Sub-1 GHz Frequency Band Wireless Coexistence for the Internet of Things

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Abstract

Motivated by the explosion of the Internet of Things (IoT), we examined Sub-1 GHz (frequencies below 1 GHz) band wireless technologies that are essential to enable various IoT applications. IEEE 802.15.4g and IEEE 802.11ah are two wireless technologies developed for outdoor IoT applications such as smart utility, smart city and infrastructure monitoring for which both technologies operate in Sub1 GHz Bands. Our coexistence simulation of IEEE 802.15.4g and IEEE 802.11ah using standard defined coexistence mechanisms shows serious interference problems due to fundamental protocol differences and channel access parameter differences. Accordingly, we proposed IEEE 802.19.3 Task Group formation to lead the IEEE 802.19.3 standard development of IEEE 802.15.4g and IEEE 802.11ah coexistence in the Sub1 GHz band. In addition to our coexistence methods contributed to IEEE 802.19.3 standard, we propose a novel Active Carrier Sense based CSMA/CA mechanism for IEEE 802.15.4g to reduce CSMA/CA failure packet discard under interference from IEEE 802.11ah traffic and to keep interoperability with conventional IEEE 802.15.4g CSMA/CA mechanism. Our proposed coexistence techniques can improve fair spectrum sharing between IEEE 802.15.4g and IEEE 802.11ah networks for IoT applications.

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ABSTRACT Motivated by the explosion of the Internet of Things (IoT), we examined Sub-1 GHz (frequencies below 1 GHz) band wireless technologies that are essential to enable various IoT applications. IEEE 802.15.4g and IEEE 802.11ah are two wireless technologies developed for outdoor IoT applications such as smart utility, smart city and infrastructure monitoring for which both technologies operate in Sub-1 GHz Bands. Our coexistence simulation of IEEE 802.15.4g and IEEE 802.11ah using standard defined coexistence mechanisms shows serious interference problems due to fundamental protocol differences and channel access parameter differences. Accordingly, we proposed IEEE 802.19.3 Task Group formation to lead the IEEE 802.19.3 standard development of IEEE 802.15.4g and IEEE 802.11ah coexistence in the Sub-1 GHz band. In addition to our coexistence methods contributed to IEEE 802.19.3 standard, we propose a novel Active Carrier Sense based CSMA/CA mechanism for IEEE 802.15.4g to reduce CSMA/CA failure packet discard under interference from IEEE 802.11ah traffic and to keep interoperability with conventional IEEE 802.15.4g CSMA/CA mechanism. Our proposed coexistence techniques can improve fair spectrum sharing between IEEE 802.15.4g and IEEE 802.11ah networks for IoT applications.

INDEX TERMS Wireless Coexistence, interference mitigation, Sub-1 GHz band, IEEE 802.19.3, IEEE 802.15.4g, IEEE 802.11ah, Smart Utility, Infrastructure Monitoring, Internet of Things.

I. INTRODUCTION

Against the backdrop of advances in Internet technology and various sensor technologies, the number of devices connected to the Internet has been rapidly increasing, not only to traditional Internet-connected devices such as laptops and smartphones, but also to smart meters, home appliances, automobiles, buildings, factories, and many other things around the world. Low Power Wide Area (LPWA) network is in the spotlight as a wireless network for the Internet of Things (IoT). The representative wireless technologies such as IEEE 802.15.4g [1] marketed as Wireless Smart Utility Network (Wi-SUN), SigFox and LoRaWAN have already been deployed in the market. These technologies are expected to be used in applications where information is collected from a large number of IoT devices, such as smart meters and environmental monitoring sensors, and have features such as long transmission distance, multi-device connectivity, low cost and low power consumption for long-term use in sensor devices. In addition to the above-mentioned wireless technologies, IEEE 802.11 Working Group has developed IEEE 802.11ah [2] as a wireless standard for outdoor IoT applications in the Sub-1 GHz band (S1G). Wi-Fi Alliance, which is promoting the spread of wireless LAN devices, brands it as Wi-Fi HaLow [3]. For outdoor IoT applications, IEEE 802.15.4g also operates in the S1G band. Both IEEE 802.15.4g and IEEE 802.11ah have communication ranges up to 1000 meters. Thus, IEEE 802.15.4g network and IEEE 802.11ah network are likely to coexist. These standards define different modulation schemes and frame structures and no coexistence mechanism like common mode signalling (CMS) [4] [5] has been defined. Furthermore, the available frequency spectrum allocation for IEEE 802.15.4g and IEEE 802.11ah in the S1G band is limited to several MHz bandwidth in certain regions and countries. 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 $\sim$ 928.1 MHz (7.6 MHz bandwidth), but the ARIB STD-T107 (250 mW, passive system) and the ARIB STD-T108 (250 mW, licensed/registered) also define operation from 920.5 $\sim$ 923.5 MHz (3.0 MHz). Therefore, 923.5 $\sim$ 928.1 MHz (4.6 MHz bandwidth) is the only reasonable frequency band for IEEE 802.15.4g applications in the unlicensed spectrum. IEEE 802.15.4g is regulated to operate over 200 kHz bandwidth channel in the S1G band. Even low duty cycle constraint applies in the S1G band, e.g., Japanese and European standards allow up to 10% transmission duty cycle [6] [7] [8] [9], when the number of IoT devices increases significantly, interference mitigation between these standards becomes 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 the maximum value of 1000 mW. IEEE 802.11ah mandates the support of 1 MHz channel, which is much narrower than the conventional IEEE 802.11 (b/g/n) channels that are at least 20 MHz wide. Furthermore, IEEE 802.11ah defines several channel bandwidths up to 16 MHz wide. The MIMO is also used in IEEE 802.11ah as well in other IEEE 802.11 standards. IEEE 802.15.4g can operate in both S1G band and 2.4 GHz band. An IEEE 802.15.4g personal area network coordinator (PANC) can associate with more than 6000 nodes. 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 802.15.4g only addresses coexistence among devices using 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 in the S1G band? Our simulation results show that IEEE 802.11ah ED-CCA coexistence mechanism does not perform well even in low duty cycle scenarios. Due to the fact that IEEE 802.11ah mandates the support of 1 MHz channel, the existing coexistence techniques designed for wide channels may not work properly. Therefore, we proposed to address the coexistence issue in the IEEE community. 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 actively led this standard development. Benjamin A. Rolfe is Task Group Chair, Jianlin Guo is Task Group Technical Editor and Yukimasa Nagai is a member of Comment Resolution Committee of IEEE 802.19.3.

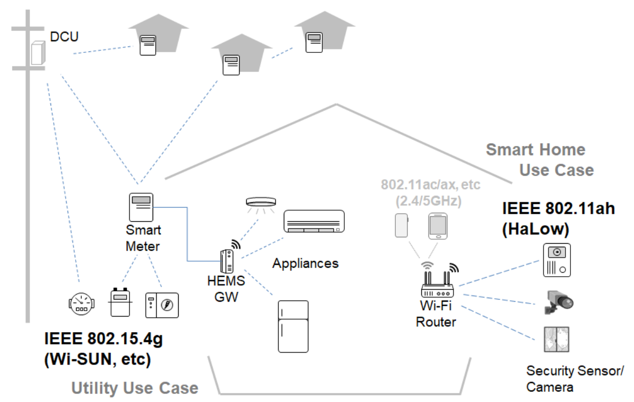

FIGURE 1. IoT application coexistence use case of smart utility using IEEE 802.15.4g and smart home using IEEE802.11ah / Wi-Fi Halow in S1G band.

Figure 1 shows typical coexistence use case of smart utility using IEEE 802.15.4g/Wi-SUN and smart home using IEEE 802.11ah/Wi-Fi Halow in the S1G band. In smart utility use case, the HEMS GW (Home Energy Management System Gateway), as an indoor data hub, connects to the appliances using IEEE 802.15.4g. The Smart Meter installed on the wall outside house uses IEEE 802.15.4g to communicate with the DCU (Data Concentrator Unit) to send messages corresponding to electricity usage and demand response. The smart meters, which cannot directly communicate with the DCU, communicate with the DCU via neighboring smart meters by the multi-hop communication. IEEE 802.15.4g can also be used for other critical infrastructures such as gas, water and storage battery. In smart home use case, IEEE 802.11ah is promising for home automation, smart appliance, health, wearable and content synchronization between home server and vehicles. In addition, the Wi-Fi Router installed in the house can use 2.4/5 GHz bands to connect to smartphones and tablets to communicate with intercoms, surveillance cameras, security sensors and other devices around house. Thus, IEEE 802.15.4g and IEEE 802.11ah are expected to be used in the same area for various IoT applications and devices. Therefore, the coexistence of IEEE 802.15.4g and IEEE 802.11ah in the S1G should be considered.

This paper is an extended version of our works in [30] [31] [32] by adding followings: 1) a novel Active Carrier Sense (ACS) based CSMA/CA for IEEE 802.15.4g to address CSMA/CA failure packet discard caused by IEEE 802.11ah transmissions; 2) the analysis of IEEE 802.15.4g and IEEE 802.11ah coexistence behaviour from protocol perspective; 3) the detailed analysis of coexistence issues about CSMA/CA failure packet discard; 4) the extensive simulations of different coexistence methods; 5) IEEE 802.19.3 S1G band coexistence standardization; and 6) the S1G band coexistence simulator.

Our ACS based CSMA/CA for IEEE 802.15.4g aims to reduce CSMA/CA failure packet discard under the interference such as IEEE 802.11ah transmissions and to keep interoperability with conventional IEEE 802.15.4g. The quantitative coexistence evaluation is performed using our Sub-1 GHz band coexistence simulator and is guided by the use case scenarios developed in the IEEE 802.19.3 Coexistence Task Group. Performance comparison among the proposed coexistence mechanisms is also conducted.

