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Abstract

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Coexistence of 802.11ah and 802.15.4g Networks

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***Abstract*—IEEE 802.11ah and IEEE 802.15.4g are two wireless technologies designed for outdoor IoT applications. 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 using standard defined coexistence mechanisms, 802.11ah network can severely interfere with 802.15.4g network and lead to significant packet loss in 802.15.4g network. As a result, additional coexistence control mechanisms are needed. Due to asymmetrical features such as modulation scheme and frame structure, 802.11ah devices and 802.15.4g devices cannot perform automatic cooperation. Thus, self-coexistence control techniques are preferred. This paper proposes learning based self-coexistence control techniques for 802.11ah devices to mitigate the interference impact of 802.11ah network on 802.15.4g network. We first present a α-Fairness based energy detection clear channel assessment (ED-CCA) method that enables 802.11ah devices to detect more ongoing 802.15.4g packet transmissions. We then introduce a Q-Learning based backoff mechanism for 802.11ah devices to avoid interfering with 802.15.4g packet transmission process. The proposed coexistence techniques can achieve fair spectrum sharing between 802.11ah network and 802.15.4g network.**

Keywords*—*Coexistence, heterogeneous wireless networks, spectrum sharing, interference control, IEEE 802.11ah, IEEE 802.15.4g.

I. Introduction

As more and more intelligent devices connect to the Internet, the Internet of Things (IoT) is becoming a reality. A broad range of wireless technologies emerge to cater the diverse applications. IEEE 802.11ah named as WiFi HaLow is primarily designed for outdoor IoT applications such as smart city and IEEE 802.15.4g is principally developed for large scale outdoor process control applications such as wireless smart utility network (Wi-SUN). 802.11ah is designed to operate on Sub-1 GHz (S1G) band. 802.15.4g can also operate on S1G band. Both technologies have communication range up to 1000 meters. Thus, 802.11ah network and 802.15.4g network are likely to coexist. Therefore, ensuring harmonious coexistence of these two types of networks on S1G band is important.

There are existing studies about the coexistence of conventional 802.11(b/g/n) network and 802.15.4(2006) network on 2.4 GHz band. The studies show that 802.11 network can cause significant interference impact on 802.15.4 network. The most difficult issue to mitigate the interference between 802.11 devices and 802.15.4 devices is due to the differences in their physical layers. 802.11 device and 802.15.4 device communicate with different modulation scheme and frame structure. One device cannot communicate with the other without significant modification to the underlying hardware. The coexistence performance of the 802.11 network and 802.15.4 network is still less well-understood [1].

802.11ah extends operation band of 802.11 to S1G band. An 802.11ah access point (AP) can associate with more than 8000 stations (STAs). The transmit power is geographic area dependent with the maximum value of 1000 mW. 802.11ah mandates the support of 1 MHz channel, which is much narrow than the conventional 802.11 (b/g/n) channels that are at least 20 MHz wide. 802.15.4g can operate on S1G band and 2.4 GHz band. An 802.15.4g personal area network coordinator (PANC) can associate with more than 6000 nodes. The transmit power is limited by local regulatory bodies with the maximum value of 1000 mW. 802.11ah provides ED-CCA mechanism to coexist with other S1G systems including 802.15.4g. However, 802.15.4g only addresses coexistence among devices with different 802.15.4g PHYs.

Using the standard defined coexistence mechanism, how well can 802.11ah network coexist with 802.15.4g network on S1G band? Our simulation results show that 802.11ah ED-CCA coexistence mechanism does not perform well in the presence of heavy traffic. Due to the fact that 802.11ah mandates the support of 1 MHz channel, the existing coexistence techniques designed for wide channels may not work properly. The cooperative busy tone scheme proposed in [2] is an example, where one 22 MHz 802.11 channel is assumed to overlap with four 802.15.4 channels.

This paper aims to address coexistence issues of 802.11ah network and 802.15.4g network on S1G band. We propose learning based coexistence technologies. Unlike the existing coexistence mechanisms, our learning based techniques do not require any pre-assumption and special device. Our objective is to add intelligence into IoT devices. We realize coexistence control at MAC layer. We design self-transmission control techniques for 802.11ah devices since 802.11ah devices are more aggressive than 802.15.4g devices in wireless channel access contention due to their higher ED threshold and faster backoff mechanism. We first present α-Fairness ED-CCA scheme that enables 802.11ah devices to detect more ongoing 802.15.4g transmissions. We then introduce Q-Learning Backoff mechanism for 802.11ah devices to avoid interfering with 802.15.4g packet transmission process. Finally, we provide methods for 802.11ah devices to locally estimate the network metrics that can be used as input parameters for α-Fairness ED-CCA and Q-Learning Backoff.

