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Abstract

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Sub-1 GHz Wireless Coexistence of IEEE 802.15.4g and IEEE 802.11ah Using Hybrid CSMA/CA

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Abstract - As more and more wireless technologies have been developed to support emerging Internet of Things (IoT) applications, the coexistence of these heterogeneous wireless technologies presents challenges. IEEE 802.15.4g and IEEE 802.11ah are two of such wireless technologies specified for the outdoor IoT applications and designed to operate in the Sub-1 GHz (S1G) frequency band. Due to the constrained spectrum allocation in the S1G band, two types of devices may be forced to coexist, i.e., share frequency spectrum. Therefore, the coexistence of 802.15.4g and 802.11ah should be addressed. To investigate coexistence behavior of these two wireless technologies, we first identify coexistence issues using our developed NS-3 based S1G band coexistence simulator. Simulation results confirm that 802.15.4g performance can significantly degrade due to the 802.11ah interference. Accordingly, we propose a hybrid CSMA/CA mechanism for 802.15.4g to address the identified coexistence issues. We then present several distributed and network assisted methods for 802.15.4g devices to estimate 802.11ah interference severity and switch channel access mode for interference mitigation. The performance analysis shows that the proposed hybrid CSMA/CA can improve 802.15.4g performance without sacrificing 802.11ah performance[1].

Keywords: Wireless coexistence, interference mitigation, hybrid CSMA/CA, Sub-1 GHz band, IEEE 802.15.4g, IEEE 802.11ah

1 INTRODUCTION

The Internet of Things (IoT) applications are rapidly growing. A broad range of wireless technologies have been developed to cater diverse applications. As heterogeneous wireless technologies are emerging, wireless coexistence becomes a critical issue to be addressed. IEEE 802.15.4g [2], marketed as Wi-SUN, operates in the Sub-1 GHz (S1G) frequency band for outdoor IoT applications. IEEE 802.11ah [1], marketed as Wi-Fi HaLow, is the first 802.11 standard designed to operate in the S1G band. The unlicensed spectrum allocation is limited, especially in the S1G band compared with other bands such as 2.4 GHz band. For example, Japan only allocates 7.6 MHz spectrum in 920 MHz band for active radio devices in the standard ARIB STD-T108 (20 mW) [3]. This standard also regulates other passive radio devices to use this spectrum. The constrained spectrum allocation indicates that 802.15.4g devices and 802.11ah devices may be forced to coexist, i.e., share frequency spectrum. In addition, 802.15.4g network and 802.11ah 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 2.4 GHz band. As a result, the existing coexistence technologies designed for 2.4 GHz band may not be suitable for the coexistence of 802.11ah and 802.15.4g in the S1G band, e.g., the cooperative busy tone method proposed in [10] assumes 22 MHz 802.11 channel. 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 [4]. Authors of this paper have been leading this standard development.

J. Guo, et al. propose a prediction based self-transmission control method for 802.11ah to ease its interference impact on 802.15.4g [6]. Y. Liu, et al. introduce α-Fairness energy detection clear channel assessment (ED-CCA) method for 802.11ah to mitigate its interference on 802.15.4g caused by its higher energy detection (ED) threshold [7]. To address the interference caused by the faster backoff of 802.11ah, Y. Liu, et al. also propose a Q-Learning based backoff mechanism for 802.11ah to avoid interfering with 802.15.4g packet transmission process [7]. However, these coexistence technologies improve the performance of 802.15.4g at the expense of 802.11ah. This paper aims to develop coexistence technologies for 802.15.4g to 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

[1]This paper is an extended version of our work published in [5]. We extend our previous work by adding distributed and network assisted methods for 802.15.4g devices to estimate 802.11ah interference severity. These methods are indispensable for 802.15.4g devices to assess 802.11ah interference and therefore, switch channel access mode for interference mitigation.

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

Reference	Year	Target System	Band	Objective	Validation Tool
This article and [5]	2020	11ah & 15.4g	Sub-1 GHz	delivery rate and latency at coexistence	ns-3
J. Guo, P. Orlik [6]	2017	11ah & 15.4g	Sub-1 GHz	delivery rate and latency at coexistence	ns-3
Y. Liu, J. Guo et al.[7]	2018	11ah & 15.4g	Sub-1 GHz	delivery rate and latency at coexistence	ns-3
W. Yuan et al. [8]	2010	11b & 15.4	2.4 GHz	throughput	OPNET
E.D.N Ndih et al. [9]	2016	11 & 15.4	2.4 GHz	delivery rate	MATLAB
X. Zhang, et al. [10]	2011	11 & 15.4	2.4 GHz	analytical model, throughput	analytical, ns-2
J.Hou et al. [11]	2009	11 & 15.4	2.4 GHz	delivery rate	experiments
J.W. Chong et al. [12]	2015	11 & 15.4	2.4 GHz	throughput	analytical
B. Badihi et al. [13]	2013	11ah & 15.4	Sub-1 GHz	throughput and energy consumption	OMNeT++
R. Ma et al. [14]	2017	11b & 15.4	2.4 GHz	analytical model, throughput	analytical & unknown simulator

coexistence simulator. We then propose a hybrid carrier sense multiple access/collision avoidance (CSMA/CA) mechanism for 802.15.4g to achieve better coexistence with 802.11ah. Furthermore, we present the distributed techniques for 802.15.4g devices to assess 802.11ah interference and switch channel access mode for interference mitigation.

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. Section 5 presents distributed methods to estimate 802.11ah interference severity. Section 6 shows network assisted 802.11ah interference severity estimation. In Section 7, we introduce our S1G band coexistence simulator. Performance evaluation of hybrid CSMA/CA mechanism is conducted in Section 8. We conclude our work in Section 9.