The rest of this paper is organized as follows. Section II presents related work in the research community including our previous works. Section III provides the current standardization trend in the S1G band. Section V describes the IEEE 802.11ah and IEEE 802.15.4g coexistence behavior and issues. We present our S1G band coexistence simulator in Section IV. Previously proposed S1G band coexistence technologies are summarized in Section VI. We introduce our Active Carrier Sense based CSMA/CA in Section VII. Simulation results of our coexistence mechanisms are presented in Section VIII. Finally, we conclude our paper in Section IX.

II. RELATED WORK

IEEE 802.15.4g and IEEE 802.11ah have led to extensive performance and coexistence studies in research community. Table 1 shows the majority of the available performance evaluation and conventional coexistence researches. These works can be divided into five categories: 1) Performance of homogeneous IEEE 802.15.4g network; 2) Performance of homogeneous IEEE 802.11ah network; 3) Coexistence of IEEE 802.11 and IEEE 802.15.4 networks; 4) Coexistence of IEEE 802.11ah and IEEE 802.15.4 networks; 5) Coexistence of IEEE 802.15.4g and IEEE 802.11ah networks.

1) Performance of Homogeneous IEEE 802.15.4g Network (Sub-1 GHz)

For homogeneous networks, IEEE 802.15.4g performance has been demonstrated in [10] [11], which focus on the PHY and MAC protocol enhancement for higher-throughput, protocol efficiency and delay via simulation and measurement result using prototypes. For example, D. Hotta et al. introduce the performance of multi-hop routing construction using Wi-SUN FAN (Field Area Network) prototypes based on IEEE 802.15.4g FSK PHY [12].

2) Performance of Homogeneous IEEE 802.11ah Network (Sub-1 GHz)

Similarly, throughput performance evaluations of IEEE 802.11ah have been demonstrated in [13] [14] [15] [16] using simulator. V. Baños-Gonzalez et al. introduce the challenge for IoT applications and IEEE 802.11ah by analytical approach [18]. Efficient ways of allocating STAs to RAW (Restricted Access Window) slots have been studied. M. Qutab-ud din et al. have proposed grouping STAs according to their back-off status [19]. In [20], N. Ahmed et al. have studied grouping of STAs according to traffic congestion.

3) Coexistence of IEEE 802.11 and IEEE 802.15.4 Networks (2.4 GHz)

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 (ZigBee) network in 2.4 GHz band [21]. 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 interferers 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 (ZigBee) network in 2.4 GHz band [22]. Proposed CBT allows a separate IEEE 802.15.4 device to hop to an adjacent channel 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 (ZigBee) specifications so that it can transmit IEEE 802.11 and IEEE 802.15.4 messages [23]. 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 device 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 [24]. 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. P. Luong et al. evaluate throughput and packet delivery rate for IEEE 802.15.4 (ZigBee) and IEEE 802.11b networks under unsaturated traffic [25]. 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 [26]. 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

TABLE 1. The majority of available performance evaluation, and conventional coexistence researches.

Reference	Year	Target System	Band	Objective	Validation Tool
C.S Sum et al. [10]	2013	15.4g	Sub-1 GHz	throughput	Qualnet, MATLAB
F. Righetti et al. [11]	2019	15.4g	Sub-1 GHz	packet delivery rate	experiments
D. Hotta et al. [12]	2020	15.4g	Sub-1 GHz	multi-hop routing construction	experiments
A. Sljivo et al. [13]	2018	11ah	Sub-1 GHz	reliability, latency, throughput & energy	ns-3
A. Kureev et al. [14]	2017	11ah	Sub-1 GHz	energy & throughput	analytical & unknown simulator
L. Tian et al. [15] [16]	2017	11ah	Sub-1 GHz	throughput	ns-3
L. Tian et al. [17]	2016	11ah	Sub-1 GHz	throughput	ns-3
V. Baños-Gonzalez et al. [18]	2016	11ah	Sub-1 GHz	throughput	analytical
M. Qutab-ud din et al [19].	2015	11ah	Sub-1 GHz	RAW scheduling	Omnet++
N. Ahmed et al. [20]	2020	11ah	Sub-1 GHz	RAW scheduling	Analytical
R. Ma et al. [21]	2017	11b & 15.4	2.4 GHz	analytical model, throughput	analytical & unknown simulator
X. Zhang, et al. [22]	2011	11 & 15.4	2.4 GHz	analytical model, throughput	analytical, ns-2
J. Hou et al. [23]	2009	11 & 15.4	2.4 GHz	packet delivery rate	experiments
J.W. Chong et al. [24]	2015	11 & 15.4	2.4 GHz	throughput	analytical
P. Luong et al. [25]	2016	11b & 15.4	2.4 GHz	throughput and packet delivery rate	analytical & unknown simulator
W. Yuan et al. [26]	2010	11b & 15.4	2.4 GHz	throughput	OPNET
E.D.N Ndih et al. [27]	2016	11 & 15.4	2.4 GHz	packet delivery rate	MATLAB
B. Badihi et al. [28]	2013	11ah & 15.4	Sub-1 GHz	throughput	OMNeT++
J. Guo, P. Orlik [29]	2017	11ah & 15.4g	Sub-1 GHz	packet delivery rate and latency for coex.	ns-3
Y. Liu, J. Guo et al. [30]	2018	11ah & 15.4g	Sub-1 GHz	packet delivery rate and latency for coex.	ns-3
Y. Nagai, J. Guo et al. [31]	2020	11ah & 15.4g	Sub-1 GHz	packet delivery rate and latency for coex.	ns-3
Y. Nagai, T. Sumi et al. [32]	2020	11ah & 15.4g	Sub-1 GHz	packet delivery rate and latency for coex.	ns-3

that under saturation condition, a 10 node IEEE 802.15.4 network can only deliver 3 % of packets, but a 10 node IEEE 802.11 network is able to deliver over 80 % of packets [27]. This paper proposes an adaptive back-off procedure for IEEE 802.15.4 devices to survive coexistence with IEEE 802.11 devices and improves packet delivery rate by 6 %.

4) Coexistence of IEEE 802.11ah and IEEE 802.15.4 Networks (Sub-1 GHz)

For coexistence of IEEE 802.11ah network and conventional IEEE 802.15.4 network, B. Badihi et al. compare performance of IEEE 802.11ah network and IEEE 802.15.4-2006 network in S1G band [28]. 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.

5) Coexistence of IEEE 802.15.4g and IEEE 802.11ah Networks (Sub-1 GHz)

To the best of our knowledge, no other existing work addresses the coexistence of IEEE 802.15.4g and IEEE 802.11ah networks in the S1G band in the research community. The forementioned coexistence technologies may not apply to the coexistence of IEEE 802.15.4g and IEEE 802.11ah networks, e.g., CBT method in [22] 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.

For coexistence of IEEE 802.15.4g and IEEE 802.11ah networks, we have developed coexistence methods for both technologies. First of all, we have proposed a prediction based self-transmission control method to address coexistence of IEEE 802.15.4g and IEEE 802.11ah networks in the S1G band [29], in which IEEE 802.11ah devices predicts the transmission time of upcoming IEEE 802.15.4g packet and suspend their transmissions to avoid interfering with upcoming IEEE 802.15.4g packet transmission. However, the prediction is not accurate when IEEE 802.15.4g packet generation rate is high.

Accordingly, we have also proposed learning based coexistence control techniques using reinforcement learning, which added the intelligence into IEEE 802.11ah devices [30]. 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 a Q-Learning based backoff mechanism for IEEE 802.11ah devices to mitigate interfering with IEEE 802.15.4g packet transmission process.

To compete with more aggressive IEEE 802.11ah for channel access, we also propose an innovative hybrid CSMA/CA mechanism for IEEE 802.15.4g [31]. Depending on severity of the IEEE 802.11ah interference, the proposed hybrid CSMA/CA switches between two modes: immediate channel access disabled mode when IEEE 802.11ah interference is not severe and immediate channel access enabled mode when 802.11ah interference is severe. In the first mode, the standard IEEE 802.15.4g CSMA/CA is applied. In the second mode, the proposed immediate channel access enabled CSMA/CA is employed.

III. S1G BAND STANDARDIZATION

This section introduces the current standardization trend in the S1G bands. In terms of the IEEE 802 standardization, IEEE 802.15.4g-2012 [1] was released as a PHY amendment to IEEE 802.15.4. IEEE 802.15.4g is now widely used in the market for infrastructure monitoring and smart utility applications such as smart meters. IEEE 802.15.4w-2020 [33] was also released as a PHY amendment to IEEE 802.15.4. IEEE 802.15.4w is targeting on Low Power Wide Area Network (LPWAN) extension to cover up to 15 km communication distance in rural areas with lower bit-rates. IEEE 802.11ah-2016 [2] was released as a MAC/PHY amendment in the S1G bands and targets IoT applications such as smart home and smart city.

The Wi-Fi Alliance is currently creating the certification program and branding for market launch of IEEE 802.11ah as Wi-Fi HaLow. Like other Wi-Fi certification programs, the Wi-Fi HaLow will be installed in consumer devices and systems.