The rest of this paper is organized as follows. Section II presents related work. Section III describes coexistence issues. We introduce our coexistence control techniques in Section IV. Performance evaluation is provided in Section V. We conclude our work in Section VI.

II. Related Work

There are existing studies on the coexistence of conventional 802.11 network and 802.15.4 network on 2.4 GHz band. Some coexistence techniques are developed for 802.15.4 devices. [3] proposes a decentralized approach for 802.15.4 devices to mitigate interference by adaptively adjusting ED threshold in the presence of severe interference. The ED threshold is calculated based on the cumulated transmission failure. The approach can reduce the packet loss due to channel access failures and enhance the performance of 802.15.4 network. However, the approach can not reduce the packet loss due to collision. [4] shows that under saturation condition, a 10 node 802.15.4 network can only deliver 3% of packets, but a 10 node 802.11 network is able to deliver over 80% of packets. The paper proposes an adaptive backoff procedure for 802.15.4 devices to survive coexistence with 802.11 network and improves packet delivery rate by 6%.

Some existing coexistence solutions require special device. [2] designs a cooperative busy tone (CBT) to enable coexistence of 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 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 802.15.4 channels and therefore, busy tone scheduler can hop to an adjacent channel to transmit busy tone to 802.11 devices. This assumption is not valid for 1 MHz 802.11ah channel. In addition, calculation of the busy tone is based on Poisson data arrival with unsaturated traffic. Thus, the application of busy tone approach is limited since the coexistence issue is not severe when network traffic is light. [5] proposes a hybrid device implementing both 802.11 and 802.15.4 specifications so that it can transmit 802.11 and 802.15.4 messages. Therefore, this hybrid device can coordinate 802.11 and 802.15.4 networks 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. [6] proposes an adaptive 802.11 network interference mitigation scheme for 802.15.4 network, where 802.15.4 network is modeled with a Markov chain concept. The scheme controls 802.15.4 frame length and device transmission based on the measured 802.11 interference. However, the scheme needs a hybrid device to transfer 802.11 channel activity to 802.15.4 network.

For 802.11ah and 802.15.4g, [7] compares performance of 802.11ah network and 802.15.4(2006) network on S1G band. The results depict that 802.11ah network achieves higher channel efficiency than 802.15.4 network. It indicates that 802.11ah devices are more aggressive than 802.15.4 devices in wireless channel access. [8] investigated the coexistence issues of 802.11b network and 802.15.4g network on 2.4 GHz band. The system consists of a 802.15.4g transmitter, a 802.15.4g receiver and multiple 802.11b transmitters. The paper proposes a packet error rate (PER) based packet collision analytical model and a link quality indicator (LQI) based channel agility scheme for 802.15.4g network to perform channel re-selection for interference avoidance. It shows that 802.11b network can significantly interfere with 802.15.4g network. However, the paper treats 802.11b devices as interferer only without considering performance of 802.11b network.

We have proposed a prediction based self-transmission control method to address coexistence of 802.11ah and 802.15.4g networks [9], in which 802.11ah devices predicts the transmission time of upcoming 802.15.4g packet and suspend their transmissions to avoid interfering with upcoming 802.15.4g packet transmission. However, the prediction is not accurate when 802.15.4g packet generation rate is high. To the best of our knowledge, no other existing work addresses the coexistence of 802.11ah network and 802.15.4g network on S1G band. We aim to address coexistence issues of 802.11ah network and 802.15.4g network using machine learning approach. Our learning based coexistence control techniques add the intelligence into 802.11ah devices. This paper addresses 802.11ah network and 802.15.4g network coexistence issues beyond the scope of the standard defined coexistence control. Due to the fact that 802.11ah devices are more aggressive than 802.15.4g nodes in wireless channel access contention and 802.15.4g network usually transfers higher priority control data, we aim to improve reliability of 802.15.4g network while making the best channel utilization for 802.11ah network.