2 RELATED WORK

There are existing coexistence technologies developed for conventional 802.15.4 to address its coexistence with 802.11 in 2.4 GHz band. W. Yuan, et al. propose a decentralized approach to mitigate interference by adaptively adjusting ED threshold [8]. E.D.N. Ndih, et al. propose an adaptive backoff mechanism to survive coexistence with 802.11 [9]. X. Zhang, et al. design a cooperative busy tone method via a special device to enable 802.11 to be aware of 802.15.4 transmission [10]. J. Hou, et al. propose a hybrid device to coordinate 802.11 and 802.15.4 transmissions [11]. J.W. Chong, et al. propose 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 [12].

Before the work in [6] and [7], to the best of our knowledge, no other existing work addresses the coexistence of 802.11ah and 802.15.4 in the S1G band. The related studies are done either for 802.11ah or 802.15.4g only. B. B. Olyaei, et al. compare the 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 [13]. R. Ma, et al. investigate the coexistence issues of 802.11b and 802.15.4g in 2.4 GHz band. It shows that 802.11b can significantly interfere with 802.15.4g [14]. However, our investigation shows that the existing studies only reveal one side of the story. Table 1 shows majority of available 802.11 and 802.15.4 performance evaluation and conventional coexistence researches.

3 802.11AH AND 802.15.4G COEXISTENCE BEHAVIOR AND ISSUE

Before conducting coexistence performance evaluation using our S1G band coexistence simulator, 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 clear channel assessment (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.

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

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

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 at packet transmission process starts to the time at 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 7.

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 nearly 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.

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.

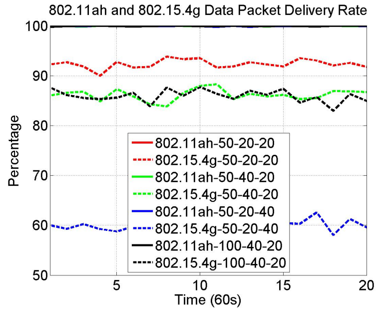

Figure 1: Packet Delivery Rate

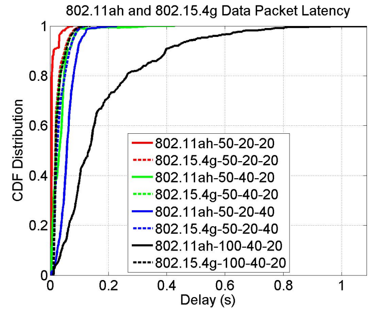

Figure 2: Packet Latency

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.

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 DCF inter frame space (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 a hybrid CSMA/CA mechanism for 802.15.4g. Depending on severity of 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 for

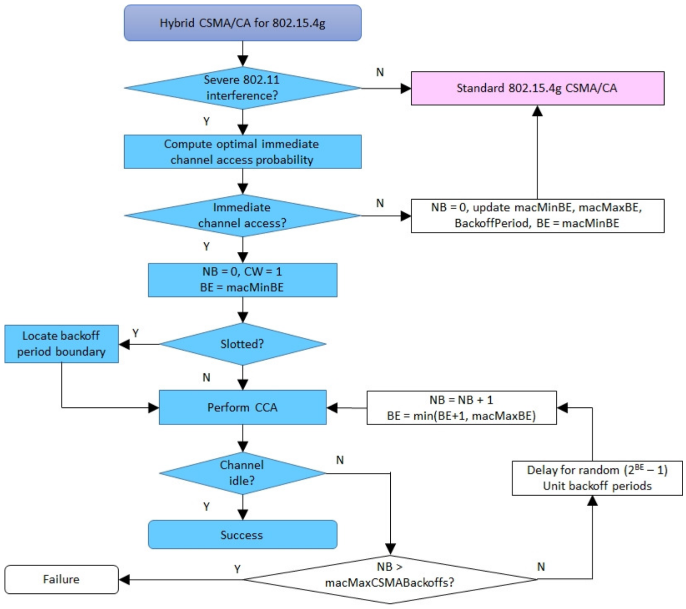

Figure 3: Hybrid CSMA/CA for IEEE 802.15.4g

802.15.4g. 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. Considering 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 the expected number of 802.15.4g devices that take immediate channel access is one 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 immediate channel access device and also give 802.11ah device opportunity to transmit next and therefore, reduces 802.11ah packet latency.

The core of the hybrid CSMA/CA is to determine 802.11ah interference severity. In Sections 5 and 6, we present pure and network assisted distributed methods to estimate 802.11ah interference severity.

5 DISTRIBUTED 802.11AH INTERFERENCE SEVERITY ESTIMATION

This section presents three pure distributed methods for 802.15.4g to estimate 802.11ah interference severity, in which 802.15.4g devices estimate 802.11ah interference severity distributively without any assistance. An 802.15.4g device should select a method for better performance based on the given performance metric.

A) Channel Access Failure Rate Caused by 802.11ah

IEEE 802.15.4g performs carrier sense before starting transmission to check if channel is available. IEEE 802.15.4g can detect other system is transmitting if received signal over IEEE 802.15.4g ED threshold cannot be decoded, and determine channel access failure caused by other system. In this paper, IEEE 802.11ah is assumed to be other system.

Let N_{caf} be the total number of channel access failure observed by an 802.15.4g device for total N_{tx} transmission attempts. N_{caf} can be decomposed into $N_{caf} = N_{caf}^h + N_{caf}^g$, where N_{caf}^h is the number of channel access failure caused by 802.11ah and N_{caf}^g is the number of channel access failure caused by 802.15.4g. 802.15.4g device is able to compute N_{caf}^g by using carrier sense mechanism. To guarantee packet header sensing, 802.15.4g device may start carrier sense early, e.g., start channel sense before backoff counter reaches to zero. Therefore, channel access failure rate caused by 802.11ah R_{caf}^h can be computed as

$$R_{caf}^h = \frac{N_{caf}^h}{N_{tx}} = \frac{N_{caf} - N_{caf}^g}{N_{tx}} \quad (1)$$

If $N_{caf} = N_{caf}^g$, no interference from 802.11ah, else (like $N_{caf} - N_{caf}^g > 0$, 802.11ah presence. 802.15.4g device switches to the immediate channel access.

