An Efficient Adaptive Backoff Algorithm for Wireless Sensor Networks

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Abstract—The IEEE 802.15.4 standard utilizes the Binary Exponential Backoff (BEB) algorithm to control nodes’ access to the shared wireless medium. The main drawback of BEB is that it updates the size of the contention window (CW) without taking into consideration the number of competing nodes and the conditions in the communications medium. Therefore, BEB has been shown to be inefficient in terms of channel utilization and fairness among the contending nodes. In this paper, we propose Adaptive Backoff Algorithm (ABA), a new backoff algorithm that adaptively determines the appropriate size of CW based on the collisions experienced by the nodes. That is, while BEB updates CW in a deterministic fashion, we introduce a probabilistic methodology to achieve that update. Our simulations compare the performance of ABA with that of BEB as well as three other algorithms proposed in the literature, namely, NO-BEB, KEB, and IBEB. The performance is studied in terms of power consumption, reliability, and channel utilization. Our results show that ABA outperforms the aforementioned algorithms while granting each node a fair access to the wireless medium.

Index Terms— Wireless Sensor Networks; Beacon-Enabled IEEE 802.15.4; Binary Exponent Backoff; Adaptive Backoff; Fairness; Power Consumption; Reliability; Channel Utilization.

I. INTRODUCTION

The IEEE 802.15.4 standard defines the specifications for the PHY layer and the MAC sub-layer for low-rate wireless personal area networks (LR-WPANs). These specifications conform to the design requirements of Wireless Sensor Networks (WSNs), like limited power resources and low data-rates. The IEEE 802.15.4 can operate in either a beacon-enabled mode or a nonbeacon-enabled mode. The former mode utilizes the slotted CSMA-CA mechanism while the latter mode incorporates the unslotted CSMA-CA mechanism. Our focus in this paper is on the beacon-enabled mode. The slotted CSMA-CA uses the Binary Exponent Backoff (BEB) algorithm to control access to the wireless medium. In this algorithm, as we explain more in Section II, each node backs off for a randomly chosen contention window (CW) before commencing any transmission. BEB updates the size of CW without considering the number of nodes in the network or the conditions in the communication medium. As a result, as shown in [1], BEB suffers from unfairness and degraded channel utilization. In this paper, we propose the Adaptive Backoff Algorithm (ABA), a probabilistic approach to update the CW. Our methodology depends on using the number of collisions as an essential parameter in reflecting how busy the wireless medium is. In other words, the probability of collision will be used directly to update the CW. The rest of the paper is organized as follows. In Section II we provide an overview of the BEB algorithm deployed in the beacon-enabled IEEE 802.15.4 standard. In Section III, we review the literature for contributions that targeted improving BEB. Section IV introduces the new ABA algorithm. Section V describes the simulations we conducted to analyze the performance of ABA. Finally, Section VI concludes the paper and provides future research directions.

II. OVERVIEW OF THE BEACON-ENABLED IEEE 802.15.4

The IEEE 802.15.4 standard defines the specifications of the PHY layer and the MAC sub-layer for LR-WPANs [2]. Both star and peer-to-peer topologies are supported. In the star topology, communications are possible between nodes and a controller node referred to as the PAN coordinator. In the peer-to-peer topology, a coordinator is also used; however, nodes may communicate among each other. In the beacon-enabled mode, a superframe structure is used to organize the communications over the wireless medium. This superframe is bounded by beacons that are sent by the PAN coordinator to synchronize the nodes. The beacon is communicated during the first slot of the superframe. The superframe is constituted by a contention access period (CAP) and an optional contention-free period (CFP).

During the CAP, the nodes compete to access the communications medium using the slotted CSMA-CA mechanism. That is, the BEB algorithm is utilized during the CAP. BEB works as follows. Before any transmission attempt, three variables are initialized, namely, the number of backoff stages (NB) (initialized to zero), the number of nodes in the network or the conditions in the communication medium. As a result, as shown in [1], BEB suffers from
the channel is found busy), and the backoff exponent (BE) (initialized to the standard defined attribute $macMinBE$).

As a node attempts to start transmission, it firstly initializes the three variables above. Then, the MAC sub-layer backs off for a duration chosen randomly from the range $[0, 2^{BE-1})$. Once the backoff period reaches zero, the node initiates the first clear channel assessment (CCA1). After that, another CCA, that is, CCA2, is initiated. If the channel is found to be idle during these two CCAs, the packet transmission starts. However, if either of the CCAs is found busy, the values of NB and BE are increased by one. The maximum values these two parameters can reach are $macMaxCSMABackoffs$ and $macMaxBE$, respectively. If NB exceeds the value $macMaxCSMABackoffs$, the packet will be dismissed. If BE reaches $macMaxBE$, it maintains that value until it is reset. Otherwise, the CSMA-CA mechanism starts the process over by randomly generating a new number of complete backoff periods. Once the node succeeds to access the medium, packet transmission starts and the acknowledgement (ACK) packet is waited for. If the ACK packet is not received, the node retransmits the packet again, up to $macMaxFrameRetries$ attempts. With every retry, the MAC sub-layer resets the BE to $macMinBE$ and re-applies the CSMA-CA mechanism. Once the $macMaxFrameRetries$ limit is reached, the packet is dismissed. Finally, it is worth mentioning that BEB was originally introduced in the IEEE 802.11 standard.

