Hybrid CSMA/CA for Sub-1 GHz Frequency Band Coexistence of IEEE 802.11ah and IEEE 802.15.4g

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Abstract

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Hybrid CSMA/CA for Sub-1 GHz Frequency Band Coexistence of IEEE 802.11ah and IEEE 802.15.4g

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Abstract - As more and more wireless technologies have been developed to support emerging IoT applications, the coexistence of heterogeneous wireless technologies presents challenges. IEEE 802.11ah and IEEE 802.15.4g are two of such wireless technologies specified for outdoor IoT applications. Due to the constrained spectrum allocation in the Sub-1 GHz (S1G) band, these two types of devices may be forced to coexist, i.e., share frequency spectrum. To investigate coexistence behavior of 802.11ah and 802.15.4g, we first identify coexistence issues using our newly developed NS-3 based S1G band coexistence simulator. Accordingly, we propose a hybrid CSMA/CA mechanism for 802.15.4g to address the identified coexistence issues. The conducted performance analysis shows that the proposed hybrid CSMA/CA improves 802.15.4g performance without degrading 802.11ah performance. The hybrid CSMA/CA also maintain overall 802.11ah packet latency.

Keywords: Wireless coexistence, hybrid CSMA/CA, Sub-1 GHz band, WLAN, WPAN.

1 Introduction

The Internet of Things (IoT) applications are rapidly growing. A broad range of wireless technologies have been developed to cater the diverse applications. As heterogeneous wireless technologies are emerging, coexistence becomes a critical issue to be addressed. IEEE 802.11ah, marketed as Wi-Fi HaLow, is the first 802.11 standard designed to operate in the Sub-1 GHz (S1G) band. IEEE 802.15.4g , marketed as Wi-SUN, also operates in the S1G band for outdoor IoT applications. The unlicensed spectrum allocation is limited, especially in the S1G band compared with other 2.4 GHz band. For example, Japan only allocates 5.8 MHz spectrum in 920 MHz band for active radio devices in the ARIB STD-T108 [1]. The constraint spectrum allocation indicates that 802.11ah devices and 802.15.4g devices may be forced to coexist, i.e., share frequency spectrum. In addition, 802.11ah network and 802.15.4g network can have thousands of nodes. Both technologies have communication range of 1000 meters for IoT applications. These features significantly increases the coexistence potential. Therefore, ensuring harmonious coexistence of these two wireless technologies is important.

802.11ah mandates the support of 1 MHz channel, which is much narrower than the 20 MHz channel for conventional 802.11 in the 2.4 GHz band. As a result, the existing coexistence technologies designed for the 2.4 GHz band may not be suitable for the coexistence of 802.11ah and 802.15.4g in the S1G band. Therefore, the coexistence of 802.11ah and 802.15.4g needs to be further investigated. 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 in the S1G frequency band [2]. Authors of this paper have been leading this standard development.

[3] proposes a prediction based self-transmission control method for 802.11ah to ease its interference impact on 802.15.4g. [4] introduces α-Fairness ED-CCA method for 802.11ah to mitigate its interference on 802.15.4g caused by its higher ED threshold. To address the interference caused by the faster backoff of 802.11ah, [4] also proposes Q-Learning based backoff mechanism for 802.11ah to avoid interfering with 802.15.4g packet transmission process. However, these coexistence technologies improve the performance of 802.15.4g at the expanse of 802.11ah. This paper aims to develop coexistence technologies that improve 802.15.4g performance without degrading 802.11ah performance. We first evaluate coexistence behavior and identify coexistence issues by using the developed S1G band coexistence simulator. We then propose a hybrid CSMA/CA mechanism for 802.15.4g to achieve better coexistence with 802.11ah.

The rest of this paper is organized as follows. Section 2 presents related work. Section 3 evaluates coexistence behavior and issue of 802.11ah and 802.15.4g. We introduce the proposed hybrid CSMA/CA mechanism in Section 4. In Section 5, we introduce our S1G band coexistence simulator. Performance evaluation of the hybrid CSMA/CA mechanism is conducted in Section 6. Then, we conclude our work.