B) 802.11ah Channel Occupancy Probability

An 802.15.4g device can estimate the channel busy time T_b by continuously sensing channel for a time period T. Its transmission time and reception time are considered as busy time. Its turnaround time is considered as idle time. In addition, 802.15.4g device is able to determine the busy time consumed by 802.15.4g transmissions T_b^g via carrier sense. Therefore, 802.11ah channel occupancy probability P_{tx}^h can be estimated as

$$P_{tx}^h = \frac{T_b - T_b^g}{T}. \quad (2)$$

If P_{ed}^h is higher than 802.15.4g system predetermined threshold, 802.15.4g device switches to the immediate channel access.

C) *802.11ah Energy Detection Ratio*

Using energy detection mechanism, an 802.15.4g device can detect energy that is higher than or equal to 802.15.4g ED threshold. Let ED_{total} be the total number of such detection by an 802.15.4g device within a time period T. Using carrier sensing mechanisms, an 802.15.4g device can determine if the detected signal is 802.15.4g signal or not. For 802.15.4g and 802.11ah coexistence, if the signal is not 802.15.4g signal, it is either 802.11ah signal or collided signal. Let ED_{ah} be the number of non 802.15.4g signal detected. 802.11ah energy detection ratio R^h_{ed} can be estimated as

$$R^h_{ed} = \frac{ED_{ah}}{ED_{total}}. \tag{3}$$

If 802.15.4g device detects ED_{ah} during observation time period T and R^h_{ed} is higher than 802.15.4g system predetermined threshold, 802.15.4g device switches to immediate channel access.

6 NETWORK ASSISTED 802.11AH INTERFERENCE SEVERITY ESTIMATION

Some of performance metrics such as packet delivery rate can not be estimated locally by an 802.15.4g device alone and therefore, network assistance is needed. The advantage is that metric can be more accurately assessed. The disadvantage is that network assistance may not be available. Due to the fact that 802.15.4g devices can not distinguish between collision caused by 802.11ah or 802.15.4g, we use the probability of the 802.11ah transmission colliding with 802.15.4g transmission as a metric to estimate 802.11ah interference severity.

This section presents a network assisted distributed method for 802.15.4g devices to estimate 802.11ah interference severity. Using this method, 802.11ah network provides its node distribution, traffic pattern, and the random backoff period length of its nodes to 802.15.4g network. Node distribution and traffic pattern only need to be provided once, and the length of random backoff period needs to be provided repeatedly, since the traffic pattern and terminal location are assumed not to change dynamically for sensor networks that enable IoT application. Node distribution is used to determine 802.11ah neighbors of an 802.15.4g node. The determined number of 802.11ah neighbors, traffic pattern and the length of random backoff period are then used to estimate the collision probability caused by 802.11ah.

An 802.11ah transmission can interfere with an 802.15.4g transmission only if their transmission time periods overlap. Fig. 4(A) shows the collision scenarios.

In the IEEE 802 standards, a data transmission is successful only if its transmission process completes. Therefore, we consider interference effect of 802.11ah transmission process on 802.15.4g transmission process.

An 802.11ah transmission process can interfere with a given 802.15.4g transmission only if the corresponding 802.11ah data arrives within a potential time period. The

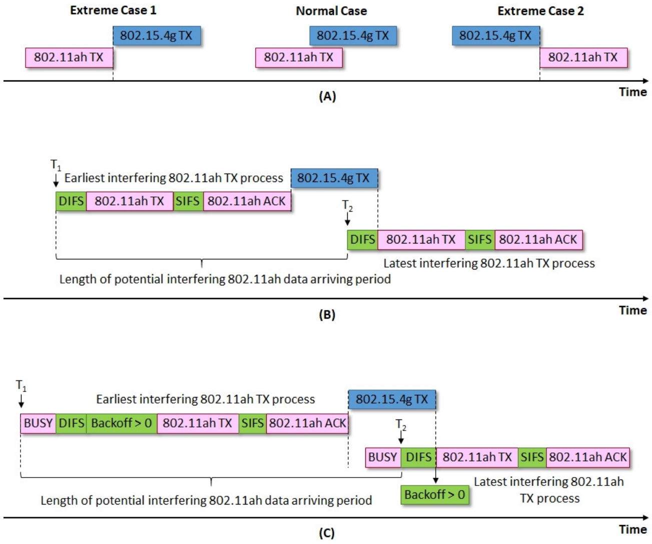

Figure 4: 802.11ah TX interfering with 802.15.4g TX

length of this time period is used to estimate the collision probability caused by 802.11ah.

In this section, we first present a method to estimate the length of potential 802.11ah data arriving time period. Based on 802.11ah traffic pattern and the estimated length of potential 802.11ah data arriving time period, we then compute the probability of 802.11ah transmission process interfering with 802.15.4g transmission process.

A) *Potential 802.11ah Data Arriving Time Period*

802.11ah channel access can be divided into

1. Immediate access, in which if data arrives, channel is idle and idle channel continues for more than DIFS time period, the data is transmitted without backoff.
2. Deferred access, in which if data arrives, channel is busy, then backoff process is invoked and data transmission is deferred.

