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Self-Transmission Control in IoT over Heterogeneous Wireless Networks

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TR2017-229 June 25, 2020

Abstract

With the increasing development of the IoT applications, heterogeneous wireless networks may coexist. IEEE 802.11ah and IEEE 802.15.4g are two wireless technologies designed for IoT applications. 802.11ah is primarily developed for outdoor applications such as smart city and 802.15.4g is principally developed for large scale outdoor process control applications such as smart utility network. Both technologies have communication range up to 1000 meters. Therefore, 802.11ah network and 802.15.4g network are likely to coexist. Our simulation results show that 802.11ah network can severely interfere with 802.15.4g network since 802.11ah devices are more aggressive than 802.15.4g devices in wireless medium access contention. This capability heterogeneity can lead to significant packet loss in 802.15.4g network. Due to asymmetrical features such as modulation scheme and packet structure, devices in different networks can not understand each other. Thus, the self-transmission control mechanism is needed for more aggressive 802.11ah devices. This paper proposes a learning based self-transmission control method for 802.11ah devices to improve their coexistence with 802.15.4g devices. Using the proposed self-transmission control technique, 802.11ah devices predict the packet transmission of 802.15.4g devices and postpone their transmissions to avoid interference. Keywords IoT, heterogeneous, interference, coexistence control, 802.11ah, 802.15.4g.

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Self-Transmission Control in IoT over Heterogeneous Wireless Networks

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***Abstract*—With the increasing development of the IoT applications, heterogeneous wireless networks may coexist. IEEE 802.11ah and IEEE 802.15.4g are two wireless technologies designed for IoT applications. 802.11ah is primarily developed for outdoor applications such as smart city and 802.15.4g is principally developed for large scale outdoor process control applications such as smart utility network. Both technologies have communication range up to 1000 meters. Therefore, 802.11ah network and 802.15.4g network are likely to coexist. Our simulation results show that 802.11ah network can severely interfere with 802.15.4g network since 802.11ah devices are more aggressive than 802.15.4g devices in wireless medium access contention. This capability heterogeneity can lead to significant packet loss in 802.15.4g network. Due to asymmetrical features such as modulation scheme and packet structure, devices in different networks can not understand each other. Thus, the self-transmission control mechanism is needed for more aggressive 802.11ah devices. This paper proposes a learning based self-transmission control method for 802.11ah devices to improve their coexistence with 802.15.4g devices. Using the proposed self-transmission control technique, 802.11ah devices predict the packet transmission of 802.15.4g devices and postpone their transmissions to avoid interference.**

***Keywords* IoT, heterogeneous, interference, coexistence control, 802.11ah, 802.15.4g.**

I. Introduction

As more and more smart devices connect to the Internet, the Internet of Things (IoT) is becoming a reality. A broad range of wireless communication technologies can be applied to cater the diverse applications. IEEE 802.15.4 is typically designed for control and monitoring. IEEE 802.11 is widely used for high speed data transfer. It is well known that both 802.11 device and 802.15.4 device can operate at 2.4 GHz band. Recent 802.11ah extends 802.11 operation band to Sub-1 GHz band. As a result, both 802.11 device and 802.15.4 device can also operate at Sub-1 GHz band. Therefore, ensuring harmonious coexistence of these two types of wireless networks is important.

There are existing studies on the conventional coexistence of 802.11(b/g/n) network and 802.15.4(2006) network at 2.4 GHz band. These studies show that 802.11 network can cause significant interference impact on 802.15.4 network. [1] reveals that 802.15.4 network faces severe interference issues in the presence of 802.11 network. [2] shows that 802.15.4 network can hardly get a chance to access the channel in the presence of severe interference from 802.11 network. Several factors such as higher energy detection threshold and faster backoff mechanism lead 802.11 devices to be more aggressive than 802.15.4 devices in contending for wireless medium access.

The most difficult issue in mitigating the interference between 802.11 devices and 802.15.4 devices is due to the differences in their physical layers. 802.11 devices and 802.15.4 devices communicate with different modulation and packet structure. One device cannot communicate with the other without significant modification to the underlying hardware. As a result, the coexistence performance of the 802.11 network and 802.15.4 network is still less well-understood [3].

