Analysis of Energy Efficiency and Power Saving in IEEE 802.15.4

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Abstract—The limited bandwidth and the finite battery power of mobile devices represent one of the greatest limitations of current WPANs. In this paper, we propose and validate an analytical model for the energy efficiency of the IEEE 802.15.4 slotted CSMA/CA which can be studied as slotted non-persistent CSMA. Key to the accuracy of our model is a careful study of the idle period after last collision, which has been studied by [1]. Specifically, we also present and evaluate a distributed mechanism to improve the energy efficiency for contention control in IEEE 802.15.4 and show that power saving and throughput maximization can be jointly achieved. Simulation results indicate that our mechanism is very effective and robust. Our mechanism can be used to extend the standard 802.15.4 access mechanism without requiring any additional hardware.

Keywords—IEEE 802.15.4; CSMA/CA; non-persistent CSMA; energy efficiency; throughput

I. INTRODUCTION

IEEE 802.15.4[2] is designed for low-data-rate and small size Wireless Personal Area Networks (WPAN). It is also considered as one of the technology candidates for wireless sensor networks [3,4].

The analytical model for IEEE 802.15.4 slotted CSMA/CA was recently evaluated using discrete time Markov chain models [5,6]. Those papers presented analytic models where each state is based on the counter values as the 802.11 model in [7] and provided steady state solutions, but the analytical results seems to fail to match the simulation results. In [8], the authors have proposed a different Markov chain model of the slotted CSMA/CA mechanism which utilizes the probability of a device in the channel sensing states instead of the channel accessing states and assumes that the backoff procedure starts at the first timeout slot both in the analytic and simulation models. Recently, [1] realized the importance of treating the timeout period after last collision and proposed an analysis model of saturation throughput.

There have been remarkable research efforts for different distributed mechanism to achieve optimal throughput and energy efficiency in other wireless networks so far. For example, in the field of IEEE 802.11 research, asymptotically optimal backoff has been developed [9]. Nevertheless, the CSMA/CA of 802.15.4 is fundamentally different from 802.11, so the mechanism can not be used in 802.15.4.

In this paper, we propose and validate an analytical model for the energy efficiency considering timeout period. Also we present a new mechanism, which dynamically adapts the backoff window size to the current network contention level and guarantees that IEEE 802.15.4 WPAN asymptotically to optimize energy efficiency. The performance of IEEE 802.15.4, with and without our mechanism, is investigated in the paper through OPNET simulation [10].

To our best knowledge, this paper is the first analytical study of energy efficiency considering timeout period. Moreover, in the case of analytical closed formulas for power saving of 802.15.4 at runtime, there is no known analysis.

II. SLOTTED CSMA/CA MECHANISM OF 802.15.4

In a star topology network, a device that sends a data frame to the coordinator using slotted CSMA/CA shall wait for at most 2.7 slots for the corresponding acknowledgment (ACK) frame to be received. The coordinator acknowledges the successful reception of the data request immediately not using slotted CSMA/CA. If an ACK is received within 2.7 slots, the transmission is considered successful, else, the device shall conclude that the attempt has failed and repeat the process of transmitting the data frame.

In the slotted CSMA-CA channel access mechanism, the backoff slot boundaries of every device in the PAN are aligned with the superframe slot boundaries of the coordinator. Each time a device wishes to transmit data frames during the CAP, it must locate the boundary of the next slot period. Each device in the network has three variables: NB, CW and BE. NB is the number of times the algorithm was required to delay while attempting the current transmission. It is initialized to 0 before every new transmission. CW is the contention window length, which defines the number of slot periods that need to be clear of activity before the transmission can start. It is initialized to 2 before each transmission attempt and reset to 2 each time the channel is assessed to be busy. BE is the backoff exponent, which is related to how many slot periods a device must wait before attempting to assess the channel. More details on IEEE 802.15.4 slotted CSMA/CA can be referred to [2].

