IEEE 802.19.3 Standardization for Coexistence of IEEE 802.11ah and IEEE 802.15.4g Systems in Sub-1 GHz Frequency Bands

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Abstract

Low power wide area wireless communication technologies are attracting attention particularly from various IoT applications. IEEE 802.11ah and IEEE 802.15.4g are two wireless technologies designed for outdoor IoT applications and installed on consumer devices and systems, for which both technologies operate in frequencies below 1 GHz (Sub-1 GHz Band). In addition, both technologies have communication range up to 1000 meters. Therefore, IEEE 802.11ah and IEEE 802.15.4g networks are likely to coexist. Our simulation results using standard defined coexistence mechanisms show that IEEE 802.11ah network can severely interfere with IEEE 802.15.4g network and lead to significant packet loss in IEEE 802.15.4g network. IEEE 802.15.4g network can also impact on packet latency in IEEE 802.11ah network. Accordingly, IEEE New Standards Committee and Standard Board formed IEEE 802.19.3 Task Group in December 2018 to develop an IEEE 802 standard for the coexistence of IEEE 802.11ah and IEEE 802.15.4g systems in the Sub-1 GHz frequency bands to guide product deployment. The authors of this paper have been actively leading this standard development. This paper introduces IEEE 802.19.3 standardization activities to address coexistence issues of IEEE 802.11ah and IEEE 802.15.4g systems and summarizes our technical contributions for interference mitigation. Simulation results show that our coexistence technologies achieve better coexistence performance.

Paper on Consumer Systems

IEEE 802.19.3 Standardization for Coexistence of IEEE 802.11ah and IEEE 802.15.4g Systems in Sub-1 GHz Frequency Bands

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Abstract: Low power wide area wireless communication technologies are attracting attention particularly from various IoT applications. IEEE 802.11ah and IEEE 802.15.4g are two wireless technologies designed for outdoor IoT applications and installed on consumer devices and systems, for which both technologies operate in frequencies below 1 GHz (Sub-1 GHz Band). In addition, both technologies have communication range up to 1000 meters. Therefore, IEEE 802.11ah and IEEE 802.15.4g networks are likely to coexist. Our simulation results using standard defined coexistence mechanisms show that IEEE 802.11ah network can severely interfere with IEEE 802.15.4g network and lead to significant packet loss in IEEE 802.15.4g network. IEEE 802.15.4g network can also impact on packet latency in IEEE 802.11ah network. Accordingly, IEEE New Standards Committee and Standard Board formed IEEE 802.19.3 Task Group in December 2018 to develop an IEEE 802 standard for the coexistence of IEEE 802.11ah and IEEE 802.15.4g systems in the Sub-1 GHz frequency bands to guide product deployment. The authors of this paper have been actively leading this standard development. This paper introduces IEEE 802.19.3 standardization activities to address coexistence issues of IEEE 802.11ah and IEEE 802.15.4g systems and summarizes our technical contributions for interference mitigation. Simulation results show that our coexistence technologies achieve better coexistence performance.

Keywords: Coexistence, Spectrum Sharing, IEEE 802.19.3, IEEE 802.11ah, IEEE 802.15.4g, Consumer Devices, IoT, LPWA, LECIM

1. Introduction

As more and more intelligent devices connect to the Internet, the Internet of Things (IoT) is becoming reality. A broad range of wireless technologies such as Low Power Wide Area (LPWA) wireless communications emerge to cater to diverse applications. IEEE 802.11ah [1] marketed as Wi-Fi HaLow [2] is primarily designed for outdoor IoT applications such as smart city and home security monitoring. Wi-Fi HaLow, like other Wi-Fi certification programs, will be installed in consumer devices and systems. IEEE 802.15.4g [3] is principally developed for large scale outdoor process applications such as low-energy critical infrastructure monitoring (LECIM) and wireless smart utility network (Wi-SUN). IEEE 802.11ah is designed to operate in the Sub-1 GHz (S1G) frequency band. For outdoor IoT applications, IEEE 802.15.4g also operates in the S1G band. Both technologies have communication ranges up to 1000 meters. Thus, IEEE 802.11ah network and IEEE 802.15.4g network are likely to coexist. These standards define different modulation schemes and frame structures, and no coexistence mechanisms like common mode sig-

naling (CMS) [4][5] have been defined. Furthermore, the available frequency spectrum allocation for IEEE 802.11ah and IEEE 802.15.4g in the S1G band is limited to several MHz bandwidth in certain regions and countries, and the allocated frequency band is also used by mobile phones, RFID and other systems. For example, Japanese standard ARIB-STD-T108 (20 mW, unlicensed) defines the use of IEEE 802.15.4g system from 920.5 ~ 928.1 MHz (7.6 MHz bandwidth), but ARIB-STD-T107 (250 mW, passive system) and ARIB-STD-T108 (250 mW, licensed/registered) also use from 920.5 ~ 923.5 MHz (3.0 MHz). Therefore, 923.5 ~ 928.1 MHz (4.6 MHz bandwidth) is the only reasonable unlicensed frequency band for IEEE 802.15.4g applications. IEEE 802.15.4g is defined to operate over 200 kHz bandwidth channel in the S1G band. Even Japanese standards allow the maximum 10 % transmission duty cycle to reduce traffic congestion [6][7][8][9], when the number of IoT devices increases significantly, interference mitigation can still become more difficult. Therefore, ensuring harmonious coexistence of the wireless systems in the S1G band is clearly important.

IEEE 802.11ah extends the operational bands of IEEE 802.11 standard family to include the S1G band. An IEEE 802.11ah access point (AP) can associate with more than 8000 stations (STAs). The transmit power is geographic area dependent with a maximum value of 1000 mW.

IEEE 802.15.4g can operate in the S1G band and 2.4 GHz

band.   An IEEE 802.15.4g personal area network coordinator (PANC) can associate with more than 6000 devices. The transmit power is limited by local regulatory bodies with the maximum value of 1000 mW.

IEEE 802.11ah provides energy detection clear channel assessment (ED-CCA) mechanism to coexist with other S1G systems including IEEE 802.15.4g. However, IEEE 802.15g only addresses coexistence mechanism among devices with different IEEE 802.15.4g PHYs. Using the standard defined coexistence mechanism, how well can IEEE 802.11ah network coexist with IEEE 802.15.4g network? Our simulation results show that IEEE 802.11ah ED-CCA coexistence mechanism does not perform well in the presence of standard allowed network offered load. Therefore, the coexistence issues of IEEE 802.11ah and IEEE 802.5.4g need to be addressed.

This paper first introduces the IEEE 802.19.3 standardization activities that address coexistence issues of IEEE 802.11ah and IEEE 802.15.4g, and summarizes our technical contributions and simulation results. We then extend our coexistence work published in [27] by adding detailed analysis of the coexistence issues between different wireless systems and frequency regulation, presenting a new coexistence fairness index to assess the fairness of the coexistence techniques and a coexistence simulation model to evaluate the performance of the coexistence methods. In addition, we perform quantitative coexistence evaluation guided by the use case scenarios developed within the IEEE 802.19.3 Coexistence Task group.

The rest of this paper is organized as follows. Section 2 describes the necessity of IEEE 802.11ah and IEEE 802.15.4g coexistence study. Section 3 presents related work in the research community. Section 4 introduces the S1G band coexistence standardization activities. The S1G band coexistence behaviour and strategy are described in Section 5. The proposed coexistence methods are presented in Section 6. Performance analysis and simulation results of our proposed coexistence control techniques are demonstrated in Section 7. Finally, we conclude our paper in Section 8.

2.   Necessity of IEEE 802.11ah and IEEE 802.15.4g Coexistence Study

IEEE 802.11ah is the first standard in IEEE 802.11 standard family operating in the S1G band. It was defined to enable better support for outdoor IoT applications. IEEE 802.11ah modifies both IEEE 802.11 PHY and MAC to enable operation of 802.11 wireless networks in the S1G band with a transmission range up to 1000 meters and a minimum data rate of 100 Kb/s. The operation frequency bands are region dependent, and 1 MHz, 2 NHz, 4 MHz, 8 MHz and 16 MHz wide channels are defined. IEEE 802.11ah defines specific channel access parameters that are different from previous IEEE 802.11 channel access parameters, e.g., CCA time is less than 40 μs, slot time is 52 μs and SIFS time 160 μs. In addition, IEEE 802.11ah defines mandatory PHY and MAC features that are not specified in conventional IEEE 802.11. For example, IEEE 802.11ah mandates the support of 1 MHz channel, which is much narrower than the conventional IEEE 802.11 (b/g/n/ac) channels that are at least 20 MHz band

wide. It also mandates the support of the second virtual Channel Sensing (CS) mechanism referred to as response indication deferral (RID). Therefore, the existing coexistence methods designed for wide channels and different channel access parameters may not work properly for IEEE 802.11ah coexistence.