2 Related Work

There are existing coexistence technologies developed for conventional 802.15.4 to address its coexistence with 802.11 in the 2.4 GHz band. [5] proposes a decentralized approach to mitigate interference by adaptively adjusting energy detection (ED) threshold. [6] proposes an adaptive backoff mechanism to survive coexistence with 802.11. [7] designs a cooperative busy tone method via a special device to enable 802.11 aware of 802.15.4 transmission. [8] proposes a hybrid device to coordinate 802.11 and 802.15.4 transmissions. [9] proposes an adaptive interference mitigation scheme for 802.15.4 to control its frame length based on the measured 802.11 interference via a hybrid device.

Before the work in [3] and [4], to the best of our

Table 1: The majority of available 802.11ah and 802.15.4g performance evaluation, and conventional coexistence researches.

Reference	**Year**	**Target System**	**Band**	**Objective**	**Validation Tool**
This article	2020	11ah & 15.4g	Sub-1 GHz	delivery rate and latency	ns-3
J. Guo, P. Orlik [3]	2017	11ah & 15.4g	Sub-1 GHz	delivery rate and latency	ns-3
Y. Liu, J. Guo et al.[4]	2018	11ah & 15.4g	Sub-1 GHz	delivery rate and latency	ns-3
W. Yuan et al. [5]	2010	11b & 15.4	2.4 GHz	throughput	OPNET
E.D.N Ndih et al. [6]	2016	11 & 15.4g	2.4 GHz	delivery rate	MATLAB
X. Zhang, et al. [7]	2011	11 & 15.4g	2.4 GHz	analytical model, throughput	analytical, ns-2
J.Hou et al. [8]	2009	11 & 15.4	2.4 GHz	delivery rate	experiments
J.W. Chong et al. [9]	2015	11 & 15.4	2.4 GHz	throughput	analytical
B. Badihi et al. [10]	2013	11ah & 15.4	2.4 GHz	throughput	OMNeT++
R. Ma et al. [11]	2017	11b & 15.4g	2.4 GHz	analytical model, throughput	analytical & unknown simulation

knowledge, no other existing work addresses the coexistence of 802.11ah and 802.15.4g in the S1G band. The related studies are done either for 802.11ah or 802.15.4g only. [10] compares performance of 802.11ah and conventional 802.15.4 in the S1G band. The results reveal that 802.11ah network achieves higher channel efficiency than 802.15.4 network. [11] investigates the coexistence issues of 802.11b and 802.15.4g in the 2.4 GHz band. It shows that 802.11b can significantly interfere with 802.15.4g. However, our investigation shows that the existing studies only reveal one side of the story. Table 1 shows majority of available 802.11ah and 802.15.4g performance evaluation and conventional coexistence researches.

3 802.11ah and 802.15.4g Coexistence Behavior and Coexistence Issue

Before conducting coexistence performance evaluation, we briefly introduce the functional differences between 802.11ah and 802.15.4g, which affect the coexistence behavior of 802.11ah and 802.15.4g.

802.11ah defines OFDM PHY and uses the ED-CCA with a threshold of -75 dBm per MHz for coexistence control with other non-802.11 systems. 802.15.4g specifies MR-FSK, MR-OFDM and MR-O-QPSK PHYs and only addresses coexistence among devices using different 802.15.4g PHYs. 802.15.4g ED threshold is lower than -75 dBm, e.g., its ED threshold is in [-100 dBm, -78 dBm] for FSK PHY.

802.11ah channel width is in the unit of MHz, i.e., 1 MHz/2 MHz/4 MHz/8 MHz/16 MHz. However, 802.15.4g channel width is in the unit of kHz, i.e., 200 kHz/400 kHz/600 kHz/800 kHz/1200 kHz. 802.11ah data rate ranges from 150 kbps to 78 Mbps for even one spatial stream. On the other hand, 802.15.4g data rate ranges from 6.25 kbps to 800 kbps.

802.11ah CSMA/CA and 802.15.4g CSMA/CA are much different. 1) 802.11ah allows immediate channel access. 802.15.4g, however, requires backoff no matter how long channel has been idle. 2) 802.11ah backoff is much faster than 802.15.4g backoff due to much smaller parameters as shown in Table 2, where 802.15.4g parameters are for FSK PHY operating in 920 MHz band. 3) 802.11ah requires backoff suspension, i.e., 802.11ah device must perform CCA in each backoff slot and can decrease backoff counter only if the channel is idle. On the other hand, 802.15.4g has no backoff suspension. 802.15.4g device performs CCA after the backoff procedure completes.

The ED threshold, channel width, data rate and first two CSMA/CA features are in favor of 802.11ah. However, the third CSMA/CA feature is in favor of 802.15.4g. Theoretically, an 802.11ah packet can be infinitely delayed, but an 802.15.4g packet has bounded delay.