An 802.11ah device ignores 802.15.4g transmission if the detected energy level is below 802.11ah CCA-ED threshold, which is -75 dBm for 1 MHz channel, and detects 802.15.4g transmission if the detected energy level is above 802.11ah CCA-ED threshold. Therefore, the 802.11ah interference scenarios can be classified into following four cases:

- **Case-1**: 802.11ah performs immediate channel access and ignores 802.15.4g transmission
- **Case-2**: 802.11ah performs delayed channel access and ignores 802.15.4g transmission
- **Case-3**: 802.11ah performs immediate channel access and detects 802.15.4g transmission
- **Case-4**: 802.11ah performs delayed channel access and detects 802.15.4g transmission

Let T_{gd}, T_{ga}, T_{hd} and T_{ha} be 802.15.4g data transmission time, 802.15.4g ACK transmission time, 802.11ah data transmission time and 802.11ah ACK transmission time, respectively.

For **Case-1**, Fig. 4(B) illustrates the length of potential 802.11ah data arriving period that can cause 802.11ah transmission process interfering with the given 802.15.4g transmission. The period length is given by $T_{im}^{ig} = T_2 - T_1 = T_{hd} + SIFS + T_{ha} + T_{gd}$. It is obvious that the latest interfering 802.11ah transmission process can take place since 802.11ah device ignores 802.15.4g transmission. Is it possible for the earliest interfering 802.11ah transmission process to occur without being detected by 802.15.4g device? Yes, 802.15.4g turnaround time is 1000 μs. 802.11ah SIFS is 160 μs. There are 840 μs left for 802.11ah data transmission and ACK transmission. Even with 1 MHz channel, 802.11ah PHY rate ranges from 300 kbps to 16 Mbps. Using 3 Mbps PHY rate, a 100 byte packet only takes 267 μs. The remaining 573 μs is long enough to transmit 802.11ah ACK.

For **Case-2**, when 802.11ah data arrives for transmission, 802.11ah CCA returns channel status as busy. Therefore, 802.11ah device has to do backoff. Fig. 4(C) depicts the length of potential 802.11ah data arriving period that can cause 802.11ah transmission process interfering with the 802.15.4g transmission. In this case, the earliest interfering 802.11ah transmission process performs backoff with backoff period length greater than zero. The latest interfering 802.11ah transmission process happens to select a zero backoff period length. The period length is given by $T_{df}^{ig} = T_2 - T_1 = \max\{T_{hd}, T_{gd}\} + T_{bo}^{h} + T_{hd} + SIFS + T_{ha} + T_{gd}$, where $\max\{T_{hd}, T_{gd}\}$ indicates that the busy channel status returned by 802.11ah CCA can be caused by 802.11ah transmission and/or 802.15.4g transmission and T_{bo}^{h} is the length of random backoff period of 802.11ah device. T_{bo}^{h} is random with a lower bound 0. For light traffic without backoff suspension, T_{bo}^{h} has an upper bound $CW_{min} * 52\mu s$, where CW_{min} is typically 15. However, for heavy traffic, T_{bo}^{h} could be theoretically unbounded.

Combining **Case-1** and **Case-2**, if 802.11ah device ignores 802.15.4g data transmission, the length of potential 802.11ah data arriving time period that can cause 802.11ah transmission process interfering with 802.15.4g data transmission can be estimated as

$$\begin{aligned} T_{itd}^{ig} &= P_i T_{im}^{ig} + (1 - P_i) T_{df}^{ig} \\ &= T_{hd} + SIFS + T_{ha} + T_{gd} \\ &+ (1 - P_i)(\max\{T_{hd}, T_{gd}\} + T_{bo}^{h}), \end{aligned} \tag{4}$$

where P_i is the channel idle probability and can be estimated as $P_i = \frac{T - T_b}{T}$ by using similar approach used in Section 5.

Case-3 is similar as **Case-1**, but in this case, the latest interfering 802.11ah transmission process can not start at the end of 802.15.4g transmission since during 802.15.4g transmission, channel is considered as busy. Therefore, the latest interfering 802.11ah transmission process can only start at the start of 802.15.4g transmission. As a result, the length of potential interfering 802.11ah data arriving time period is $T_{im}^{dt} = T_{hd} + SIFS + T_{ha}$.

Similarly, for **Case-4**, the length of potential interfering 802.11ah data arriving time period is given by $T_{df}^{dt} = \max\{T_{hd}, T_{gd}\} + T_{bo}^{h} + T_{hd} + SIFS + T_{ha}$.

Combining **Case-3** and **Case-4**, if 802.11ah device detects 802.15.4g data transmission, the length of potential 802.11ah data arriving time period that can cause 802.11ah transmission process interfering with 802.15.4g data transmission can be estimated as

$$\begin{aligned} T_{itd}^{dt} &= P_i T_{im}^{dt} + (1 - P_i) T_{df}^{dt} \\ &= T_{hd} + SIFS + T_{ha} \\ &+ (1 - P_i)(\max\{T_{hd}, T_{gd}\} + T_{bo}^{h}). \end{aligned} \tag{5}$$

B) Collision Probability Caused by 802.11ah

The probability of 802.11ah transmission colliding with 802.15.4g transmission depends on traffic pattern of 802.11ah network. This section considers Poisson data arrival and uniform data arrival traffic scenarios.

In addition, we also assume that 802.15.4g transmission device has N_h 802.11ah neighbors with $N_h > 0$. Otherwise, the 802.15.4g transmission device does not switch CSMA/CA mode and always applies standard CSMA/CA.