IEEE 802.15.4g is an amendment to IEEE 802.15.4 to support outdoor low data rate smart metering utility network (SUN) applications. Three new PHYs, SUN-FSK PHY, SUN-OFDM PHY and SUN-O-QPSK PHY, are defined. Accordingly, new MAC functions are specified to support new PHYs, e.g., some frame definitions have been changed. IEEE 802.15.4g operation frequency bands are also region dependent and 200 kHz, 400 kHz, 600 kHz and 800 kHz channels are defined. The SUN PHYs support multiple data rates with a minimum data rate of 6.25 kb/s. New symbol duration values for MAC and PHY timing parameters are defined. Channel access parameters have different values from previous IEEE 802.15.4 channel access parameters, e.g., the UnitBackoffPeriod is at least 1 ms, both turnaround time and ACK waiting time are 1 ms for SUN-FSK PHY, the minimum inter-frame space is also 1 ms. The communication range of IEEE 802.15.4g is also up to 1000 meters. Due to the introduction of new PHYs and new channel access parameters, the behaviour of IEEE 802.15.4g is different from conventional IEEE 802.15.4. Therefore, the existing coexistence methods designed for conventional IEEE 802.15.4 may also not work properly for IEEE 802.15.4g coexistence.

As a result, the coexistence of IEEE 802.11ah and IEEE 802.15.4g needs further investigation and study. Accordingly, IEEE New Standards Committee and Standard Board formed 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 systems in the S1G frequency bands. The formation of IEEE 802.19.3 Task Group indicates the necessity of IEEE 802.11ah and IEEE 802.15.4g coexistence study. The authors of this paper have been actively leading this standard development. Task Group Chair Benjamin A. Rolfe is affiliated with Mitsubishi Electric Research Laboratories, Jianlin Guo is Task Group Technical Editor, and Yukimasa Nagai is a member of Comment Resolution Committee.

Though entire IEEE 802 standard body has recognized the importance of IEEE 802.11ah and IEEE 802.15.4g coexistence study, there is very limited work on the coexistence of IEEE 802.11ah network and IEEE 802.15.4g network. We have proposed a prediction based self-transmission control method to address coexistence of IEEE 802.11ah and IEEE 802.15.4g networks in S1G band [26], in which IEEE 802.11ah devices predict the transmission time of the upcoming IEEE 802.15.4g packet and suspend their own transmissions to avoid interfering with IEEE 802.15.4g packet transmission. However, the prediction is not accurate when IEEE 802.15.4g packet generation rate is high. We have also proposed a hybrid CSMS/CA method for IEEE 802.15.4g devices in [28] to switch channel access mode to improve their coexistence performance. However, IEEE 802.15.4g is the main victim in the coexistence of IEEE 802.11ah and IEEE 802.15.4g because IEEE 802.11ah is much more aggressive than IEEE 802.15.4g in channel access contention. Therefore, it is

more efficient to address the coexistence issues on IEEE 802.11ah side.

To the best of our knowledge, no other existing work addresses the coexistence of IEEE 802.11ah and IEEE 802.15.4g in the research community. The related works either address coexistence of IEEE 802.11ah and conventional IEEE 802.15.4 or coexistence of conventional IEEE 802.11 and IEEE 802.15.4g as described in Section 3.

This paper extends our work in [27] to provide machine learning based coexistence methods for IEEE 802.11ah to improve overall coexistence performance with IEEE 802.15.4g. Our machine learning based coexistence control techniques add the intelligence to IEEE 802.11ah devices. We first present an α-Fairness based ED-CCA method that enables IEEE 802.11ah devices to better detect ongoing IEEE 802.15.4g packet transmissions. We then introduce an Q-Learning based backoff mechanism for IEEE 802.11ah devices to avoid interfering with IEEE 802.15.4g packet transmission process.

3.　Related Work in the Research Community

IEEE 802.11ah and IEEE 802.15.4g have led to extensive performance evaluation and coexistence studies in the research community. The related work can be divided into four categories: 1) performance evaluation of homogeneous network; 2) coexistence of conventional IEEE 802.11 network and conventional IEEE 802.15.4 network; 3) coexistence of conventional IEEE 802.11 network and IEEE 802.15.4g network; and 4) coexistence of IEEE 802.11ah network and conventional IEEE 802.15.4 network. On the other hand, coexistence of IEEE 802.11ah network and IEEE 802.15.4g network has not been considered.

For homogeneous networks, throughput performance evaluation of IEEE 802.11ah has been demonstrated in [10][11][12][13] using a simulator. V. Baños-Gonzalez, et al. introduce the challenges for IoT applications and IEEE 802.11ah [15]. Similarly, IEEE 802.15.4g performance has been demonstrated in [16] [17], which focus on the PHY and MAC protocol enhancement for higher-throughput, protocol efficiency and delay via simulation, and measurement results using prototypes.

For coexistence of conventional IEEE 802.11 network and conventional IEEE 802.15.4 network, R. Ma, et al. investigate the coexistence issues of IEEE 802.11b network and IEEE 802.15.4 network in 2.4 GHz band [25]. The system consists of an IEEE 802.15.4 transmitter, an IEEE 802.15.4 receiver and multiple IEEE 802.11b transmitters. The paper proposes a packet error rate (PER) based packet collision analytical model and a link quality indicator (LQI) based channel agility scheme for IEEE 802.15.4 network to perform channel re-selection for interference avoidance. It shows that IEEE 802.11b network can significantly interfere with IEEE 802.15.4 network. However, the paper treats IEEE 802.11b devices as interferer only without considering performance of IEEE 802.11b network. Some existing coexistence solutions require special devices. X. Zhang et al. design a cooperative busy tone (CBT) to enable coexistence of IEEE 802.11 network and IEEE 802.15.4 network [21]. CBT allows a separate IEEE 802.15.4 device to schedule a busy tone concurrently with the desired IEEE 802.15.4 transmission, thereby improving

the visibility of IEEE 802.15.4 devices to IEEE 802.11 devices. However, calculation of the busy tone is based on Poisson data arrival with unsaturated traffic. Thus, the application of busy tone approach is limited since the coexistence issue is not severe when network offered load is light. J. Hou et al. propose a hybrid device implementing both IEEE 802.11 and IEEE 802.15.4 specifications so that it can transmit IEEE 802.11 and IEEE 802.15.4 messages [22]. Therefore, this hybrid device can coordinate IEEE 802.11 and IEEE 802.15.4 networks and acts as a mediator between two heterogeneous networks. Even the hybrid device can signal long channel occupation to IEEE 802.11 devices, the approach is not practical due to the need of the hybrid device. In addition, collaboration between regular IEEE 802.15.4 devices and hybrid devices is difficult. J. W. Chong et al. propose an adaptive IEEE 802.11 network interference mitigation scheme for IEEE 802.15.4 network, where IEEE 802.15.4 network is modeled with a Markov chain concept [23]. The scheme controls IEEE 802.15.4 frame length and device transmission based on the measured IEEE 802.11 interference. However, the scheme needs a hybrid device to transfer IEEE 802.11 channel activity to IEEE 802.15.4 network.

There are existing studies on the coexistence of conventional IEEE 802.11 network and IEEE 802.15.4g network operating in the 2.4 GHz band [18]. Some coexistence techniques are developed for IEEE 802.15.4g. W. Yuan, et al. propose a decentralized approach for IEEE 802.15.4 devices to mitigate interference by adaptively adjusting ED threshold in the presence of severe interference [19]. The ED threshold is calculated based on the accumulated transmission failure. The approach can reduce the packet loss due to channel access failures and enhance the performance of IEEE 802.15.4g network. However, this approach cannot reduce the packet loss due to collision. E. D. N. Ndih et al. show that under saturation condition, a 10 device IEEE 802.15.4 network can only deliver 3 % of packets, but a 10 device IEEE 802.11 network is able to deliver over 80 % of packets [20]. This paper proposes an adaptive backoff procedure for IEEE 802.15.4 devices to survive coexistence with IEEE 802.11 devices and improves packet delivery rate by 6 %.

For coexistence of IEEE 802.11ah network and conventional IEEE 802.15.4 network, B. Badihi Olyaei, et al. compare performance of IEEE 802.11ah network and IEEE 802.15.4 (2006) network in S1G band [24]. The results depict that IEEE 802.11ah network achieves higher channel efficiency than IEEE 802.15.4 network. It indicates that IEEE 802.11ah devices are more aggressive than IEEE 802.15.4 devices in wireless channel access.