Table 2: 802.11ah and 802.15.4g CSMA/CA Parameters

802.11ah Param.	Value	802.15.4g Param.	Value
CCA Time	40 μs	phyCCADuration	160 μs
Slot Time	52 μs	UnitBackoffPeriod	1160 μs
SIFS Time	160 μs	AIFS Time	1000 μs
DIFS Time	264 μs	SIFS Time	1000 μs

Based on forementioned functional differences, the purpose of 802.11ah and 802.15.4g coexistence simulation is to explore how network traffic and network size affect the coexistence behavior of 802.11ah and 802.15.4g as well as what are the critical coexistence issues to be addressed.

We use packet delivery rate and packet latency as metrics to evaluate the coexistence performance. The packet delivery rate is measured as the ratio of number of packets successfully delivered and total number of packets transmitted. The packet latency is measured as time difference from the time packet transmission process starts to the time the packet receiving is successfully confirmed. In other words, the packet latency is given by $BackoffTime + DataTXTime + AckWaitingTime + AckRXTime$. The simulation setup is described in section 5.

In Figs. 1 and 2, solid lines represent 802.11ah network performance and dash lines illustrate 802.15.4g network performance. In addition, 50-20-20 indicates 50 nodes for each network, 20 kbps offered load for 802.11ah network, 20 kbps offered load for 802.15.4g network, and so on.

Fig. 1 shows packet delivery rate of 802.11ah network and 802.15.4g network. We have following findings: 1) For all scenarios, 802.11ah network delivers near 100% of the packet, which indicates that network traffic and network size have less impact on 802.11ah packet delivery rate. 2) 802.11ah network traffic has impact on 802.15.4g packet delivery rate. 802.15.4g network packet delivery rate decreases as 802.11ah network traffic increases. 3) 802.15.4g network traffic affects more on its packet delivery rate. 802.15.4g network packet delivery rate decreases significantly as its network traffic doubles. 4) The network size has little effect on 802.15.4g network packet delivery rate.

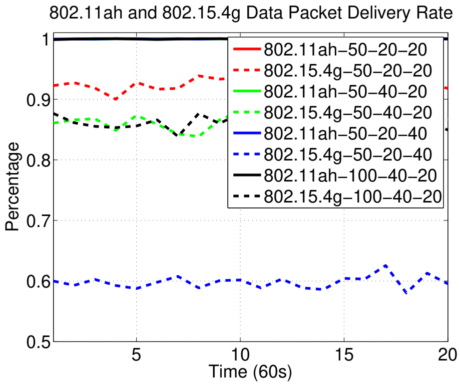


Figure 1: Packet Delivery Rate

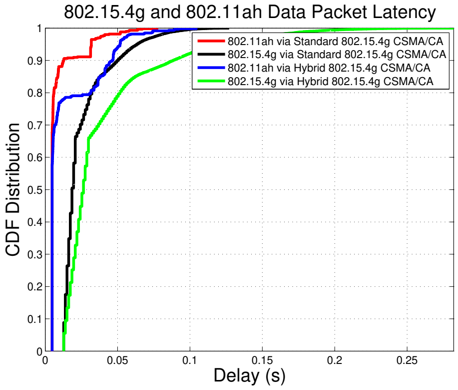


Figure 2: Packet Latency

Fig. 2 depicts the corresponding packet latency. We have following observations: 1) For all scenarios, 802.15.4g network achieves similar packet latency, which indicates that 802.15.4g packet is either delivered with the bounded delay or dropped and therefore, network traffic and network size have little impact on 802.15.4g packet latency. 2) 802.11ah network traffic has impact on its packet latency. 802.11ah packet latency increases as its network traffic increases. 3) 802.15.4g network traffic has more impact on 802.11ah packet latency. 802.11ah network packet latency increases more as 802.15.4g network traffic doubles. 4) Network size has major influence on 802.11ah packet latency. 802.11ah packet latency increases significantly as the number of nodes doubles, which verifies that 802.11ah packet can be infinitely delayed. These results show that 802.11ah network and 802.15.4g network interfere with each other. This observation is different from that drawn by existing studies that only reveal the 802.11ah interference on 802.15.4g. Based on these findings, coexistence technologies need to improve 802.15.4g delivery rate and reduce 802.11ah packet latency.

