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 for 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, 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, 802.11ah and 802.15.4g networks are likely to coexist. Our simulation results using standard defined coexistence mechanisms show that 802.11ah network can severely interfere with 802.15.4g network and leads to significant packet loss in 802.15.4g network. 802.15.4g network can also cause packet latency in 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 802.11ah and 802.15.4g systems in the Sub-1 GHz frequency bands to guide product deployment. Authors of this paper have been leading this standard development. This paper introduces the IEEE 802.19.3 standardization activities that address coexistence issues of 802.11ah and 802.15.4g systems, and summarizes our technical contributions and simulation results.

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

1. Introduction

As more and more intelligent devices connect to the Internet, the Internet of Things (IoT) is becoming reality. A broadband 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 smart utility network (Wi-SUN). IEEE 802.11ah is designed to operate in Sub-1 GHz (S1G) frequency band. For outdoor IoT applications, IEEE 802.15.4g also operates in 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 signaling (CMS) [4][5] has 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 STD-T107 (250 mW, passive system) and STD-T108 (250 mW, licensed/registered) also operate 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 on S1G band. Even, Japanese standards allow up to 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 S1G band is clearly important.

IEEE 802.11ah extends the operational bands of IEEE 802.11 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. Furthermore, IEEE 802.11ah defines several channel bandwidths up to 16 MHz band wide.

IEEE 802.15.4g can operate in 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 ED-CCA mechanism to coexist with other S1G systems including IEEE 802.15.4g. However, IEEE 802.15g only addresses coexistence 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 in S1G band? 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. Due to the fact that 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, the existing coexistence techniques designed for wide channels may not work properly. 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. Authors of this paper have been leading this

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standard development.

This paper introduces the IEEE 802.19.3 standardization activities that address coexistence issues of 802.11ah and 802.15.4g, and summarizes our technical contributions and simulation results.

The rest of this paper is organized as follows. Section 2 presents related works in the research community. Section 3 describes the status of standardization. Coexistence strategy in IEEE 802.19.3 is shown in Section 4. Simulation results of our coexistence control techniques were introduced in Section 5. Finally, we conclude in Section 6.

2. Related Works in the Research Community

IEEE 802.11ah and IEEE 802.15.4g have led to performance evaluations and overviews of the key features of the technology in the research community. Throughput performance evaluations for key features of IEEE 802.11ah have been demonstrated in [10][11][12][13] using simulator. [14] introduces the advantage and challenges in the performance by analytical approach. Similarly, IEEE 802.15.4g performance has been demonstrated in [15][16], which focus on the PHY and MAC protocol enhancement for higher-throughput, protocol efficiency and delay via simulation, and measurement results using prototypes. On the other hand, heterogeneous network performance evaluation has not been considered.

There are existing studies on the coexistence of conventional IEEE 802.11 and IEEE 802.15.4g networks operating in the 2.4 GHz band [17]. Some coexistence techniques are developed for IEEE 802.15.4g. [18] proposes a decentralized approach for IEEE 802.15.4 devices to mitigate interference by adaptively adjusting ED threshold in the presence of severe interference. 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. [19] shows 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. 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 %.

Some existing coexistence solutions require special devices. [20] designs a cooperative busy tone (CBT) to enable coexistence of IEEE 802.11 network and IEEE 802.15.4 network. 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, CBT 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. In addition, 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. [21] proposes 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. 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. [22] proposes 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. 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.

For IEEE 802.11ah and IEEE 802.15.4g, [23] compares performance of IEEE 802.11ah network and IEEE 802.15.4 (2006) network in S1G band. 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. [24] investigates the coexistence issues of IEEE 802.11b network and IEEE 802.15.4g network in 2.4 GHz band. The system consists of an IEEE 802.15.4g transmitter, an IEEE 802.15.4g 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 802.15.4g network to perform channel re-selection for interference avoidance. It shows that IEEE 802.11b network can significantly interfere with IEEE 802.15.4g network. However, the paper treats IEEE 802.11b devices as interferer only without considering performance of IEEE 802.11b 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 [25], 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 addressed coexistence issues of IEEE 802.11ah network and IEEE 802.15.4g network in S1G band using machine learning approach [26]. Our learning based coexistence control techniques added the intelligence into IEEE 802.11ah devices. We first present an α-Fairness based energy detection clear channel assessment (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 mechanisms for IEEE 802.11ah devices to avoid interfering with IEEE 802.15.4g packet transmission process.