The forementioned coexistence technologies may not apply to the coexistence of IEEE 802.11ah network and IEEE 802.15.4g network, e.g., CBT method in [21] assumes that one 22 MHz IEEE 802.11 channel overlaps with four IEEE 802.15.4 channels and therefore, busy tone scheduler can hop to an adjacent channel to transmit busy tone to IEEE 802.11 devices. This assumption is not valid for 1 MHz IEEE 802.11ah channel.

Table 1 summarizes the main related work and our coexistence contribution.

Table 1   Summary of Main Related Work and Our Coexistence Contribution.

Reference	Year	Target System	Band	Objective	Validation Tool
A. Sljivo et al. [10]	2018	11ah	Sub-1 GHz	reliability, latency, throughput & energy	ns-3
A. Kureev et al. [11]	2017	11ah	Sub-1 GHz	energy & throughput	analytical & unknown simulator
L. Tian et al. [12][13]	2017	11ah	Sub-1 GHz	throughput	ns-3
L. Tian et al. [14]	2016	11ah	Sub-1 GHz	throughput	ns-3
V. Boños-Gonzalez et al. [15]	2016	11ah	Sub-1 GHz	throughput	analytical
C.S Sum et al. [16]	2013	15.4g	Sub-1 GHz	throughput	Qualnet, MATLAB
F. Righetti et al. [17]	2019	15.4g	Sub-1 GHz	packet delivery rate	experiments
P. Luong et al. [18]	2016	11b & 15.4	2.4 GHz	throughput and packet delivery rate	analytical & unknown simulator
W. Yuan et al. [19]	2010	11b & 15.4	2.4 GHz	throughput	OPNET
E.D.N Ndih et al. [20]	2016	11 & 15.4	2.4 GHz	packet delivery rate	MATLAB
X. Zhang, et al. [21]	2011	11 & 15.4	2.4 GHz	analytical model, throughput	analytical, ns-2
J.Hou et al. [22]	2009	11 & 15.4	2.4 GHz	packet delivery rate	experiments
J.W. Chong et al. [23]	2015	11 & 15.4	2.4 GHz	throughput	analytical
B. Badihi et al. [24]	2013	11ah & 15.4	Sub-1 GHz	throughput	OMNeT++
R. Ma et al. [25]	2017	11b & 15.4	2.4 GHz	analytical model, throughput	analytical & unknown simulator
J. Guo, P. Orlik [26]	2017	11ah & 15.4g	Sub-1 GHz	packet delivery rate and latency for coexistence	ns-3
Y. Liu, J. Guo et al. [27]	2018	11ah & 15.4g	Sub-1 GHz	packet delivery rate and latency for coexistence	ns-3
Y. Nagai, J. Guo et al. [28]	2020	11ah & 15.4g	Sub-1 GHz	packet delivery rate and latency for coexistence	ns-3

4. The S1G Band Standardization Activities

This section introduces the current standardization trend in the S1G bands. In terms of the IEEE 802 standardization, IEEE 802.15.4g-2012 was released as a PHY amendment to IEEE 802.15.4 to support Wireless Smart Utility Network (Wi-SUN) applications. IEEE 802.15.4g is now widely used in the market for low-energy infrastructure monitoring and smart utility applications such as smart meters. IEEE 802.11ah-2016 was released as a MAC/PHY amendment in the S1G bands and targets IoT applications such as smart city. The Wi-Fi Alliance is currently creating the certification program and branding for market launch as Wi-Fi HaLow. The Wi-Fi HaLow, like other Wi-Fi certification programs, will be installed in consumer devices and systems.

Accordingly, 802.11ah Promotion Council (AHPC) was established in 2018 to realize commercialization of IEEE 802.11ah products and solutions into Japanese market.

Looking ahead to the further spread of IEEE 802.15.4g and IEEE 802.11ah deployment, IEEE New Standards Committee and Standard Board formed IEEE 802.19.3 Task Group in December 2018 to develop an IEEE 802 standard for the coexistence of IEEE 802.11ah and IEEE 802.15.4g systems in the S1G frequency bands.

4.1 IEEE 802.19.3 Standardization

Development of IEEE 802.19.3 standard is close to completion. We have successfully resolved all comments received from Working Group Ballots and Sponsor Ballots. Accordingly, IEEE 802 Executive Committee has forwarded IEEE 802.19.3 to IEEE Standards Review Committee for final publication approval. The IEEE-SA Standards Board approved the IEEE 802.19.3 in March 2021.

4.1.1 IEEE 802.19.3 Task Group Formation

We gave an initial presentation on the challenges and solutions for IEEE 802.11ah and IEEE 802.15.4g coexistence, and proposed to establish a standardization group on Sub-1 GHz coexistence under IEEE 802.19 Working Group in November 2017 Plenary Meeting [29]. The presentation received interests from the IEEE 802.19 Working Group. Accordingly, the Sub-1 GHz Interest Group was established, and started operation from May 2018 [30]. After activities over three meetings, the Sub-1 GHz Study Group was created and developed a Project Authorization Request (PAR) and a Criteria for Standards Document (CSD). Accordingly, IEEE New Standards Committee (NesCom) and Standard Board formed IEEE 802.19.3 Task Group in December 2018 [31][32]. The first IEEE 802.19.3 Task Group meeting was held in January 2019. Authors of this paper are key contributors of this Task Group formation. Details of IEEE 802.19.3 can be found on [33]. The project scope of IEEE 802.19.3 Task Group is to develop a Recommendation Practice (RP) to provide guidance on the implementation, configuration and commissioning of systems based on IEEE Std 802.11 S1G PHY and/or IEEE Std 802.15.4 Smart Utility Networking (SUN) FSK PHY operating in the Sub-1 GHz frequency bands to achieve the best possible performance when sharing spectrum. And this recommended practice includes recommendations to address regional regulatory requirements and constrains for license exempt operation.

4.1.2 IEEE 802.19.3 Contributions

IEEE 802.19.3 Task Group started technical discussion towards preparation of draft standard in July 2019. The authors of this paper have been leading this standard development. J. Guo et al. introduced the difference of CSMA/CA mechanisms of IEEE 802.11ah and IEEE 802.15.4g to make clear one of root causes of performance degradation [35]. And, Y. Nagai et al. presented the limitation of frequency band in Japan [36]. We showed the coexistence performance of IEEE 802.11ah and IEEE 802.15.4g based on discussion of use cases and simulation profiles using network simulator [37][38][39]. The solutions for interference mitigation between IEEE 802.11ah and IEEE 802.15.4g were also presented. J. Guo et al. also addressed coexistence issues and solutions of IEEE 802.11ah network and IEEE 802.15.4g network using machine learning approach [40]. Our α-Fairness based energy detection clear channel assessment (ED-CCA) method enables IEEE 802.11ah devices to better detect ongoing IEEE 802.15.4g packet transmissions. Our Q-Learning based backoff mechanisms for IEEE 802.11ah devices is to avoid interfering with IEEE 802.15.4g packet transmission process. We then proposed hy-

brid CSMA/CA for IEEE 802.15.4g to improve IEEE 802.15.4g reliability with more aggressive channel access to compete with IEEE 802.11ah channel access [41]. We also proposed the Fairness Index to evaluate performance of the IEEE 802.11ah and IEEE 802.15.4g coexistence mechanisms [42]. From other parties, the S1G band measurement results and use cases were presented. K. Yano, et al. showed the measurement result of radio noise and interference over 920 MHz band in Japan [43]. The results shows that noises in 920 MHz band may give a severe impact on the performance of both IEEE 802.11ah and IEEE 802.15.4g SUN. Similarly, J. Robert presented the level of interference in 920 MHz band in EU [44].

4.2   Wi-Fi HaLow

At the time of writing this paper, Wi-Fi alliance is planning to release new certification program of Wi-Fi HaLow based on IEEE 802.11ah technology in the S1G bands to offer longer range and lower power community. The Wi-Fi HaLow is targeting outdoor IoT applications in industrial, agricultural, smart building, and smart city environments [2]. Wi-Fi alliance has released white papers of technical overview and IoT applications in 2021.

4.3   802.11ah Promotion Council (AHPC)

802.11ah Promotion Council (AHPC) was established in November 2018 aiming at promoting commercialization of IEEE 802.11ah products and solutions in Japanese market with the participation of voluntary companies and organizations. Currently, more than 100 companies and organizations are affiliated with AHPC. In order to realize the use of IEEE 802.11ah/HaLow, which is not marketed in Japan at this stage, AHPC has been promoting technical studies, demonstration experiments, information gathering, advocacy to related organizations, and promotion of the standard. Use cases for home, office, industry, infrastructure, and mobility have been defined by AHPC [45][46]. Accordingly, AHPC has conducted the first indoor demonstration experiment in Japan with test license in June 2019 [47]. AHPC also announced the first field trial in July 2019 towards the practical use of IEEE 802.11ah/HaLow in Japan [48]. Through the AHPC, the upcoming Wi-Fi HaLow will be deployed to various consumer devices and systems.