This paper aims to address coexistence issues of 802.11ah network and 802.15.4g network at Sub-1 GHz band. 802.11ah is primarily designed for outdoor IoT applications such as smart city and 802.15.4g is principally developed for large scale outdoor process control applications such as smart utility network. Thus, these two types of networks are likely to coexist. In addition, both 802.11ah and 802.15.4g have communication range up to 1000 meters, which further increases chances of 802.11ah network coexisting with 802.15.4g network. Therefore, these two types of networks should harmonically coexist. Notice that 802.11ah mandates the support of 1 MHz channel, which may cause existing coexistence techniques designed for wide channels to not work properly. The cooperative busy tone scheme proposed in [4] is an example, where one 22 MHz 802.11 channel is assumed to overlap with four 5 MHz 802.15.4 channels. We propose a self-transmission control method for 802.11ah devices due to their aggressiveness in wireless medium access contention. 802.11ah devices predict the packet transmission of the 802.15.4g devices and postpones their transmissions to let 802.15.4g devices complete transmission without interference.

The rest of this paper is organized as follows. Section II presents related work. We describe our network system in Section III. Section IV demonstrates the interference impact of 802.11ah network on 802.15.4g network. We introduce our self-transmission control technique in Section V. Performance evaluation is provided in Section VI. We conclude our work in Section VII.

II. Related Work

There are existing studies on the coexistence of 802.11(b/g/n) network and 802.15.4(2006) network at 2.4 GHz band. Some coexistence techniques are proposed for 802.15.4 devices. [2] proposes a decentralized approach to help 802.15.4 devices mitigate interference by adaptively adjusting energy detection threshold in the presence of severe interference. The energy detection threshold is calculated based on the cumulated transmission failure. Although this approach can reduce the amount of discarded packets due to channel access failure it can not reduce the collision loss. [5] shows that under saturation condition, a 10 node 802.15.4 network can deliver only 3% of packets, but a 10 node 802.11 network can deliver over 80% of packets. The paper then proposes an adaptive backoff procedure for 802.15.4 devices to survive coexistence with 802.11 network. If the busy channel is caused by 802.11 packet transmission, 802.15.4 backoff duration is adaptively selected. Otherwise, standard backoff procedure continues. This mechanism improves packet delivery rate by about 6%. However, this paper assumes that 802.15.4 devices can determine if the busy channel is caused by 802.11 transmission.

There are existing coexistence solutions that require special device. [4] designs a cooperative busy tone (CBT) to enable coexistence between 802.11 network and 802.15.4 network. CBT allows a separate 802.15.4 device to schedule a busy tone concurrently with the desired 802.15.4 packet transmission, thereby improving the visibility of 802.15.4 devices to 802.11 devices. However, CBT assumes that one 22 MHz 802.11 channel overlaps with four 5 MHz 802.15.4 channels and thus, busy tone scheduler can hop to an adjacent channel to transmit busy tone to 802.11 devices. This assumption is not valid for 802.11ah, which mandates the support of 1 MHz channel. In addition, calculation of the busy tone is based on Poisson data arrival rate with unsaturated traffic, which limits the application of busy tone approach since the coexistence issue is not severe when data traffic is light. [1] proposes a hybrid device implementing both 802.11 and 802.15.4 functions so that it can transmit 802.11 message and 802.15.4 message. Therefore, this hybrid device can coordinate messages between 802.11 network and 802.15.4 network and acts as a mediator between two networks. Even the hybrid device can signal long channel occupation to 802.11 devices, the approach is not practical due to the need of the hybrid device. In addition, collaboration between regular 802.15.4 devices and hybrid devices is difficult.

Some coexistence analytical models are also proposed. For example, [3] presents a comprehensive mathematical model to evaluate the throughput performance of coexisting 802.11 network and 802.15.4 network. Results show that packet arrival rate can significantly affect network throughput. However, the existing analytical models are based on assumptions such as Poisson data arrival rate and constant collision probability, which limit model's usage in practice.