To the best of our knowledge, no other existing work addresses the coexistence of IEEE 802.11ah network and IEEE 802.15.4g network in S1G band in the research community.

3. The status of standardization

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

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 802.11ah and 802.15.4g systems in the S1G frequency bands.

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

3.1 IEEE 802.19.3 Standardization

3.1.1 IEEE 802.19 Working Group

IEEE 802.19 Wireless Coexistence Working Group (WG) meets three times a year for plenary meetings and three times in between for interim meetings, where attendees work on draft standards. Each of these meetings is held every two months for one week. Standards works are carried out in groups called Task Groups (TG) and Study Groups (SG), with their own goals and schedules. The launch of any SG or TG will begin with a proposal in the IEEE 802.19 WG. Once sufficient support is obtained from participants, a SG is established by the Working Group. Alternatively, an Interest Group (IG) may be organized prior to the launch of SG in order to develop a deeper understanding of the related topic. The goal of SG is to produce two documents, strictly speaking, a Project Authorization Request (PAR) and a Criteria for Standards Document (CSD). The PAR describes the need for the project and the technical scope of the project. The CSD indicates that the proposed standard meets the requirements of the IEEE 802.19 standard. Once the PAR and CSD are approved, a formal TG will be organized.

3.1.2 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 [27]. The presentation received interests from the Working Group. Accordingly, the Sub-1 GHz Interest Group was established, and started operation from May 2018 [28]. After that, the Sub-1 GHz Study Group was created and developed PAR and CSD. Accordingly, IEEE New Standards Committee and Standard Board formed IEEE 802.19.3 Task Group in December 2018. The first IEEE 802.19.3 Task Group meeting was held in January 2019. Authors of this paper are key contributors of this TG formation.

The project scope of IEEE 802.19.3 Task Group is to develop a recommendation practice (PR) 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.

3.1.3 IEEE 802.19.3 timeline

Table 1 shows the official timeline at IEEE 802.19.3 TG, but schedule was forced to delay because of COVID-19 situation [30]. Plenary Meeting and Interim Meetings from March 2020 were canceled and shifted to online meeting from July 2020. As a result, IEEE 802.19.3 Task Group schedule is about several months behind to start IEEE SA ballot.

3.1.4 IEEE 802.19.3 Contributions

IEEE 802.19.3 TG started technical discussion towards preparation of draft standard in July 2019.

Authors of this paper have been leading this standard development. The difference of CSMA/CA mechanisms of IEEE 802.11ah and IEEE 802.15.4g was introduced to make clear one of root causes of performance degradation [31]. And, [32] presents the limitation of frequency band in Japan. Authors 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 [33][34][35]. The solutions for interference mitigation between IEEE 802.11ah and IEEE 802.15.4g were also presented. [36] addresses coexistence issues and solutions of IEEE 802.11ah network and IEEE 802.15.4g network using machine learning approach. 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. Hybrid CSMA/CA for IEEE 802.15.4g was also proposed to improve IEEE 802.15.4g reliability with more aggressive channel access to compete with IEEE 802.11ah channel access [37]. Fairness Index was proposed to evaluate performance of the IEEE 802.11ahd and IEEE 802.15.4g coexistence mechanisms [38]. From other parties, measurement results and use cases were presented. [39] shows the measurement result of radio noise and interference over 920 MHz band in Japan. 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, [40] presents the level of interference in 920 MHz band in EU.