5.   Coexistence Behaviour and Strategy in S1G Band

This section describes coexistence behaviour of IEEE 802.11ah and IEEE 802.15.4g and coexistence strategies in the S1G band.

5.1   Coexistence Impact and Issues in S1G Band
5.1.1   Impact of 802.11ah and 802.15.4g Coexistence

In this sub-section, we first evaluate the interference impact of coexisting IEEE 802.11ah network and IEEE 802.15.4g network. There are different factors that can impact on the coexistence performance of IEEE 802.11ah network and IEEE 802.15.4g network. As an example, we examine the impact of network offered load on network reliability by simulating IEEE 802.11ah network and IEEE 802.15.4g network using NS-3 based simu-

lator [49]. For the heterogeneous network performance evaluation, we use IEEE 802.11ah package [14] and implemented necessary IEEE 802.15.4g functions and mutual interference functions in NS-3 simulator. Figure 1 shows our NS-3 based architecture proposed for IEEE 802.19.3 Task Group to evaluate coexistence performance of heterogeneous wireless systems. Both IEEE 802.11ah module and IEEE 802.15.4g module are implemented in NS-3 simulator. Additional coexistence interfaces and functions in PHY/channel modules are provided to notify *"Tx Information (Tx Info)"* between IEEE 802.11ah module and IEEE 802.15.4g module to calculate mutual interference. *Tx Info* includes transmitting timing, device position and Tx Power. Each PHY layer calculates Frame Error Rate (FER) using SINR versus Bit Error Rate (BER) table in consideration of frame transmissions from other system and notifies *"Tx Info"* to other channel module. In the channel module, receive power can be calculated with propagation model. SEAMCAT Extended Hata Model (Suburban) model for propagation between terminals from below rooftop height to near street level is applied as Figure 3. SEAMCAT Extended Hata Model (Suburban) is represented by a combination of NLOS and LOS.

IEEE 802.19.3 Task Group has defined the simulation use cases and scenarios for coexistence evaluation between IEEE 802.11ah and IEEE 802.15.4g [37][38]. All IEEE 802.11ah STAs and IEEE 802.15.4g devices are deployed in a 200 m diameter area with density of 500 /km^2 as show in Figure 2. 15 STAs/devices for each of IEEE 802.11ah network and IEEE 802.15.4g network accommodated in the area. Simulation is performed in 920 MHz band with 1 MHz IEEE 802.11ah channel and 400 kHz IEEE 802.15.4g channel. IEEE 802.11ah PHY data rate is set to 300 kbps of BPSK $R = 1/2$ and $N_{ss} = 1$. We select Binary FSK PHY for IEEE 802.15.4g with data rate of 100 kbps to evaluate if IEEE 802.15.4g devices can compete with IEEE 802.11ah STAs. Transmission power is set to 20 mW for both IEEE 802.11ah and IEEE 802.15.4g based of regulation of ARIB STD-T108. Payload for both IEEE 802.11ah packet and IEEE 802.15.4g packet is 100 bytes. Network offered load, i.e., application data, is uniformly distributed among STAs/devices so that IEEE 802.11ah STAs send packets to IEEE 802.11ah AP and IEEE 802.15.4g devices send packets to IEEE 802.15.4g PANC in star network topology. Each traffic follows a Poison distribution. This uplink traffic model is typical use case for smart utility such as smart meter using IEEE 802.15.4g and for home security with sensors and camera using IEEE 802.11ah that has been discussed in IEEE 802.19.3 Task Group. We use same simulation parameters for this paper.

Table 2 shows data packet delivery rate and latency variations versus different network offered load scenarios. It can be seen that IEEE 802.15.4g network suffers even if IEEE 802.11ah network offered load is reasonable, e.g., IEEE 802.15.4g network delivery only 75.9% of packets when IEEE 802.11ah network offered load is 40 kbps per STA with transmission duty cycle less than 10 % in consideration of regulation and IEEE 802.15.4g network offered load is 10 kbps. On the other hand, IEEE 802.11ah network nearly achieves 100 % of packet delivery rate for all traffic scenarios. IEEE 802.15.4g network impacts on IEEE 802.11ah
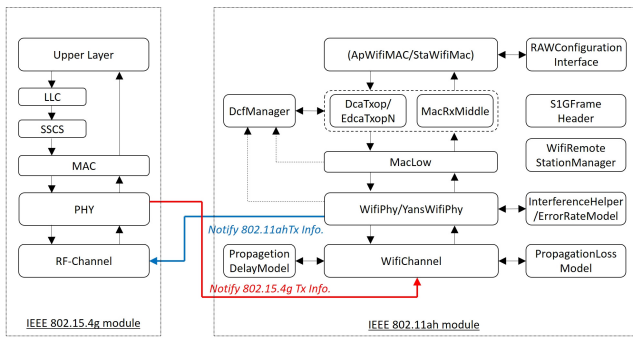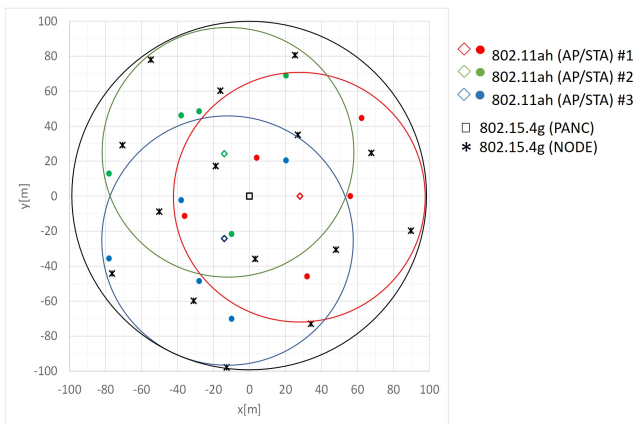
Fig. 1 Coexistence Simulation Architecture

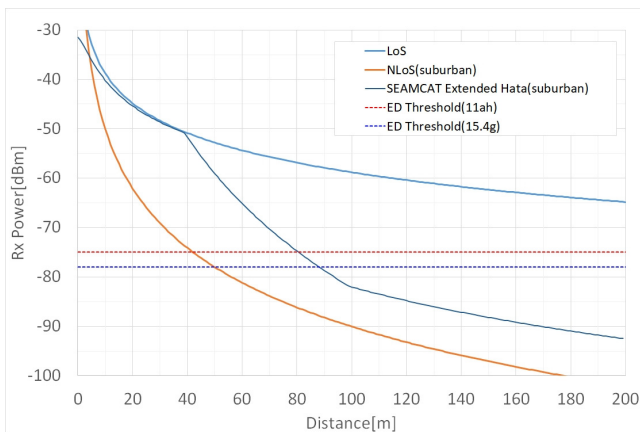**Fig. 2** IEEE 802.11ah and IEEE 802.115.4g Device Deployment Scenario

Fig. 3 Propagation Model

network packet latency, e.g., average IEEE 802.11ah packet latency increases from 10 ms to 15.2 ms (52 % increases) as IEEE 802.15.4g network offered load increases from 10 kbps to 20 kbps. These results indicate that additional coexistence control is needed. Moreover, the need for coexistence control increases rapidly as network offered load grows. In practice, the need for additional coexistence control depends on network size, device deployment, application traffic and other factors. We also evaluated various coexistence scenarios between IEEE 802.11ah and IEEE 802.15.4g in IEEE 802.19.3 WG [29][37]. In the following two sub-sections, we present the causes of the interference that we have analyzed.