III. CHANNEL MODEL OF 802.15.4 SLOTTED CSMA/CA

According to slotted CSMA/CA of 802.15.4, if the channel is sensed idle the device transmits the packet; else it schedules
the retransmission of the packet to some later time, so we can study it as slotted non-persistent CSMA. To analyze energy efficiency of 802.15.4 in saturation conditions, we propose a channel model of non-persistent CSMA, similar to [1] studying saturation throughput, where the channel is observed at the end of each successful transmission, as shown in Fig. 1. In particular, each renewal interval is made up of idle slots followed by a successful or colliding transmission attempt.

<table>
<thead>
<tr>
<th>Last Success</th>
<th>Idle_success</th>
<th>Coll</th>
<th>Idle_coll</th>
<th>Coll</th>
<th>...</th>
<th>Idle_coll</th>
<th>Succ</th>
</tr>
</thead>
</table>

Fig. 1. channel model of 802.15.4 CAP.

To analyze energy efficiency, we define the normalized energy consumption $Ed$, which is the average energy consumption to transmit one slot amount of payload. We assume that a device enables its receiver only when it performs a CCA to transmit a packet or waits for an ACK. Except for those cases, zero energy consumption is assumed. According to [1], after each collision the medium must remain idle for an interval equal to the time to CCA twice. Thus $Ed$ and $tv$ is denoted as the following:

$$Ed = \frac{E_{CCA} + E_C + E_s}{L - 1.5}$$  \hspace{1cm} (1)

$t_s = N_c \cdot T_{idle \_coll} + T_\text{idle \_suc} + (N_c + 1) \cdot 2 \cdot T_{CCA} + N_c \cdot T_{coll} + T_s$ \hspace{1cm} (2)

$E_{CCA}$ is the consumed energy for performing CCA and is given by:

$$E_{CCA} = \frac{1}{P_{CCA}(1-\tau)^{n-1}} \cdot [1 - Ncn_0] \cdot T_{CCA} \cdot E_{rx} + (1 + Ncn_0) \cdot 2T_{CCA} \cdot E_{rx}$$  \hspace{1cm} (3)

where $\tau$ is the conditional probability that a device performs the first CCA state when it is in the backoff states; $N_c$ is the number of collisions in a renewal interval; $T_{CCA}$ is 1 slot, the length of the time to CCA once; $P_{CCA}$ is the probability of unsuccessful two successive CCA; $n_0$ is the average number of devices attending the collision and $E_{rx}$ is the energy consumption to receive a packet during one slot. $P_{CCA}$ can be found by:

$$P_{CCA} = \frac{T_{v2}}{T_{v1}} = \frac{(N_c + 1) \cdot (T_{idle \_coll} + 2T_{CCA} - 1)}{T_v - 1}$$  \hspace{1cm} (4)

where $T_{v2}$ is the number of two successive idle slots in each renewal interval and $T_{v1}$ is the number of two successive slots in each renewal interval. Also

$$\frac{1}{P_{CCA}(1-\tau)^{n-1}} \cdot [1 - Ncn_0] \cdot T_{CCA} \cdot E_{rx}$$  \hspace{1cm} (5)

is the consumed energy for performing CCA when channel is busy, and

$$\frac{1 + Ncn_0}{P_{CCA}(1-\tau)^{n-1}} \cdot 2T_{CCA} \cdot E_{rx}$$  \hspace{1cm} (6)

is the consumed energy for performing CCA when channel is idle.

$E_s$ is the consumed energy for the successful transmission, and is given by:

$$E_s = L \cdot E_{rx} + 3 \cdot E_{rx}$$  \hspace{1cm} (7)

Where $L$ is the packet length; $E_{tx}$ is the energy consumption to transmit a packet during one slot and $3E_{rx}$ is the energy consumption to receive acknowledgments.

$Ec$ is the consumed energy for the collision, and is given by:

$$E_c = N_c \cdot n_0 \cdot L \cdot E_{rx} + N_c \cdot n_0 \cdot 3 \cdot E_{rx}$$  \hspace{1cm} (8)

where $N_c n_0 \cdot L \cdot E_{rx}$ is the energy consumption of all collisions in a renewal interval and $N_c n_0 \cdot 3 \cdot E_{rx}$ is the energy consumption of all the devices in timeout period.