Table 1: IEEE 802.19.3 Official Timeline

Time schedule	Meeting overview
2019/01	TG organization and first technical input, outline for PR content, initial call for proposals
2019/03	Review contributions and prepare call for proposals
2019/05	Call for proposals
2019/07	Hear technical proposals – start drafting process
2019/09	More proposals, draft development
2019/11	Draft Ready for WG ballot
2020/01	Comment resolution and recirculation draft
2020/03 (delayed)	EC approval for Standards Association Ballot
2020/04 (delayed)	SA Ballot Comment Resolution, Recirculation
2020/05 (delayed)	SA Ballot Comment Resolution
2020/06 (delayed)	Final recirculation(s) (Stable Draft)
2020/07 (delayed)	EC approval to RevCom

3.2 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 S1G bands to offer longer range and lower power community. The Wi-Fi HaLow is targeting outdoor IoT applications used in industrial, agricultural, smart building, and smart city environments [2]. Wi-Fi alliance has released white papers of technical overview and IoT applications in 2020.

3.3 802.11ah 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 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 [41][42]. Accordingly, AHPC has conducted the first indoor demonstration experiment in Japan with test license in June 2019 [43]. AHPC also announced the first field trial in July 2019 towards the practical use of IEEE 802.11ah / HaLow in Japan [44]. Through the AHPC, the upcoming Wi-Fi HaLow will be deployed to various consumer devices and systems.

4. Coexistence Strategy in IEEE 802.19.3 TG

4.1 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 the coexistence performance of IEEE 802.11ah network and IEEE 802.15.4g network. As a sample, 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 simulator [45]. For the heterogeneous network evaluation, we use IEEE 802.11ah package [46] and implemented necessary IEEE 802.15.4g functions and mutual interference functions in NS-3 simulation. Figure 1 shows our NS-3 based architecture proposed for IEEE 802.19.3 TG to evaluate coexistence performance of heterogeneous wireless systems. Both IEEE 802.11ah module and IEEE 802.15.4g module are implemented in NS3 simulator. Additional coexistence interfaces and functions on 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. ITU-R P1411 model for propagation between terminals from below roof-top height to near street level is applied.

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 [34]. All IEEE 802.11ah STAs and IEEE 802.15.4g nodes are deployed in a 100 m x 100 m area with density of 500 / km^2 as shown in Figure 2. 15 STAs/nodes for each of IEEE 802.11ah and IEEE 802.15.4g accommodated in the area. Simulation is performed in 920 MHz band with 1 MHz IEEE 802.11ah channel and 200 kHz IEEE 802.15.4g channel. IEEE 802.11ah PHY data rate is set to 300 kbps. We select Binary FSK PHY for IEEE 802.15.4g with data rate of 100 kbps to evaluate if IEEE 802.15.4g nodes can compete with IEEE 802.11ah STAs. 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/nodes so that IEEE 802.11ah STAs send packets to IEEE 802.11ah AP and IEEE 802.15.4g nodes send packets to IEEE 802.15.4g PANC in star network topology. This is typical use case for sensor networks 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.

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 impacts on IEEE 802.11ah 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, node 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 [27][33].