Table 2 Packet Delivery Rate and Latency

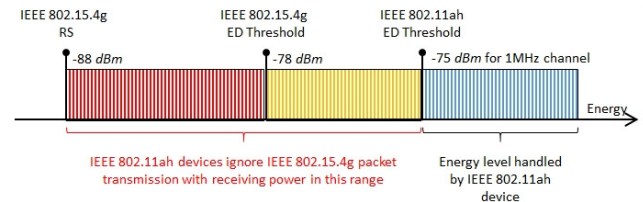| Net. Offered Load [kbps]		Packet Delivery Rate [%]		Packet Latency Avg. [ms]	
802.11ah	802.15.4g	802.11ah	802.15.4g	802.11ah	802.15.4g
10	10	100	96.4	8.7	32.3
20	10	100	91.9	10.0	33.6
40	10	100	75.9	15.2	36.8
20	20	99.9	82.1	15.2	43.6
40	20	99.9	60.7	25.4	46.3

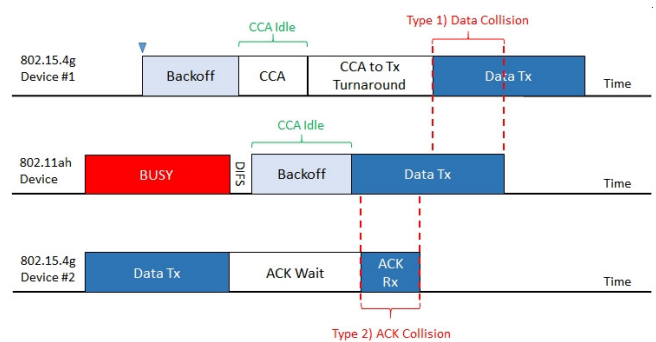**Fig. 4** Interference Caused by Higher 802.11ah ED Threshold

Fig. 5 Interference Caused by Faster Backoff

5.1.2 Interference Caused by Higher 11ah ED Threshold

The IEEE 802.11ah ED threshold is -75 *dBm* for 1 MHz channel, -72 *dBm* for 2 MHz channel, -69 *dBm* for 4 MHz channel and -66 *dBm* for 8 MHz channel. IEEE 802.15.4g ED threshold depends on PHY types and is generally lower than IEEE 802.11ah ED threshold. For OFDM PHY, ED threshold is in [-100 *dBm*, -78 *dBm*]. For O-QPSK PHY, ED threshold is in [-100 *dBm*, -80 *dBm*]. For FSK PHY, ED threshold is in [-100 *dBm*, -78 *dBm*] with FEC and in [-94 *dBm*, -72 *dBm*] without FEC. IEEE 802.15.4g receiver sensitivity (RS) is 10 *dB* lower than the corresponding ED threshold. Figure 4 shows the difference of ED and RS Thresholds for IEEE 802.11ah and IEEE 802.15.4g.

The higher ED threshold of IEEE 802.11ah can cause interference with IEEE 802.15.4g packet transmission. If the detected energy level of an IEEE 802.15.4g packet transmission is above IEEE 802.15.4g RS and below IEEE 802.11ah ED threshold, the energy level is high enough for IEEE 802.15.4g device to successfully decode the packet. However, the packet transmission is disregarded by IEEE 802.11ah device. In this case, IEEE 802.11ah ED-CCA should report busy channel, but it reports idle channel instead. If its backoff counter reaches to zero, an IEEE 802.11ah device will start packet transmission that collides with ongoing IEEE 802.15.4g packet transmission.

5.1.3 Interference Caused by Faster 11ah Backoff Scheme

IEEE 802.11ah backoff process is much faster than IEEE 802.15.4g backoff process due to the smaller time parameters. An IEEE 802.11ah time slot is 52 *μs*, CCA time is less than 40 *μs* and CCA to transmission (TX) turnaround time is less than 5

μs. For IEEE 802.15.4g, the corresponding time parameters depend on symbol rate. With 50 ksymbol/s symbol rate, backoff period is $400\,\mu s$, CCA time is $160\,\mu s$ and CCA to TX turnaround time is $240\,\mu s$. These backoff parameters are even larger for smaller symbol rates. The smaller time parameters give IEEE 802.11ah devices advantage in wireless channel access. For example, IEEE 802.15.4g CCA to TX turnaround time is $240\,\mu s$ that is long enough for an IEEE 802.11ah device to complete a backoff procedure with 4 or less time slots and start packet transmission, which may collide with IEEE 802.15.4g data packet transmission. With 50 ksymbol/s symbol rate, IEEE 802.15.4g ACK waiting time could be up to $1600\,\mu s$ that is long enough for an IEEE 802.11ah device to complete a backoff procedure with 30 or less time slots and start packet transmission, which may collide with IEEE 802.15.4g ACK packet transmission.

As a result, two types of interference are caused as follows: 1) Data packet collision when a) IEEE 802.11ah device ignores low power IEEE 802.15.4g data packet transmission or b) IEEE 802.11ah device starts packet transmission while IEEE 802.15.4g device performs CCA-to-TX turnaround; 2) ACK packet collision when a) IEEE 802.11ah device ignores low power IEEE 802.15.4g ACK transmission or b) IEEE 802.11ah device starts packet transmission when IEEE 802.15.4g device is waiting for ACK packet. Case a) interference is caused by the higher ED threshold of IEEE 802.11ah and case b) interference is caused by the faster backoff mechanism of IEEE 802.11ah. In case a) interference, IEEE 802.11ah device should consider low power nature of IEEE 802.15.4g transmissions. In case b) interference, IEEE 802.11ah device does not violate any protocol. Instead, IEEE 802.11ah CCA mechanism is not able to detect ongoing IEEE 802.15.4g transmission process. Figure 5 shows the interference caused by faster 802.11ah backoff scheme.

5.2 Coexistence Control Techniques

Coexistence architectures recommended for IEEE 802.11ah and IEEE 802.15.4g were proposed in IEEE 802.19.3 Task Group [50]. The architecture classifies coexistence mechanisms based on network coordination and level of coexistence operation.

5.2.1 Coexistence Model Based on Network Coordination

Figure 6 shows the architecture of coexistence model based on network coordination. Coordinated coexistence requires coordination among networks, i.e., the involved networks work collaboratively to mitigate interference. On the other hand, distributed coexistence does not need any coordination among networks, i.e., each network/device performs coexistence operation independently.

5.2.2 Coexistence Model Based on Scope of Coexistence Operation

Figure 7 shows the architecture of coexistence model based on scope of coexistence operation. Coexistence can be performed at network level or device level. Network level coexistence requires all devices in a network to perform same coexistence operation, e.g., channel switching. Device level coexistence does not need all devices in a network to perform same coexistence operation. Coexistence operation is performed by a group of devices or a single device, e.g., deferring transmission.
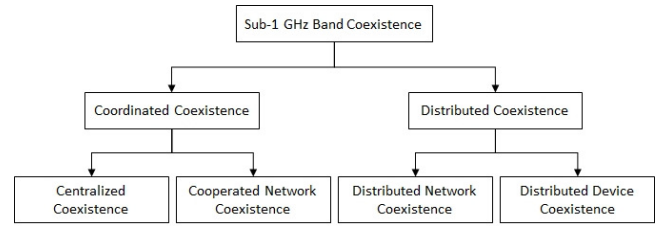

Fig. 6   Coexistence Model Based on Network Coordination
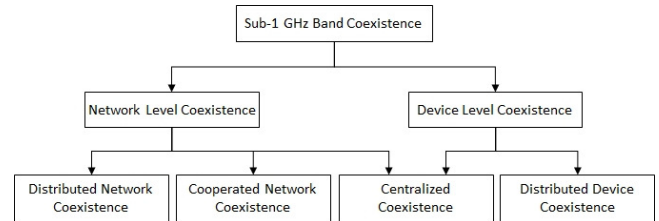

Fig. 7   Coexistence Model Based on Scope of Coexistence Operation

5.2.3 Coexistence Approaches

Three types of coexistence approaches were proposed [50][51]. Table 3 shows the summary of coexistence approaches.

A) Centralized Coexistence

A powerful coordinator can completely manage the coexistence between IEEE 802.11ah and IEEE 802.15.4g networks, in which coordinator collects information from both networks, analyses information and make decision on coexistence control. Once a coexistence decision is made, coordinator sends the coexistence command to both systems.

B) Cooperated Network Coexistence

The coordinator has limited capability. Therefore, the coordinator is not able to manage coexistence between IEEE 802.11ah and IEEE 802.15.4g networks. It only relays information between networks. Based on information collected and exchanged, IEEE 802.11ah AP and IEEE 802.15.4g PANC makes decision and shares their coexistence operation status via the coordinator.

C) Distributed Coexistence

IEEE 802.11ah network and IEEE 802.15.4g network need to have capability to perform distributed coexistence without assistance of coordinator. Without coordinator, it is difficult for an IEEE 802.11ah network/IEEE 802.15.4g network to be aware of coexistence of IEEE 802.15.4g network/IEEE 802.11ah network. However, using conventional ED mechanisms, and statistical information like packet error ratio, retry number, channel occupancy time, each network can detect if other system exists. The distributed coexistence can be divided into Network level operation and device level operation.