From the description above it is quite evident that BEB neither examines the status over the communications medium nor does it consider the intensity of the traffic load in its operation. This behavior contributed to degraded performance, as we demonstrate later in Section V, and motivated several research efforts to introduce better backoff algorithms.

### III. RELATED WORK

In this section we review some related work that targeted modifying the BEB algorithm to enhance its performance.

In [3], the Non-Overlapping BEB (NO-BEB) algorithm is introduced for 802.11 networks, and in [4] its performance is evaluated over 802.15.4 networks. Basically, NO-BEB proposes two modifications to the original BEB, 1) Reduce the level of contention by choosing CW from the interval $[CW_{i,1}, CW_{i}]$ rather than $[0, CW_{i}]$ (CW is “the contention window of the $i$th backoff stage” [3]), and 2) Decrement the backoff counter by one instead of resetting CW to its minimum. The first modification guarantees that nodes with different number of failures to access the medium are more likely to be allocated to the non-overlapping regions [4]. This can effectively reduce the possibility of collisions. The second modification guarantees that the node remains at the backoff stage which is optimal for the traffic of that period of time. In [4], the authors provide a Markov-based model for NO-BEB and study its performance in terms of throughput, probability of collision and average access delay. The provided data show that NO-BEB outperforms BEB in terms of these parameters.

In [5], the Improved BEB (IBEB) algorithm is proposed. The authors introduce the Interim Backoff (IB) and unit Interim Period (IP) to help reduce the level of packet collisions. Basically, each node not only chooses BE randomly, but also chooses an IB which is between 10% to 40% of the selected backoff delay. The idea here is that nodes have a low probability of choosing, randomly, the same BE as well as IB. The details of computing IB and IP can be found in [5]. The simulation study conducted show that IBEB outperforms BEB in terms of average setup time, average channel idle time, average goodput, and average number of collisions.

In [6], the Knowledge-based Exponential Backoff (KEB) algorithm is proposed. This algorithm aims at enhancing the channel utilization based on the channel state information local to each node. The Exponential Weighted Moving Average (EWMA) principle is employed to compute the collision rate at any time instant. BE is decreased (increased) whenever the collision rate is less (more) than a predefined threshold. That is, as the level of collisions decreases, the node backs off for a shortened duration and vice versa. KEB is analytically modeled using Markov Chain and then simulated to compare its performance to BEB. The provided results show that KEB’s performance in terms of saturation throughput is superior to BEB’s.

### IV. ADAPTIVE BACKOFF ALGORITHM

In this section we introduce the new Adaptive Backoff Algorithm (ABA). The motivation behind this algorithm is to enhance the channel utilization (U) in WSNs. These enhancements should take into consideration that power consumption should be as low as possible in order not to affect the lifetime of the network. The degradation of U results from two main factors. The first factor is having the wireless medium idle for extended periods, due to selecting large backoff periods. The second factor is experiencing excessive level of collisions. As more nodes attempt to access the medium at the same time, the probability of collision ($p_c$) increases. Therefore, including $p_c$ in the computation of CW can adapt the latter’s value in accordance to the conditions in the communication channel. In other words, we propose that the value of CW be updated as follows:

$$CW_t = p^t_c CW_{max}$$

where, $CW_t$ is the selected contention window at time $t$, $CW_{max}$ is IEEE 802.15.4’s maximum contention window (set to $2^{macMaxBE}$), and $p^t_c$ is the probability of collision at time $t$. When a node has a packet to send, it backs off for a period of time randomly chosen from an interval that has (1) as its upper limit (note that at startup $p^0_c$ cannot be estimated by the node, since it has not sent any packets yet. Therefore, we assume that $p^0_c$ is initialized with a value of 0.5 and then
updated according to the collisions experienced by the sending node). If the node finds the medium busy during CCA1 or CCA2, it repeats the backoff process. The value of CW will be updated in accordance to the level of collisions detected. In this manner, as the level of collisions increases in the medium, nodes tend to backoff for extended durations. This will effectively reduce the contention among nodes and will give better opportunities for successful packet transmissions. Hence, improved channel utilization can be achieved. On the other hand, as the level of collisions decreases in the medium, nodes tend to backoff for shortened durations, which reflects in better utilization of the channel. This algorithm requires no hardware upgrades and can be easily implemented using software updates for the sensor node’s platform. Also, the simplicity of Equation (1) implies that ABA is not burdening the sensor nodes with additional power consumption requirements (as we demonstrate in Section V). In Fig. 1 we show the flow diagram of ABA.

