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Adaptive CCA for IEEE 802.15.4 Wireless Sensor Networks to Mitigate Interference

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Abstract—IEEE 802.15.4 Wireless Sensor Networks (WSNs) share the 2.4 GHz Industrial, Scientific, and Medical (ISM) license-free band with many other wireless technologies such as IEEE 802.11b/g Wireless Local Area Networks (WLANs). Because of the low-power, however, IEEE 802.15.4 WSNs are potentially vulnerable to the interference introduced by the other wireless technologies such as IEEE 802.11b/g WLANs, which have much higher power. Particularly, in the presence of heavy interference, IEEE 802.15.4 nodes can hardly get a chance to access the channel, which could result in discarding a large amount of packets.

In this paper, we propose a decentralized approach to help IEEE 802.15.4 nodes mitigate interference. By adaptively and distributively adjusting Clear Channel Assessment (CCA) thresholds of IEEE 802.15.4 nodes in the presence of heavy interference, the approach can substantially reduce the amount of discarded packets due to channel access failures, and therefore significantly enhance the performance of IEEE 802.15.4 WSNs. The approach is robust, responsive and easy to be implemented at a low cost. The effectiveness of the approach is validated by OPNET simulation.

Index Terms—IEEE 802.15.4, IEEE 802.11, Coexistence, Interference, Clear Channel Assessment, Energy Detection, Inhibition Loss

I. INTRODUCTION

IEEE 802.15.4 Wireless Sensor Networks (WSNs) are becoming increasingly popular. As IEEE 802.15.4 WSNs share the 2.4 GHz Industrial, Scientific, and Medical (ISM) license-free band with many other wireless technologies such as IEEE 802.11b/g Wireless Local Area Networks (WLANs), Bluetooth, etc., a coexistence issue arises. Because of the low-power, IEEE 802.15.4 WSNs are particularly vulnerable to the interference introduced by the other wireless technologies which have much higher power, e.g. IEEE 802.11b/g WLANs.

Traditional approaches for the coexistence of wireless devices focus on transmit power control. For instance in [2], the allowable transmit power is determined in order to guarantee a protected radius to primary users that should not be interfered with. This is especially useful to enable spectrum sharing between systems with different levels of regulatory status, e.g., primary and secondary users, but not fit the coexistence

situation of systems with equal regulatory status, e.g. IEEE 802.15.4 WSNs and IEEE 802.11b/g WLANs [1]. Furthermore, as a low power technology, IEEE 802.15.4 WSNs are not supposed to have a large adjustable transmit power scope.

Another category of solutions focuses on dynamic frequency selection to avoid interference. In [3], an adaptive scheme using multiple radios has been proposed, but it is centralized, which requires a reliable communication between nodes, even in spite of heavy interference happening on that channel. This is not robust to the extreme interference patterns which are encountered in the context that this paper will address. To minimize the impact of the 802.11 interference, some distributed and adaptive frequency channel selection algorithms for IEEE 802.15.4 nodes are proposed in [1]. However, the algorithms are based on either increased spectrum scanning, resulting in much more energy consumption and additional hardware requirements, or increased learning, requiring sophisticated algorithms as function of the environment and its dynamic behavior.

In this paper we propose a decentralized approach to enhance the robustness of IEEE 802.15.4 WSNs in the presence of heavy interference. The approach is robust, responsive and easy to be implemented at a low cost. The remainder of the paper is organized as follows: Section II gives an overview of the IEEE 802.15.4 standard and the coexistence issue. Section III presents an adaptive Clear Channel Assessment (CCA) algorithm for IEEE 802.15.4 WSNs to mitigate interference. Simulation results are given in Section IV. Section V concludes the paper and proposes some potential future work.