4 Hybrid CSMA/CA for 802.15.4g to Coexist Better with 802.11ah

This section presents the proposed hybrid CSMA/CA for 802.15.4g to improve 802.15.4g delivery rate and reduce 802.11ah packet latency. The proposed hybrid CSMA/CA for 802.15.4g allows 802.14.g device to perform immediate channel access.

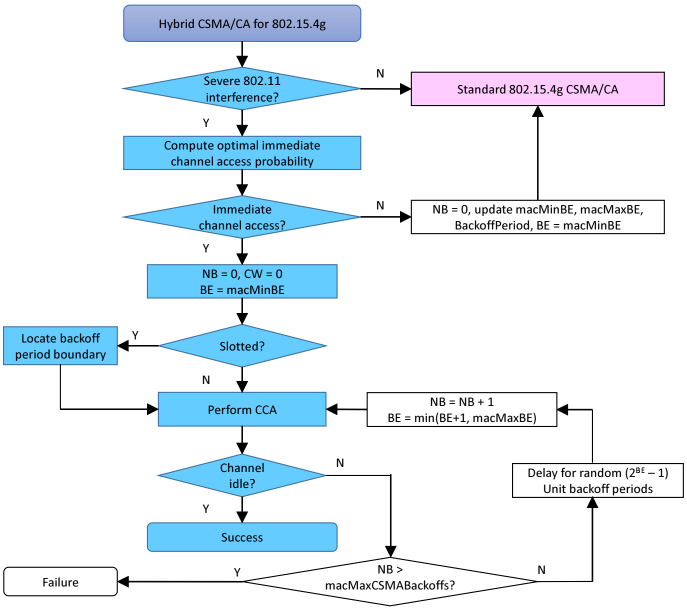


Figure 3: Hybrid CSMA/CA for IEEE 802.15.4g

An 802.15.4g device cannot communicate with an 802.11ah device. Therefore, 802.15.4g devices cannot coordinate with 802.11ah devices for interference mitigation without special assistance. However, 802.15.4g devices can explore the weakness of 802.11ah devices to increase their channel access opportunity when they detect severe interference from 802.11ah devices. An 802.11ah device must perform backoff process after the busy channel. Before the backoff process, 802.11ah device must wait for a DIFS (264 μs) time period. This 264 μs waiting time plus random backoff time gives 802.15.4g devices opportunity to start transmission before 802.11ah devices if 802.15.4g devices are allowed to have immediate channel access capability, which is not allowed in the 802.15.4g standard.

To compete with more aggressive 802.11ah for channel access, we propose an innovative hybrid CSMA/CA mechanism for 802.15.4g. Depending on severity of the 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 802.15.4g CSMA/CA is applied. In the second mode, the proposed immediate channel access enabled CSMA/CA is employed.

Fig. 3 shows the hybrid CSMA/CA mechanism. To decide a CSMA/CA mode, the hybrid CSMA/CA first determines the severity of 802.11ah interference. If the 802.11ah interference is not severe, the standard 802.15.4g CSMA/CA is applied. If the 802.11ah interference is severe, the immediate channel access enabled CSMA/CA is used. In this mode, the hybrid CSMA/CA enables 802.15.4g devices to have immediate channel access capability. The blue blocks show the flow chart of the immediate channel access. Consider that the immediate channel access by multiple 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 backoff.

To compute the optimal probability, an 802.15.4g device first determines number of 802.15.4g neighbors by monitoring neighbor's packet transmission. Assume there are N_g 802.15.4g devices in a neighborhood and each device has probability p to take immediate channel access and probability $1-p$ to perform backoff. 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 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 802.15.4g transmissions due to immediate channel access, optimal strategy is that only one 802.15.4g device take immediate channel access and rest of 802.15.4g devices perform backoff, 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 backoff 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 backoff. To do so, 802.15.4g device increases backoff parameters to avoid collision with transmission process of the immediate channel access device and also give 802.11ah device opportunity to transmit next and therefore, reduces 802.11ah packet latency.

