 802.11ah and IEEE 802.15.4g as example technologies to evaluate performance of the coexistence methods recommended by IEEE 802.19.3 standard.

References

[1] J. Guo and P. Orlik, "Self-Transmission Control in IoT over Heterogeneous Wireless Networks," in *International Conference on Ubiquitous and Future Networks*, 2017.

[2] Y. Liu *et al.*, "Coexistence of 802.11ah and 18 802.15.4g Networks," in *IEEE Wireless Communications and Networking Conference*, 2018.

[3] T. Sumi *et al.*, "Sub-1 GHz Coexistence Using Reinforcement Learning based IEEE 802.11ah RAW scheduling," in *30th Conference of Information Processing Society Japan on Consumer Devices and Systems"*, 2021.

[4] Y. Nagai *et al.*, "Hybrid CSMA/CA for Sub-1 GHz Frequency Band Coexistence of IEEE 802.11ah and IEEE 802.15.4g," in *2020 International Workshop on Informatics (IWIN)*, 2020.

[5] ——, "Sub-1 GHz Frequency Band Wireless Coexistence for the Internet of Things," *IEEE Access*, vol. 9, pp. 19 648–119 665, 2021.

[6] IEEE, "IEEE Std 802.19.3-IEEE Recommended Practice for Local and Metropolitan Area Networks—Part 19: Coexistence Methods for IEEE 802.11 and IEEE 802.15.4 Based Systems Operating in the Sub-1 GHz Frequency Bands," IEEE, 2021.

[7] FCC, "Federal Communications Commission, Code of Federal Regulations Title 47: Telecommunication PART 15—RADIO FREQUENCY DEVICES," 2019.

[8] ETSI, "ETSI EN 300 220-2, Short Range Devices (SRD) operating in the frequency range 25 MHz to 1 000 MHz; Part 2: Harmonized Standard for access to radio spectrum for non specific radio equipment," 2018.

[9] CEPT, "CEPT ERC Recommendation 70-03, Relating to the use of Short Range Devices (SRD)," 2020.

[10] ARIB, "ARIB STD-T106: 920MHz-Band RFID Equipment for Premises Radio Station and Land Mobile Radio Station," 2019.

[11] ——, "ARIB STD-T107, 920MHz-Band RFID Equipment for Specified Low Power Radio Station," 2017.

TABLE VIII: 802.11ah and 802.15.4g Data Packet Delivery Rate Variation versus Coexistence Mechanism

Case	Offered Load [kb/s]		Packet Delivery Rate [%]											
			1) Standard Defined Coexistence Mechanisms		IEEE 802.11ah Enhancement						IEEE 802.15.4g Enhancement			
					2) α-Fairness		3) Q-Learning		4) αF+QL		5) ACS		6) ACS+Hybrid	
	11ah	15.4g	11ah	15.4g	11ah	15.4g	11ah	15.4g	11ah	15.4g	11ah	15.4g	11ah	15.4g
A	20	20	100	98.1	100	98.0	99.9	98.0	99.9	98.1	100	99.1	100	99.0
B	40	20	100	94.0	100	94.4	99.9	94.2	99.9	94.5	100	96.0	100	96.2
C	60	20	100	84.7	100	86.3	96.4	87.1	95.5	87.9	100	87.5	100	89.2
D	80	20	99.9	67.9	99.7	72.3	85.8	78.3	84.8	80.4	99.9	72.1	99.9	74.3
E	100	20	99.7	49.1	82.2	70.6	75.3	70.6	69.8	79.1	99.7	51.8	99.2	51.7
F	120	20	97.0	28.2	68.7	70.4	60.8	72.1	57.0	80.0	94.0	32.6	87.8	41.6
G	20	30	100	94.2	99.9	94.5	99.9	94.4	99.9	94.5	100	96.4	100	96.2
H	40	30	100	86.6	99.9	87.2	99.9	86.7	99.9	87.1	100	89.0	100	89.2
I	60	30	100	71.4	99.9	72.9	86.5	78.5	85.7	79.4	100	73.9	99.9	73.9
J	80	30	99.8	54.6	91.6	63.1	75.3	71.0	71.1	75.4	99.8	54.8	99.5	52.2
K	100	30	99.5	35.7	73.6	62.8	59.3	71.4	60.1	73.0	98.5	33.9	90.2	35.3
L	100	30	99.4	21.6	61.5	62.7	54.4	65.7	47.8	74.9	86.1	28.0	76.0	34.5