II. OVERVIEW OF IEEE 802.15.4 AND COEXISTENCE ISSUE

A. IEEE 802.15.4

The IEEE 802.15.4 standard defines the MAC sublayer and the PHY layer. Its operational frequency bands include the 2.4 GHz ISM band. The IEEE 802.15.4 MAC employs the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. CCA is used in the physical layer to determine the channel occupancy [4]. CCA performs Energy Detection (ED),

or Carrier Sense (CS), or a combination of two, i.e., CCA shall report a busy channel upon detecting any energy above a preset ED threshold, or a signal with the known features, e.g. the modulation and spreading characteristics, or a known signal with energy above a preset ED threshold. Owing to involving only integrating the square of the received signal if implemented in the analog domain or summing squares of its samples in the digital domain, ED is a universal mechanism that can be deployed in all systems without requiring any knowledge of the type of underlying modulation scheme employed at the physical layer [5]. Therefore, in a heterogeneous network environment, only ED can sense the channel occupancy of other types of networks. Since we address the coexistence issue of a heterogeneous network environment in this paper, ED is always assumed as the only employed CCA mode.

Before initiating a transmission, an IEEE 802.15.4 node performs CCA by detecting the energy intensity on the channel over a sensing period of time and then comparing the energy intensity to a preset ED threshold. If the detected energy intensity is less than the ED threshold, the IEEE 802.15.4 node will transmit a packet. Otherwise, the node will defer its transmission for a random backoff delay uniformly chosen in a Contention Window (CW), i.e., $[0, W]$, where W is the size of the CW. When the backoff timer counts down to zero, the node performs CCA again. If the channel is sensed busy again, the size of CW doubles. When the number of the channel access attempts exceeds $macMaxCSMABackoffs$, i.e. the maximum number of backoffs the CSMA/CA algorithm will attempt before declaring a channel access failure [6], the pending packet is discarded.

B. Coexistence Issue

IEEE 802.15.4 WSNs share the 2.4 GHz ISM band with many other wireless technologies such as IEEE 802.11b/g WLANs, Bluetooth, etc. Since the ISM band is license-free, a coexistence issue arises. In [8] [9], the coexistence issue between IEEE 802.15.4 WSNs and IEEE 802.11b/g WLANs was addressed in detail by analysis and experiments, respectively. As IEEE 802.11b/g nodes and IEEE 802.15.4 nodes transmit typically at 100 mW [4] and 1 mW [6], respectively, the significant difference in the transmit power can result in three distinct regions as illustrated in Fig. 1:

R1: a region in which IEEE 802.15.4 nodes and IEEE 802.11b/g nodes can sense each other;

R2: a region in which IEEE 802.15.4 nodes can sense IEEE 802.11b/g nodes, but not *vice versa*;

R3: a region in which neither can sense the other, but IEEE 802.15.4 nodes could still suffer IEEE 802.11b/g interference in case of very weak IEEE 802.15.4 links. The R1, R2 and R3 are $<35\text{m}$, $35\text{m}\sim 80\text{m}$, $>80\text{m}$, respectively, according to the experimental results in [9] and the path loss model [12] with the path loss exponent of 4.

Thus, the mutual interferences of IEEE 802.15.4 WSNs and IEEE 802.11b/g WLANs are asymmetrical, i.e. IEEE 802.15.4 WSNs are more vulnerable to the IEEE 802.11b/g interference,

but not *vice versa*. Even in R1, where both IEEE 802.15.4 nodes and IEEE 802.11b/g nodes can sense each other, with a much longer backoff period of time on average, the IEEE 802.15.4 nodes still cannot fairly compete with the IEEE 802.11b/g nodes in the channel access [8]. In the following section, we will propose an approach to enhance the IEEE 802.15.4 WSNs competence in the channel access under heavy interference and therefore substantially reduce the amount of discarded packets due to channel access failures [6].

III. ADAPTIVE CCA ALGORITHM

In the presence of heavy interference, two types of IEEE 802.15.4 packet loss are identified in [9], i.e. **inhibition loss** and **collision loss**. The inhibition loss is due to channel access failures, i.e. an IEEE 802.15.4 packet shall be discarded after $M+1$ times channel access failures, where M is the maximum number of backoffs the CSMA-CA algorithm will attempt before declaring a channel access failure. The collision loss is due to collisions with interference.