6. Proposed Coexistence Mechanisms

In this section, we briefly introduce our machine learning based coexistence mechanisms, α-Fairness based ED-CCA and Q-Learning based CSMA/CA, for the coexistence of IEEE 802.11ah and IEEE 802.15.4g published in [27]. Both methods are distributed coexistence mechanisms proposed for IEEE 802.19.3 coexistence standard development [40]. α-Fairness based ED-CCA enables IEEE 802.11ah devices to detect more ongoing IEEE 802.15.4g packet transmission. Q-Learning based CSMA/CA al-

Table 3 Coexistence Approaches [50]

Type	Approach
Centralized Coexistence	• Channel switching (if possible) • IEEE 802.11ah RAW scheduling • IEEE 802.15.4g superframe structuring • IEEE 802.11 beamforming • Transmission power setting
Cooperated Network Coexistence	Share information: • ED, packet delivery rate • Packet latency Coexistence Operation: • Channel switching (if possible) • IEEE 802.11ah RAW scheduling • IEEE 802.15.4g superframe structuring • IEEE 802.11ah beamforming • Transmission power setting
Distributed Coexistence	Distributed Network Coexistence: • Channel switching • ED Threshold setting • Transmission power setting • Backoff parameter setting • Frequency hopping Distributed Device Coexistence: • Beamforming • Transmission time delay • α-Fairness based ED-CCA [27][40] • Q-Learning based CSMA/CA [27][41] • Prediction based transmission delay • Frame size setting

lows IEEE 802.11ah devices to reduce probability of interfering with IEEE 802.15.4g packet transmission process.

6.1 α-Fairness ED-CCA

The α-Fairness ED-CCA is proposed to mitigate IEEE 802.11ah interference impact on IEEE 802.15.4g caused by the higher ED threshold of IEEE 802.11ah as described in Section 5.1.2. We define a generalized α-Fairness objective function as

$$U(P_i, P_b) = \frac{P_i^{1-\alpha}}{1-\alpha} \frac{M_h^{1-\alpha}}{M_h^{1-\alpha} + M_g^{1-\alpha}} + \frac{P_b^{1-\alpha}}{1-\alpha} \frac{M_g^{1-\alpha}}{M_h^{1-\alpha} + M_g^{1-\alpha}}, \quad (1)$$

where $\alpha > 0, \alpha \neq 1$, is the fairness parameter to favor IEEE 802.11ah or IEEE 802.15.4g, $P_i \geq 0$ is the probability of IEEE 802.11ah ED-CCA reports idle channel, $P_b \geq 0$ is the probability of IEEE 802.11ah EC-CCA reports busy channel, $M_h \geq 0$ is the locally observed performance metric of 802.11ah network, $M_g \geq 0$ is the locally observed performance metric of 802.15.4g network. The network performance metric can be packet transmission rate, packet delivery rate, channel utilization etc. The locally observed network metric is device dependent and therefore, different from the metric for whole network. The locally observed inputs assume that each IEEE 802.11ah device performs independent coexistence control. α-Fairness wireless medium sharing between IEEE 802.11ah network and IEEE 802.15.4g network corresponding to maximization of objective function $U(P_i, P_b)$ subject to condition $P_i + P_b = 1$. Hence, our optimization problem has a unique solution given by

$$P_i^o = \frac{1}{1 + (\frac{M_h}{M_g})^{\frac{\alpha-1}{\alpha}}}, \quad and \quad P_b^o = \frac{1}{1 + (\frac{M_h}{M_g})^{\frac{1-\alpha}{\alpha}}}. \quad (2)$$

It can be seen that if $\alpha > 1$, more medium access opportunity is given to the network with the smaller performance metric and if $\alpha < 1$, more medium access opportunity is given to the network with the greater performance metric. More information on

α-Fairness ED-CCA is given in [27][40].

Typically, an IEEE 802.11ah device may apply α-Fairness ED-CCA mechanism when the detected energy level by CCA operation is in between IEEE 802.15.4g RS and IEEE 802.11ah ED threshold.

6.2   Q-Learning based CSMA/CA

Q-Learning based CAMA/CA is proposed to mitigate 802.11ah interference impact on IEEE 802.15.4g transmission process caused by the faster CSMA/CA of IEEE 802.11ah as described in Section 5.1.3. Q-Learning is formulated as

$$Q_{t+1}(s, a) = (1 - \tau_t)Q_t(s, a) + \tau_t(R_t(s, a) + \gamma V_t(s', b)),$$

$$V_t(s', b) = \max_{b \in B(s')} Q_t(s', b), \quad (3)$$

where $Q_t(s, a)$ is Q-Learning objective function, s' is the state reached from state s by taking action a, $B(s')$ is action set that can be taken at state s', $0 < \tau_t < 1$ is the learning rate, $0 < \gamma < 1$ is the discount factor and $R_t(s, a)$ is the reward obtained by performing action a at state s at time t.

To apply Q-Learning for wireless medium sharing, state set S is defined as $S = \{S_1, S_2\} = \{Idle\ Channel, Busy\ Channel\}$, action set A is defined as $A = \{a_1, a_2\} = \{Transmit, Backoff\}$. We can obtain the maximum value of the Q-Learning objective function as $V_t(s', b)$. The reward is defined based on α-Fairness as

$$R_t(s, a) = \begin{cases} \frac{1}{|U^o - U_i^o| + 1}, & (s_1, a_1) \\ \sigma, & (s_1, a_2) \\ 0, & (s_2, a_1) \\ \frac{1}{|U^o - U_b^o| + 1}, & (s_2, a_2) \end{cases} \quad (4)$$

where $U^o = U(P_i^o, P_b^o)$ is the α-Fairness objective function with optima probability P_i^o and P_b^o, $\sigma > 0$ is small parameter and U_i^o and U_b^o are given by

$$U_i^o = \frac{(P_i^o)^{1-\alpha}}{1-\alpha} \frac{M_h^{1-\alpha}}{M_h^{1-\alpha} + M_g^{1-\alpha}}, \quad and$$

$$U_b^o = \frac{(P_b^o)^{1-\alpha}}{1-\alpha} \frac{M_g^{1-\alpha}}{M_h^{1-\alpha} + M_g^{1-\alpha}}. \quad (5)$$

Following is the rational of the Q-Learning reward assignment: 1) If the channel is idle, IEEE 802.11ah device is encouraged to transmit packet. Therefore, we assign positive reward to $\{s_1, a_1\}$ pair; 2) If the channel is idle, backoff is a generous operation to perform. Thus, we assign a very small reward to $\{s_1, a_2\}$ pair; 3) It definitely causes interference to transmit packet when the channel is already busy. As a result, we assign zero reward to $\{s_2, a_1\}$ pair to punish the behavior; 4) If the channel is busy, backoff is the right action to take. So, we assign positive reward to $\{s_2, a_2\}$ pair to encourage IEEE 802.11ah device to perform backoff. If $P_i^o > P_b^o$, the channel is more likely idle. $P_i^o > P_b^o$ also indicates that $\{s_1, a_1\}$ pair has a larger reward. Therefore, Q-Learning tends to choose the action a_1 for IEEE 802.11ah device. On the other hand, if $P_i^o < P_b^o$, the channel is more likely busy. $P_i^o < P_b^o$ also implies that $\{s_2, a_2\}$ pair has a larger reward. Thus,

Q-Learning tends to choose the action a_2 for IEEE 802.11ah device. If $P_i^o = P_b^o$, Q-Learning tends to select action a_1 or action a_2 with equal probability. Notice that for $\alpha > 1$, $P_i^o > P_b^o$ indicates $M_h < M_g$. Therefore, it is reasonable for 802.11ah device to transmit more packets. Similarly, $P_i^o < P_b^o$ indicates $M_h > M_g$. As a result, it is appropriate for IEEE 802.11ah device to do more backoff. More information on Q-Learning based CSMA/CA is given in [27][40].

Typically, an IEEE 802.11ah device may apply Q-Learning based CSMA/CA mechanism when the CCA operation returns idle channel and its backoff counter reaches to zero.

6.3   Implementation of α-Fairness based ED-CCA and Q-Learning based CSMA/CA

The proposed coexistence methods can be implemented in different ways depending on the availability of performance metrics from both IEEE 802.11ah network and IEEE 802.15.4g network and application requirements.