B.1) Poisson Data Arrival

Assume 802.11ah device has Poisson data arriving distribution with mean arriving rate λ. In a time period T, the probability an 802.11ah neighbor having no data arriving is $e^{-\lambda T}$ and the probability all 802.11ah neighbors having no data arriving is $e^{-N_h \lambda T}$. Let P_{pd}^{h} be the probability at least one 802.11ah neighbor having data arriving in time period T, and P_{pd}^{h} is given by

$$P_{pd}^{h} = 1 - e^{-N_h \lambda T}. \tag{6}$$

For the immediate access, plugging T_{itd}^{ig} into (6), we obtain the probability 802.11ah transmission process interfering with the given 802.15.4g data transmission as

$$P_{pd}^{ig} = 1 - e^{-\lambda N_h T_{itd}^{ig}}. \tag{7}$$

Similarly, for the deferred access, the probability 802.11ah transmission process colliding with the given 802.15.4g data transmission is given by

$$P_{pd}^{dt} = 1 - e^{-\lambda N_h T_{itd}^{dt}}. \tag{8}$$

Notice that $P_{pd}^{dt} < P_{pd}^{ig}$ since $T_{itd}^{dt} < T_{itd}^{ig}$, which is reasonable because if 802.11ah detects 802.15.4g transmission, it takes action to avoid interference.

Besides interfering with 802.15.4g data transmission, 802.11ah transmission can also interfere with 802.15.4g ACK transmission. 802.15.4g ACK transmission waiting time AIFS is 1000 μs, which is much longer than 802.11ah DIFS time of 264 μs. Therefore, 802.11ah devices can start transmission process in between 802.15.4g data and 802.15.4g ACK. The transmission process can interfere with 802.15.4g ACK transmission.

Consider that 802.15.4g ACK is transmitted only if 802.15.4g data transmission is successful, the probability of 802.15.4g ACK transmission is $1 - P_c^g$, where P_c^g is the 802.15.4g collision probability caused by both 802.11ah transmission and 802.15.4g transmission. 802.15.4g device can compute P_c^g using number of transmission attempts and number of ACK received.

The probability of 802.11ah transmission process interfering with 802.15.4g ACK transmission can be similarly computed as for the 802.15.4g data transmission. In this case, however, the busy channel is caused by 802.15.4g data transmission.

For the immediate access, the probability 802.11ah transmission process colliding with 802.15.4g ACK transmission is given by

$$P_{pa}^{ig} = (1 - P_c^g)(1 - e^{-\lambda N_h T_{ita}^{ig}}), \tag{9}$$

where $T_{ita}^{ig} = T_{hd} + SIFS + T_{ha} + T_{ga} + (1 - P_i)(T_{gd} + T_{bo}^h)$.

For the deferred access, the probability 802.11ah transmission process interfering with 802.15.4g ACK transmission is given by

$$P_{pa}^{dt} = (1 - P_c^g)(1 - e^{-\lambda N_h T_{ita}^{dt}}), \tag{10}$$

where $T_{ita}^{dt} = T_{hd} + SIFS + T_{ha} + (1 - P_i)(T_{gd} + T_{bo}^h)$.

We can also see that $P_{ca}^{dt} < P_{ca}^{ig}$ since $T_{ita}^{dt} < T_{ita}^{ig}$.

Finally, combining all cases, the probability of 802.11ah transmission process colliding with the given 802.15.4g transmission process for Poisson 802.11ah data arriving P_c^p is given by

$$P_c^p = \begin{cases} P_{pd}^{ig} + P_{pa}^{ig}, & \text{if 15.4g data \& ACK ignored} \\ P_{pd}^{dt} + P_{pa}^{ig}, & \text{if only 15.4g data detected} \\ P_{pd}^{ig} + P_{pa}^{dt}, & \text{if only 15.4g ACK detected} \\ P_{pd}^{dt} + P_{pa}^{dt}, & \text{if 15.4g data \& ACK detected.} \end{cases} \tag{11}$$

B.2) Uniform Data Arrival

Assume 802.11ah device has uniform data arriving with time interval T_i^h, i.e., one data arriving per T_i^h time period. For a time period T, the probability of no 802.11ah packet arriving is 0 if $T \geq T_i^h$ and is $((T_i^h - T)/T_i^h)^{N_h}$ if $T < T_i^h$. Therefore, the probability at least one 802.11ah neighbor having data arriving P_{ud}^h is given by

$$P_{ud}^h = \begin{cases} 1, & \text{if } T \geq T_i^h \\ 1 - (\frac{T_i^h - T}{T_i^h})^{N_h}, & \text{if } T < T_i^h. \end{cases} \tag{12}$$

For uniform data arriving, if $T \geq T_i^h$, the hybrid CSMA/CA is always on the immediate access enabled mode. Otherwise, the hybrid CSMA/CA switches mode based on the collision probability caused by 802.11ah.

For the case $T < T_i^h$, P_{ud}^h is simplified as

$$P_{ud}^h = 1 - (\frac{T_i^h - T}{T_i^h})^{N_h}. \tag{13}$$

Similarly as for Poisson data arriving scenario, plugging T_{itd}^{ig}, T_{itd}^{dt}, T_{ita}^{ig} or T_{ita}^{dt} into Eq.(13), we can obtain the probability P_{ud}^{ig}, P_{ud}^{dt}, P_{ua}^{ig} or P_{ua}^{dt}. The probability of the 802.11ah transmission process colliding with the given 802.15.4g transmission process P_c^u is given by

$$P_c^u = \begin{cases} P_{ud}^{ig} + P_{ua}^{ig}, & \text{if 15.4g data \& ACK ignored} \\ P_{ud}^{dt} + P_{ua}^{ig}, & \text{if only 15.4g data detected} \\ P_{ud}^{ig} + P_{ua}^{dt}, & \text{if only 15.4g ACK detected} \\ P_{ud}^{dt} + P_{ua}^{dt}, & \text{if 15.4g data \& ACK detected.} \end{cases} \tag{14}$$