III. 802.11AH AND 802.15.4G COEXISTENCE ISSUES

802.11ah provides ED-CCA mechanism for coexistence control. An 802.11ah device uses ED-CCA with a threshold of -75 dBm per MHz to improve coexistence with other S1G systems including 802.15.4g. If an 802.11ah device detects energy above that threshold on its channel, it may (i) change operating channel or (ii) sectorize beamforming to another sector or (iii) change the schedule of restricted access window (RAW), target wake time (TWT) service period or subchannel selective transmission (SST) or (iv) defer transmission for a particular interval.

802.15.4g only defines common signaling mode (CSM) for coexistence among devices with different 802.15.4g PHYs, i.e., multi-rate and multi-regional frequency shift keying (MR-FSK) PHY, multi-rate and multi-regional orthogonal frequency division multiplexing (MR-OFDM) PHY and multi-rate and multi-regional offset quadrature phase-shift keying (MR-O-QPSK) PHY.

A. Impact of 802.11ah and 802.15.4g Coexistence

We first 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 [10] 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 on 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. We select O-QPSK PHY for 802.15.4g to evaluate if 802.15.4g device can compete with 802.11ah device using wider channel and higher PHY data rate of 250 kbps. 802.11ah packet payload is 500 bytes and 802.15.4g packet payload is 50 bytes. 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.

Table I shows data packet delivery rate variations versus different network traffic rates. It can be seen that 802.15.4g network suffers if 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 if 802.11ah traffic rate is higher than 600 kbps and 802.15.4g traffic rate is higher than 100 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, node deployment, application traffic and other factors.

TABLE I: 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%	28.77%
400	50	99.99%	84.27%
400	10	99.99%	98.99%
200	50	99.98%	99.98%

B. Interference Caused by Higher 802.11ah ED Threshold

The 802.11ah ED threshold is -75 dBm for 1 MHz channel, -72 dBm for 2 MHz channel, -69 dBm for 4 MHz channel and -66 dBm for 8 MHz channel. 802.15.4g ED threshold is generally lower than 802.11ah ED threshold. For OFDM PHY, ED threshold is in [-100 dBm, -78 dBm]. For O-QPSK PHY, ED threshold is in [-100 dBm, -80 dBm]. For FSK PHY, ED threshold is in [-100 dBm, -78 dBm] with FEC and in [-94 dBm, -72 dBm] without FEC. 802.15.4g receiver sensitivity (RS) is 10 dB lower than the corresponding ED threshold. The higher ED threshold of 802.11ah can cause interference with 802.15.4g packet transmission. If the detected energy level of an 802.15.4g packet transmission is above 802.15.4g RS and below 802.11ah ED threshold, the energy level is high enough for 802.15.4g device to successfully decode the packet. However, the packet transmission is disregarded by 802.11ah device. In this case, 802.11ah ED-CCA should report busy channel, but it reports idle channel instead. If its backoff counter reaches to zero, an 802.11ah device will start packet transmission that collides with ongoing 802.15.4g packet transmission.

C. Interference Caused by Faster 802.11ah Backoff Scheme

802.11ah backoff process is much faster than 802.15.4g backoff process due to the smaller time parameters. An 802.11ah time slot is 52 μs, CCA time is less than 40 μs and CCA to transmission (TX) turnaround time is less than 5 μs. For 802.15.4g, the corresponding time parameters depend on symbol rate. With 50 ksymbol/s symbol rate, backoff period is 400 μs, CCA time is 160 μs and CCA to TX turnaround time is 240 μs. These backoff parameters are even larger for smaller symbol rates. The smaller time parameters give 802.11ah devices advantage in wireless channel access. For example, 802.15.4g CCA to TX turnaround time is 240 μs that is long enough for an 802.11ah device to complete a backoff procedure with 4 or less time slots and start packet transmission, which may collide with 802.15.4g data packet transmission. With 50 ksymbol/s symbol rate, 802.15.4g ACK waiting time could be up to 1600 μs that is long enough for an 802.11ah device to complete a backoff procedure with 30 or less time slots and start packet transmission, which may collide with 802.15.4g ACK packet transmission. These types of the interference are caused by the faster backoff mechanism of 802.11ah. In these scenarios, 802.11ah devices do not violate any protocol. Instead, they are not able to detect ongoing 802.15.4g transmission process.