For 802.11ah and 802.15.4g, [6] compares performance of 802.11ah and 802.15.4 at Sub-1 GHz band. The results show that 802.11ah network achieves higher channel efficiency than 802.15.4 network. [7] also compares performance of 802.11ah and 802.15.4 at Sub-1 GHz band. The results show that 802.11ah network outperforms 802.15.4 network in terms of association time, throughput, delay and coverage range, but not in energy efficiency. [8] investigates the coexistence issues of 802.15.4g network and 802.11b network at 2.4 GHz band. The system consists of one 802.15.4g transmitter, one 802.15.4g receiver and multiple 802.11b transmitters. It shows that 802.11b network has significant interference impact on 802.15.4g network. A link quality indicator (LQI) based channel agility scheme for 802.15.4g network is proposed to perform channel re-selection for interference avoidance.

To the best of our knowledge, no existing work addresses the coexistence of 802.11ah network and 802.15.4g network at Sub-1 GHz band.

III. IoT System over Heterogeneous Wireless Networks

We consider an IoT system that operates over heterogeneous 802.11ah network and 802.15.4g network. 802.11ah network consists of one access point (AP) and N stations (STAs) and 802.15.4g network contains one personal area network coordinator (PANC) and M nodes. In the system, 802.11ah network can be used for high speed data transfer such as stream video. 802.11ah AP can collect to a visual display to monitor smart city activities and personal safety. 802.15.4g network can be used to transfer control data. 802.15.4g PANC can connect to a smart utility network controller to control smart utility equipments and actions of the utility workers. Fig. 1 illustrates a sample system, where 802.11ah network consists of one AP connected to a monitor and 10 STAs: STA1, STA2, ..., STA10 and 802.15.4g network consists of one PANC connected to a controller C and 4 nodes: N1, N2, N3 and N4. We consider the case where 802.11ah network and 802.15.4g network coexist. In other words, two networks operate on overlapping frequency channels and share the wireless medium. As a result, packet transmissions of two networks can interfere with each other. Therefore, interference control is needed. Because 802.11ah devices are more aggressive than 802.15.4g nodes in wireless medium access contention and 802.15.4g network transfer high priority control data, we aim to improve reliability of 802.15.4g network while making the best channel utilization for 802.11ah network.

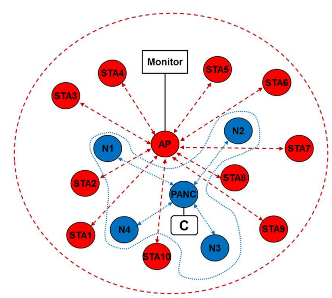

Fig. 1: Heterogeneous 802.11ah and 802.15.4g Network System

In this paper, an 802.11ah device is either 802.11ah AP or an 802.11ah STA. Similarly, an 802.15.4g device can be 802.15.4g PANC or an 802.15.4g node.

IV. Interference Impact of the Coexisting 802.11ah Network and 802.15.4g Network

Both 802.11ah and 802.15.4g provide energy detection (ED) based clear channel assessment (CCA) mechanism for coexistence with other networks. However, 802.11ah ED threshold is typically higher than 802.15.4g ED threshold. If an 802.11ah device or 802.15.4g node detects energy level above the specified threshold, it defers transmission for random amount of time.

In this section, we evaluate the interference impact of coexisting 802.11ah network and 802.15.4g network. We examine the effect of network traffic on network reliability by simulating an 802.11ah network with one AP and 5 STAs and an 802.15.4g network with one PANC and 5 nodes using NS3 simulator, in which 802.11ah is implemented by [9] and we implemented necessary 802.15.4g functions. All 802.11ah devices and 802.15.4g devices are deployed in a $50m \times 50m$ area. Simulation is performed in 900 MHz band with 1 MHz 802.11ah channel and 2 MHz 802.15.4g channel. 802.11ah PHY data rate is set to 2.4 mbps and 802.15.4g PHY data rate is set to 250 kbps. Network traffic, i.e., application data, is uniformly distributed among STAs/nodes so that 802.11ah

STAs send packets to 802.11ah AP and 802.15.4g nodes send packets to 802.15.4g PANC. 802.11ah packet payload is 500 bytes and 802.15.4g packet payload is 50 bytes.