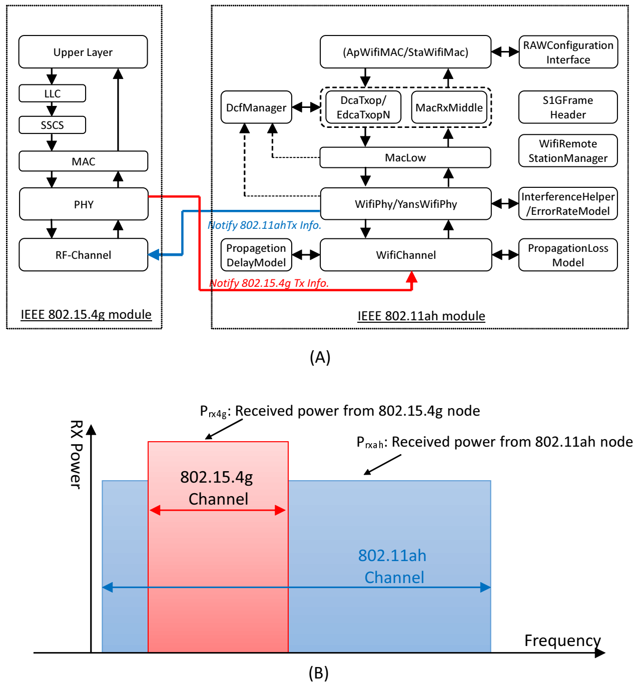

Figure 5: Sub-1 GHz Band Coexistence Simulator Model Interface

7 802.11AH AND 802.15.4G COEXISTENCE SIMULATOR

The existing simulation tools for 802.11 and 802.15.4, e.g., NS-3 [15], MATLAB, QualNet and OMNeT++, do not implement 802.11ah and 802.15.4g. Accordingly, 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 [16] and implement 802.15.4g FSK PHY in 920 MHz band. NS-3 (version 3.23) is used because of supported version in [16]. The challenges include the interfacing independent 802.11ah module and 802.15.4g module and the received power conversion.

Fig. 5(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* (Transmission Information) 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. 5(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

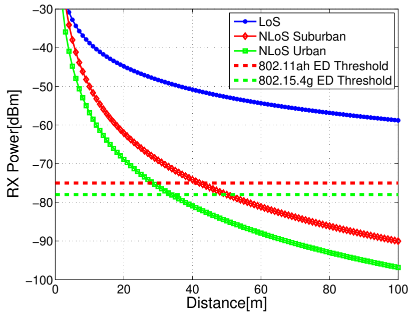

Figure 6: ITU-R P.1411-9 Propagation Model

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

$$P_{int}^{4g} = P_{rxah}[dBm] - 10\log_{10}(CH_{ah}/CH_{4g})[dBm],$$
$$P_{int}^{ah} = P_{rx4g}[dBm], \tag{15}$$

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.

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

$$L_{NLoS}^{median}(d) = 9.5 + 45\log_{10} f + 40\log_{10}(d/1000) + L_{urban}, \tag{16}$$

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. 6 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.

Table 3: Simulation Scenarios

	Network Size [node]		Offered Load [kbps]		Propagation Model
	11ah	15.4g	11ah	15.4g	
Scenario-1	50	50	20	20	Suburban NLoS
Scenario-2	50	50	40	20	
Scenario-3	50	50	20	40	
Scenario-4	100	100	40	20	
Scenario-5	100	100	40	20	Urban NLoS

8 HYBRID CSMA/CA PERFORMANCE EVALUATION

In this section, we evaluate the performance of Hybrid CSMA/CA proposed in Section 4 to compare with standard 802.15.4g CSMA/CA. We adopt the simulation parameters recommended by IEEE 802.19 Working Group [17]. Table 4 shows simulation parameters for IEEE 802.11ah and IEEE 802.15.4g coexistence performance. The frequency is in 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. And, ITU-R P.1411-9 propagation model is employed in the simulations. We use 802.11ah energy detection ratio method to assess 802.11ah interference severity. We define PDR (Packet Delivery Rate) and packet latency as metrics to evaluate the coexistence performance.

Five typical scenarios for 50-node and 100-node are simulated with simulation conditions in [17]. Table 3 shows the simulation cases. One 802.15.4g network consists of 50 or 100 nodes uniformly deployed in a circle centered at PANC (Personal Area Network Coordinator) with radius of 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 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.

In addition to five typical scenarios, individual performance of IEEE 802.11ah and IEEE 802.15.4g was conducted for $(node, offeredload) = (50\,nodes, 20\,kbps)$. Packet arrival rate in a single network for is 100% for IEEE 802.11ah and 98.5 % for IEEE 802.15.4g, respectively. Packet latency at CDF 0.9 is 10 ms for IEEE 802.11ah and 40 ms for IEEE 802.15.4g.

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 [3]. With 100 bytes of packet size, each node generates 0.5 packet per second. For both standard CSMA/CA and hybrid CSMA/CA, Fig. 7 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

Table 4: Simulation parameters for IEEE 802.11ah and IEEE 802.15.4g coexistence performance

Parameters	Value [Unit]	Note
Network offered load	20-40 kbps	11ah
Network offered load	20-40 kbps	15.4g
Tx Power	20 mw	11ah & 15.4g
11ah Bandwidth	1 MHz	11ah
15.4g Bandwidth	400 kHz	15.4g
aSlotTime	52 usec	11ah
aSIFSTime	160 usec	11ah
aCCATime	<40 usec	11ah
aRxTxTurnaroundTIme	Less than 5 usec	11ah
CW (min, max)	15, 1023	11ah
phyCCADuration	140 usec	15.4g
aTurnaroundTime	1000 usec	15.4g
Rx to Tx TrunaroundTime	300 usec or more, 1000 usec or less	15.4g
Tx to Rx TurnaroundTIme	Less than 300 usec	15.4g
macMinLIFSPeriod	1000 usec	15.4g
aUnitBackoffPeriod	1140 usec	15.4g
macAckWaitDuration	5 ms	15.4g
macMaxBE	3 to 8 (Default 5)	15.4g
macMinBE	0 to macMaxBE (Default 3)	15.4g
macMaxCSMABackoffs	0 to 5 (Default 4)	15.4g
macMaxFrameRetries	0 to 7 (Default 4)	15.4g

802.15.4g packet, i.e., 3.4 % improvement without degrading 802.11ah packet delivery. Fig. 8 shows that packet latency 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.

