An Enhanced CSMA-CA Algorithm for IEEE 802.15.4 LR-WPANs

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***Abstract*— Two mechanisms are proposed to enhance throughput and energy efficiency of IEEE 802.15.4 CSMA-CA. The first one is an enhanced collision resolution (ECR) mechanism that adjusts the backoff exponent (BE) based on both consecutive clear channel assessment (CCA) busy results and a packet transmission. The second one is an enhanced backoff (EB) mechanism that shifts the range of backoff counters by utilizing the CCA outcome. The simulation results demonstrate that the proposed mechanisms significantly enhance both throughput and energy efficiency of IEEE 802.15.4.**

***Index Terms*— IEEE 802.15.4, LR-WPAN, CSMA-CA.**

I. Introduction

THE carrier sense multiple access with collision avoidance (CSMA-CA) is widely employed in wireless networking due to its simplicity and performance efficiency. It has been adopted as a medium access control (MAC) protocol by many standards such as the IEEE 802.11 Wireless Local Area Networks (WLANs) [1], IEEE 802.15.3 and IEEE 802.15.4 Wireless Personal Area Networks (WPANs) [2], etc. The CSMA-CA variants employed in these standards provide robustness against unstable channel conditions and higher capacity than other random access algorithms.

IEEE 802.15 Task Group 4 for low-rate WPANs (LR-WPANs) tailored the CSMA-CA to meet the objectives for energy efficiency and performance robustness [3]. We found two distinctive features developed to reduce energy consumption and related problems in the 802.15.4 CSMA-CA algorithm. First, instead of continuously sensing the medium, the 802.15.4 adopts a sporadic channel assessment that performs the CCA to check the medium when it has finished the collision avoidance–random backoff delay. Although the CCA provides information about whether there is an ongoing transmission at the cost of expensive receiving energy consumption, the 802.15.4 does not utilize it efficiently. Second, the energy consumed by retransmissions may not be ignorable to the 802.15.4 so that the standard adopts a fast collision resolution mechanism that increases the backoff exponent (BE) when the clear channel assessment (CCA) reports the channel busy. However, this fast collision resolution mechanism is problematic since an instantaneous channel busy status does not efficiently reflect the level of channel contention.

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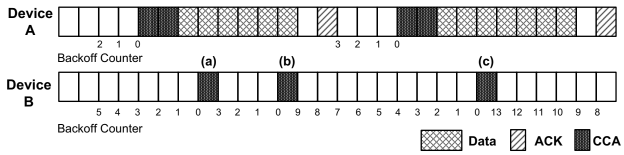

Fig. 1. Progress of slotted CSMA-CA of two devices

In this letter, two mechanisms are proposed to enhance throughput and energy efficiency of the 802.15.4 CSMA-CA algorithm. The first one is an enhanced collision resolution (ECR) mechanism that adjusts the BE to efficiently reflect the level of channel contention. The second one is an enhanced backoff (EB) mechanism that shifts the range of backoff counters to reduce redundant backoffs and CCAs by utilizing the CCA outcome.

II. CSMA-CA Algorithm of IEEE 802.15.4

The rest of this letter considers only the slotted CSMA-CA of IEEE 802.15.4. However, the proposed algorithms can be easily extended to the case of the unslotted one because their basic operations are similar.

For the ease of understanding, the operation of the slotted CSMA-CA by two devices is described in Fig. 1. In the standard, a device waits for a random number of backoff periods (BPs)[1] in the range from 0 to $2^{BE}-1$, and performs two CCAs at the backoff boundaries after the backoff. The BE is increased by one at a time up to the maximum value when a CCA finds the channel busy, and then the BE is reset to the the initial value after the fixed number of consecutive CCA busy results or after a packet transmission. Note that device B increases its own BE at (a), (b) and (c) in Fig. 1 even though the traffic load or the number of contenders in the network does not change. *In other words, the mechanism to adjust the BE in the 802.15.4 is so sensitive that the BE impetuously increases, easily reaches the maximum value, and then is reset to the initial value.* Therefore, the collision resolution mechanism does not effectively reflect the degree of channel contention, thereby deteriorating both throughput and energy efficiency, especially when the degree of channel contention is high.