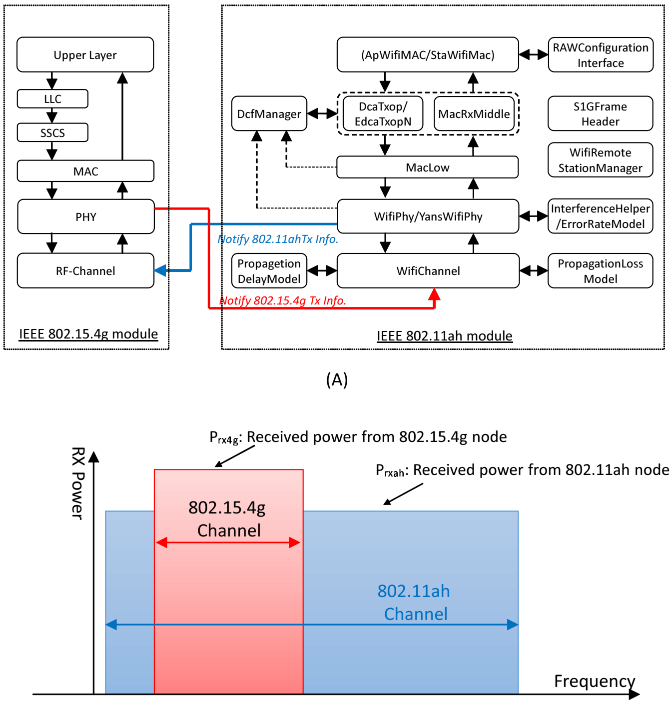
5 802.11ah and 802.15.4g Coexistence Simulator

The existing simulation tools for 802.11 and 802.15.4, e.g., NS-3 [12] and OMNeT++, do not implement 802.11ah and 802.15.4g. Furthermore, to the best of our knowledge, there is no simulation tool that supports coexisting 802.11 and 802.15.4. We have developed an NS-3 based coexistence simulator for 802.11ah and 802.15.4g, in which we adopt the third party 802.11ah module [13] and implement 802.15.4g FSK PHY in the 920 MHz band. The challenges include the interfacing independent 802.11ah module and 802.15.4g module and the received power conversion.

Fig. 4(A) shows the developed interface between 802.11ah module and 802.15.4g module, where two modules notify each other with their transmission via a TX Info message that contains device position, transmission duration, transmission power, frequency, bandwidth, antenna gain, etc. Upon receiving TX Info message from other party, 802.11ah device and 802.15.4g device first compute the corresponding RX power P_{rx4g} and P_{rxah}, respectively, as shown in Fig. 4(B), where same transmission power is assumed. In other words, 802.11ah device computes 802.15.4g received power P_{rx4g} as if it was an 802.15.4g device and 802.15.4g device computes 802.11ah received power P_{rxah} as if it was an 802.11ah device. Using the received power computed, 802.11ah device and 802.15.4g device compute interference power level from other party as

$$\begin{aligned} P_{int}^{4g} &= P_{rxah}[dBm] - 10\log_{10}(CH_{ah}/CH_{4g})[dBm], \\ P_{int}^{ah} &= P_{rx4g}[dBm], \end{aligned} \tag{1}$$

where P_{int}^{ah} is interference power to 802.11ah from 802.15.4g transmission, P_{int}^{4g} is interference power to 802.15.4g from 802.11ah transmission, CH_{ah} and CH_{4g} represent the channel width of 802.11ah channel and 802.15.4g channel, respectively. Using the interference power level and transmission duration, 802.11ah device and 802.15.4g device perform the enhanced CCA operation such that if the interference power is above the corresponding CCA-ED threshold, the channel status is considered as busy no matter what channel status is returned by their respective CCA operation.



(A)

(B)

Figure 4: Sub-1 GHz Band Coexistence Simulator Model Interface

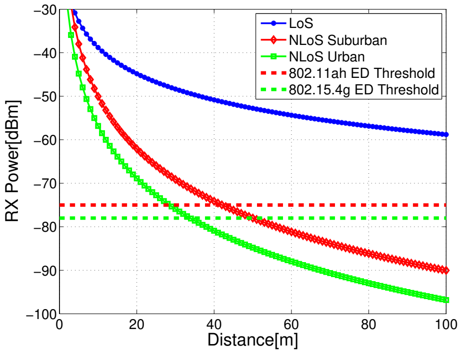


Figure 5: ITU-R P.1411-9 Propagation Model

Propagation model is another key component for practical simulation. NS-3 implements eight propagation models designed for general use scenarios without considering the emerging IoT applications. Both 802.11ah and 802.15.4g target the outdoor applications such as smart utility and smart city. Therefore, we adopt ITU-R P.1411-9 model for propagation between terminals located from below roof-top height to near street level. The median value of the