In case of R1, heavy IEEE 802.11b/g interference can cause a high inhibition loss but few collision loss to IEEE 802.15.4 WSNs if the CSMA/CA works well. In case of R2, besides causing the inhibition loss, IEEE 802.11b/g interference could cause collision loss to some extent depending on Signal to Interference plus Noise Ratio (SINR). In case of R3, IEEE 802.11b/g interference could cause only the collision loss. As R1 could cover as much as 35m, the inhibition loss accounts for a major part of the total loss, especially for an indoor environment. Even for the farer region, R2, the inhibition loss could also account for a major part of the total loss in case of a good IEEE 802.15.4 links (e.g. $\text{SINR} > 5\text{-}6\text{ dB}$, an IEEE 802.15.4 packet could be successfully received with a probability of 99% [6]). In addition, a high inhibition loss suggests that for transmitting a single packet, an IEEE 802.15.4 node needs to perform CCA many times in general, which results in a high power consumption for the IEEE 802.15.4 node. Therefore, an approach of reducing the inhibition loss can not only improve the performance but also save energy for IEEE 802.15.4 WSNs in the presence of heavy IEEE 802.11b/g interference.

We now present such an approach to reduce the inhibition loss to an acceptable low level by adaptively and distributively adjusting ED thresholds of IEEE 802.15.4 nodes. The following notations will be used in our algorithm:

- γ : instant ED threshold
- γ_0 : initial ED threshold
- Γ_{max} : maximum allowable ED threshold
- M : number of channel access failures
- N : total number of the channel access attempts
- ζ : channel access failure ratio, defined as $\zeta = M/N$
- ζ_{max} : maximum allowable channel access failure ratio
- η : packet inhibition loss proportion, defined as $\eta = \zeta^{M+1}$
- η_{max} : maximum acceptable packet inhibition loss proportion
- η_{min} : minimum acceptable packet inhibition loss proportion

Fig. 1. Coexistence regions of 802.15.4 and 802.11b/g networks

- δ_i : step-up size to adjust the ED threshold, γ
- δ_d : step-down size to adjust the ED threshold, γ

Given a η_{max} and a η_{min} , we can correspondingly get a ζ_{max} and a ζ_{min} , respectively, by

$$\eta = \zeta^{M+1} \quad (1)$$

Then, as $\zeta > \zeta_{max}$, γ is adjusted by

$$\gamma = \min(\Gamma_{max}, \gamma + \delta_i) \quad (2)$$

and as $\zeta < \zeta_{min}$, γ is adjusted by

$$\gamma = \max(\gamma_0, \gamma - \delta_d) \quad (3)$$

Thus, as an IEEE 802.15.4 WSN encounters heavy interference, the nodes will distributively reduce their inhibition losses by increasing their ED thresholds, and as the interference disappears, the nodes will decrease their ED thresholds back to the initial values so as to avoid having a permanent channel access privilege over their peers.

IV. SIMULATION RESULTS

We first consider a simple scenario where there are only one pair of IEEE 802.15.4 nodes and one pair of IEEE 802.11b nodes in the region R1. As shown in Fig. 2, for each pair, one node is a transmitter, Tx, and the other is a receiver, Rx. The physical channel condition is assumed ideal, i.e. no packet error occurs. Therefore, the IEEE 802.11b Tx can always receive ACKs after transmitting data packets, keeping its contention window the initial value. There are 3m between the IEEE 802.11b Tx and the Rx, 0.1m between the IEEE 802.15.4 Tx and the Rx, and 3m between the IEEE 802.11b Tx and the IEEE 802.15.4 Tx. Given the parameter values in Table I, these distances can guarantee that the IEEE 802.11b nodes and the IEEE 802.15.4 nodes are in the region R1, i.e. they can hear each other, and therefore the packet loss of IEEE 802.15.4 nodes is due to only the inhibition loss.

According to the frequency agility function described in the ZigBee standard [10], a node shall report to a network manager when its transmission failure exceeds 25%. In our simulation, we also choose $\eta_{max} = 25\%$. (Certainly, η_{max} can be chosen as other values according to applications.) Correspondingly, $\zeta_{max} = 0.758$ by Eq. (1) given $M = 4$, the default value. Furthermore, we choose a $\eta = 3\%$ for example and get a