Now let us look at the behavior of device B when it senses the transmission of device A at (a) in Fig. 1. Even with the fact that there is an ongoing transmission learned from the CCA, device B resumes the backoff procedure immediately. In Fig. 1, since device B re-drew a small backoff counter,

[1] A "backoff period (BP)" is the fundamental unit of channel access in 802.15.4 CSMA-CA, which is usually inter-changeably used with a "slot" in the literature. The length of a BP is 20 symbols.

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it performs a meaningless backoff and an additional CCA at (b). *That is, the 802.15.4 CSMA-CA does not exploit the information that there is an ongoing transmission acquired from the expensive CCA operations when it proceeds with the sequential backoff procedure.* As a result, such unnecessary backoffs decrease throughput, and the additional CCAs end up consuming more energy.

III. Enhanced CSMA-CA Algorithm

A. Enhanced Collision Resolution Mechanism

The ECR mechanism adjusts the BE based on not only CCA results but also a packet transmission. First, since a CCA busy result is not enough to be convinced of the channel contention, the ECR mechanism increases the BE after a fixed number of consecutive CCA busy results. In other words, when the number of consecutive CCA busy results reaches macMAXCSMABackoffs in [3], the ECR increases the BE. Second, instead of resetting the BE after a transmission, the ECR mechanism adjusts the BE according to the result of the transmission. Since high channel contention can be expected from a transmission failure, the ECR mechanism increases the BE when a device fails to receive an ACK packet as IEEE 802.11 MAC does. Instead of resetting the BE, the ECR mechanism decreases the BE after a successful packet transmission. As discussed in [6], the ECR mechanism slowly decreases the BE to avoid resetting the information about the channel contention after a successful transmission. Since a packet collision and consecutive CCA busy results by the contention increase the BE and the increased BE is not reset by a transmission, the proposed method better reflects the overall contention of a network, which ends up enhancing the performance of the 802.15.4 CSMA-CA.

B. Enhanced Backoff Mechanism

The EB mechanism shifts the range of backoff counters in order to reduce redundant backoffs and CCAs due to an ongoing transmission. This approach is similar to the policy of IEEE 802.11, in which a node freezes its backoff counter during other's transmission. However, due to its sporadic channel assessment, an 802.15.4 node can not determine the exact remaining time of the ongoing transmission. Therefore, we introduce an expected number, D_{ccax}, to avoid an ongoing transmission. After the x-th ($x = 1$ or 2) CCA reports the busy channel, the EB mechanism draws a backoff counter in the range from D_{ccax} to $D_{ccax} + 2^{BE} - 1$, where D_{ccax} corresponds to the expected number of busy BPs that follows the current busy BP, which was confirmed by the x-th CCA. D_{ccax} is derived as follows.

$$\begin{aligned} D_{ccax} = \lceil & P\left(DATA\ sensed \mid CCA_x\ busy\right) \\ & \cdot \{E[R_{datax}] + (1-p_c)\cdot(E[L_{idle}] + L_{ack})\} \\ & + P\left(ACK\ sensed \mid CCA_x\ busy\right) \cdot E[R_{ack}]\rceil, \end{aligned} \tag{1}$$

where R_{data} is a random variable that indicates the remaining number of BPs in an ongoing data transmission which was sensed by the x-th CCA, p_c indicates the probability of a packet collision when a packet is transmitted, R_{ack} is a random variable that represents the remaining number of BPs in an ongoing ACK transmission, L_{ack} is 2 BPs occupied by an ACK transmission, and L_{idle} is a random variable that indicates one or zero idle BP between a data and an ACK packet, respectively. As discussed in [4], this idle BP may appear depending on the length of a data packet.