Due to the limit of paper length, more details about $N_c n_0 \cdot T_{idle \_coll}, T_{idle \_suc}$ can be referred to [1].

IV. ADAPTED OPTIMAL BACKOFF MECHANISM

Now we consider an IEEE 802.15.4 protocol in which the energy efficiency is optimized by the computed window size, at run time, via a distributed algorithm.

By [11], we find that when non-persistent CSMA is optimized for energy efficiency, throughput and delay are impacted negatively, whereas p-persistent CSMA can effectively optimize both with the same network settings. So, in order to obtain high $Ed$, 802.15.4 stations need to issue long backoff periods between transmissions, leading to higher idle time in the channel. Therefore, we see that throughput can be greatly sacrificed if 802.15.4 is tuned only to achieve optimal energy efficiency. But by simulation we find if 802.15.4 is tuned only to achieve optimal throughput, energy efficiency can be improved effectively. Specifically, we will show that power saving and throughput maximization can be jointly achieved.

To optimize the throughput, with a minimization algorithm of $t_s$, a station can obtain the exact value of $t_{opt}$. This is however very complex from a computational standpoint and it is not suitable for a run-time. In [9], a simple approach is proposed for P-CSMA, but we find this method is not suitable for non-persistent CSMA due to the additional CCA period which is a particular period between idle period and transmission. Our heuristic is based on the similar approximation proposed in [12] for Aloha CSMA protocol. It is interesting to observe that this optimal point occurs where the time spent on idle slots not including CCA period is approximately equal to that spent on collisions. Hence, we propose to maximize the throughput with $\tau$ that satisfies the following relationship:

$$1 + N_c \cdot T_{idle} = N_c \cdot T_{coll}$$  \hspace{1cm} (9)

Note that not consider timeout period here and the time of CCA is not included in $Tidle$, although the channel is idle when any device performs CCA after last communication. After some algebraic manipulations of (7), the
optimal \( \tau \), \( \tau_{opt} \) is derived by solving:

\[
L = \frac{(1-\tau_{opt})^n}{(1-(1-\tau_{opt})^n - n\tau_{opt}(1-\tau_{opt})^{n-1}} \quad (8)
\]

Taking the derivative of (8) with respect to \( \tau_{opt} \), and imposing it equal to 0 by Taylor series provided that \( n \cdot \tau \ll 1 \), a closed formula for \( \tau_{opt} \) can be further derived as the following:

\[
\tau_{opt} = -1 + \frac{\sqrt{2}L - 1}{(L-1)n} \quad (9)
\]

So the backoff window size \( BW \) can be found from (9):

\[
BW = \frac{2}{\tau_{opt} - 1} = \frac{2(L-1)n}{-1 + \sqrt{2L - 1}} - 1 \quad (10)
\]

From (10), we can see that \( n \) and \( L \) determine the optimal backoff window size. Here, by exploiting our analytical formulas above we are able to exactly compute \( n \) provided that the average times of CCA between successive successful CCA, \( N_{CCA} \) is known by every device. From (4), we have:

\[
N_{CCA} = \frac{1}{P_{CCA}} \quad (11)
\]

Taking the derivative of (11) with respect to \( n \), and imposing it equal to 0 by assuming that \((1-\tau)^n = (1-\tau)^{n-1} \approx 1-\tau n\), a closed formula for \( n \) can be further derived as the following:

\[
n = \frac{L + 3 - \sqrt{(L+3)^2 - 8(N_{CCA} - 1)}}{4\tau} \quad (12)
\]

By noting that each network device can estimate \( N_{CCA} \) easily, from (12) the parameter \( n \) can be tuned at runtime. To avoid sharp changes in the estimated value of \( n \), we adopt a smoothing factor \( w=0.99 \). Specifically

\[
\text{estimated } n_{i+1} = w \cdot \text{estimated } n_i + (1-w) \cdot n_i \quad (13)
\]

where \( \text{estimated } n_i \) is the estimated value \( n \) used in the \( i \)th successful CCA, and \( n_i \) is the value computed at the end of the \( i \)th successful CCA, by applying (12) to the times of CCA in that successful CCA interval.