![ABA algorithm](image)

Figure 1: ABA algorithm.

V. SIMULATIONS & PERFORMANCE ANALYSIS

In this section we compare the performance of ABA against that of BEB, NO-BEB, IBEB, and KEB algorithms. The performance parameters we study in our evaluation are: channel utilization, probability of collisions, power consumption, and reliability. We also study how fair ABA is.

Our simulations are conducted using a user-defined simulator written in C language. We simulate a network of a peer-to-peer topology. The simulation parameters are listed in Table I (we partially depend on the parameters defined in [7]). In this table, CCA power refers to the power consumed during CCA1 or CCA2. We assume that the network is operating in the beacon-enabled IEEE 802.15.4 mode with the superstructure composed of only the active periods (i.e., no CFP or inactive periods are assumed). Assuming only active periods means that nodes always follow the standard slotted CSMA-CA approach to access the communication medium. We implement a saturated acknowledged data traffic (i.e., each node has always something to send). The following subsections provide the results of our simulations along with discussions and comments.

### Table I: Simulation Parameters

<table>
<thead>
<tr>
<th>Power Consumed (mW)</th>
<th>Rx</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tx</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>CCA</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Sleep</td>
<td>0.8</td>
</tr>
<tr>
<td>Durations</td>
<td>1 timeslot</td>
<td>0.32 ms (80 bits)</td>
</tr>
<tr>
<td></td>
<td>Packet Length (L)</td>
<td>14 timeslots</td>
</tr>
<tr>
<td></td>
<td>ACK Packet Length (L_ACK)</td>
<td>2 timeslots</td>
</tr>
<tr>
<td></td>
<td>Simulation Time</td>
<td>320 s</td>
</tr>
<tr>
<td>802.15.4 Parameter Settings</td>
<td>macMaxCSMABeckoffs</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>macMinBE</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>macMaxBE</td>
<td>8</td>
</tr>
</tbody>
</table>

A. Fairness

We mentioned earlier that BEB suffers from being unfair in the way it manages nodes’ access to the medium. In this sub-section we focus on the performance of ABA in terms of fairness. A fair algorithm should allow nodes an equal opportunity to access the communication medium. We depend on Jain’s fairness index [8] to measure ABA’s fairness:

\[
\text{fairness index} = \frac{\left(\sum x_i\right)^2}{N \sum x_i^2} \tag{3}
\]

where, \(N\) denotes the total number of nodes in the network and \(x_i\) denotes the \(i\)th node’s share of the medium. A fair algorithm should achieve a fairness index close to 1. In Fig. 2 we show ABA’s fairness index. The graph clearly shows that ABA is capable of treating the active contending nodes equally.
B. Channel Utilization

Improving channel utilization (U) is the main motivation behind proposing ABA. It refers to the percentage of time the wireless medium is being used to successfully transmit packets. We define U as the ratio of the packet length (L) to the total duration T that covers the backoff periods (T_{BO}), packet transmission time (L_s), and the time wasted due to experiencing j collisions (jL_c). Therefore, channel utilization is computed by the following formula:

\[ U = \frac{L}{T} = \frac{L}{T_{BO} + L_s + jL_c} \]  \hspace{1cm} (2)

We show in Fig. 3 the performance in terms of U for ABA compared to BEB, IBEB, NO-BEB, and KEB. The graph clearly shows that ABA outperforms BEB and IBEB. The improvement in the performance becomes significant as we increase the number of nodes beyond 10 nodes (for a number of nodes below 10, the slight difference in performance between ABA and BEB is negligible). For example, at 45 nodes, ABA achieves a U of 50.78%, while BEB and IBEB achieve 39.76% and 20.36%, respectively. We also observe that NO-BEB performs the same as ABA until the network size reaches 25 nodes. Beyond that, ABA starts showing its superiority. The problem with NO-BEB is that although it manages to reduce the probability of collisions, due to concentrating on selecting non-overlapping CWs, it keeps the original problem of BEB which is resetting its CW to its minimum after successful/failed transmissions, regardless of the conditions over the medium. On the other hand, it is worth mentioning that KEB starts to match ABA’s performance at 44 nodes. The problem with KEB is that it controls the value of CW based on a thresholds, which is difficult to quantify. The latter problem is evident in the graph as KEB keeps achieving a lower U than that of ABA for all network sizes below 44 nodes.