A. IEEE 802.19.3 STANDARD

IEEE 802.19.3 standard was published in April 2021. IEEE 802.19.3 Task Group started technical discussion in July 2019. Authors of this paper have actively led this standard development. The difference of the CSMA/CA mechanisms in IEEE 802.15.4g and IEEE 802.11ah was clearly identified as one of the root causes for performance degradation [34]. We investigated the S1G band spectrum allocation in United States, Europe and Japan [35]. We presented the coexistence performance of IEEE 802.15.4g and IEEE 802.11ah based on use cases and simulation profiles designed by IEEE 802.19.3 Task Group to identify the coexistence issues [36] [37] [38]. The machine learning based solutions for interference mitigation between IEEE 802.15.4g and IEEE 802.11ah were also presented, which include prediction based transmission time delay, α-Fairness based ED-CCA, Q-Learning based backoff and hybrid CSMA/CA [29] [39] [40]. We also proposed the fairness index to evaluate performance of the IEEE 802.15.4g and IEEE 802.11ah coexistence mechanisms [41]. From other parties, the S1G band measurement results were presented. K. Yano et al. presented the measurement results of interference and radio noise over 920 MHz band in Japan [42]. The results shows that mobile device signals and radio noise in 920 MHz band may cause severe impact on the performance of both IEEE 802.15.4g and IEEE 802.11ah systems. In addition, J. Robert presented the levels of interference signals from LoRa and SigFox devices in 920 MHz band in Europe [43]. Most importantly, various coexistence recommendations were provided to guide application developers for better IoT system deployment.

B. 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 consumption. THe certification program of Wi-Fi HaLow is expected to be available in later 2021. The Wi-Fi HaLow is targeting outdoor IoT applications in industrial, agricultural, smart building, and smart city environments [3]. Wi-Fi alliance has released white papers of technical overview and IoT applications.

IV. S1G BAND COEXISTENCE SIMULATOR

It is critical to evaluate coexistence behavior of S1G band communication technologies. The existing simulation tools for conventional IEEE 802.11 and IEEE 802.15.4, e.g., NS-3, MATLAB, QualNET and OMNeT++, do not implement IEEE 802.11ah and IEEE 802.15.4g. Furthermore, to the best of our knowledge, there is no simulation tool that supports coexisting IEEE 802.11ah with 1 MHz channel and new IEEE 802.15.4g PHYs in S1G band. Accordingly, we have developed an novel NS-3 based coexistence simulator for IEEE 802.11ah and IEEE 802.15.4g, in which we adopt the third party IEEE 802.11ah module [17] and implemented IEEE 802.15.4g FSK-PHY in S1G band. NS-3 (version 3.23) is used because of supported version on [17]. The challenges include the interfacing independent IEEE 802.11ah module and IEEE 802.15.4g module and the received power conversion.

Figure 2 shows our NS-3 based coexistence simulation architecture proposed for IEEE 802.19.3 Task Group to evaluate coexistence performance between IEEE 802.11ah and IEEE 802.15.4g in S1G. Both IEEE 802.11ah module and IEEE 802.15.4g module are implemented in one 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 module 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. IEEE 802.15.4g FSK-PHY is also newly implemented in PHY module. In the channel module on both IEEE 802.11ah and IEEE 802.15.4g, receive power can be calculated with propagation model in consideration of channel bandwidth difference between 1 MHz for IEEE 802.11ah and 400 kHz for IEEE 802.15.4g. In our simulations, we use the same center frequency for IEEE 802.11ah and IEEE 802.15.4g channels. SEAMCAT Extended Hata Model (Suburban) 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 Non-Line-Of-Sight (NLOS) and Line-Of-Sight (LOS).

V. IEEE 802.15.4G AND IEEE 802.11AH COEXISTENCE BEHAVIOR AND INTERFERENCE CAUSES

This section presents coexistence behavior, interference causes and coexistence issues of IEEE 802.15.4g and IEEE 802.11ah based systems.

A. COEXISTENCE BEHAVIOR

Before analyzing interference causes, we first explore IEEE 802.15.4g and IEEE 802.11ah coexistence behavior [36] via simulation. IEEE 802.19.3 Task Group has defined simulation use cases and scenarios for coexistence evaluation between IEEE 802.11ah and IEEE 802.15.4g [37]. All IEEE

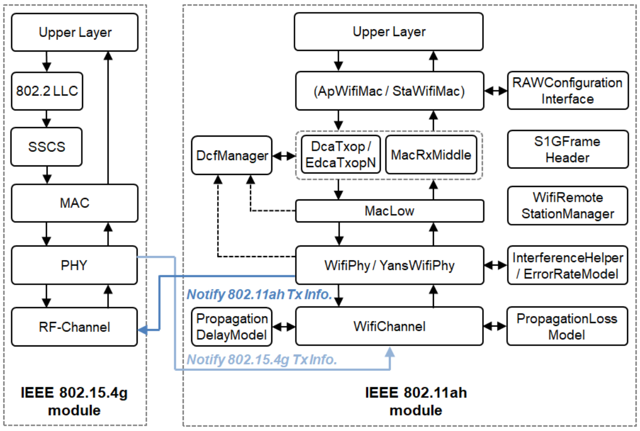

FIGURE 2. IEEE 802.11ah and IEEE 802.15.4g coexistence simulation architecture using NS3 based simulator. Additional coexistence interfaces and functions on PHY/channel modules are provided to notify "*Tx Information (Tx Info)*" between 802.11ah module and 802.15.4g module to calculate mutual interference.

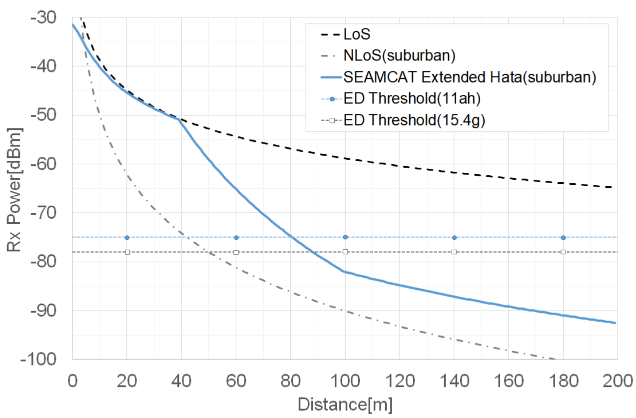

FIGURE 3. SEAMCAT Extended Hata Model (Suburban) for propagation between terminals from below rooftop height to near street level.

802.11ah STAs and IEEE 802.15.4g nodes are deployed in a 200 m diameter area with density of 500 / km^2. 15 STAs/nodes for each of IEEE 802.11ah network and IEEE 802.15.4g network are accommodated in the area. Simulation is performed in 920 MHz band with 1 MHz for IEEE 802.11ah channel and 400 kHz for IEEE 802.15.4g channel. IEEE 802.11ah OFDM-PHY data rate is set to 300 kbps with $BPSK, R = 1/2, N_{ss} = 1$. We select Binary FSK PHY for IEEE 802.15.4g with data rate of 100 kbps. Payload for both IEEE 802.11ah packet and IEEE 802.15.4g packet is 100 bytes. Use case scenario shown in Figure 1 is applied. IEEE 802.15.4g devices transmit infrastructure monitoring data such as regular meter reading of smart meter to IEEE 802.15.4g PNC. IEEE 802.11ah STAs transmit sensor data such as security sensors and surveillance camera data to IEEE 802.11ah AP. Traffic is generated according to a Poisson distribution. The offered network load is uniformly distributed among 15 STAs/nodes. The highest duty cycle for IEEE 802.11ah STA is 2.2% and for IEEE 802.15.4g node is 2%.

TABLE 2. Coexistence Performance of Packet Delivery Rate and Latency for IEEE 802.11ah and IEEE 802.15.4g Using Standard Defined Coexistence Mechanisms.

Network Offered Load [kbps]		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

Table 2 shows coexistence performance of packet delivery rate (PDR) and latency for IEEE 802.11ah and IEEE 802.15.4g networks using standard defined parameters. For PDR, it can be seen that IEEE 802.15.4g PDR decreases significantly as IEEE 802.11ah offered load increases. On the other hand, even if the total offered load of IEEE 802.11ah and IEEE 802.15.4g networks increases, the impact on IEEE 802.11ah PDR is small. This means that when IEEE 802.11ah and IEEE 802.15.4g networks coexist, the transmission of IEEE 802.15.4g packet can be significantly suppressed. For packet latency, even average latency for both IEEE 802.11ah and IEEE 802.15.4g packets increases as the offered load increases because of saturation of bandwidth and retransmission, IEEE 802.11ah packet latency increase (1800% increase from 9.9 ms to 189.8 ms) is much more than IEEE 802.15.4g packet latency increase (118% increase from 22.3 ms to 48.2 ms). We analyze the root causes in the next sub-section.

B. INTERFERENCE CAUSE ANALYSIS FROM PROTOCOL PERSPECTIVE

From coexistence simulation results of IEEE 802.15.4g and IEEE 802.11ah using standard defined coexistence mechanisms, we identified four main cases for coexistence issues between IEEE 802.15.4g and IEEE 802.11ah: 1) Interference caused by higher IEEE 802.11ah ED threshold; 2) Interference caused by faster IEEE 802.11ah back-off scheme; 3) Interference caused by lower IEEE 802.15.4g PHY Data Rate; and 4) CSMA/CA failure packet discard caused by IEEE 802.11ah traffic. The differences between IEEE 802.15.4g and IEEE 802.11ah are due to the different backgrounds in which they were specified.

1) IEEE 802.15.4g Transmission Collision Caused by Higher IEEE 802.11ah 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. On the other hand, IEEE 802.15.4g ED threshold 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 IEEE 802.15.4g RS and ED threshold for FSK PHY and IEEE 802.11ah ED threshold. 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 below IEEE 802.15.4g RS or above IEEE 802.11ah ED threshold, 802.11ah ED-CCA correctly handles the IEEE 802.15.4g packet transmission. However, 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 devices. In this case, IEEE 802.11ah ED-CCA should report busy channel, but it reports idle channel instead. If its backoff counter reaches zero, an IEEE 802.11ah device will start packet transmission that collides with ongoing IEEE 802.15.4g packet transmission.