TABLE I: Data Packet Delivery Rate with 802.11ah Coexistence Control

802.11ah Traffic (kbps)	802.15.4g Traffic (kbps)	Delivery Rate (802.11ah)	Delivery Rate (802.15.4g)
800	150	99.99%	4.32%
600	150	99.99%	15.38%
600	100	99.99%	23.51%
800	80	99.99%	35.19%
400	50	99.99%	84.27%
400	10	99.99%	98.99%
200	50	99.98%	99.98%

Table I shows data packet delivery rate variations versus different network traffic rates. It can be seen that 802.15.4g network suffers when network traffic is heavy. 802.15.4g network delivers only 84% of packets even if 802.15.4g traffic rate is 50 kbps and 802.11ah traffic rate is 400 kbps. On the other hand, 802.11ah network nearly achieves 100% of packet delivery rate for all traffic scenarios. These results indicate that additional coexistence control is needed when 802.11ah traffic rate is higher than 600 kbps and 802.15.4g traffic rate is higher than 80 kbps. Moreover, the need for coexistence control increases rapidly as network traffic grows. In practice, the need for additional coexistence control depends on network size, network deployment, network traffic and other factors.

Our simulation results show that ED CCA based coexistence mechanism does not perform well unless network traffic is light. There are several causes leading to poor performance of 802.15.4g network. One reason is that 802.11ah ED threshold is higher than 802.15.4g ED threshold. An energy level that is high enough for an 802.15.4g device to successfully decode packet may be disregarded by an 802.11ah device. Another reason is that 802.11ah device performs backoff process much faster than 802.15.4g device does. The time needed for an 802.15.4g device to perform CCA to transmission turnaround is long enough for an 802.11ah device to complete backoff process and start packet transmission, which may collide with 802.15.4g data packet transmission. Acknowledgment (ACK) packet waiting time of the 802.15.4g is also long enough for an 802.11ah device to complete backoff process and start packet transmission, which may collide with 802.15.4g ACK packet transmission. Failure of receiving ACK packet results in retransmission or packet drop. The higher transmission power of the 802.11ah devices also contributes to packet loss of 802.15.4g network.

V. Learning Based Self-Transmission Control for 802.11ah Device

This section presents the proposed learning based self-transmission control technique. Unlike existing coexistence mechanisms, our learning based approach does not need any pre-assumption on netowrk and special device. We aim to add the intelligence into IoT devices.

Due to the fact that 802.11ah device and 802.15.4g can not communicate with each other and 802.11ah device is more aggressive in wireless medium access contention, we propose self-transmission control mechanism for 802.11ah devices to learn the transmission history of 802.15.4g devices and predict next 802.15.4g packet transmission time to avoid interference. We first propose a probabilistic method for 802.11ah devices to determine 802.11ah packets and 802.15.4g packets. We then introduce a prediction based self-transmission control technique for 802.11ah devices.

A. Determine 802.11ah packet and 802.15.4g Packet

In the heterogeneous wireless network system shown in Fig. 1, there are two types of packet transmissions: 802.11ah packet transmission and 802.15.4g packet transmission. 802.11ah packet transmission includes successful packet transmission and the collided packet transmission. 802.11ah devices first determine successful packet transmissions and then probabilistically determine collided packet transmissions.

802.11ah AP can determine all successfully transmitted 802.11ah packets using carrier sense (CS) mechanism since all associated 802.11ah STAs must be within AP's transmission range.

To avoid interfering with 802.15.4g packet transmission, an 802.11ah STA also needs to determine successful 802.11ah packet transmission. An 802.11ah STA can decode 802.11ah packets transmitted by 802.11ah AP and 802.11ah STAs within its transmission range. However, an 802.11ah STA can not determine 802.11ah packets transmitted by 802.11ah STAs outside of its transmission range. We propose a method to address this issue. We use STA1 and STA5 in Fig.1 as examples to describe the proposed method. Assume STA1 is the packet transmitter and STA5 is the packet detector.