IV. Proposed Coexistence Control Techniques

This section presents our learning based coexistence control techniques. We aim to improve 802.15.4g reliability while making the best channel utilization for 802.11ah. We address the first interference issue by proposing a novel α-Fairness ED-CCA mechanism for 802.11ah devices to detect more ongoing 802.15.4g packet transmissions. We tackle the second interference issue through a Q-Learning based backoff technique to enable 802.11ah devices to avoid interfering with ongoing 802.15.4g transmission process. In addition, we also propose a method for 802.11ah devices to estimate the locally observed network metrics for both 802.11ah network and 802.15.4g network. Our coexistence control techniques are designed in distributed fashion such that each 802.11ah device runs the proposed coexistence methods independently.

A. The α-Fairness ED-CCA

If the energy level detected by 802.11ah ED-CCA falls in between 802.15.4g RS and 802.11ah ED threshold, there are two possibilities: 1) The energy comes from 802.15.4g packet transmission. 802.11ah ED-CCA should report busy channel. 2) The energy comes from other S1G systems. 802.11ah ED-CCA should report idle channel. The challenge is that 802.11ah device does not know the source of the detected energy. Reporting idle channel gives 802.11ah device more channel access opportunity to transmit packets. However, the transmission of 802.11ah packet may collide with lower power 802.15.4g packet transmission. Reporting busy channel enables 802.15.4g packet with lower transmission power to be transmitted without interference. However, it is not spectrum efficient because if the detected energy comes from non-802.15.4g packet transmission, the transmission should be ignored and 802.11ah device should continue its transmission process.

Therefore, we propose a α-Fairness ED-CCA method to consider the fair channel access between 802.11ah network and 802.15.4g network. With the proposed control, 802.11ah ED-CCA reports channel status based on a probability determined by the α-Fairness technique, which has been applied in network resource sharing [11]. We define following generalized α-Fairness utility function

$$U(P_1, P_2) = \frac{P_1^{1-\alpha}}{1-\alpha}\frac{M_h^{1-\alpha}}{M_h^{1-\alpha}+M_g^{1-\alpha}} + \frac{P_2^{1-\alpha}}{1-\alpha}\frac{M_g^{1-\alpha}}{M_h^{1-\alpha}+M_g^{1-\alpha}}$$
$$P_i \geq 0,\ i = 1, 2,\ \alpha > 0,\ \alpha \neq 1$$

where P_1 is the probability of the α-Fairness ED-CCA reports idle channel, P_2 is the probability of the α-Fairness ED-CCA reports busy channel, α is the parameter to control fair spectrum sharing between 802.11ah network and 802.15.4g network. The input parameters M_h and M_g are the locally observed network metrics for 802.11ah network and 802.15.4g network, respectively. The metric can be packet transmission rate, data throughput, packet delivery rate or channel utilization. The locally observed network metric is device dependent and therefore, different from the metric for whole network. The locally observed inputs assure that each 802.11ah device performs independent coexistence control. In section IV-C, we provide methods for 802.11ah devices to locally estimate M_h and M_g.

The α-Fairness spectrum sharing corresponds to the maximization of utility function $U(P_1, P_2)$ subject to condition $P_1 + P_2 = 1$. Because function $f(x) = x^{1-\alpha}$ is concave, our optimization problem has a unique solution given by

$$P_1^* = \frac{1}{1 + (\frac{M_h}{M_g})^{\frac{\alpha-1}{\alpha}}} \text{ and } P_2^* = \frac{1}{1 + (\frac{M_h}{M_g})^{\frac{1-\alpha}{\alpha}}} \quad (1)$$

Eq. (1) shows that for $\alpha > 1$, more channel access opportunity is given to the network with smaller metric and for $\alpha < 1$, more channel access opportunity is given to the network with larger metric. For $\alpha > 1$, if an 802.11ah device estimates $M_h > M_g$, which indicates $P_1^* < P_2^*$, its α-Fairness ED-CCA algorithm more likely reports busy channel. As a result, the 802.11ah device will perform more backoff. On the other hand, if an 802.11ah device estimates $M_h < M_g$, which implies $P_1^* > P_2^*$, its α-Fairness ED-CCA algorithm more likely reports idle channel. Therefore, the 802.11ah device will perform more packet transmission. Figs. 1 and 2 show the α-Fairness ED-CCA idle channel probability P_1^* and busy channel probability P_2^*, where $\beta = \frac{M_h}{M_g}$. if $\beta > 1$, P_1^* decreases as α increases and P_2^* increases as α increases, $\lim_{\alpha\to\infty} P_1^* \to 0$ and $\lim_{\alpha\to\infty} P_2^* \to 1$. If $\beta < 1$, P_1^* increases as α increases and P_2^* decreases as α increases, $\lim_{\alpha\to\infty} P_1^* \to 1$ and $\lim_{\alpha\to\infty} P_2^* \to 0$. $\beta = 1$ results in $P_1^* = P_2^* = \frac{1}{2}$.