S is defined as a random variable that follows the packet length distribution in the unit of symbols. Let the number of BPs occupied by a packet be $L = \lceil \frac{S}{20} \rceil$, where L varies from $L_{min} = 2$ to $L_{max} = 13$ BPs[2]. From the packet length distribution, $p_S(s)$, we can easily derive the distribution for L; $p_L(l) = \sum_{s=1}^{20} p_S\left((l-1)\cdot 20 + s\right)$.

If it is assumed that the r-th BP of an ongoing transmission sensed by the first CCA follows an uniform distribution, the expected remainder of the data transmission is given as $E[R_{data1}] = \sum_{l=L_{min}}^{L_{max}} p_L(l) \sum_{r=0}^{l-1} \frac{r}{l} = \frac{1}{2}\{E[L]-1\}$. $E[R_{ack}]$ is easily calculated as $\frac{1}{2}\{E[L_{ack}] - 1\} = \frac{1}{2}$ BP. $E[L_{idle}]$ is computed from p_{idle}, which is the probability that an idle BP exists between a data and the corresponding ACK packet. Since the last BP occupied more than 9 (symbols) by the data requires an idle BP before an ACK transmission, it can be calculated as $p_{idle} = \sum_{l=L_{min}}^{L_{max}} \sum_{s=9}^{20} p_S((l-1)\cdot 20+s)$.

As the probability that a packet is sensed by the first CCA is proportional to the length of the packet, and an ACK packet does not follow the data packet if it collided, the probability that the first CCA senses an ACK transmission when the first CCA reports busy status can be derived as

$$\begin{aligned} P(ACK\ sensed \mid CCA1\ busy) &= (1-p_c)\cdot\frac{L_{ack}}{E[L]+L_{ack}} \\ &= 1 - P(DATA\ sensed \mid CCA1\ busy). \end{aligned} \tag{2}$$

Now let us consider the case that the second CCA reports the channel busy. The second CCA can report the channel busy if and only if the first CCA was conducted at an idle BP just before a data transmission or an idle BP between a data and an ACK packet. Therefore, $E[R_{data2}] = E[L]-1$ and the probability that an ACK packet is sensed by the second CCA can be derived as

$$\begin{aligned} P(ACK\ sensed \mid CCA2\ busy) &= \frac{p_{idle}(1-p_c)}{1+p_{idle}(1-p_c)} \\ &= 1 - P(DATA\ sensed \mid CCA2\ busy). \end{aligned} \tag{3}$$

$E[L]$ can be estimated from the application or measured from the transmitted and received packets. Although p_c and p_{idle} cannot be practically learned by an 802.15.4 device, the impact of p_c and p_{idle} on D_{ccax} defined as δ_x are relatively small. Therefore, D_{cca1} and D_{cca2} can be approximated from Eqs. (1), (2) and (3) as functions of sole $E[L]$ as follows:

$$\begin{aligned} D_{cca1} &\simeq \left\lceil \frac{1}{2}\cdot\{E[L]-1\} + L_{ack} + \delta_1 \right\rceil, \\ D_{cca2} &\simeq \left\lceil E[L] - 1 + \delta_2 \right\rceil. \end{aligned} \tag{4}$$

Therefore, only with the average packet length of a network, D_{cca1} and D_{cca2} can be properly set for the EB mechanism, which facilitates the reduction of unnecessary backoffs and CCA operations of the 802.15.4 CSMA-CA.

[2]The minimum length and the maximum length of a physical packet are defined by [3].

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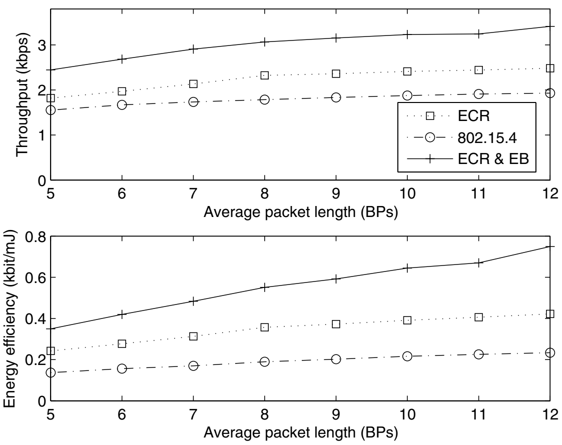