2) IEEE 802.15.4g Transmission Process Interruption Caused by Faster IEEE 802.11ah 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 μs, CCA time is 160 μs and CCA to TX turnaround time is 240 μs. These backoff parameters are even larger for smaller symbol rates. Especially for IEEE 802.15.4g PHYs operating in the 920 MHz band and 950 MHz band, backoff period is at least 1000 μs and CCA to TX turnaround time is 1000 μs. The smaller time parameters give IEEE 802.11ah devices advantage in wireless channel access. For example, 240 μs IEEE 802.15.4g CCA to TX turnaround time 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 μs 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. Figure 5 shows the interference caused by faster IEEE 802.11ah backoff scheme.

3) IEEE 802.11ah Packet Latency Caused by Lower 802.15.4g PHY Data Rate

IEEE 802.11ah CSMA/CA mechanism performs *"CCA + Backoff"* operation. In other words, IEEE 802.11ah performs CCA first. If channel is idle for more than DIFS time period, transmission starts immediately. Otherwise, random backoff starts. IEEE 802.11ah packets are discarded when the number of retransmissions exceeds the *RetryCount* threshold.

IEEE 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. If the channel is determined to be busy within a time slot, the backoff procedure is suspended and the backoff counter is not decremented. During IEEE 802.11ah backoff suspension, IEEE 802.15.4g devices may start transmission. The lower PHY data rate of IEEE 802.15.4g means that an IEEE 802.15.4g packet transmission can take more time relative to the IEEE 802.11ah packet transmission duration, and therefore can cause longer delay for IEEE 802.11ah packet transmission. Theoretically, an IEEE 802.11ah packet can be infinitely delayed.

4) IEEE 802.15.4g CSMA/CA Failure Packet Discard Caused by IEEE 802.11ah Traffic

In IEEE 802.15.4g, data transmission failure is incurred by 1) CSMA/CA failure or 2) transmission failure. The CSMA/CA failure occurs when CSMA/CA algorithm terminates with a status of failure because the number of backoffs (*NB*) exceeds the threshold *macMaxCSMABackoffs*. Transmission failure occurs because of unsuccessful packet transmission or unsuccessful acknowledgement transmission. For each CSMA/CA failure or transmission failure, the number of transmission attempts is incremented by 1. An IEEE 802.15.4g packet is discarded with *CHANNEL_ACCESS_FAILURE* status when the number of transmission attempts exceeds the threshold *macMaxFrameRetries* due to CSMA/CA failure. An IEEE 802.15.4g packet is discarded with *NO_ACK* status when the number of transmission attempts exceeds the threshold *macMaxFrameRetries* due to transmission failure. We have proposed α-Fairness based ED-CCA and Q-Learning based CSMA/CA for IEEE 802.11ah to reduce IEEE 802.15.4g transmission failure. In this paper, we propose a novel ACS based CSMA for IEEE 802.15.4g to address CSMA/CA failure packet discard caused by IEEE 802.11ah transmissions.

IEEE 802.15.4g CSMA/CA mechanism is different from IEEE 802.11ah CSMA/CA mechanism. IEEE 802.15.4g CSMA/CA performs *"Backoff + CCA"* operation. In other words, IEEE 802.15.4g senses channel after random backoff completes. If channel is idle, transmission starts. Otherwise, it retries *"Backoff + CCA"* by updating *NB = NB + 1*.

IEEE 802.15.4g backoff procedure is not interrupted. In other words, IEEE 802.15.4g does not perform CCA during backoff process. Accordingly, there is no backoff suspension. The *NB* denotes the number of backoffs performed for the current transmission attempt. When the number of *"Backoff + CCA"* reaches the specified threshold, i.e., *"NB > macMaxCSMABackoffs"*, IEEE 802.15.4g CSMA/CA algorithm terminates with status *"Failure"*. IEEE 802.15.4g packet is discarded when the total number of CSMA/CA failure exceeds the threshold *macMaxFrameRetries*.

The CSMA/CA difference and PHY data rate difference cause IEEE 802.15.4g and IEEE 802.11ah behave differently when the bandwidth is saturated.

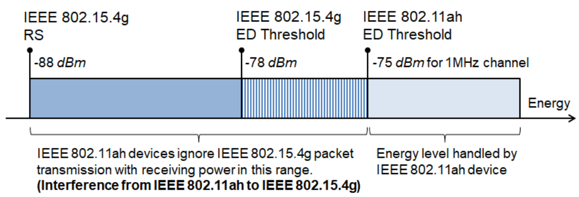

FIGURE 4. Interference caused by higher IEEE 802.11ah ED threshold.

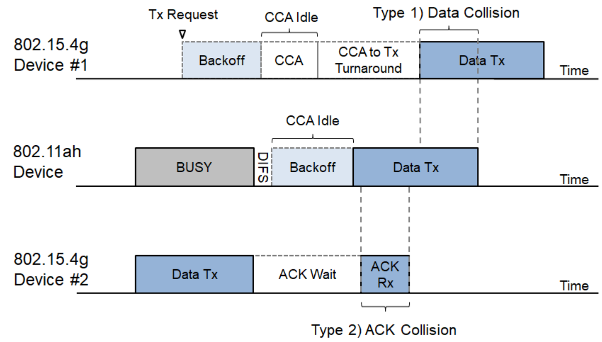

FIGURE 5. Interference caused by faster IEEE 802.11ah backoff.

Our simulation results in Table 2 show that IEEE 802.15.4g discards more packets than IEEE 802.11ah does under saturated condition. A more serious problem is that IEEE 802.15.4g repeatedly performs *"Backoff + CCA"* during the aggressive transmissions by IEEE 802.11ah and terminates ongoing transmission attempt once *"NB > macMaxCSMABackoffs"*. Figure 6 illustrates CSMA/CA failure when the *NB* exceeds predefined *macMaxCSMABackoffs* caused by IEEE 802.11ah traffic.

On the other hand, IEEE 802.11ah packets are delayed longer than IEEE 802.15.4g packets when the bandwidth is saturated with increasing of offered load.

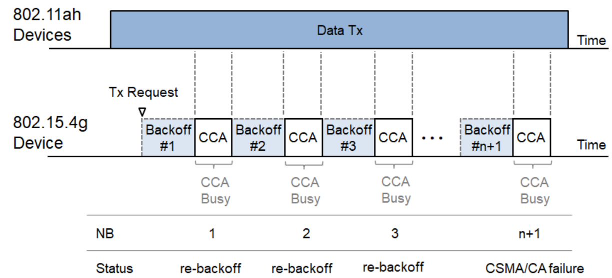

FIGURE 6. Channel access failure caused by IEEE 802.11ah traffic, where n = *macMaxCSMABackoffs*.

C. COEXISTENCE ISSUES

IEEE 802.11ah and IEEE 802.15.4g interfere with each other. However, the coexistence issues are different for two technologies.

For IEEE 802.15.4g, there are three main interference consequences from IEEE 802.11ah: 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; and 3) Data packet discard when IEEE 802.11ah devices aggressively occupy channel that causes IEEE 802.15.4g backoffs exceeding the specified limit. Case a) interference is caused by the higher ED threshold of IEEE 802.11ah and case b) interference is caused by the faster back-off 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. Therefore, IEEE 802.11ah devices need to be more intelligent.

For IEEE 802.11ah, the main interference consequence from IEEE 802.15.4g is data packet delay caused by lower data rate of IEEE 802.15.4g, which results in IEEE 802.15.4g packet takes more transmission time.

VI. SUMMARY OF PREVIOUSLY PROPOSED S1G BAND COEXISTENCE TECHNOLOGIES

We have proposed the coexistence methods for both IEEE 802.11ah and IEEE 802.15.4g that have been adopted by IEEE 802.19.3 standard. The first approach is to enhance IEEE 802.11ah to give more transmission opportunities to IEEE 802.15.4g by inhibiting IEEE 802.11ah channel access. We have proposed α-Fairness based ED-CCA and Q-Learning based CSMA/CA as methods that apply reinforcement learning [30] [44]. The second approach is to enhance IEEE 802.15.4g. We have proposed Hybrid CSMA/CA to improve the performance of IEEE 802.15.4g by more aggressive channel access while considering the IEEE 802.15.4g intra-system interference [31]. Summary is presented in Section VI-C.

A. α-FAIRNESS BASED ED-CCA FOR IEEE 802.11AH

This section presents the proposed α-Fairness based ED-CCA [30] [44] for IEEE 802.11ah to improve IEEE 802.15.4g packet delivery rate. The α-Fairness is a technique used in various network resource sharing. Our proposed α-Fairness based ED-CCA mitigates IEEE 802.11ah interference impact on IEEE 802.15.4g caused by the higher ED threshold as described in V-B1.

The issues is that if the energy level of IEEE 802.15.4g transmission detected by IEEE 802.11ah falls in [*IEEE 802.15.4g Receiver Sensitivity (RS), IEEE 802.11ah ED Threshold*], the transmission is readable by IEEE 802.15.4g.

However, IEEE 802.11ah ignores the transmission. The challenge is that IEEE 802.11ah may not be able to identify the source of the energy, which could be IEEE 802.15.4g node, far away IEEE 802.11ah STA or other device.

Using α-Fairness based ED-CCA, if the detected energy level is with in [*IEEE 802.15.4g Receiver Sensitivity (RS), IEEE 802.11ah ED Threshold*], IEEE 802.11ah ED-CCA reports channel status based on a probability generated by the α-Fairness technique.

We define following generalized α-Fairness utility function as

$$\begin{aligned} U(P_i, P_b) = &\frac{P_i^{1-\alpha}}{1-\alpha}\frac{M_h^{1-\alpha}}{M_h^{1-\alpha}+M_g^{1-\alpha}} \\ &+ \frac{P_b^{1-\alpha}}{1-\alpha}\frac{M_g^{1-\alpha}}{M_h^{1-\alpha}+M_g^{1-\alpha}}, \end{aligned} \tag{1}$$

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 ED-CCA report busy channel. The input parameters M_h and M_g are the locally observed network metrics for IEEE 802.11ah network and IEEE 802.15.4g network, respectively. The metric can be packet transmission rate, data throughput, packet delivery rate or channel utilization. The locally observed network metric is device dependent and therefore, different from the metric for whole network. The locally observed inputs assure that each IEEE 802.11ah device performs independent coexistence control. More information on α-Fairness ED-CCA implementation is given in our previous proposals [30].