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. 9 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. 10 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, i.e., the hybrid CSMA/CA does not degrade 802.11ah performance.

Scenario-3: The offered load is 20 kbps for 802.11ah network and 40 kbps for 802.15.4g network, i.e., the offered load is 400 bps for 802.11ah node and 800 bps for 802.15.4g node, which leads to 0.13 % duty cycle and 0.8 % duty cycle, respectively. These duty cycles are much lower than the 10 % duty cycle limit. Each 802.11ah node generates 0.5 packet per second and each 802.15.4g node generates 1 packet per

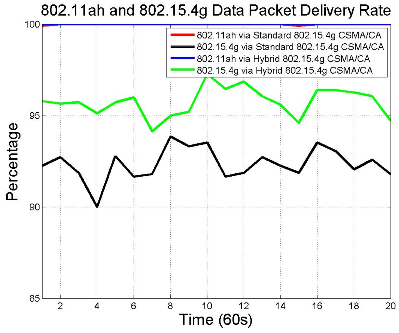

Figure 7: Scenario-1: Packet Delivery Rate

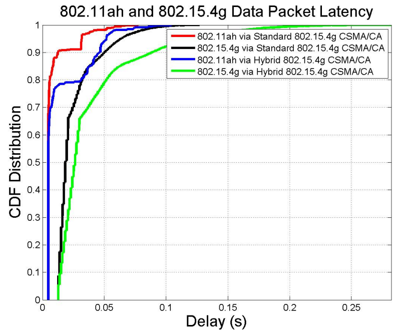

Figure 8: Scenario-1: Packet Latency

second. Fig. 11 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 59.8 % given by standard CSMA/CA to 61.3 %, i.e., 1.5 % of improvement without degrading 802.11ah packet delivery. It indicates that as 802.15.4g traffic increases, the hybrid CSMA/CA provides less improvement on 802.15.4g packet delivery rate. Fig. 12 shows that 802.11ah delay packet longer than 802.15.4g does due to high 802.15.4g network traffic. For both 802.11ah and 802.15.4g, standard CSMA/CA achieves slightly shorter packet latency than the hybrid CSMA/CA due to less 802.15.4g packet delivered. In this case, the hybrid CSMA/CA delays 802.11ah further longer.

Scenario-4: In this case, each of 802.11ah network and 802.15.4g network has 100 nodes. The offered load, the duty cycle and the number of packet per second are same as in the Scenario-2 of the 50-node scenario. Fig. 13 shows that both standard CSMA/CA and hybrid CSMA/CA deliver near 100 % of 802.11ah packet. For 802.15.4g, the hybrid CSMA/CA improves packet delivery rate from 86.1 % given by standard CSMA/CA to 92.9 % without degrading 802.11ah packet delivery rate. This 6.8 % improvement is better than 4.5 % improvement in the Scenario-2 of 50-Node scenario. Fig. 14 shows that 802.15.4g achieves lower packet latency than 802.11ah. For 802.15.4g, the standard CSMA/CA delays packet shorter than the hybrid CSMA/CA due to less 802.15.4g packet delivered. For 802.11ah, however, the hybrid CSMA/CA achieves shorter packet delay than the standard CSMA/CA does. This is because for the standard CSMA/CA, the range of the 802.15.4g backoff period length

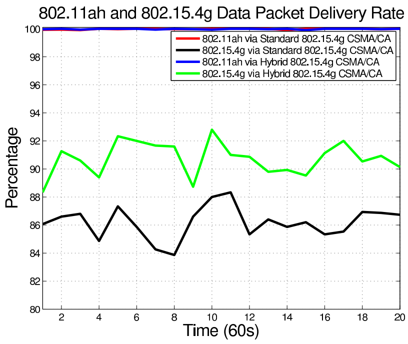

Figure 9: Scenario-2: Packet Delivery Rate

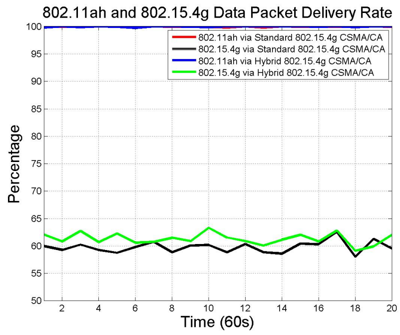

Figure 11: Scenario-3: Packet Delivery Rate

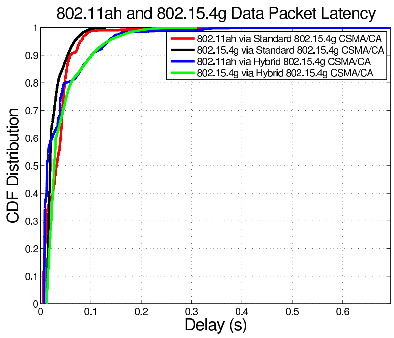

Figure 10: Scenario-2: Packet Latency

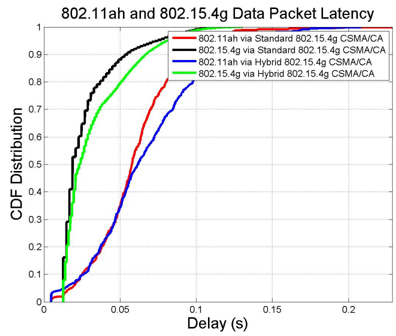

Figure 12: Scenario-3: Packet Latency

is smaller, which results in more concentrated 802.15.4g packet transmission and therefore, causes the longer delay of 802.11ah transmission. On the other hand, the hybrid CSMA/CA allows the longer range of the 802.15.4g backoff period, which spreads 802.15.4g transmission and gives 802.11ah opportunity to transmit early. Therefore, 802.11ah achieves shorter packet delay. In this case, the hybrid CSMA/CA not only improves 802.15.4g packet delivery rate but also improves 802.11ah packet latency. This case also demonstrates that as the number of network node increases, the hybrid CSMA/CA becomes more effective.