TABLE IX: 802.11ah and 802.15.4g Data Packet Latency Variation versus Coexistence Mechanism

Case	Offered Load [kb/s]		Packet Latency Average [ms]											
			1) Standard Defined Coexistence Mechanisms		IEEE 802.11ah Enhancement						IEEE 802.15.4g Enhancement			
					2) α-Fairness		3) Q-Learning		4) αF+QL		5) ACS		6) ACS+Hybrid	
	11ah	15.4g	11ah	15.4g	11ah	15.4g	11ah	15.4g	11ah	15.4g	11ah	15.4g	11ah	15.4g
A	20	20	9.9	22.3	12.9	22.4	13.2	22.5	15.7	22.6	9.7	22.9	9.8	22.6
B	40	20	16.7	26.9	20.5	27.1	25.2	27.6	28.0	27.5	16.9	28.7	17.6	26.3
C	60	20	45.4	34.6	49.9	33.5	205.9	33.5	213.9	33.3	49.5	37.3	51.5	33.0
D	80	20	145.3	39.2	224.7	37.7	247.1	36.1	288.2	35.4	153.7	43.8	164.2	41.0
E	100	20	169.1	44.2	238.4	37.9	279.6	36.8	293.1	35.6	178.2	51.5	194.2	52.7
F	120	20	173.3	54.1	238.3	38.0	293.0	35.7	299.8	35.4	186.3	60.8	200.9	59.5
G	20	30	12.1	26.4	16.2	26.6	19.5	26.9	23.0	27.0	12.3	28.6	12.8	26.6
H	40	30	23.7	32.3	28.8	31.9	54.8	33.0	58.7	33.0	24.8	35.3	26.8	32.8
I	60	30	101.1	38.7	133.5	38.4	289.1	36.7	303.8	36.6	119.2	43.8	139.0	41.1
J	80	30	175.8	42.4	265.5	39.9	344.0	37.7	366.7	37.2	192.6	50.7	218.1	52.1
K	100	30	187.8	48.2	266.2	40.0	366.6	37.0	348.5	37.7	203.7	59.0	234.1	64.2
L	120	30	190.5	56.7	266.1	40.0	336.4	37.8	364.8	37.2	206.3	62.7	231.7	64.3

[12] ——, "ARIB STD-T108: 920MHz-Band Telemeter, Telecontrol and Data Transmission Radio Equipment," 2019.

[13] K. Yano *et al.*, "Measurement of Radio Noise and Interference over 920 MHz Band in Japan," https://mentor.ieee.org/802.19/documents, 2019.

[14] J. Robert, "EU Measurements," https://mentor.ieee.org/802.19/documents, 2019.

[15] J. Guo *et al.*, "Coexistence of 802.11ah and 802.15.4g in the S1G Band," https://mentor.ieee.org/802.19/documents, 2017.

[16] ——, "802.11ah and 802.15.4g Coexistence Simulation and Coexistence Issues," https://mentor.ieee.org/802.19/documents, 2019.

[17] ——, "Impact of Network Profiles on 802.11ah and 802.15.4g Coexistence Performance," https://mentor.ieee.org/802.19/documents, 2019.

[18] ——, "S1G Band Coexistence Simulation Update," https://mentor.ieee.org/802.19/documents, 2018.

[19] ——, "Update on Coexistence Simulation, 802.11ah and 802.15.4g," https://mentor.ieee.org/802.19/documents, 2018.

[20] ——, "Reliability of Coexisting 802.11ah and 802.15.4g Networks in the Sub-1 GHz Band," https://mentor.ieee.org/802.19/documents, 2018.

[21] Y. Nagai *et al.*, "S1G Coexistence Simulation Update," https://mentor.ieee.org/802.19/documents, 2019.

[22] ——, "S1G Coexistence Simulation Profile," https://mentor.ieee.org/802.19/documents, 2019.

[23] J. Robert, "Draft 0.1 of TG4w Coexistence Document," https://mentor.ieee.org/802.15/documents, 2019.

[24] B. Rolfe, "Frequency Diversity with 802.15.4 SUN FSK," https://mentor.ieee.org/802.19/documents, 2019.

[25] ——, "Contribution for 9.1.1 Frequency Hopping," https://mentor.ieee.org/802.19/documents, 2019.