Fig. 2. Per node throughput and energy efficiency of the saturated network

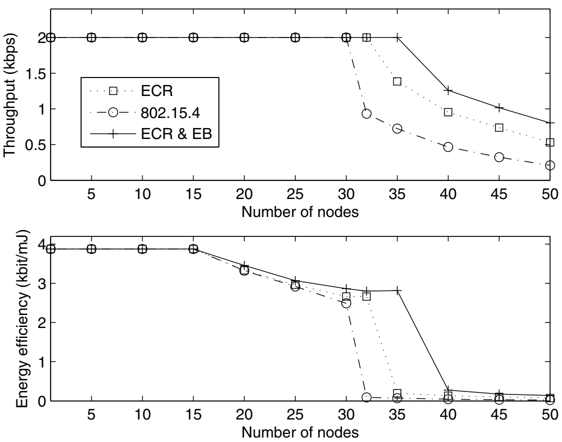

Fig. 3. Per node throughput and energy efficiency of the unsaturated network

IV. Simulation Results

Simulations are conducted using the 802.15.4 module included in the ns-2 simulator. In the simulation, each device transmits data packets to the coordinator, and there is no hidden device. For the energy consumption, the corresponding powers in the RF transceiver and the baseband modem for different radio states are obtained from [5]. The CSMA-CA which adopts only the ECR mechanism to adjust BE (denoted as ECR) is evaluated in order to observe the impact of individual mechanisms.

Fig. 2 shows throughput and energy efficiency of a device under a saturation condition, i.e., every device always has a packet to transmit. Although most target applications of the 802.15.4 has very low traffic load, each device might be saturated by low duty cycle of radio and network congestion. Energy efficiency is defined as the ratio of throughput and energy consumption. There are 25 devices and one coordinator in the simulation. In the simulation, the average packet length, $E[L]$, varies from 5 to 12 BPs. According to $E[L]$, appropriate D_{cca1} and D_{cca2} are set from Eqs. (4), respectively. Since the ECR mechanism effectively adapts the channel contention, 29.9% and 86.8% of improvement are observed in terms of throughput and energy efficiency with $E[L] = 8$, respectively. Further, the EB mechanism helps reduce unnecessary backoffs and CCAs so that the CSMA-CA algorithm with both proposed mechanisms (denoted as ECR & EB) outperforms that with only ECR mechanism by up to 31.9% and 53.8% in terms of throughput and energy efficiency, respectively. As shown in Fig. 2, the EB consistently enhance performance with various average packet lengths and the corresponding D_{ccax} values.

Fig. 3 shows the performance as the number of unsaturated devices increases. The traffic load of each device is a constant bit rate (CBR) with 2 kbps that is a typical traffic model for periodic reporting in wireless sensor networks. The average packet length is 8 BPs. It is evident that there is not much performance difference as the problems observed in Section II barely occur when the channel is lightly loaded. However, as the number of devices increases, the channel becomes saturated and packet drop starts to happen. As shown in Fig. 3, the 802.15.4 and the ECR & EB can accommodate 30 and 35 devices without packet drop, respectively. In other words, the manageable network load is expanded from 60 to 70 kbps (16.7% enhanced) by the proposals. Also, the energy efficiency is improved from 2.49 to 2.81 kb/mJ (12.9% enhanced) under the manageable network load.

V. Conclusion

In this letter, two mechanisms are proposed to enhance throughput and energy efficiency of IEEE 802.15.4 CSMA-CA algorithm. The ECR mechanism increases the BE based on both consecutive CCA busy results and a packet collision, and decreases the BE after a successful transmission. The EB mechanism shifts the range of backoff counters by utilizing the CCA outcome. Through our work, it is shown that despite the fact that the 802.15.4 adopts a sporadic channel assessment for energy efficiency, the CSMA-CA was not designed properly for its distinct characteristics and can be enhanced through our proposed mechanisms.

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