- **Determine unicast packet**: If the 802.11ah packet is an unicast packet, 802.11ah AP will send an ACK packet back to STA1 after a short inter-frame space (SIFS) time period. STA5 is able to decode ACK packet using CS mechanism since 802.11ah AP is within STA5's transmission range. Upon decoding ACK packet, STA5 can determine that the packet is an 802.11ah packet transmitted by STA1. Therefore, an 802.11ah STA can determine all unicast 802.11ah packets transmitted by 802.11ah STAs that are outside of its transmission range.
- **Determine ACK packet**: If the 802.11ah packet is an ACK packet, 802.11ah AP must be recipient. This indicates that the previous packet must be an unicast packet transmitted by 802.11ah AP and the unicast packet transmission must have been overheard by STA5. If this is true, the packet is an 802.11ah ACK packet. Otherwise, the packet is not an 802.11ah ACK packet.
- **Determine multicast packet**: If the 802.11ah packet is a multicast packet, 802.11ah AP will not send an ACK packet even if it is a receiver. Therefore, STA5 can not determine type of the packet. To address this issue, we propose that 802.11ah AP sends an ACK packet to itself whenever it receives or overhears a multicast packet transmitted by any 802.11ah STA. Once STA5 overhears this self-ACK packet, it can determine that the previous packet is a multicast 802.11ah packet.

The remaining packet transmissions are either the collided 802.11ah packet transmissions or 802.15.4g packet transmissions, which 802.11ah devices can not distinguish. We use 802.11ah packet collision probability (P_C) in decision making. Notice that 802.15.4g CS threshold is lower than 802.11ah CS threshold. Therefore, 802.11ah devices consider a detected candidate packet only if the energy level is greater than

802.15.4g CS threshold. Otherwise, 802.11ah devices will treat channel as idle. A candidate packet is considered as a collided 802.11ah packet with the probability of P_C and as an 802.15.4g packet with the probability of (1-P_C). The P_C can be estimated by an 802.11ah device using its number of attempted packet transmissions and its number of ACK packets received.

B. Track 802.15.4g Packet Transmission Time

802.11ah devices record 802.15.4g packet transmission time. An 802.11ah device first records starting time of any packet transmission if the detected energy level is higher than 802.15.4g CS threshold. At the end of transmission, if the packet is determined to be an 802.11ah packet, the recorded time is deleted. Otherwise, the record time is stored. The stored time sequence is used to predict next 802.15.4g packet transmission time. Algorithm 1 describes time recording procedure.

Algorithm 1 802.15.4g Transmission Time Recording

Detected energy on the channel;
Recording the time of detection;
if Detected energy level $<$ 802.15.4g CS threshold **then**
    Treat channel status as idle;
    Delete the time recorded;
else if The detected packet is a successful 802.11ah packet **then**
    Delete the time recorded;
    Perform normal packet receiving process;
else
    Draw an uniform random number R in [0, 1];
    if $R < P_C$ **then**
        Treat the detected packet as collided 802.11ah packet;
        Delete the time recorded;
    else
        Treat the detected packet as 802.15.4g packet;
        Store the recorded time;
    end if
end if

C. Predict Next 802.15.4g Packet Transmission Time

The recorded 802.15.4g packet transmission time sequence is a co-related time sequence because a node's previous transmissions can affect node's current transmission, a node's transmission can affect other node's transmission and one network's transmission can impact other network's transmission due to the fact that both 802.11ah and 802.15.4g use carrier sense multiple access with collision avoidance (CSMA/CA) mechanism and wireless medium is the shared medium. Therefore, it is feasible to predict next 802.15.4g packet transmission time using the history.