The α-Fairness wireless medium sharing between IEEE 802.11ah network and IEEE 802.15.4g network corresponding to the maximization of objective function $U(P_i, P_b)$ subject to condition $P_i + P_b = 1$. According to optimization theory, our optimization problem has a unique solution given by

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

Eq. (2) shows that for $\alpha > 1$, more channel access opportunity is given to the network with smaller metric and for $\alpha < 1$, more channel access opportunity is given to the network with larger metric. For $\alpha > 1$, if an IEEE 802.11ah device estimates $M_h > M_g$, which indicates $P_i^o < P_b^o$, its α-Fairness IEEE 802.11ah ED-CCA algorithm more likely reports busy channel. As a result, the 802.11ah device will perform more backoff. On the other hand, if an IEEE 802.11ah device estimates $M_h < M_g$, which implies $P_i^o > P_b^o$, its α-Fairness IEEE 802.11ah ED-CCA algorithm more likely reports idle channel. Therefore, the IEEE 802.11ah device will perform more packet transmission.

B. Q-LEARNING BASED CSMA/CA FOR IEEE 802.11AH

This section presents our reinforcement learning based coexistence control techniques. We proposed Q-learning based CSMA/CA [30] [44] to mitigate IEEE 802.11ah interference impact on IEEE 802.15.4g transmission process caused by the faster IEEE 802.11ah CSMA/CA as described in V-B2. The challenge is that IEEE 802.11ah devices do not know if any IEEE 802.15.4g transmission process is in progress. As a result, IEEE 802.11ah device can either transmit packet or perform more back-off. To make optimal decision in stochastic environment, we propose Q-Learning based CSMA/CA for IEEE 802.11ah device to decide transmission or back-off. Using Q-learning based CSMA/CA, IEEE 802.11ah device performs normal back-off process if back-off counter is greater than zero $BC > 0$ or IEEE 802.11ah ED-CCA reports busy channel. Q-learning decision is applied when back-off counter reaches to zero $BC = 0$ and IEEE 802.11ah ED-CCA reports idle channel. Notice that even IEEE 802.11ah ED-CCA reports idle channel, α-Fairness based ED-CCA is may still report busy channel. Thus α-Fairness based ED-CCA is applied to determine channel status in Q-Learning algorithm. We define state set $S = \{s_1, s_2\} = \{$Channel Idle, Channel Busy$\}$ and action set $A = \{a_1, a_2\} = \{$Transmit, Back-off$\}$. Q-learning utility function is formulated as

$$\begin{aligned} &Q_{t+1}(s,a) = (1-\tau_t)Q_t(s,a) + \tau_t(R_t(s,a) + \gamma V_t(s',b)), \\ &\quad V_t(s',b) = \max_{b\epsilon B(s')} Q_t(s',b), \end{aligned} \tag{3}$$

where $Q_t(s,a)$ is Q-Learning object 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', τ_t is the learning rate $(0 < \tau_t < 1)$, γ is discount factor $(0 < \gamma < 1)$, and $R_t(s,a)$ is the reward obtained by performing action a at state s at time t. By taking action b, we can obtain the maximum value of the Q-Learning objective function as $V_t(s',b)$. The reward $R_t(s,a)$ can be fixed or variable. The key for Q-Learning is to design proper reward for each $\{state, action\}$ pair so that the expected utility is maximized. For spectrum sharing, the reward is defined based on α-Fairness as

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

where $U^o = U(P_i^o, P_b^o)$ is the α-Fairness objective function with optimal probability P_i^o and P_b^o. $\sigma > 0$ is a small parameter, P_i^o is the optimal probability to report idle channel and P_i^o represents the optimal probability to report busy channel. U_i^o and U_b^o are given by

$$\begin{aligned} U_i^o &= \frac{(P_i^o)^{1-\alpha}}{1-\alpha}\frac{M_h^{1-\alpha}}{M_h^{1-\alpha}+M_g^{1-\alpha}}, \\ U_b^o &= \frac{(P_b^o)^{1-\alpha}}{1-\alpha}\frac{M_g^{1-\alpha}}{M_h^{1-\alpha}+M_g^{1-\alpha}}. \end{aligned} \tag{5}$$

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, back-off is a generous action to take. Thus, we assign a very small reward γ 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, back-off 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 back-off.

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 greater rewards. 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 greater rewards. 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 possibility. Notice that for $\alpha > 1, P_i^o > P_b^o$ indicates $M_h > M_g$. Therefore, it is reasonable for IEEE 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 back-off. More information on Q-Learning based CSMA/CA implementation is given in our previous proposals [30].

C. HYBRID CAMA/CA FOR IEEE 802.15.4G

This section presents the proposed Hybrid CSMA/CA [31] for IEEE 802.15.4g to improve IEEE 802.15.4g packet delivery rate and reduce IEEE 802.11ah packet latency. The proposed Hybrid CSMA/CA for IEEE 802.15.4g allows IEEE 802.15.4g device to perform immediate channel access. Since IEEE 802.15.4g device cannot communicate with an IEEE 802.11ah device, IEEE 802.15.4g devices cannot coordinate with IEEE 802.11ah devices for interference mitigation without special assistance. However, IEEE 802.15.4g devices can explore the weakness of IEEE 802.11ah devices to increase their channel access opportunity when they detect severe interference from IEEE 802.11ah devices. An IEEE 802.11ah device must perform back-off process after DIFS (264 μs) time period. This 264 μs DIFS waiting time plus random back-off time gives IEEE 802.15.4g devices opportunity to start transmission before IEEE 802.11ah devices if IEEE 802.15.4g devices are allowed to have immediate channel access capability, which is not allowed in the conventional IEEE 802.15.4g standard.

To compete with more aggressive IEEE 802.11ah for channel access, we propose a Hybrid CSMA/CA mechanism for IEEE 802.15.4g. Depending on severity of the IEEE 802.11ah interference, the Hybrid CSMA/CA switches between two modes: immediate channel access disabled mode when 802.11ah interference is not severe and immediate channel access enabled mode when 802.11ah interference is severe. In the first mode, the standard IEEE 802.15.4g CSMA/CA is applied. In the second mode, the proposed immediate channel access enabled CSMA/CA is employed.

Figure 7 shows the hybrid CSMA/CA mechanism. To decide a CSMA/CA mode, the hybrid CSMA/CA first de-

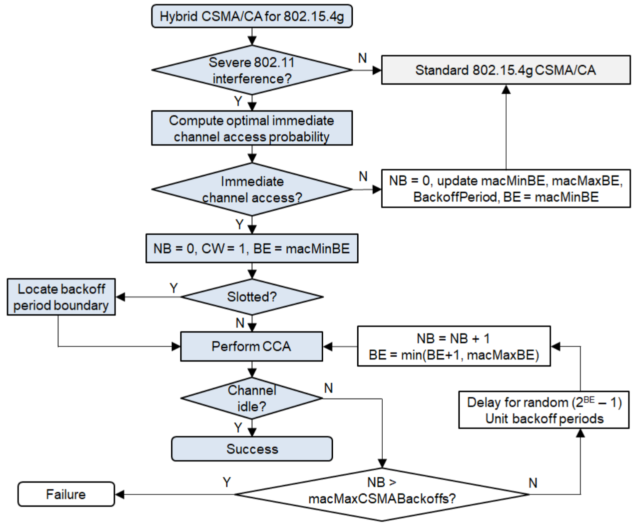

FIGURE 7. Hybrid CSMA/CA for IEEE 802.15.4g to make more aggressive channel access under interference from IEEE 802.11ah. Hybrid CSMA/CA allows IEEE 802.15.4g device to select optimal CSMA/CA parameters.

termines the severity of IEEE 802.11ah interference. The IEEE 802.11ah interference severity can be estimated by the channel access failure rate by IEEE 802.11ah, IEEE 802.11ah channel occupancy probability, and IEEE 802.11ah energy detection ratio [31]. If the IEEE 802.11ah interference is not severe, the standard IEEE 802.15.4g CSMA/CA is applied. If the IEEE 802.11ah interference is severe, the immediate channel access enabled CSMA/CA is used. In this mode, the Hybrid CSMA/CA enables IEEE 802.15.4g devices to have immediate channel access capability. The blue blocks show the flow chart of the immediate channel access. In the beacon-enabled Personal Area Network (PAN), the slotted CSMA/CA is used. IEEE 802.15.4g device first locates back-off period boundary and then performs CCA at the located backoff period boundary. In the non-beacon-enabled PAN, the unslotted CSMA/CA is used. IEEE 802.15.4g device performs CCA immediately. Considering that the immediate channel access by multiple IEEE 802.15.4g devices within a neighborhood may also cause collision, the Hybrid CSMA/CA computes an optimal probability for stochastic decision making, i.e., perform immediate channel access or back-off.

To compute the optimal probability, an IEEE 802.15.4g device first determines number of 802.15.4g neighbors by monitoring neighbor's packet transmission. Assume there are N_g IEEE 802.15.4g devices in a neighborhood and each device has probability p to take immediate channel access and probability $1-p$ to perform back-off. Let X denote binomial random variable $\sum_{i=1}^{N_g} X_i^g$, where $X_i^g (i = 1, 2, ..., N_g)$ is random variable representing decision of IEEE 802.15.4g neighbor i. Then $P(X = k) = \binom{N_g}{k} p^k (1-p)^{N_g - k}$ and $\mathbb{E}[X] = N_g p$. To avoid collision among IEEE 802.15.4g transmissions due to immediate channel access, optimal strategy is that only one IEEE 802.15.4g device take immediate channel access and rest of 802.15.4g devices perform back-off, i.e., $\mathbb{E}[X] = 1$, which gives optimal probability $p_o = \frac{1}{N_g}$.