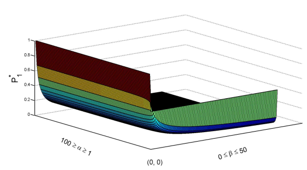

Fig. 1: Idle Probability for $\alpha > 1$

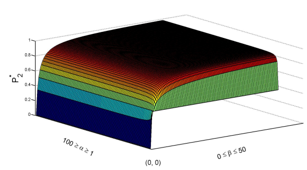

Fig. 2: Busy Probability for $\alpha > 1$

Figs. 3 and 4 show the α-Fairness ED-CCA idle channel probability P_1^* and busy channel probability P_2^* for $\alpha < 1$, where $\beta = \frac{M_h}{M_g}$. $\beta > 1$, i.e., $M_h > M_g$, indicates $P_1^* > P_2^*$, its α-Fairness ED-CCA algorithm more likely reports idle channel. As a result, the 802.11ah device will transmit more packet. Similarly, $\beta < 1$ implies $P_1^* < P_2^*$, its α-Fairness ED-CCA algorithm more likely reports busy channel. Therefore, the 802.11ah device will perform more backoff. If $\beta > 1$, P_1^* increases as α decreases and P_2^* decreases as α decreases, $\lim_{\alpha\to 0} P_1^* \to 1$ and $\lim_{\alpha\to 0} P_2^* \to 0$. If $\beta < 1$, P_1^* decreases as α decreases and P_2^* increases as α decreases, $\lim_{\alpha\to 0} P_1^* \to 0$ and $\lim_{\alpha\to 0} P_2^* \to 1$. $\beta = 1$ results in $P_1^* = P_2^* = \frac{1}{2}$.

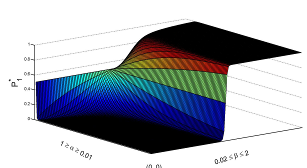

Fig. 3: Idle Probability for $\alpha < 1$

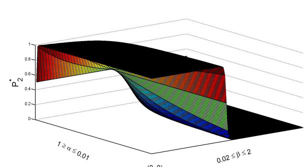

Fig. 4: Busy Probability for $\alpha < 1$

The α-Fairness parameter α and metrics M_h and M_g control channel access allocation. For given M_h and M_g, α affects P_1^* and P_2^*, which in turn influence M_h and M_g. The new M_h and M_g again make impact on α. For each 802.11ah STA, the objective is to select α that produces appropriate metrics M_h and M_g. 802.11ah AP may coordinate STA's α selection to achieve the desired network performance. For spectrum sharing, $P_1^* = P_2^*$ is not necessarily the best solution. Many factors such as network traffic, network size, PHY data rate and packet size need to be taken in account.

The α-Fairness ED-CCA can be applied at every backoff slot. At last slot, if α-Fairness ED-CCA reports busy channel, it indicates that an 802.15.4g transmission might be in progress. To avoid colliding with 802.15.4g packet transmission, 802.11ah device can apply a larger contention window instead of using standard exponential contention window increase.

B. *The Q-Learning Backoff*

At last backoff slot, even 802.11ah ED-CCA does not detect any energy on the channel, there might be ongoing 802.15.4g transmission in progress. The challenge is that 802.11ah devices do not know if any 802.15.4g transmission is in progress. As a result, 802.11ah device can either transmit packet or perform more backoff.

To make optimal decision in stochastic environment, we propose Q-Learning Backoff for 802.11ah device to decide transmission or backoff at last backoff slot. Using Q-Learning Backoff, 802.11ah device performs normal backoff process if backoff counter is greater than zero. Q-Learning decision is applied when backoff counter reaches to zero and 802.11ah ED-CCA reports idle channel. Notice that even 802.11ah ED-CCA reports idle channel, α-Fairness ED-CCA may still report busy channel. Thus, α-Fairness ED-CCA is applied to determine channel status in Q-Learning algorithm. We define state set $S = \{s_1, s_2\} = \{\text{Channel Idle, Channel Busy}\}$ and action set $A = \{a_1, a_2\} = \{\text{Transmit, Backoff}\}$.