We use Holt's additive trend prediction method to predict next 802.15.4g packet transmission time. The Holt additive trend prediction is described in [10], which is an algorithm that forecasts trend of data points in a series. For a series $X_1, X_2, ..., X_t$, the forecast gives an estimate of the series m steps ahead. The forecast algorithm is formulated as following:

$$\begin{aligned} &S_t = \alpha X_t + (1-\alpha)(S_{t-1} + T_{t-1}) \\ &T_t = \gamma(S_t - S_{t-1}) + (1-\gamma)T_{t-1} \\ &\widehat{X_t}(m) = S_t + mT_t \end{aligned} \tag{1}$$

where S_t is the current level (local level), T_t represents current slope (local growth), m is a positive integer representing the steps ahead, $\widehat{X_t}(m)$ is the m-step-ahead forecast, α is the level smoothing parameter ($0 < \alpha < 1$) and γ is the slope smoothing parameter ($0 < \gamma < 1$). For one step forecast, $m = 1$ and in our case, $\widehat{X_t}(1)$ is the predicted time for next 802.15.4g packet transmission.

Each 802.11ah device performs the prediction process independently because different 802.11ah devices have different neighborhoods and therefore, have different observations.

D. Defer 802.11ah Packet Transmission

With the proposed 802.15.4g packet transmission time prediction, an 802.11ah device learns next 802.15.4g packet transmission time. If the 802.11ah device can not complete its transmission sequence before the predicted time, it defers its transmission. A transmission sequence indicates a series of packet transmissions without requiring channel access contention. For example, an unicast packet and an ACK packet form a transmission sequence. In this sequence, ACK packet transmission does not need to contend for channel access. ACK packet is transmitted after a SIFS time period upon the completion of unicast packet transmission.

To avoid interfering with 802.15.4g packet transmission sequence, an 802.11ah device defers amount of time needed to complete a typical 802.15.4g packet transmission, plus 802.15.4g ACK packet waiting time and 802.15.4g ACK transmission time. During this time period, transmission of 802.11ah packet is suspended. Notice that even 802.15.4g ACK packet waiting time (1600 μs for 50 ksymbol/s symbol rate) is much longer than 802.11ah SIFS time (52 μs), 802.11ah devices should not transmit any packet during this time period since 802.15.4g ACK packet transmission can commence between 240 μs and 640 μs for 50 ksymbol/s symbol rate. ACK packet loss will cause 802.15.4g device to retransmit the packet. Therefore, 802.11ah devices should avoid colliding with 802.15.4g ACK packet as much as possible.

VI. Performance Evaluation and Analysis

We present performance evaluation and analysis of our self-transmission control technique with the simulation setup described in Section IV. We set 802.11ah network traffic rate as 800 kbps and 802.15.4g network traffic rate as 80 kbps. For Holt prediction algorithm, α is set to 0.5, γ is also set to 0.5 and m is set to 1. We use the accuracy of the predicted 802.15.4g packet transmission time, data packet delivery rate, system throughput and data packet latency as metrics to evaluate our self-transmission control technique.

We simulated two control scenarios: 1) With standard 802.11ah ED CCA control and 2) With proposed self-transmission control. In addition, we also compared our self-transmission technique with existing coexistence scheme proposed in [2].

A. 802.15.4g Packet Transmission Time Prediction Accuracy

We first evaluated accuracy of the predicted 802.15.4g transmission time. We use a metric called time step, which is the time gap between two consecutive 802.15.4g packet transmissions observed by an 802.11ah device. The predicted time steps are compared with the measured time steps. Fig. 2 shows simulation results of an 802.11ah STA with both 802.11ah network and 802.15.4g network using constant packet generation rates. The measured time step curve is shifted up by

80 ms. At the start, 802.11ah network performs association process and transmits much less packets. Therefore, 802.15.4g nodes transmit more data packets and as a result, time steps are much smaller. Once 802.11ah network completes association process, 802.11ah STAs start data packet transmissions, which result in larger time steps for 802.15.4g packet transmission. If the prediction error exceeds 10ms, a warning is generated. The black curve shows that about 13 predictions have error exceeding 10ms. Overall, the predicted time steps match well with the measured time steps.