Scenario-5: In this case, network size, the offered load, the duty cycle and the number of packet per second are same as in Scenario-4. The difference from Scenario-4 is propagation model from Suburban NLoS model to Urban NLoS Propagation model. Again, Fig 15 shows that both standard CSMA/CA and hybrid CSMA/CA deliver near 100 % of 802.11ah packet. The standard CSMA/CA delivers 76.87 % of 802.15.4g packet. The hybrid CSMA/CA delivers 82.18 % of 802.15.4g packet, i.e., 5.31 % improvement without degrading 802.11ah packet delivery. However, using Urban NLoS model, both standard CSMA/CA and hybrid CSMA/CA achieve lower packet delivery rate compared with the corresponding results using Suburban NLoS model (as on Scenario-4) due to the higher node density, which causes more channel access failure for 802.15.4g nodes. It indicates that as node density increases, 802.15.4g packet delivery rate decreases. Fig. 16 shows that packet latency for both 802.11ah and 802.15.4g, the standard CSMA/CA delays packet less than the hybrid CSMA/CA due to more packet drop by standard CSMA/CA. However, compared with the Suburban NLoS mode case (as on Scenario-4), Urban NLoS model has shorter packet delay due to less 802.15.4g packet delivery.

Table 5: Packet Delivery Rate Comparison

	802.11ah		802.15.4g		
	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-3	100 %	100 %	59.8 %	61.3 %	1.5 %
Scenario-4	100 %	100 %	86.1 %	92.9 %	6.8 %
Scenario-5	100 %	100 %	78.8 %	82.1 %	5.3 %

In summary of all network traffic and network size scenarios, simulation results show that the proposed hybrid CSMA/CA improves 802.15.4g packet delivery rate without degrading 802.11ah packet delivery rate. In some case, it can improve performance of both 802.11ah network and 802.15.4g network. As number of the node increases, the hybrid CSMA/CA demonstrated more superiority. In addition, the Suburban NLoS model outperforms Urban NLoS model. 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 are shown in Table 5.

9 CONCLUSION

The heterogeneous wireless technologies developed for IoT applications increase the coexistence potential and present coexistence challenges. This paper takes IEEE 802.15.4g and IEEE 802.11ah as target technologies to investigate the Sub-1 GHz band coexistence. We evaluated 802.15.4g and 802.11ah coexistence behavior and identified 802.15.4g packet delivery rate and 802.11ah packet latency

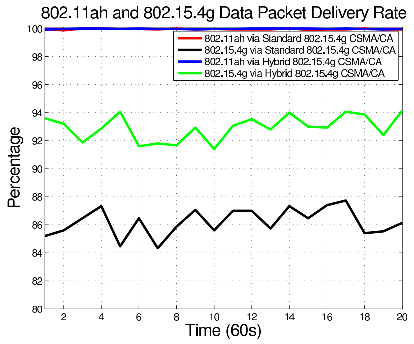

Figure 13: Scenario-4: Packet Delivery Rate

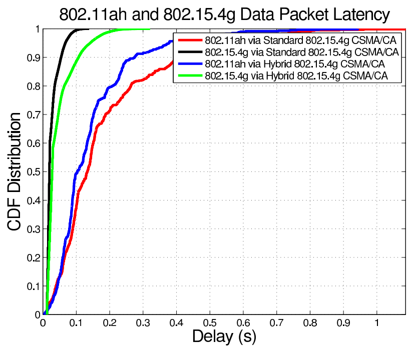

Figure 14: Scenario-4: Packet Latency

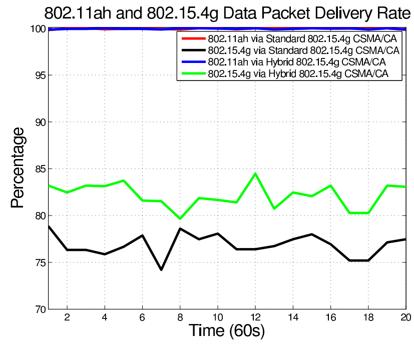

Figure 15: Scenario-5: Packet Delivery Rate

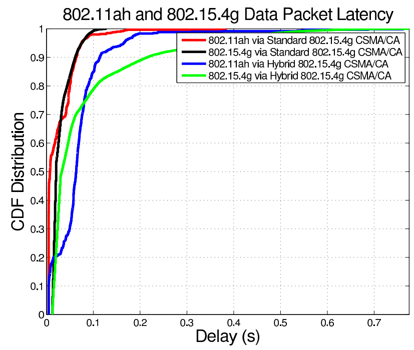

Figure 16: Scenario-5: Packet Latency

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. Two classes of the distributed methods are introduced for 802.15.4g devices to estimate the severity of 802.11ah interference and switch the CSMA/CA mode for interference mitigation. Using the developed Sub-1 GHz band coexistence simulator with use case scenarios and parameters proposed by IEEE 802.19.3 Task Group, 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 6.8% without degrading 802.11ah packet delivery rate in our scenario. As the number of nodes in the network traffic increases under the same conditions, the hybrid CSMA/CA can also reduce 802.11ah packet latency.

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