For the α-Fairness based ED-CCA method, we use the case $\alpha > 1$ as an example to illustrate the implementation procedure. The implementation only needs to compute the channel idle probability P_i^o as shown in Eq. (2). If a network coordinator such as a common gateway is available to provide network wide metrics such as packet delivery rate for both IEEE 802.11ah network and IEEE 802.15.4g network, IEEE 802.11ah device can use IEEE 802.11ah network packet delivery rate as M_h and IEEE 802.15.4g network packet delivery rate as M_g. IEEE 802.11ah device selects an initial α value, e.g., 10, and uses initial available M_h and M_g values to compute probability P_i^o, which is then used in CCA channel status report when the detected energy level on its channel is between IEEE 802.15.4g RS and IEEE 802.11ah ED threshold. When updated packet delivery rates become available later, the IEEE 802.11ah device can adjust the α value accordingly. If M_h is greater than M_g and two networks desire close packet delivery rate M_h and M_g, the α value should be increased. This will decrease channel idle probability P_i^o. As a result, the IEEE 802.11ah CCA mechanism will more likely report channel busy status. Therefore, the IEEE 802.11ah devices will perform more backoff and the more channel access opportunity will be given to IEEE 802.15.4g devices to increase IEEE 802.15.4g packet delivery rate M_g. Similarly, if M_h is less than M_g, the α value should be decreased. The IEEE 802.11ah devices can also adjust the α value to achieve other desired M_h and M_g. If network wide metric is not available, an IEEE 802.11ah device can use one of the locally observed metrics as M_h and M_g. The estimation of locally observed metrics is described in [27]. For example, an IEEE 802.11ah device can use locally observed channel occupancy time as M_h and M_g. In this case, IEEE 802.11ah devices can adjust channel access time of two networks by using different α value.

For Q-Learning based CSMA/CA, the implementation can apply standard Q-Learning implementation since we use typical Q-Learning formulation as shown in Eq. (3). To implement Q-Learning, the reward $R_t(s, a)$ needs to be computed. Even other types of reward can be defined, we define α-Fairness based reward as shown in Eq. (4). IEEE 802.11ah device can use

Table 4   Simulation parameters for IEEE 802.11ah and IEEE 802.15.4g coexistence performance defined in IEEE 802.19.3 Task Group

Parameters	Value [Unit]	Note
Network offered load	30 kbps	11ah
Network offered load	10 - 60 kbps	15.4g
Tx Power	20 mw	11ah & 15.4g
11ah Bandwidth	1 MHz	11ah
15.4g Bandwidth	400 kHz	15.4g
aSlotTime	52 usec	11ah
aSIFSTime	160 usec	11ah
aCCATime	<40 usec	11ah
aRxTxTurnaroundTIme	Less than 5 usec	11ah
CW (min, max)	15, 1023	11ah
phyCCADuration	140 usec	15.4g
aTurnaroundTime	1000 usec	15.4g
Rx to Tx TrunaroundTIme	300 usec or more, 1000 usec or less	15.4g
Tx to Rx TurnaroundTIme	Less than 300 usec	15.4g
macMinLIFSPeriod	1000 usec	15.4g
aUnitBackoffPeriod	1140 usec	15.4g
macAckWaitDuration	5 ms	15.4g
macMaxBE	3 to 8 (Default 5)	15.4g
macMinBE	0 to macMaxBE (Default 3)	15.4g
macMaxCSMABackoffs	0 to 5 (Default 4)	15.4g
macMaxFrameRetries	0 to 7 (Default 4)	15.4g
Fair Factor: α	10	α-Fairness
Discount Factor: γ	0.5	Q-Learning
Learning Rate: τ_t	0.5 (initial)	Q-Learning

one of available performance metrics as M_h and M_g to compute channel status probabilities P_i^o, P_b^o and objective function values U^o, U_i^o, U_b^o, which are then used to compute the reward $R_t(s, a)$. Given the channel status, the Q-Learning will learn an action to maximize the Q-Learning objective function.

7.   Performance Evaluation and Analysis

We evaluated performance of the proposed coexistence techniques with simulation setup same as in Section 5.1.1. We set IEEE 802.15.4g network offered load as 30 kbps and IEEE 802.11ah network offered load as 10 - 60 kbps. Table 4 shows simulation parameters for IEEE 802.11ah and IEEE 802.15.4g coexistence performance. We used mutual interference effect on both packet delivery rate, packet latency and fairness index as performance metrics. The simulation has been conducted for typical IoT use case scenarios that have been defined in IEEE 802.11ah, IEEE 802.15.4g and IEEE 802.19.3. For our proposed method, α is set to 10, γ is set to 0.5 and τ_t is initially set to 0.5, respectively. The locally observed data packet transmission rate is used as input metrics for α-Fairness ED-CCA. Four coexistence control scenarios are simulated for various combination: 1) Conventional IEEE 802.11ah ED-CCA; 2) α-Fairness ED-CCA; 3) Q-Learning backoff; 4) combination of α-Fairness ED-CCA and Q-Learning backoff;

7.1   Packet Delivery Rate

Figure 8 shows the variation of IEEE 802.11ah and IEEE 802.15.4g data packet delivery rate (PDR) with respect to different coexistence mechanisms, where Y-axis represents the ratio of the packet successfully delivered, and X-axis represents the simulation time. The offered load for both IEEE 802.11ah network and IEEE 802.15.4g network is set to 30 kbps. 1) Using IEEE 802.11ah ED-CCA, IEEE 802.15.4g network drops 46.0

% because of interference from IEEE 802.11ah network. 2) α-Fairness ED-CCA can improve IEEE 802.15.4g PDR from 54.0 % to 68.9 %. 3) Q-Learning backoff can increase IEEE 802.15.4g PDR from 54.0 % to 71.7 % and 4) Combined α-Fairness ED-CCA and Q-Learning backoff can also improve IEEE 802.15.4g PDR from 54.0 % 77.5 %. In all scenarios, IEEE 802.11ah network achieves nearly 100 % PDR.

Table 5 shows the variation of IEEE 802.11ah and IEEE 802.15.4g data packet delivery rate (PDR) with respect to different coexistence mechanisms and network offered load for IEEE 802.11ah. IEEE 802.15.4g PDR degrades as IEEE 802.11ah network offered load increase. Cases a) to d) show the similar tendency that the IEEE 802.15.4g PDR is improved over the proposed method without degradation of IEEE 802.11ah PDR. Although our coexistence techniques improve IEEE 802.15.4g PDR, Case e) to f) show the improvement is in the expense of IEEE 802.11ah PDR. It is because the total network offered load exceeds the network capacity, and the improvement of IEEE 802.15.4g PDR is saturated.

7.2   Data Packet Latency

Data packet latency is defined as time difference from the time a packet transmission process starts to the time packet is successfully confirmed. Therefore, the latency is $T_{Backoff} + T_{DataTX} + T_{WaitingACK} + T_{ACKRX}$. Figure 9 shows the variation of IEEE 802.11ah and IEEE 802.15.4g latency with respect to different coexistence mechanisms, where Y-axis represents the Cumulative Distribution Function (CDF), and X-axis represents the delay time. Both IEEE 802.11ah and IEEE 802.15.4g offered loads are set to 30 kbps. Using 1) IEEE 802.11ah ED-CCA, IEEE 802.15.4g packet has longer latency than IEEE 802.11ah packet. With our coexistence methods 2) to 4), IEEE 802.15.4g packet improved latency slightly. Furthermore, IEEE 802.15.4g packet has much shorter latency than IEEE 802.11ah packet since we add transmission control to IEEE 802.11ah device. Overall, most of the delivered IEEE 802.15.4g packets are confirmed within 200 ms. On the other hand, latency of IEEE 802.11ah packet increases with each coexistence control method added since our coexistence methods suppress the transmission of IEEE 802.11ah in exchange for IEEE 802.15.4g transmission opportunity.