Based on the optimal probability p_o, the hybrid CSMA/CA decides if immediate channel access or back-off is performed. The **Yes** decision leads to CCA operation. If the CCA returns idle channel, the immediate channel access takes place. The **No** decision leads to back-off. To do so, IEEE 802.15.4g device increases back-off parameters to avoid collision with transmission process of the immediate channel access device and also give IEEE 802.11ah device opportunity to transmit next and therefore, reduces IEEE 802.11ah packet latency.

VII. ACTIVE CARRIER SENSE BASED CSMA/CA FOR IEEE 802.15.4G

In this section, we present a novel ACS based CSMA/CA method for IEEE 802.15.4g to reduce CSMA/CA failure packet discard under interference from IEEE 802.11ah traffic and to keep interoperability with conventional IEEE 802.15.4g CSMA/CA. Conventional IEEE 802.15.4g CSMA/CA discards the packet with *CHANNEL_ACCESS_FAILURE* status when the total number of CSMA/CA failure exceeds the *macMaxFrameRetries*. The CSMA/CA algorithm fails when the *NB* exceeds the predefined *macMaxCSMABackoffs* as illustrated in Figure 6.

We propose a novel ACS based CSMA/CA for IEEE 802.15.4g to address channel access failure packet discard caused by IEEE 802.11ah traffic. The standard IEEE 802.15.4g CSMA/CA mechanism is designed for channel access contention among homogeneous IEEE 802.15.4g devices. However, when IEEE 802.15.4g devices compete with much more aggressive IEEE 802.11ah devices for channel access, the IEEE 802.15.4g CSMA/CA mechanism needs to be enhanced to increase the aggressiveness of IEEE 802.15.4g devices.

Figure 8 shows flow chart of the proposed ACS based CSMA/CA for IEEE 802.15.4g. This function is combination of the proposed Hybrid CSMA/CA (blue) and ACS (dark blue). The ACS based CSMA/CA includes three key functions, macMaxCSMABackoffs adaptation, consecutive CCA and optimal channel access decision making. The ACS based CSMA/CA is to address CSMA/CA failure packet discard caused by IEEE 802.11ah interference.

The ACS based CSMA/CA first checks if IEEE 802.11ah interference is severe. if **No**, the standard IEEE 802.15.4g CSMA/CA algorithm is applied. if **Yes**, it performs one round of backoff + CCA operation. In the beacon-enabled PAN, IEEE 802.15.4g device first locates backoff period boundary and then performs random backoff at the located backoff period boundary followed by the CCA operation. In the non-beacon-enabled PAN, IEEE 802.15.4 device performs random backoff immediately followed by the CCA operation. After completion of the CCA operation, if the channel is idle, packet transmission starts. If the channel is busy, it updates *NB* and *BE* as standard CSMA/CA does, then goes to the proposed ACS mechanism.

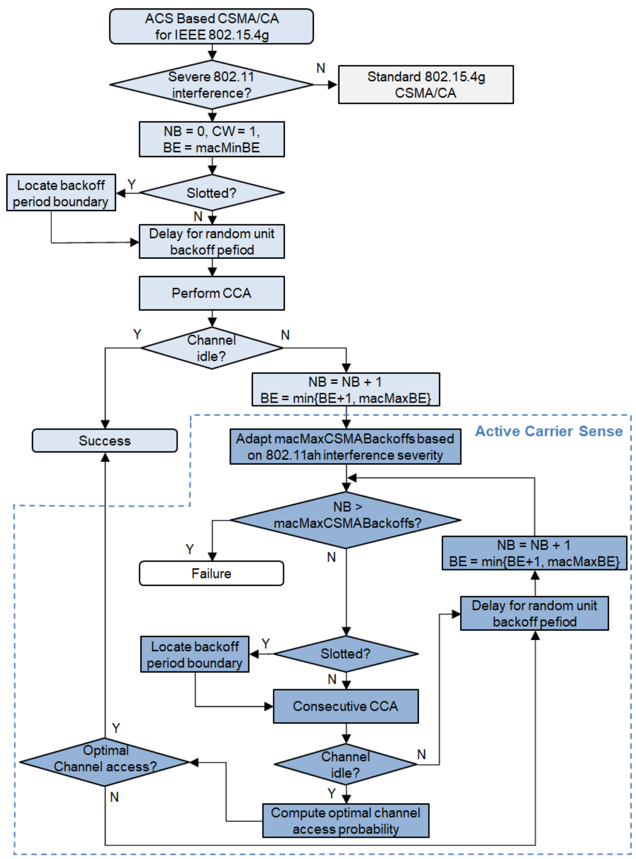

FIGURE 8. Active Carrier Sense Based CSMA/CA for IEEE 802.15.4g to address channel access failure packet discard caused by IEEE 802.11ah traffic.

In the ACS mechanism, the ACS based CSMA/CA dynamically adapts the *macMaxCSMABackoffs* based on the severity of the IEEE 802.11ah interference because the larger *macMaxCSMABackoffs* will reduce packet discard probability due to the CSMA/CA failure. More specifically, it increases the value of the *macMaxCSMABackoffs* to the value of *AHInterferenceFactor*×*macMaxCSMABackoff*, where IEEE 802.11ah interference factor *AHInterferenceFactor* ≥ *1* can be computed based on specific IEEE 802.11ah interference metric. Take channel occupancy time ratio for example, let $CHOR_{ah}$ be the channel occupancy time ratio of IEEE 802.11ah, we can define *AHInterferenceFactor* as

$$AHInterferenceFactor = \left\lceil \frac{1}{1 - CHOR_{ah}} \right\rceil. \quad (6)$$

The ACS based CSMA/CA then performs consecutive CCA operation as shown in Figure 9, where we define the maximum number of consecutive *CCAs (MaxConCCAs)* ≥ *1*, a CCA is performed within a standard *phyCCADuration/aCCATime* period and the *NCCA* denotes the number of consecutive CCAs performed for current ACS procedure. The CCA is repeatedly performed until the channel becomes idle or the *MaxConCCAs* consecutive CCAs have been performed. After the *MaxConCCAs* consecutive CCAs have been performed, the channel is still busy, channel busy status is returned. Otherwise, channel idle status is returned. As a result, consecutive CCA procedure will either return channel idle or channel busy status. If the channel status is idle, the ACS based CSMA/CA can attempt immediate transmission or perform another backoff+CCA operation as shown in Figure 10. For the immediate transmission, the ACS based CSMA/CA computes an optimal channel access probability as in Section VI-C to decide whether transmission starts immediately or not. This mechanism is to avoid collision among transmissions by multiple IEEE 802.15.4g devices.

Figure 10 illustrates the interoperability of ACS based CSMA/CA and standard CSMA/CA for IEEE 802.15.4g. The *phyCCADuration/aCCATime* time period of IEEE 802.15.4 is used for each active CCA slot considering the affinity with conventional methods.

The proposed ACS based CSMA/CA mechanism allows IEEE 802.15.4g devices to detect channel status transition and to maintain interoperability with conventional IEEE 802.15.4g devices by adopting the same IEEE 802.15.4 CSMA/CA mechanism before data transmission. The proposed method can greatly reduce the possibility of CSMA/CA failure packet discard caused by channel access failure when the *NB* exceeds the threshold *macMaxCSMABackoffs* during IEEE 802.11ah transmissions.

It is necessary to note that even power saving is critical for the battery-powered devices, the devices such as smart meters connected to power-line can proactively perform carrier sense to mitigate interference from other systems without having energy constraint. In addition, using carrier sense mechanism, an IEEE 802.15.4g device is able to determine if the busy channel is caused by IEEE 802.15.4g transmission or interference signal.

It is also necessary to note that the definition of the severe interference depends on the application requirement and the interference metric. Take channel occupancy time as an example of the interference metric. If the application requires 90% of data packet delivery rate, the actual data packet delivery rate is 50% and IEEE 802.15.4g channel occupancy time is less than IEEE 802.11ah channel occupancy time, the IEEE 802.11ah interference can be considered as severe.

Furthermore, even this paper uses IEEE 802.11ah as the interference source to IEEE 802.15.4g, the proposed ACS based CSMA/CA mechanism can be applied to the coexistence of IEEE 802.15.4g system with any other system that uses CSMA/CA mechanism, e.g., the coexistence of IEEE 802.15.4g and IEEE 802.11n in the 2.4 GHz band.

VIII. COEXISTENCE EVALUATION

We evaluated performance of the proposed coexistence techniques using our simulator with simulation set up same as in Section V. Table 3 shows simulation parameters for IEEE 802.11ah and IEEE 802.15.4g coexistence performance. We evaluated mutual interference effect using packet delivery rate, packet latency and coexistence fairness index as performance metrics. The simulation has been conducted for

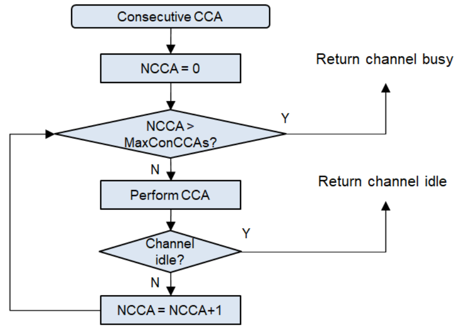

FIGURE 9. Consecutive CCA for IEEE 802.15.4g on the proposed Active Carrier Sense.