Q-Learning is a reinforcement learning technique and can be used to find an optimal action selection policy in decision process. At each step, Q-Learning chooses the action that maximizes the utility function. Q-Learning utility function is formulated as [12]:

$$Q_{t+1}(s, a) = (1 - \tau_t)Q_t(s, a) + \tau_t(R_t(s, a) + \gamma V_t(s', b))$$
$$V_t(s', b) = \max_{b \epsilon B(s')} Q_t(s', b)$$

where $Q_t(s, a)$ is the utility function, τ_t is the learning rate $(0 < \tau_t < 1)$, γ is discount factor $(0 < \gamma < 1)$, $R_t(s, a)$ is the reward obtained by performing action a at state s at time t, s' is the state that can be reached from state s when performing action a, $B(s')$ is action set that can be taken at state s'. By taking action b, we can obtain the maximum value of the utility function as $V_t(s', b)$.

The reward $R_t(s, a)$ can be fixed or variable. The key for Q-Learning is to design proper reward for each {state, action} pair so that the expected utility is maximized. There are different ways to design the rewards. For spectrum sharing, we define α-Fairness based reward as follows:

$$R_t(s, a) = \begin{cases} \frac{1}{|U^* - U_1^*| + 1} & (s_1, a_1) \\ 0 & (s_1, a_2) \\ -1 & (s_2, a_1) \\ \frac{1}{|U^* - U_2^*| + 1} & (s_2, a_2) \end{cases} \quad (2)$$

where $U^* = U(P_1^*, P_2^*)$ is the optimal α-Fairness utility with P_1^* and P_2^* given by Eq. (1). P_1^* is the optimal probability to report idle channel and P_2^* represents the optimal probability to report busy channel. $U_1^* = \frac{(P_1^*)^{1-\alpha}}{1-\alpha} \frac{M_h^{1-\alpha}}{M_h^{1-\alpha} + M_g^{1-\alpha}}$ and $U_2^* = \frac{(P_2^*)^{1-\alpha}}{1-\alpha} \frac{M_g^{1-\alpha}}{M_h^{1-\alpha} + M_g^{1-\alpha}}$.

Following is the rational of the Q-Learning reward assignment: 1) If the channel is idle, 802.11ah device is encouraged to transmit packet. Therefore, we assign positive reward to $\{s_1, a_1\}$ pair; 2) If the channel is idle, backoff is a generous operation to perform. Thus, we assign a zero reward to $\{s_1, a_2\}$ pair; 3) It definitely causes interference to transmit packet when the channel is already busy. As a result, we assign the negative reward to $\{s_2, a_1\}$ pair to punish the behavior; 4) If the channel is busy, backoff is the right action to take. So, we assign positive reward to $\{s_2, a_2\}$ pair to encourage 802.11ah device to perform backoff.

If $P_1^* > P_2^*$, the channel is more likely idle. $P_1^* > P_2^*$ also indicates that $\{s_1, a_1\}$ pair has a larger reward. Therefore, Q-Learning tends to choose the action a_1 for 802.11ah device. On the other hand, if $P_1^* < P_2^*$, the channel is more likely busy. $P_1^* < P_2^*$ also implies that $\{s_2, a_2\}$ pair has a larger reward. Thus, Q-Learning tends to choose the action a_2 for 802.11ah device. If $P_1^* = P_2^*$, Q-Learning tends to select action a_1 or action a_2 with equal probability. Notice that for $\alpha > 1$, $P_1^* > P_2^*$ indicates $M_h < M_g$. Therefore, it is reasonable for 802.11ah device to transmit more packets. Similarly, $P_1^* < P_2^*$ indicates $M_h > M_g$. As a result, it is appropriate for 802.11ah device to do more backoff. We use $\alpha > 1$ in Q-Learning algorithm since in our case $M_h > M_g$.

Learning rate τ_t determines Q-Learning convergence and τ_t can vary with time for different converge rates [12]. We use the linear learning rate [12] as $\tau_t = \frac{1}{t+1}$. Since $\sum\limits_i \frac{1}{t_i+1} = \infty$, $\sum\limits_i (\frac{1}{t_i+1})^2 < \infty$ and the reward $|R_t(s, a)| \leq 1$, our Q-Learning converges.

If the optimal Q-Learning decision is transmission, the 802.11ah device transmits packet. Otherwise, the 802.11ah device goes back to backoff again. Backoff decision indicates that an 802.15.4g transmission process is likely in progress. To avoid interference, the 802.11ah device can apply a larger contention window instead of using standard exponential contention window increase.