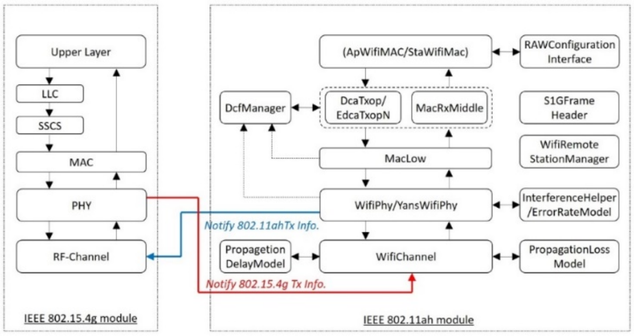

Figure 1. Coexistence Simulation Architecture

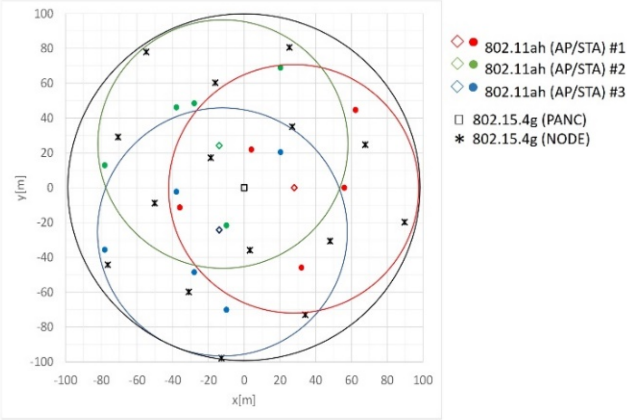

Figure 2. 802.11ah and 802.15.4g device deployment

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

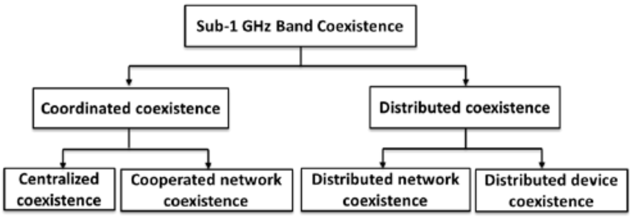

Figure 3: Coexistence Model Based on Network Coordination

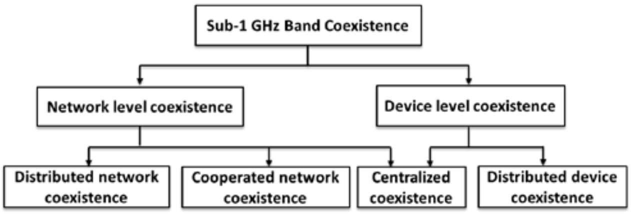

Figure 4: Coexistence Model Based on Scope of Coex. Operation

4.2 Proposed Coexistence Control Techniques

Coexistence architectures recommended for IEEE 802.11ah and IEEE 802.15.4g were proposed in IEEE 802.19.3 TG [47]. The architecture classifies coexistence mechanisms based on network coordination and level of coexistence operation.

4.2.1 Coexistence model based on network coordination

Figure 3 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.

Table 3: Coexistence Approaches [47]

Type	Approach
Centralized network coexistence	· Channel switching (if possible) · IEEE 802.11ah RAW scheduling · IEEE 802.15.4g superframe structuring · IEEE 802.11ah beamforming · Transmission power setting
Cooperated network coexistence	Share information: · ED, packet delivery ratio · Packet Latency Coexistence operation: · Channel Switching (if possible) · IEEE 802.11ah RAW scheduling · IEEE 802.15.4g superframe structuring · IEEE 802.11ah beam foaming · 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 [36] · Q-Learning based CSMA/CA [37] · Prediction based transmission delay · Frame size setting

4.2.2 Coexistence model based on scope of coexistence operation

Figure 4 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.

4.2.3 Coexistence Approaches

Three types of coexistence approaches were proposed. 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 send the coexistence command to both systems.

B) Cooperated 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.

5. Proposed Coexistence Mechanisms

We introduce the abstract of our coexistence mechanisms between IEEE 802.11ah and IEEE 802.15.4g using machine learning approach. Both α-Fairness based ED-CCA coexistence and Q-Learning based CSMA/CA coexistence for distributed coexistence were proposed at IEEE 802.19.3 TG [36] - [38]. α-Fairness that enables IEEE 802.11ah devices to detect more ongoing IEEE 802.15.4g packet transmission. Q-Learning for IEEE 802.11ah devices enable to avoid interfering with IEEE 802.15.4g packet transmission process.

We evaluated performance of the proposed coexistence control techniques with simulation set up same as in Section 4. We set IEEE 802.15.4g network offered load as 30 kbps and IEEE 802.11ah network offered load as 30 kbps. 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. We used mutual interference effect on packet delivery rate and fairness index as performance metrics. Details for simulation set up and simulation results are described in [36] - [38]. The data packet delivery rate performance and fairness index were shown in Figure 5 and Figure 6, respectively.

Coexistence Mechanism #1 shows the conventional method, thus, standard defined coexistence mechanisms for both IEEE 802.15.4g and IEEE 802.15.4g. IEEE 802.15.4g PDR (packet delivery rate) is degraded by IEEE 802.11ah. IEEE 802.15.4g PDR dropp to 53.7%, IEEE 802.11ah PDR keeps around 99.9%. Fairness Index is 0.916.