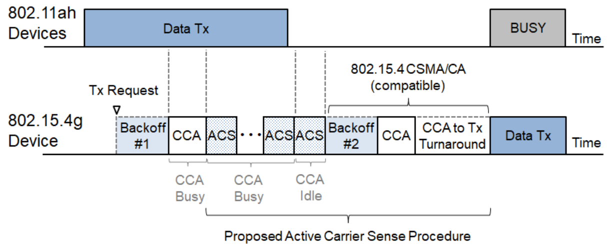

FIGURE 10. Active carrier sense for IEEE 802.15.4g to reduce CSMA/CA failure packet discards because of inadvertently increasing *"NB"*.

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 α-Fairness ED-CCA, fair factor α is set to 10. For Q-Learning based CSMA/CA, discount factor γ is set to 0.5 and learning rate τ_t is initially set to 0.5. Typical HW implementation values for *Rx to Tx TurnaroundTime* and *Tx to Rx TurnaroundTime* are used. The locally observed data packet transmission rate is used as input metrics for α-Fairness ED-CCA [30]. Optical probability p_o is set to $\frac{1}{N_g}$ for Hybrid CSMA/CA [31].

Six coexistence control scenarios are simulated for various combination:

1) Standard defined coexistence mechanism for both IEEE 802.11ah and IEEE 802.15.4g (baseline);
2) α-Fairness based ED-CCA for IEEE 802.11ah;
3) Q-Learning based CSMA/CA for IEEE 802.11ah;
4) Combination of α-Fairness based ED-CCA and Q-Learning based CSMA/CA for IEEE 802.11ah (αF+QL);
5) Active Carrier Sense for IEEE 802.15.4g (ACS);
6) Combination of Active Carrier Sense and Hybrid CSMA/CA for IEEE 802.15.4g (ACS+Hybrid).

A. PACKET DELIVERY RATE

Figure 11 and Figure 12 show the variation of IEEE 802.11ah and IEEE 802.15.4g data packet delivery rate (PDR) with respect to different coexistence mechanisms for one of simulation scenarios, where Y-axis represents the ratio of the packet successfully delivered and X-axis represents the sim-

TABLE 3. Simulation parameters for IEEE 802.11ah and IEEE 802.15.4g coexistence performance proposed in IEEE 802.19.3.

Parameters	Value [Unit]	Note
Network offered load	20 - 120 kbps	11ah
Network offered load	20, 30 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 (300 usec for Sim.)	15.4g
Tx to Rx TurnaroundTime	Less than 300 usec (299 usec for Sim.)	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
Optimal probability: p_o	$\frac{1}{N_g}$	Hybrid

ulation time. The granularity of the X-axis is 40 seconds. The PDR is calculated as the total number of data packets successfully acknowledged divided by the total number of data packets transmitted. The PDRs for both IEEE 802.11ah and IEEE 802.15.4g show a large variation with respect time in a simulation time of 1000 sec.

Table 5 shows simulation results of IEEE 802.11ah and IEEE 802.15.4g PDR for all simulation scenarios with respect to different coexistence mechanisms and different network offered load in a simulation time of 1000 sec. Figure 13 and Figure 14 show IEEE 802.11ah and IEEE 802.15.4g data packet delivery rate variations versus different network offered loads and different coexistence mechanisms based on Table 5.

IEEE 802.15.4g PDR degrades as IEEE 802.11ah network offered load increase. Cases a) to d), and g) to i) show the similar tendency that the IEEE 802.15.4g PDR is improved over the proposed methods without degradation of IEEE 802.11ah PDR. Since the total network offered load is not close to the network capacity, the proposed methods can provide transmission opportunity for IEEE 802.15.4g by improving channel access efficiency. Although our coexistence techniques improve IEEE 802.15.4g PDR for Case e)-f), and k)-l), the improvement is in the expense of IEEE 802.11ah PDR. It is because the total network offered load is close to the network capacity, and the improvement of IEEE 802.15.4g PDR is saturated.

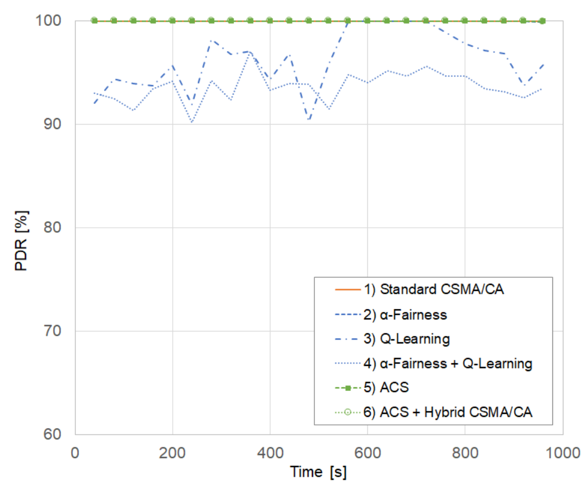

FIGURE 11. Coexistence performance of IEEE 802.11ah Packet Delivery Rate (Case c): Network offered load {11ah, 15.4g} = {60 kbps, 20 kbps}.

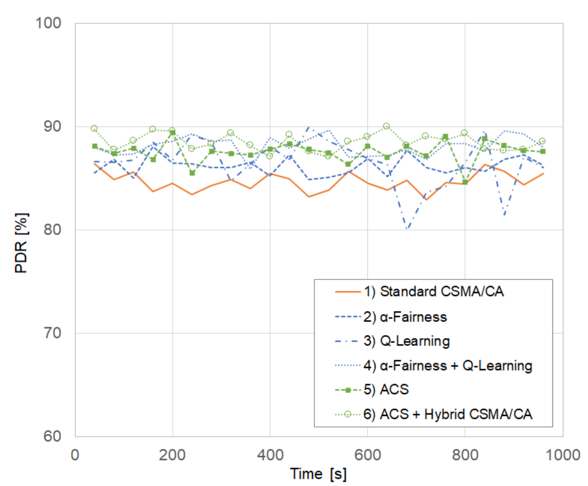

FIGURE 12. Coexistence performance of IEEE 802.15.4g Packet Delivery Rate (Case c): Network offered load {11ah, 15.4g} = {60 kbps, 20 kbps}.

The coexistence enhancement schemes for IEEE 802.11ah and IEEE 802.15.4g have very different effect. IEEE 802.11ah enhancements (α-Fairness, Q-Learning, αF+QL) are active coexistence mechanisms and can achieve more improvement on IEEE 802.15.4g PDR in exchange for the degradation of IEEE 802.11ah PDR. Therefore, IEEE 802.11ah PDR degrades rapidly as total network offered load approaches the network capacity, but more PDR improvement is obtained for IEEE 802.15.4g. On the other hand, IEEE 802.15.4g enhancements (ACS, Hybrid, ACS+Hybrid) are passive coexistence mechanisms and aim to improve IEEE 802.15.4g PDR without suppressing IEEE 802.11ah transmission. Therefore, the tendency of IEEE 802.11ah channel access advantage remains unchanged. The PDR improvement for IEEE 802.15.4g can be realized when the total network offered load does not exceed the network capacity so that coexistence mechanism can achieve more efficient spectrum sharing or in cases where CSMA/CA failure packet

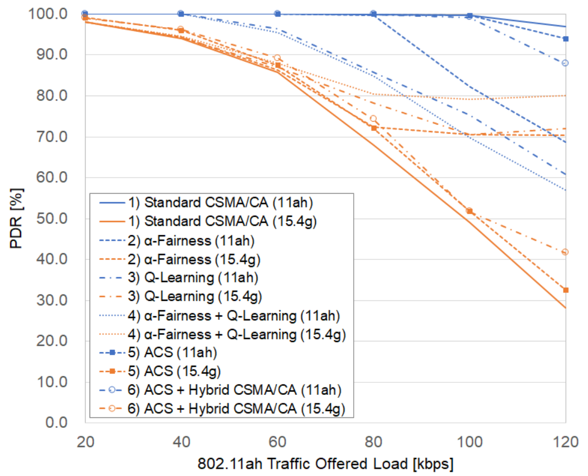

FIGURE 13. IEEE 802.11ah and IEEE 802.15.4g data packet delivery rate variations versus different network offered loads and different coexistence mechanisms {11ah, 15.4g} = {20 - 120 kbps, 20 kbps}.

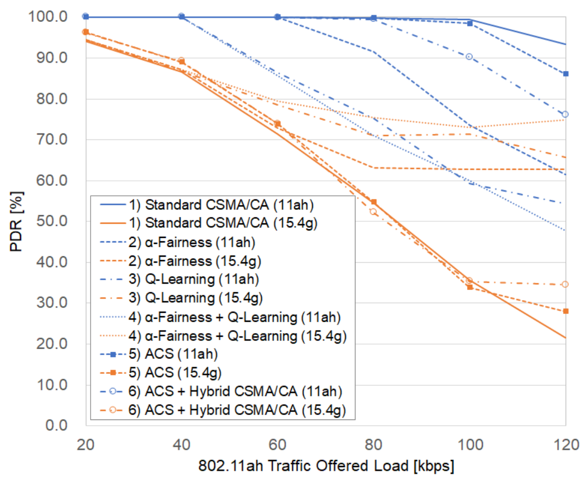

FIGURE 14. IEEE 802.11ah and IEEE 802.15.4g data packet delivery rate variations versus different network offered loads and different coexistence mechanisms {11ah, 15.4g} = {20 - 120 kbps, 30 kbps}.

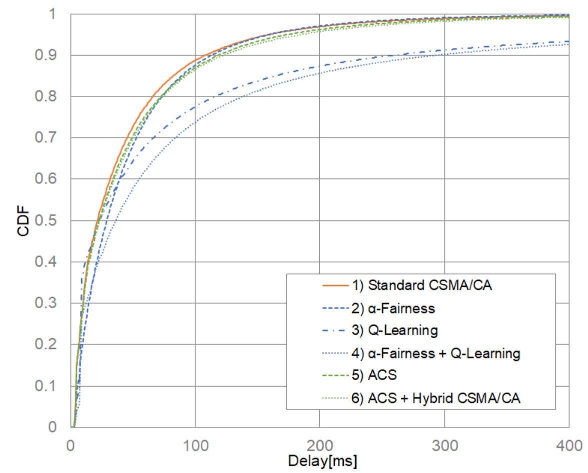

FIGURE 15. Coexistence performance of IEEE 802.11ah Latency (Case c): Network offered load {11ah, 15.4g} = {60 kbps, 20 kbps}.