Fig. 2. 802.11b interferers and 802.15.4 WSN are in R1

TABLE I
IEEE 802.15.4 AND IEEE 802.11b SIMULATION PARAMETERS

	IEEE 802.15.4	IEEE 802.11b
Transmit power	0 dBm	17 dBm
Receiver sensitivity	-85 dBm	-76 dBm
Data rate	250 kbps	11 Mbps
ED default threshold	-85 dBm	-84 dBm
Center frequency	2410 MHz	2412 MHz
Payload size	30 bytes	1500 bytes
ACK	No	Yes
Transmit pattern	Every 30 ms	Saturated, UDP

corresponding $\zeta_{min} = 0.496$. Finally, we set the step size $\delta_i = \delta_d = 1$ dB. The simulation runs five times in each case of using adaptive CCA and NOT using adaptive CCA, respectively. For each time, the simulation runs 360 seconds, among which the IEEE 802.15.4 Tx starts to send packets at the 15th second to make certain that the IEEE 802.15.4 network has been established before. The IEEE 802.11b Tx starts a saturated User Datagram Protocol (UDP) traffic at the 120th second and does not stop until the simulation ends. Other simulation parameters are shown in Table I.

Simulation results on the IEEE 802.15.4 WSN are shown in Fig. 3. In case of not using adaptive CCA, as IEEE 802.11b interference does not start, the IEEE 802.15.4 WSN throughput, TP , keeps 8000 b/s, whereas it drops down dramatically to 3700 b/s on average, only 46.25% of 8000 b/s, as the IEEE 802.11b interference appears. In case of using adaptive CCA, however, TP drops down to about 3700 b/s first, but after a short time, as the Tx ED threshold is increased from the default -85 dBm to -45 dBm, TP goes up to around 7400 b/s on average, i.e. 92.5% of 8000 b/s. This shows that our adaptive CCA approach can significantly improve the IEEE 802.15.4 WSN throughput performance under the heavy IEEE 802.11b interference by 46.25%, i.e. 100% performance increment, in this case.

Fig. 4 shows the IEEE 802.15.4 WSN's impacts on the IEEE 802.11b WLAN in the region R1. The throughput values are averaged ones of the five simulation runs. The curve of "No 802.15.4 Traffic" is shown to give a benchmark of the maximum IEEE 802.11b WLAN throughput achievable in this case, i.e. about 6.2 Mb/s, as there is no any IEEE 802.15.4 traffic. The curve of "802.15.4 Adaptive CCA is NOT used" shows the IEEE 802.11b WLAN throughput as

Fig. 3. Adaptive CCA for 802.15.4 WSN to mitigate 802.11b/g interference in R1

Fig. 4. 802.11b WLAN throughput in R1

the IEEE 802.15.4 traffic is ongoing but the adaptive CCA mechanism is not used. The throughput is approximately 5.95 Mb/s, which is 4.03% lower than the maximum value. The curve of “802.15.4 Adaptive CCA is used” shows the IEEE 802.11b WLAN throughput as the IEEE 802.15.4 traffic is ongoing and the adaptive CCA mechanism is used. The throughput is approximately 5.75 Mb/s, 3.36% lower than the one in the case that the adaptive CCA mechanism is not used. This result is reasonable because the adaptive CCA adjustment gives the IEEE 802.15.4 Tx more chances to access the channel and then send packets, which reduces the IEEE 802.11b WLAN’s throughput. The further reduction in the IEEE 802.11b throughput can be expected as the IEEE 802.15.4 traffic is more intensive, but in case of the typical 1% low duty-cycle operations of IEEE 802.15.4 WSNs [7], the impact of IEEE 802.15.4 traffic on IEEE 802.11b WLAN performance would be limited.

Next, we consider another scenario, where an IEEE 802.15.4 WSN and the same pair of IEEE 802.11b nodes in the last scenario are in the region R2, i.e. the IEEE 802.15.4 nodes

Fig. 5. 802.11b interferers and 802.15.4 WSN are in R2

Fig. 6. Adaptive CCA for 802.15.4 WSN to Mitigate Interference in R2

can hear the IEEE 802.11b traffic but not *vice versa*. The IEEE 802.15.4 WSN has 16 nodes deployed as a square array with a coordinator in the center, as shown in Fig. 5. There are 5m between two neighboring nodes. A pair of IEEE 802.11b nodes are 40m away from the WSN. Given the parameter values in Table I, the distances above guarantee that the IEEE 802.11b nodes and the IEEE 802.15.4 nodes are in the region R2 and the packet loss of IEEE 802.15.4 nodes is due to only the inhibition loss. Each IEEE 802.15.4 node sends packets to randomly chosen destination nodes in an exponential packet generation mode every 50 ms on average. The adaptive CCA is used and the adaptive CCA step size $\delta_i = \delta_d = 1$ dB. There is 3m between the pair of IEEE 802.11b nodes. The IEEE 802.11b traffic is saturate, which starts at 100th second and ends at 400th second. The simulation runs 1200 seconds.