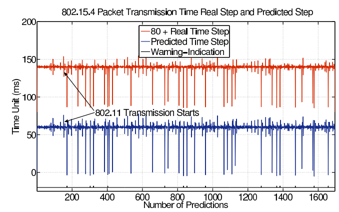

Fig. 2: Predicted Time Step vs Measured Time Step

Fig. 3 depicts simulation results with 802.15.4g nodes having burst transmission, during which 802.15.4g nodes generate 10 times more packets. Therefore, 802.15.4g nodes obtain much more channel access opportunities to transmit packets. As a result, the time steps are much smaller. Overall, the predicted time steps still match well with the measured time steps.

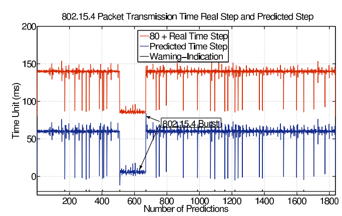

Fig. 3: Prediction with 802.15.4g Burst Transmission

Fig. 4 illustrates simulation results with 802.11ah STAs having burst transmission, during which 802.11ah STAs generate 10 times more packets. Therefore, 802.11ah STAs transmit much more packets, which reduces chances for 802.15.4g nodes to transmit packets. As a result, the time steps of 802.15.4g packet transmissions become much larger. Even overall predicted time steps still match well with the measured time steps, the prediction error increases during 802.11ah burst transmission. From the black curve, we can see more predictions have error exceeding 10ms.

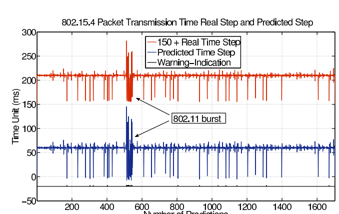

Fig. 4: Prediction with 802.11ah Burst Transmission

B. Data Packet Delivery Rate

The data packet delivery rate indicates the ability of a network to successfully deliver data to destinations. Fig.5 shows that with standard ED CCA control, 802.15.4g network drops 65% of data packets once 802.11ah network completes association process and starts data packet transmission. The proposed self-transmission control technique can improve 802.15.4g data packet delivery rate by 35% from 35% to 70%.

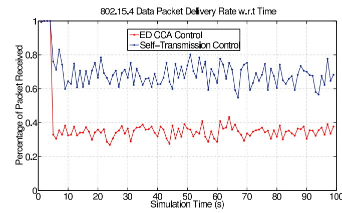

Fig. 5: 802.15.4g Data Packet Delivery Rate

Although the proposed self-transmission control technique improves 802.15.4g data packet delivery rate, Fig.6 shows that the improvement is in the expense of 802.11ah network. As a result, 802.11ah network sacrifices. With standard ED CCA control, 802.11ah network achieves a near 100% of data packet delivery rate. With self-transmission control, 802.11ah data packet delivery rate decreases by 20% to 80% since self-transmission control technique defers 802.11ah packet transmission when an 802.11ah STA predicts an up coming 802.15.4g packet transmission. When its queue is full, an 802.11ah STA is forced to drop packets.

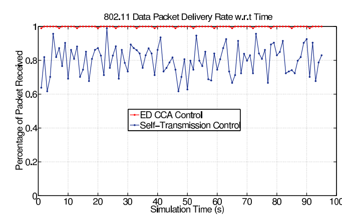

Fig. 6: 802.11ah Data Packet Delivery Rate

We also compared our self-transmission control technique with the adaptive CCA control scheme proposed by Yuan et al in [2]. Fig.7 shows 802.15.4g data packet delivery rates with different coexistence control mechanisms. Yuan's scheme improves data packet delivery rate by about 7% from 35% to 42%. Our self-transmission control technique improves data packet delivery rate by about 35% from 35% to 70%. These results indicate that major cause of 802.15.4g packet loss is not because of channel access failure, instead it is due to the collision caused by 802.11ah packet transmission.