C. Probability of Collision

Each node computes p_c based on its packets that suffered from collisions. That is, as the nodes cannot overhear the medium while backing off, their computation of p_c over the medium is just an estimate. It is important to note that each node, after sending a number of packets, observes the proportion of packets that suffer from collisions and based on that it computes p_c. Given that ABA is fair (see sub-section A above), the locally computed p_c can validly approximate the global p_c over the medium for the whole network. We should also mention that the initial value of p_c is set to 0.5 (see Section IV). We need this initialization so that a node can use Equation (1) to compute its first contention window. Although this value seems too high, it will not affect the overall performance of ABA since a node will eventually correct this value in accordance with the collisions it observes.

Fig. 4 shows the performance in terms of p_c. The graph clearly shows that, compared to BEB, IBEB, and KEB, ABA is capable of achieving the lowest level of collisions. NO-BEB slightly outperforms ABA for networks composed of 24 nodes or less, but falls behind ABA for bigger networks. KEB manages to match ABA’s performance when we have 45 or more nodes in the network. As mentioned before, the way NO-BEB and KEB update their CWs contribute to these results. ABA still shows that directly controlling CW in accordance to p_c can strongly keep the collisions low as the network’s size increases.
D. Power Consumption

In WSNs, sensor nodes have scarce power resources. Therefore, any devised algorithm should have reasonable power consumption requirements that will not negatively affect the lifetime of the network. In Fig. 5 we show the performance in terms of power consumption. Interestingly, all of the algorithms consume the same level of power for different number of network nodes. However, in Fig 6 we show the amount of power consumed due to packet collisions. We can see that both ABA and NO-BEB are wasting the minimum level of power due to collisions. This indicates that most of the power is being consumed in useful activities, especially transmitting packets.

E. Reliability

Finally, we study the performance of ABA in terms of reliability (R). We define R as the probability of transmitting a packet successfully. In Fig. 7 we show our results for R. Again, ABA is showing promising results, especially at 22 nodes and beyond where ABA performs the best compared to the other algorithms. Although NO-BEB achieves a comparable performance for small networks, its R degrades with bigger networks to be 38.89% at 50 nodes while ABA achieves an R of 48.1% at the same network’s size.

In Table II, we summarize our findings in this section and show the general performance of ABA compared to the other four algorithms.
### Table II: Overall Performance Comparison

<table>
<thead>
<tr>
<th>Backoff Algorithm</th>
<th>Network Size</th>
<th>Channel Utilization</th>
<th>Collision Avoidance</th>
<th>Power Savings</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEB</td>
<td>Small</td>
<td>Best</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>Poor</td>
<td>Average</td>
<td>Good</td>
<td>Average</td>
</tr>
<tr>
<td>IBEB</td>
<td>Small</td>
<td>Good</td>
<td>Average</td>
<td>Poor</td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>Worst</td>
<td>Worst</td>
<td>Worst</td>
<td>Worst</td>
</tr>
<tr>
<td>NO-BEB</td>
<td>Small</td>
<td>Good</td>
<td>Best</td>
<td>Best</td>
<td>Best</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>Good</td>
<td>Average</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>KEB</td>
<td>Small</td>
<td>Worst</td>
<td>Worst</td>
<td>Worst</td>
<td>Worst</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>Best</td>
<td>Best</td>
<td>Best</td>
<td>Good</td>
</tr>
<tr>
<td>ABA</td>
<td>Small</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>Best</td>
<td>Best</td>
<td>Best</td>
<td>Best</td>
</tr>
</tbody>
</table>

**VI. CONCLUSION & FUTURE DIRECTIONS**

In this paper we introduce the Adaptive Backoff Algorithm (ABA), a new backoff algorithm to improve the performance of the beacon-enabled IEEE 802.15.4-based WSNs. The algorithm is motivated by the pitfalls of the original BEB algorithm that has an unfavorable performance in terms of channel utilization and fairness. ABA is based on the fact that controlling the contention window should be directly associated with the level of collisions over the medium of communication. If the medium is experiencing high level of collisions, nodes should refrain from sending packets persistently. On the other hand, as the level of collisions starts to decrease, we need to avoid having an idle medium for extended periods. Abiding by that can effectively improve the utilization of the wireless channel. ABA’s performance is simulated and compared to that of BEB as well as three other algorithms. Our results show that the general performance of ABA is promising, with superior results for large networks (with 20 nodes and above).

In our future research, we will work on developing a mathematical model for ABA. Similar to the significant number of available studies on IEEE 802.15.14, we will depend on Markov chain due to its accuracy in modeling the working of many backoff algorithms.

**REFERENCES**


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