Simulation results are shown in Fig. 6. We see that before the IEEE 802.11b traffic starts, the IEEE 802.15.4 WSN throughput TP is around 32 kb/s and the global average ED threshold, $\bar{\gamma}$, of the IEEE 802.15.4 WSN, stays the default value of -85 dB. When the IEEE 802.11b traffic starts at 100th second, TP drops down dramatically to 22 kb/s. At the moment, $\bar{\gamma}$ starts to increase. After a short time, as $\bar{\gamma}$ reaches around 81.7 dB, TP increases to around 27 kb/s, i.e. 22.7% increment. Note that compared to the 100% increment in the last case, the 22.7% increment looks not much. It is because in the region R2, the IEEE 802.11b Tx cannot sense the traffic of the IEEE 802.15.4 WSN, making the situation for the IEEE 802.15.4 WSN even worse than in the region R1 [8].

As the IEEE 802.11b traffic ends at 400th second, we see

Fig. 7. Global average ED threshold $\bar{\gamma}$ return rates with different step-down size δ_d

Fig. 8. 802.11b WLAN throughput in R2

that $\bar{\gamma}$ starts to decline, while TP goes back to the initial level, i.e. around 32 kb/s. As the time goes, $\bar{\gamma}$ would eventually return to the default value of -85 dB so as to avoid having a permanent channel access privilege. However, the return rate of $\bar{\gamma}$ is low due to the small step-down size δ_d of 1 dB. We expect a larger δ_d would help. In Fig. 7, the simulation results are shown in case of $\delta_d = 1$ dB, 3 dB and 5 dB, respectively. We see that with a larger δ_d , the return rate of $\bar{\gamma}$ is improved indeed. Besides, Fig. 8 shows the IEEE 802.15.4 WSN's impact on the IEEE 802.11b WLAN in the region R2. As expected, the IEEE 802.11b WLAN throughput is not tangibly affected by the traffic of the IEEE 802.15.4 WSN as the IEEE 802.11b Tx is not able to sense the IEEE 802.15.4 traffic in R2 and therefore can transmit freely.

To sum up, the simulation results above validate that our adaptive CCA approach can significantly improve the robustness and therefore the performance of IEEE 802.15.4 WSNs in the presence of heavy interference. Note that although the interference in the simulations are from the IEEE 802.11b nodes, the adaptive CCA approach can actually work under

any other type of interference as long as it causes the inhibition packet loss of IEEE 802.15.4 WSNs.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we proposed an approach enabling an IEEE 802.15.4 WSN to mitigate heavy interference by adaptively adjusting ED thresholds of its nodes in a distributed manner. As the heavy interference appears, the ED thresholds are increased in order to reduce the inhibition loss, whereas the ED threshold gets decreased so as to avoid having a permanent channel access privilege over peers as the interference disappears. Compared to the centralized interference management approaches, e.g. the frequency agility approach specified in [10], which inappropriately assumes a reliable two-way communication between nodes even in the presence of heavy interference, our adaptive CCA approach is simpler but more robust, more responsive, and easier to be implemented at a lower cost. Simulation results validate that our adaptive CCA approach can significantly improve IEEE 802.15.4 WSNs performance in the presence of heavy interference.

However, regardless of being able to reduce the inhibition loss effectively, our approach alone cannot reduce the collision loss. Thus, combining this approach with solutions to the collision loss would be the next step. Besides, the parameters such as η_{max} , η_{min} , δ_i , δ_d , etc. in our algorithm may be optimized according to applications. Furthermore, although the scenarios in this paper suggest that the increased IEEE 802.15.4 ED thresholds have a limited impact on the IEEE 802.11b WLAN performance, this may not universally true, especially in case of high intensive IEEE 802.15.4 operations and/or as IEEE 802.15.4 WSNs coexist with other wireless technologies operating on the same spectrum. Hence, it would be interesting to do more extensive investigations.

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