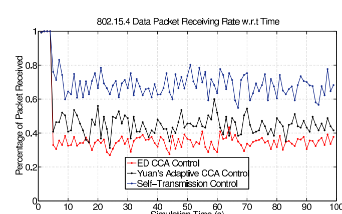

Fig. 7: Coexistence Control Method Comparison

C. System Throughput

Throughput describes capacity of a system to transfer data. We measured application layer throughput for combined 802.11ah network and 802.15.4g network and calculated in kbps shown in Fig.8. System achieves the higher throughput of 820 kbps with standard ED CCA control. The proposed self-transmission control reduces system throughput to 650 kbps because 35%

of data packet delivery rate gain by 802.15.4g network cannnot make up 20% of data packet delivery rate drop by 802.11ah network due to the fact that payload of 802.11ah packet is 10 times larger than payload of 802.15.4g packet. Thus, the larger packet has advantage in system throughput improvement.

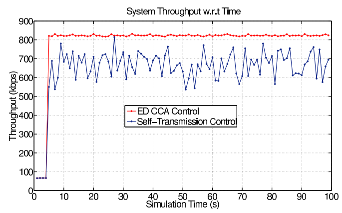

Fig. 8: System Throughput

D. Data Packet Latency

We calculated data packet latency as the time difference from the time a packet transmission process starts to the time the packet is successfully confirmed. Therefore, the latency includes backoff time, data packet transmission time, ACK packet waiting time and ACK packet receiving time. Fig.9 illustrates the latency of 802.11ah packets. We can see that with the standard ED CCA control, 802.11ah network confirms 98% of packets within $0.002s$. The proposed self-transmission control delays 802.11ah packets and the packets are confirmed from $0.002s$ to $0.108s$. Therefore, 802.11ah network gives more transmission opportunities to 802.15.4g network.

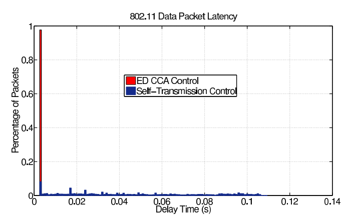

Fig. 9: 802.11ah Packet Delay

Fig.10 shows latency of 802.15.4g packets. With the standard ED CCA control, most of 802.15.4g packets confirmed from $0.004s$ to $0.02s$. With the proposed self-transmission control, majority of 802.15.4g packets are confirmed from $0.004s$ to $0.015s$. This result verifies that our self-transmission control mitigates interference impact of 802.11ah devices on 802.15.4g device and reduces 802.15.4g packet transmission process. In general, 802.15.4g packets have much shorter latency than 802.11ah packets, which indicates that 802.15.4g packets are either delivered or dropped. On the other hand, transmission of 802.11ah packet may be suspended during the predicted 802.15.4g packet transmission.

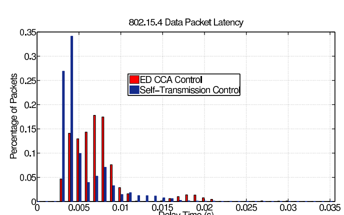

Fig. 10: 802.15.4g Packet Delay

VII. Conclusion

With the addition of 802.11ah and 802.15.4g, 802.11 network and 802.15.4 network become more suitable for IoT applications. An 802.11ah AP can associate with thousands of STAs and an 802.15.4g PANC can also associate with thousands of nodes, which indicates that the interference could be significant when these two types of networks coexist. Our simulation results confirm that 802.11ah network can severely interfere with 802.15.4g network. Therefore, additional coexistence control mechanism is needed for 802.11ah devices to harmonically coexist with 802.15.4g devices. To address this issue, we propose a learning based self-transmission control technique for 802.11ah devices. The proposed technique enables 802.11ah devices to learn the detected packet type and track 802.15.4g packet transmission time. Using 802.15.4g packet transmission history, 802.11ah devices predict next 802.15.4g packet transmission time and suspend their packet transmissions to avoid interference. Simulation results shows that the predicted transmission time matches well with the actual transmission time. Compared with standard ED CCA control mechanism, the proposed self-transmission control technique can improve data packet delivery rate of 802.15.4g network by 35% from 35% to 70% while still maintaining 80% of data packet delivery rate for 802.11ah network. The proposed self-transmission control technique also reduces the latency of 802.15.4g packet. In addition, our self-transmission control technique outperforms the existing adaptive CCA control method in terms of data packet delivery rate.

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