Table 6 shows the variation of IEEE 802.11ah and IEEE 802.15.4g latency average with respect to different coexistence mechanisms and network offered load for IEEE 802.11ah. IEEE 802.15.4g latency does not change greatly as IEEE 802.11ah network offered load increases. For all IEEE 802.11ah network offered load, IEEE 802.15.4g latency shows the similar tendency such that IEEE 802.15.4g latency is improved over the proposed coexistence methods. On the other hand, latency of IEEE 802.11ah packet increases significantly as IEEE 802.11ah network offered load increases. Furthermore, IEEE 802.11ah packet latency increases over our proposed coexistence control methods since our coexistence method suppress the transmission of IEEE 802.11ah in exchange for IEEE 802.15.4g transmission opportunity.
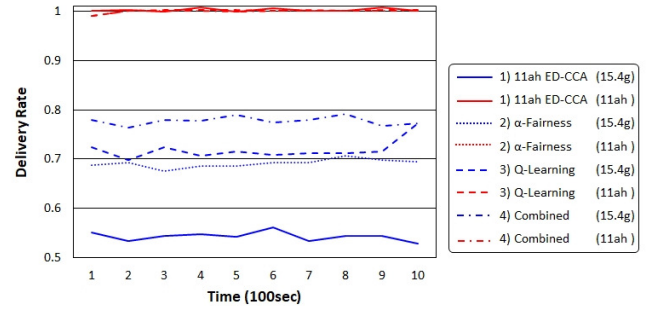
Fig. 8   IEEE 802.11ah and IEEE 802.15.4g PDR (Case c): Both IEEE 802.11ah and IEEE 802.15.4g network offered loads are set to 30 kbps
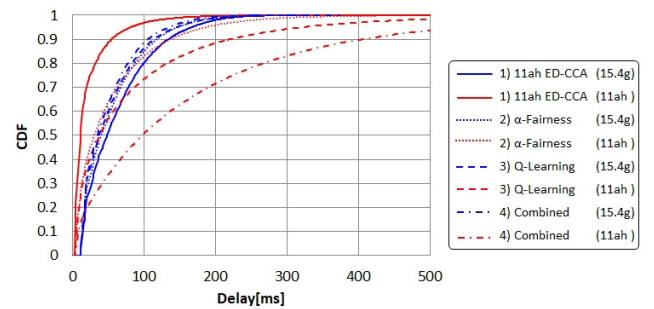
Fig. 9   IEEE 802.11ah and IEEE 802.15.4g CDF (Case c): Both IEEE 802.11ah and IEEE 802.15.4g network offered loads are set to 30 kbps
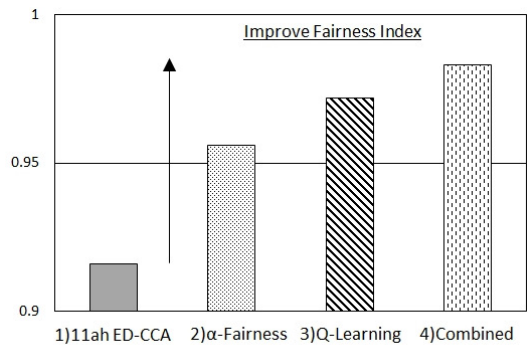
Fig. 10   Fairness Index for coexistence (Case c): 1) IEEE 802.11ah ED-CCA; 2)α-Fairness ED-CCA; 3) Q-Learning backoff; 4) Combined α-Fairness ED-CCA and Q-Learning backoff. Both IEEE 802.11ah and IEEE 802.15.4g network offered loads are set to 30 kbps

7.3   Fairness Index

We provide a novel method to evaluate coexistence fairness when IEEE 802.11ah and IEEE 802.15.4g share frequency spectrum and the wireless resource on this paper. Jain's Fairness Index (FI) is well known for TCP flow fairness that shares media resource by several flows [52]. We apply Jain's Fairness Index to IEEE 802.15.4g and IEEE 802.11ah coexistence situation to evaluate the effect of degradation by mutual interference as [53]:

$$\frac{(\sum_{i=1}^{n} x_i)^2}{n \sum_{i=1}^{n} x_i^2} \Rightarrow \frac{(\sum_{i=1}^{m} x_{i_{4g}} + \sum_{i=1}^{n} x_{i_{ah}})^2}{(m+n)(\sum_{i=1}^{m} x_{i_{4g}}^2 + \sum_{i=1}^{n} x_{i_{ah}}^2)}, \tag{6}$$

where $x_{i_{4g}}$, $x_{i_{ah}}$ are the normalized throughput, m and n are the number of stations/devices respectively. Normalized throughput is denoted as $x = t/o$, where t is measured throughput (kpbs), and

Table 5   IEEE 802.11ah and IEEE 802.15.4g data packet delivery rate variations versus different network offered loads

Case	Offered Load [kbps]		1) 11ah ED-CCA		2) α-Fairness		3) Q-Learning		4) Combined	
			Packet Delivery Rate [%]							
	11ah	15.4g	11ah	15.4g	11ah	15.4g	11ah	15.4g	11ah	15.4g
a	10	30	100	87.2	100	89.3	100	90.9	99.9	91.7
b	20	30	100	73.5	99.9	81.0	100	85.0	99.9	87.0
c	30	30	99.9	54.0	99.9	68.9	99.9	71.7	99.9	77.5
d	40	30	99.9	30.0	99.9	53.0	99.9	61.4	99.7	62.7
e	50	30	99.9	12.8	99.8	37.8	98.4	59.3	80.3	62.9
f	60	30	99.9	9.1	86.8	35.3	85.7	58.1	68.4	62.0

Table 6   IEEE 802.11ah and IEEE 802.15.4g data packet latency variations versus different network offered loads

Case	Offered Load [kbps]		1) 11ah ED-CCA		2) α-Fairness		3) Q-Learning		4) Combined	
			Packet Latency Avg. [ms]							
	11ah	15.4g	11ah	15.4g	11ah	15.4g	11ah	15.4g	11ah	15.4g
a	10	30	10.5	42.8	22.3	40.0	29.4	37.6	54.9	37.5
b	20	30	15.1	53.8	33.0	47.5	46.2	43.7	82.7	42.3
c	30	30	23.4	63.9	55.9	56.0	86.1	53.9	167.1	50.4
d	40	30	40.4	72.3	115.2	64.8	230.5	58.3	343.3	58.8
e	50	30	95.6	79.9	251.9	71.4	346.5	57.0	371.6	58.9
f	60	30	159.7	80.0	283.6	71.3	358.3	56.4	364.6	58.6

o is offered load (kbps).

Figure 10 shows Fairness Index to compare 1) IEEE 802.11ah ED-CCA; 2) α-Fairness ED-CCA; 3) Q-Learning backoff; 4) Combined α-Fairness ED-CCA and Q-Learning backoff. Conventional IEEE 802.11ah ED-CCA shows 0.916 for Fairness Index because of IEEE 802.15.4g throughput degradation compared to IEEE 802.11ah throughput. Proposed 2) α-Fairness ED-CCA improves Fairness Index to 0.965 (+ 49 points), because of IEEE 802.15.4g PDR and throughput improvement. Proposed 3) Q-Learning backoff also improves Fairness Index to 0.972 (+ 56 points) as same manner. Furthermore, proposed 3) combination of α-Fairness ED-CCA and Q-Learning backoff achieves Fairness Index 0.983 (+ 67 points). These proposed methods increased IEEE 802.15.4g throughput by suppression of IEEE 802.11ah throughput. Thus, these results shows effectiveness of the proposed methods for IEEE 802.15.4g and IEEE 802.11ah coexistence.

8.   Conclusions

IEEE 802.11ah and IEEE 802.15.4g are two wireless technologies designed for outdoor IoT applications. IEEE 802.15.4g technology has been widely installed in smart meters and LECIM devices. Wi-Fi Alliance and Japan AHPC are promoting commercialization of IEEE 802.11ah technology for consumer products. For IoT applications, both technologies operate in the S1G frequency bands. Therefore, interference free coexistence of these two wireless technologies is critical. Accordingly, IEEE New Standards Committee and Standard Board formed IEEE 802.19.3 Task Group in December 2018 to develop an IEEE 802 standard for the coexistence of IEEE 802.11ah and IEEE 802.15.4g systems in the S1G frequency bands. The authors of this paper have been leading this standard development and made major contributions. This paper first presents the related coexistence work in the research community. We then introduce the IEEE 802.19.3 standardization status and activities. We also categorize coexistence approaches in IEEE 802.19.3. IEEE 802.11ah/HaLow and

AHPC use cases and applications toward deployment are presented next. Furthermore, we summarize our α-Fairness based ED-CCA and Q-Learning based CSMA/CA coexistence mechanisms, which are two of coexistence methods recommended by IEEE 802.19.3. The simulation results adopted in IEEE 802.19.3 are also presented, which confirm that the proposed α-Fairness based ED-CCA and Q-Learning based CSMA/CA coexistence mechanisms improve IEEE 802.15.4g reliability and coexistence fairness of IEEE 802.11ah network and IEEE 802.15.4g network. For next step, we will investigate more use cases in consideration of various offered load and deployment scenarios.

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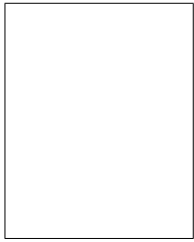
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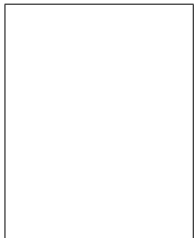
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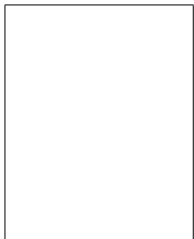
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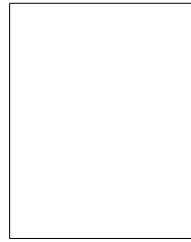
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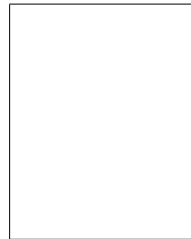
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