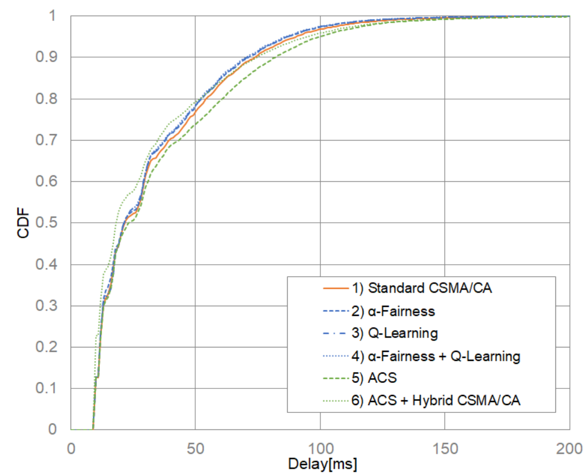

FIGURE 16. Coexistence performance of IEEE 802.15.4g Latency (Case c): Network offered load {11ah, 15.4g} = {60 kbps, 20 kbps}.

discards caused by IEEE 802.11ah traffic can be reduced. Accordingly, these schemes improve IEEE 802.15.4g PDR without significant affecting IEEE 802.11ah PDR.

B. 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 15 and Figure 16 show 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. The values of CDF(0.9) for each method were compared in Table 4.

Table 6 also 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 both IEEE 802.11ah and IEEE 802.15.4g. 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 mechanisms (α-Fairness, Q-learning, αF+QL) since our coexistence methods for IEEE 802.11ah side suppress the transmission of IEEE 802.11ah in the exchange of IEEE 802.15.4g. IEEE 802.15.4g enhancements (ACS, ACS + Hybrid) increase the IEEE 802.11ah packet latency because IEEE 802.11ah is forced to wait during IEEE 802.15.4g transmission. IEEE 802.15.4g packet latency is slightly in-

TABLE 4. CDF(0.9) of IEEE 802.11ah and 802.15.4g latency (Case c): Network offered load {11ah, 15.4g} = {60 kbps, 20 kbps}.

	CDF (0.9) [ms]	
Coexistence Control methods	802.11ah	802.15.4g
1) Standard CSMA/CA	108.1	73.8
2) α-Fairness	113.0	70.7
3) Q-Learning	260.9	70.6
4) α-Fairness + Q-Learning	294.0	70.0
5) ACS	123.0	74.5
6) ACS + Hybrid CSMA/CA	119.4	82.3

creased in exchange for IEEE 802.15.4g PDR improvement because IEEE 802.15.4g packet discards do to back-off attempts are suppressed by ACS.

C. FAIRNESS INDEX

We provide a method to evaluate coexistence fairness when IEEE 802.11ah and IEEE 802.15.4g share frequency spectrum and the wireless resource. Jain's Fairness Index (FI) is well known for TCP flow fairness that shares media resource by several flows [45]. 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:

$$\frac{(\sum_{i=1}^{n} x_i)^2}{n\sum_{i=1}^{n} x_i^2} \Rightarrow \frac{(\sum_{i=1}^{m} x_{i_{4g}} + \sum_{i=1}^{n} x_{i_{ah}})^2}{(m+n)(\sum_{i=1}^{m} x_{i_{4g}}^2 + \sum_{i=1}^{n} x_{i_{ah}}^2)}, \quad (7)$$

where $x_{i_{4g}}$, $x_{i_{ah}}$ are the normalized throughput, m and n are the number of devices. Normalized throughput is denoted as $x = t/o$, where t is measured throughput (kbps), and o is offered load (kbps) [46].

Table 7 shows the variation of fairness index with respect to different coexistence mechanisms and network offered load for both IEEE 802.11ah and IEEE 802.15.4g. The fairness index has improved for all the combinations of the proposed coexistence mechanisms and the network offered load compared to the baseline using conventional standardized parameters.

In case a)-c) and g)-h), where the total network offered load is relatively low, IEEE 802.15.4g enhancements (ACS, ACS+Hybrid) improve the Fairness Index more than IEEE 802.11ah enhancements (α-Fairness, Q-Learning, and αF+QL). This is because the IEEE 802.15.4g enhancements (ACS, ACS+Hybrid) allow IEEE 802.15.4g devices to increase their transmission opportunities, while the IEEE 802.11ah enhancements (α-Fairness, Q-Learning, and combined) suppress IEEE 802.11ah transmissions but have less effect on IEEE 802.15.4g transmission opportunities.

In case d)-f) and i)-l), where the total network offered load is high or exceeds the network capacity, the fairness index improvement is low compared to IEEE 802.11ah enhancements since IEEE 802.15.4g enhancements do not increase the transmission opportunities of IEEE 802.15.4g devices.

IX. CONCLUSION

We examined the Sub-1 GHz band wireless coexistence technologies that are essential to enable various IoT applications. IEEE 802.15.4g and IEEE 802.11ah are two wireless technologies developed for outdoor IoT application such as smart utility, smart city, smart home/office, industry, infrastructure and mobility, for which both technologies operate in the Sub-1 GHz band. Our coexistence simulations of IEEE 802.11ah and IEEE 802.15.4g using standard defined parameters show serious interference problems due to fundamental protocol differences and parameter differences. Accordingly, we proposed IEEE 802.19.3 Wireless Coexistence Task Group formation to lead the standard development of IEEE 802.11ah and IEEE 802.15.4g coexistence in the Sub-1 GHz bands. In addition to our previous coexistence methods proposed to IEEE 802.19.3 standard, we presents a novel Active Carrier Sense based CSMA/CA scheme for IEEE 802.15.4g to reduce the CSMA/CA failure packet discard under interference from IEEE 802.11ah, and to keep interoperability with conventional IEEE 802.15.4g CSMA/CA mechanism. Using the developed Sub-1 GHz band coexistence simulator with use cases and protocol parameters proposed by IEEE 802.19.3 Task Group, we conducted the performance analysis of six coexistence scenarios: 1) Conventional IEEE 802.11ah and IEEE 802.15.4g (baseline); 2) α-Fairness based ED-CCA for IEEE 802.11ah; 3) Q-Learning based CSMA/CA for IEEE 802.11ah; 4) Combination of α-Fairness based ED-CCA and Q-Learning based CSMA/CA for IEEE 802.11ah; 5) Active Carrier Sense based CSMA/CA for IEEE 802.15.4g; 6) Combination of Active Carrier Sense (ACS) and Hybrid CSMA/CA for IEEE 802.15.4g. Simulation results show that the trend is very different between the coexistence enhancements for IEEE 802.11ah and IEEE 802.15.4g. IEEE 802.11ah enhancements (α-Fairness, Q-Learning, αF+QL) are active coexistence methods and improve IEEE 802.15.4g PDR in exchange for the degradation of IEEE 802.11ah PDR. Therefore, IEEE 802.11ah PDR degrades rapidly when the total network offered load exceeds the network capacity, but the more improvement on the IEEE 802.15.4g side can be obtained. On the other hand, IEEE 802.15.4g enhancements (ACS based CSMA/CA, Hybrid CSMA/CA, ACS+Hybrid) are passive coexistence mechanisms and improve IEEE 802.15.4g own PDR without suppressing IEEE 802.11ah transmission, but the less improvement on the IEEE 802.15.4g side can be achieved. Therefore, the tendency of IEEE 802.11ah channel access advantage remains unchanged. Performance improvement for IEEE 802.15.4g can be achieved when the total network offered load does not exceed the network capacity or in cases where the CSMA/CA failure packet discards caused by IEEE 802.11ah traffic can be reduced. We also provide a method to evaluate coexistence fairness when IEEE 802.11ah and IEEE 802.15.4g share frequency spectrum and the wireless resource. All proposed coexistence techniques can improve fair spectrum sharing between IEEE 802.11ah and IEEE 802.15.4g networks for IoT applications.

TABLE 5. IEEE 802.11ah and IEEE 802.15.4g data packet delivery rate variations versus different network offered loads and different coexistence mechanisms

Case	Offered Load [kbps]		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 6. IEEE 802.11ah and IEEE 802.15.4g data packet latency variations versus different network offered loads and different coexistence mechanisms

Case	Offered Load [kbps]		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

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TABLE 7. Fairness Index variations versus different network offered loads and different coexistence mechanisms

			Fairness Indesx					
Case	Offered Load [Kbps		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	-	-	-	-	-	-
a	20	20	1.000	0.999	0.999	0.999	1.000	1.000
b	40	20	0.999	0.999	0.999	0.999	1.000	1.000
c	60	20	0.993	0.995	0.995	0.996	0.996	0.997
d	80	20	0.965	0.975	0.974	0.978	0.975	0.980
e	100	20	0.897	0.994	0.941	0.973	0.910	0.913
f	120	20	0.767	0.999	0.947	0.953	0.810	0.885
g	20	30	0.999	0.999	0.999	0.999	1.000	1.000
h	40	30	0.995	0.995	0.995	0.995	0.997	0.997
i	60	30	0.973	0.976	0.981	0.983	0.979	0.980
j	80	30	0.922	0.967	0.944	0.962	0.924	0.916
k	100	30	0.819	0.993	0.935	0.957	0.820	0.844
l	120	30	0.719	0.999	0.939	0.927	0.794	0.879

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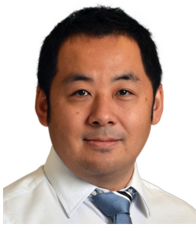

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