C. Locally Observed Network Metric Estimation

We provide methods for 802.11ah devices to estimate the network metrics by using locally available information, i.e., the locally observed network metrics, which can be used as the input parameter for both α-Fairness ED-CCA and Q-Learning Backoff. One method is to estimate the locally observed data packet transmission rate and another method is to estimate the locally observed data throughput.

The locally observed data packet transmission rate is defined as the number of data packets transmitted by neighbors of the observing device within a time period. An 802.11ah device can count the number of data packets transmitted (N_{11ah}) by its 802.11ah neighbors via monitoring 802.11ah packet transmission. The locally observed data packet transmission rate for 802.11ah network can be estimated as

$$TR_{11ah} = \frac{N_{11ah}}{ObservationTime} \tag{3}$$

To estimate number of data packets transmitted by 802.15.4g devices, the observing 802.11ah device needs to count unreadable packet transmission with the detected energy level greater than 802.15.4g receiver sensitivity. These packets include 802.15.4g packets, the collided 802.11ah packets and the 802.11ah packets with sender outside of the observing device's communication range. Using ACK sent by 802.11ah AP, the observing device can eliminate the third type of packets. Let $NoP_{15.4g}$ denote the number of the first type and the second type packets (potential 802.15.4g packets), the number of data packets transmitted by 802.15.4g devices can be estimated as $N_{15.4g} = \frac{(1-P_c)*NoP_{15.4g}}{2}$, where P_c is the observed 802.11ah packet collision probability and can be calculated using the number of attempted data packet transmissions and the number of ACK packets received. The denominator 2 accounts for 802.15.4g ACK packets. The locally observed data packet transmission rate for 802.15.4g network can be estimated as

$$TR_{15.4g} = \frac{N_{15.4g}}{ObservationTime} \tag{4}$$

Using $N_{15.4g}$ and N_{11ah}, we can estimate the locally observed data throughput, which is defined as the number of data bits transferred by neighboring devices within an time period. The locally observed 802.11ah data throughput can be estimated as

$$NT_{11ah} = \frac{\sum_{i=1}^{N_{11ah}} B_i}{ObservationTime} \tag{5}$$

where B_i is the number of data bits in monitored 802.11ah data packet. Notice that an 802.11ah device can obtain B_i from the data packet with the sender in its communication range.

Similarly, the locally observed 802.15.4g data throughput can be estimated as

$$NT_{15.4g} = \frac{N_{15.4g} * B_{15.4g}}{ObservationTime} \tag{6}$$

where $B_{15.4g}$ is the number of data bits in a typical 802.15.4g data packet.

V. Performance Evaluation and Analysis

We evaluated performance of the proposed coexistence control techniques with simulation setup same as in Section III. We set 802.11ah traffic rate as 600 kbps and 802.15.4g traffic rate as 100 kbps. α is set to 10, γ is set to 0.5 and τ_t is initially set to 0.5. The locally observed data packet transmission rate is used as input metrics for α-Fairness ED-CCA. We use data packet delivery rate and data packet latency as performance metrics. Four coexistence control scenarios are simulated: 1) 802.11ah ED-CCA; 2) α-Fairness ED-CCA; 3) Q-Learning Backoff; 4) Combined α-Fairness ED-CCA and Q-Learning Backoff.

A. Data Packet Delivery Rate

Fig.5 shows the variation of 802.15.4g data packet delivery rate (PDR) with respect to different coexistence mechanisms, where Y-axis represents the percentage of the packets successfully delivered by 802.15.4g network. Using 802.11ah ED-CCA, 802.15.4g network drops 78% packets once 802.11ah network completes association process and starts data packet transmission. The α-Fairness ED-CCA can improve 802.15.4g PDR from 28% to 54% and the Q-Learning Backoff can increase 802.15.4g PDR from 28% to 57%. Combined α-Fairness ED-CCA and Q-Learning Backoff can improve 802.15.4g PDR from 28% to 65%.