So an adapted optimal backoff mechanism, where \( BW \) is computed at runtime in every successful CCA interval, can be used in contention control of 802.15.4. \( N_{CCA} \) is used as a feedback signal to control the devices' behavior. This mechanism is simple and can be obtained by exploiting information that is already available in the standard protocol and not require any additional hardware. Uppermost, energy consumption is improved effectively because devices need not to keep awake all the time to monitor the channel status like devices in 802.11 [9].

V. Model Validation

To validate our analytical model, we account for all the protocol details and using default parameters for 2.4GHz frequency such as 3, 5 and 4 for macMinBE, aMaxBE and macMaxCSMABackoff, respectively. We also use the parameter values in [13] such as \( Etx \) and \( Erx \) are 0.0100224 and 0.0113472 mJ, respectively. But energy consumption during the turnaround time is not considered in our model. We create saturation conditions by feeding devices with high rate constant bit rate traffic generators and the devices (no hidden terminals [14]) transmit fixed size packets. The other model parameters are reported in the following table.

<table>
<thead>
<tr>
<th>packet payload</th>
<th>55 or 115 bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>overhead</td>
<td>15 bytes</td>
</tr>
<tr>
<td>ACK length</td>
<td>11 bytes</td>
</tr>
<tr>
<td>Channel bit rate</td>
<td>250 kbps</td>
</tr>
<tr>
<td>Propagation Delay</td>
<td>0</td>
</tr>
<tr>
<td>Backoff unit</td>
<td>10 bytes</td>
</tr>
</tbody>
</table>

As can be seen in Fig. 2, our model gives accurate results for the energy efficiency of IEEE 802.15.4 slotted CSMA/CA with considering timeout periods. Fig.3 presents the comparison of a key estimate in our model, \( P_{CCA} \).

![Fig. 2. Energy efficiency of 802.15.4 CAP](image-url)
As expected the energy efficiency deteriorated rapidly when \( n \) increases. This is obviously due to the backoff mechanism not taking into consideration the number of active devices.

The slotted non-persistent CSMA model and formula (4) provides a close approximation of the real behavior of IEEE 802.15.4 slotted CSMA/CA.

To validate adapted optimal backoff our mechanism, in Fig.4, we have compared analytic optimal results with that obtained using (10) with simulation model. The results presented indicate that the simulation results of throughputs using \( BW \) of the closed formula remains very close to the theoretical bound when number of devices varies from 5 to 40. At the same time, \( Ed \) is improved effectively and power saving is achieved.

Also, to analyze the robustness of our mechanism, we run several simulation experiments in which the packet lengths are 7 slots and \( n \) is initialized to 5, but there are significantly more active devices in the network later. Specifically, Fig. 5 shows the performance of 802.15.4 in one case: 35 devices become active after 80 seconds (1000000 slots). The results presented show that our mechanism correctly follows the contention level when \( n \) varies and guarantees that 802.15.4 asymptotically achieves its optimal throughput and improve the energy efficiency very effectively. There are short transients whose length is mainly caused by the smoothing factor.

In this paper, we propose and validate an analytical model for the energy efficiency of the IEEE 802.15.4 slotted CSMA/CA which can be studied as slotted non-persistent CSMA. Key to the accuracy of our model is a careful study of the idle period after last collision, which has been studied by [1]. Specifically, we also present and evaluate a distributed mechanism to achieve power saving for contention control in IEEE 802.15.4. The network contention level is measured independently by each device by an index that is simple to estimate: times of CCA in every successful CCA interval. This estimate is used as a feedback signal to control the devices’ behavior. Simulation results indicate that our mechanism is very effective and robust.

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