Coexistence Mechanism #2 shows α-Fairness coexistence mechanism for IEEE 802.11ah. IEEE 802.15.4g PDR is improved without degradation of IEEE 802.11ah PDR. IEEE 802.15.4g PDR is improved to 68.1%, IEEE 802.11ah PDR keeps 99.9%, and Fairness Index is 0.965.

Coexistence Mechanism #3 shows Q-Learning coexistence mechanism for IEEE 802.11ah. IEEE 802.15.4g PDR is improved without degradation of IEEE 802.11ah PDR as well. IEEE 802.15.4g PDR is improved to 71.0%, IEEE 802.11ah PDR keeps 99.9%, and Fairness Index is 0.972.

Coexistence Mechanism #4 shows the combination of α-Fairness and Q-Learning coexistence mechanisms for IEEE 802.11ah. IEEE 802.15.4g PDR is improved with negligible degradation of IEEE 802.11ah PDR. IEEE 802.15.4g PDR is improved to 77.0%, IEEE 802.11ah PDR is 99.8%, and Fairness Index is 0.983.

From the results of Coexistence Mechanisms #2 - #4, our proposed coexistence mechanisms improve IEEE 802.15.4g PDR and Fairness Index. These results lead that α-Fairness and Q-Learning approaches on IEEE 802.11ah enable to mitigate mutual interference for IEEE 802.11ah and IEEE 802.15.4g coexistence. Further investigation for many use cases in consideration of various offered loads and deployments are important.

6. Conclusions

IEEE 802.11ah and IEEE 802.15.4g are two wireless technologies designed for outdoor IoT applications and installed on consumer devices, for which both technologies operate in the S1G frequency band. 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 802.11ah and 802.15.4g systems in the S1G frequency bands. Authors have been leading this standard development. This paper first presents the related works in the research community. We then introduce the IEEE 802.19.3 standardization activities that address coexistence issues of 802.11ah and 802.15.4g with timeline and contributions. Coexistence approaches in IEEE 802.19.3 Task Group are categorized. IEEE 802.11ah/HaLow and AHPC are also introduced with use cases and applications toward deployment. We also summarize our proposed approaches of both α-Fairness based ED-CCA coexistence and Q-Learning based CSMA/CA coexistence for distributed coexistence. These simulation results listed in IEEE 802.19.3 draft standard are introduced. The results lead that our coexistence approaches using machine learning improves the performance of IEEE 802.15.4g PDR and Fairness index for coexistence of IEEE 802.11ah and IEEE 802.15.4g. Further investigation for many use cases in consideration of various offered loads and deployments are important.

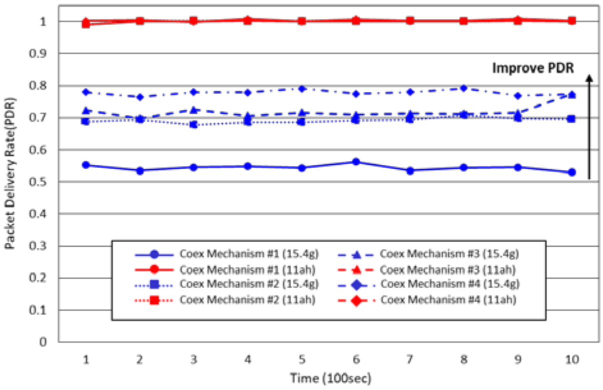

Figure 5 Packet Delivery Rate

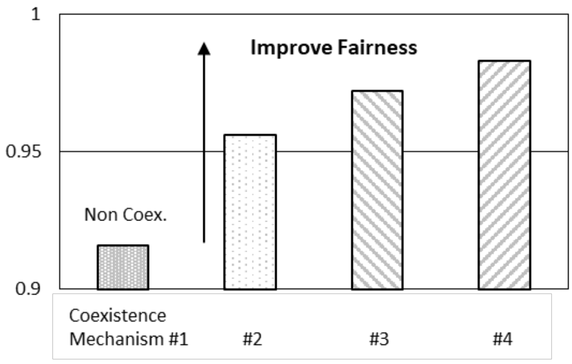

Figure 6 Fairness Index for Coexistence

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