Non-Line-of-Sight (NLoS) loss is given by

$$L_{NLoS}^{median}(d) = 9.5+45\log_{10} f+40\log_{10}(d/1000)+L_{urban}, \quad (2)$$

where f is the frequency, L_{urban} depends on the urban category and is 0 dB for suburban, 6.8 dB for urban, and d is the distance. Fig. 5 shows the propagation loss of LoS model, Suburban NLoS model and Urban NLoS model for transmission power of 13 dBm. With -78 dBm ED threshold, the intersection of the red curve and green dash line represents the effective energy detection distance for 802.15.4g, which is about 50 meters for Suburban NLoS model and 34 meters for Urban NLoS model. For 802.11ah with -75 dBm ED threshold, the corresponding distances are 42 meters and 28 meters, respectively.

6 Hybrid CSMA/CA Performance Evaluation

In this section, we evaluate the proposed CSMA/CA performance compared with standard 802.15.4g CSMA/CA. We adopt the simulation parameters recommended by IEEE 802.19 Working Group [14]. The frequency is in the 920 MHz band, transmission power is 13 dBm, 1 MHz channel for 802.11ah, 400 kHz channel for 802.15.4g, 802.11ah OFDM PHY rate is 300 kbps and 802.15.4g FSK PHY rate is 100 kbps. ITU-R P.1411-9 propagation model is employed in the simulation.

Typical two scenarios of [14] are simulated. One 802.15.4g network consists of 50 nodes uniformly deployed in a circle centered at PANC (Personal Area Network Coordinator) with radius of the effective energy detection distance. The PANC is located at (0, 0). Three 802.11ah networks are deployed inside 802.15.4g network with each 802.11ah network having 17 or 33 nodes uniformly distributed in a circle centered at corresponding AP with radius of the effective energy detection distance. Based on propagation model, three APs are located at (8, 0), (-4, 6.928), (-4, -6.928) and (6, 0), (-3, 5.196), (-3, -5.196), respectively. The offered network load is 20 kbps or 40 kbps. The offered network load is uniformly distributed among network nodes. The packet size is 100 bytes.

Scenario-1: The offered load for both networks is 20 kbps, i.e., 400 bps offered load per node, which leads to 0.13% duty cycle for 802.11ah node and 0.4% duty cycle for 802.15.4g node. These duty cycles are much lower than the 10% duty cycle specified in ARIB STD T108 standard [1]. With 100 bytes of packet size, each node generates 0.5 packet per second. For both standard CSMA/CA and hybrid CSMA/CA, Fig. 6 shows that 802.11ah network delivers 100% of the packet. The standard CSMA/CA delivers 92.37% of 802.15.4g packet. The hybrid CSMA/CA delivers 95.77% of 802.15.4g packet, i.e., 3.4% improvement without degrading 802.11ah packet delivery.

Fig. 7 shows that for both 802.11ah and 802.15.4g, standard CSMA/CA achieves shorter packet latency than the hybrid CSMA/CA due to less 802.15.4g packet delivered. 802.11ah has shorter packet latency than 802.15.4g. In this case, the hybrid CSMA/CA increases 802.11ah packet latency slightly.

Table 3: Packet Delivery Rate Comparison

	11ah		15.4g		
	Standard	Hybrid	Standard	Hybrid	Diff.
Scenario 1	100 %	100 %	92.4 %	95.8 %	3.4 %
Scenario 2	100 %	100 %	86.2 %	90.7 %	4.5 %

Scenario-2: The offered load is 40 kbps for 802.11ah network and 20 kbps for 802.15.4g network, i.e., the offered load is 800 bps for 802.11ah node and 400 bps for 802.15.4g node, which leads to 0.26% duty cycle and 0.4% duty cycle, respectively. These duty cycles are much lower than the 10% duty cycle limit. Each 802.11ah node generates 1 packet per second and each 802.15.4g node generates 0.5 packet per second. Fig. 8 shows that both standard CSMA/CA and hybrid CSMA/CA deliver near 100% of 802.11ah packet. The hybrid CSMA/CA improves 802.15.4g packet delivery rate from 86.2% given by standard CSMA/CA to 90.7%. This 4.5% improvement is done without degrading 802.11ah packet delivery. It indicates that as 802.11ah network traffic increases, the hybrid CSMA/CA provides more improvement on 802.15.4g packet delivery rate. Fig. 9 shows that 802.11ah and 802.15.4g have similar packet latency. For 802.15.4g, standard CSMA/CA achieves slightly shorter packet latency than the hybrid CSMA/CA due to less 802.15.4g packet delivered. However, the hybrid CSMA/CA maintain overall 802.11ah packet latency compared with [4].