Although our coexistence techniques improve 802.15.4g PDR, Fig.6 shows that the improvement is in the expense of 802.11ah PDR, where Y-axis represents the percentage of

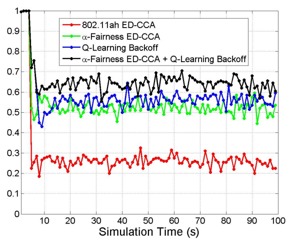

Fig. 5: 802.15.4g Network PDR

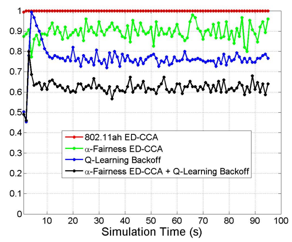

Fig. 6: 802.11ah Network PDR

the packets successfully delivered by 802.11ah network. As a result, 802.11ah network sacrifices. With 802.11ah ED-CCA, 802.11ah network achieves near 100% of PDR. With α-Fairness ED-CCA, 802.11ah PDR decreases to 90% and with Q-Learning Backoff, 802.11ah PDR reduces to 76%. If both α-Fairness ED-CCA and Q-Learning Backoff are applied, 802.11ah PDR decreases to 64%. It is because both coexistence methods defer 802.11ah transmission when control mechanisms conclude that 802.11ah network has advantage over 802.15.4g network in channel access contention. When queue is full, 802.11ah device is forced to drop packets.

B. Data Packet Latency

Data packet latency is defined as time difference from the time a packet transmission process starts to the time the packet is successfully confirmed. Therefore, the latency is $T_{Backoff} + T_{DataTX} + T_{WaitingACK} + T_{ACKRX}$. Fig.7 shows the latency of 802.15.4g packet. Using 802.11ah ED-CCA, 802.15.4g packet has longer latency than 802.11ah packet. With our coexistence methods, 802.15.4g packet has much shorter latency than 802.11ah packet since we add transmission control to 802.11ah device. The control scenario achieving higher PDR delays packet longer. Overall, most of the delivered 802.15.4g packets are confirmed within 0:005s.

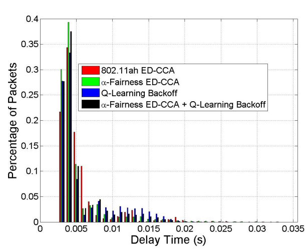

Fig. 7: 802.15.4g Packet Delay

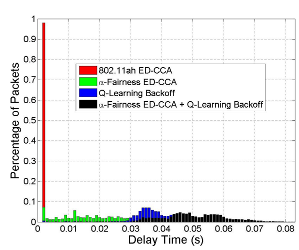

Fig. 8: 802.11ah Packet Delay

Fig.8 illustrates the latency of 802.11ah packets. We can see that with 802.11ah ED-CCA, 802.11ah confirms 98% of packets within $0.002s$. The α-Fairness ED-CCA delays 802.11ah packets, most of packets are confirmed from $0.002s$ to $0.03s$. Q-Learning Backoff delays 802.11ah packet longer than α-Fairness ED-CCA, most of packets are confirmed from $0.03s$ to $0.045s$. Combined α-Fairness ED-CCA and Q-Learning Backoff results in the longest delay for 802.11ah packet, most of packets are confirmed from $0.03s$ to $0.07s$. Therefore, latency of 802.11ah packet statistically increases with each coexistence control method added.

VI. Conclusion

IEEE 802.11ah and IEEE 802.15.4g are designed to operate on S1G band. Interference free coexistence of these two wireless technologies is critical. Simulation results show that 802.11ah network can severely interfere with 802.15.4g network. The higher ED threshold and faster backoff mechanism of 802.11ah are two identified interference causes. This paper proposes α-Fairness ED-CCA scheme and Q-Learning Backoff technique to mitigate the interference impact of 802.11ah network on 802.15.4g network. Our learning based coexistence techniques are designed to add the intelligence into 802.11ah devices. The α-Fairness ED-CCA method enables 802.11ah devices to detect more 802.15.4g packet transmissions. The Q-Learning Backoff technique enables 802.11ah devices to avoid interference with ongoing 802.15.4g transmission process. We evaluated the proposed coexistence methods for heavy network traffic, the α-Fairness ED-CCA and the Q-Learning Backoff can improve 802.15.4g packet delivery rate by 26% and 29%, respectively. On the other hand, both α-Fairness ED-CCA and Q-Learning Backoff reduce 802.11ah packet delivery rate because they restrict the channel access opportunity of the 802.11ah devices and give 802.15.4g devices more transmission opportunity. As a result, combination of the α-Fairness ED-CCA and the Q-Learning Backoff achieves fair packet delivery rates, 65% for 802.15.4g network and 64% for 802.11ah network.

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