Table 3 shows Packet Delivery Rate of 802.11ah and 802.15.4g for both standard 802.15.4g CSMA/CA and the proposed hybrid CSMA/CA for 802.15.4g. The hybrid CSMA/CA can improve 802.15.4g packet delivery rate by 4.5 % without degrading 802.11ah packet delivery rate in Scenario 2.

7 Conclusion

The heterogeneous wireless technologies developed for IoT applications increase the coexistence potential and present coexistence challenges. This paper takes IEEE 802.11ah and IEEE 802.15.4g as target technologies to investigate the Sub-1 GHz band coexistence. We evaluated 802.11ah and 802.15.4g coexistence behavior and identified 802.15.4g packet delivery rate and 802.11ah packet latency as the coexistence issues to be addressed. Accordingly, we proposed a hybrid CSMA/CA mechanism for 802.15.4g to achieve better coexistence with 802.11ah. To contend for channel access with more aggressive 802.11ah, the hybrid CSMA/CA allows 802.15.4g to perform immediate channel access. Using the developed Sub-1 GHz band coexistence simulator, we conducted the performance analysis of the proposed hybrid CSMA/CA. Compared with the standard 802.15.4g CSMA/CA, simulation results show that the hybrid CSMA/CA can improve 802.15.4g packet delivery rate by 4.5 % without degrading 802.11ah packet delivery rate. The hybrid CSMA/CA also maintain overall 802.11ah packet latency compared with conventional work [4].

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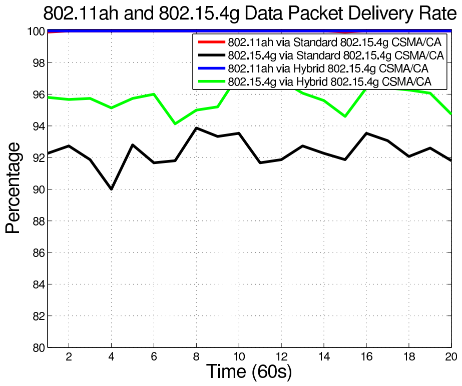

Figure 6: Packet Delivery Rate (Scenario 1)

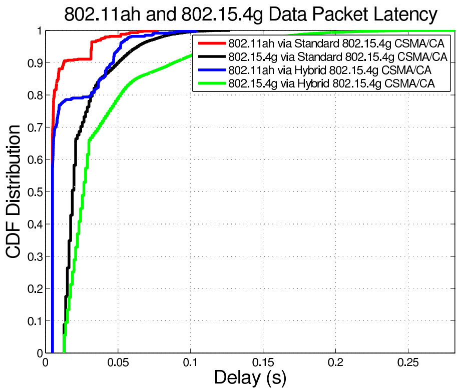

Figure 7: Packet Latency (Scenario 1)

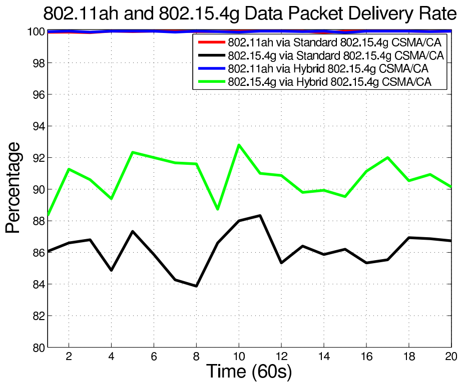

Figure 8: Packet Delivery Rate (Scenario 2)

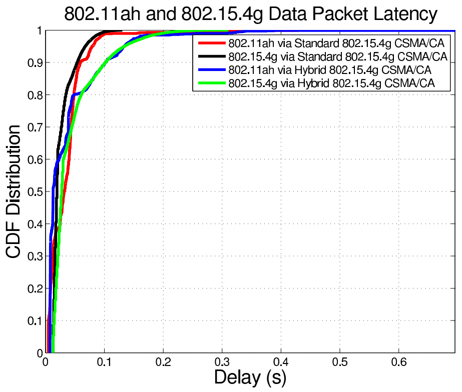

Figure 9: Packet Latency (Scenario 2)