

Optimizing the IEEE 802.15.4 MAC

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Abstract—This paper optimally determines the IEEE 802.15.4 medium access control (MAC) attributes *macBeaconOrder* (BO) and *macSuperframeOrder* (SO) (by which the periods of time that the sensor is active and non-active can be computed) such that the overall energy consumption of the network is minimized. Considering an IEEE 802.15.4 beacon-enabled network laid out in a single-hop star topology, we evaluated the performance of the IEEE 802.15.4 MAC through simulation. Numerical results show that the optimal solutions of BO and SO can be obtained for a range of user-specific quality of service requirements, such as proportion of successful packet transmissions and maximum delay constraint.

I. INTRODUCTION

The IEEE 802.15.4 standard defines the medium access control (MAC) and physical layer specifications for low-rate low-power wireless networks [1]. Some performance evaluations of the standard have been conducted in [2], [3] and [4]. To the best of our knowledge, the problem to optimally determine the IEEE 802.15.4 MAC attributes, such as *macBeaconOrder* (BO) and *macSuperframeOrder* (SO) remains unaddressed in the literature thus far. In this paper, we optimally choose BO and SO (by which the periods of time that the sensor is active and non-active can be computed), such that the energy consumption per unit time in the entire network is minimized, while at the same time some user-specific quality of service (QoS) requirements, such as proportion of successful packet transmissions and maximum delay constraint need to be satisfied.

II. IEEE 802.15.4 MAC

An IEEE 802.15.4 network can be organized in either star or peer-to-peer topology, depending on the requirements of the intended application. The IEEE 802.15.4 MAC protocol can operate with beacon-enabled or non-beacon-enabled modes. In this paper, we restrict our attention to beacon-enabled networks laid out in a single-hop star topology.

A. Superframe Structure

In such a network, one node is appointed as the network coordinator. The network operates with a superframe structure, which may consist of active and inactive portions, as depicted in Fig. 1. Let time be divided into consecutive time intervals called *beacon intervals* (BI). At the beginning of a BI, the

nodes simultaneously wake up and the coordinator broadcasts a message called the *beacon frame* (BF) to the nodes. The BF includes, among other things, the next wake-up time, and as a result, network synchronization is achieved. The BF is immediately followed by the contention access period (CAP), in which backlogged nodes can contend for the medium and transmit their packets.

The superframe duration (SD), which denotes the active portion of the superframe, may consist of a BF, a CAP and a contention free period (CFP). If a node is allowed to transmit in CFP, it will be allocated guaranteed transmission slots and can transmit without contention. In this work, we set the length of CFP to 0. The MAC attributes BO and SO describe the lengths of BI and SD, respectively, where BO and SO are integers and $0 \leq SO \leq BO \leq 14$. More specifically, the lengths of BI and SD (measured in symbols) are given by $aBaseSlotDuration \times aNumSuperframeSlots \times 2^{BO}$ and $aBaseSlotDuration \times aNumSuperframeSlots \times 2^{SO}$, respectively, where $aBaseSlotDuration$ is set equal to 60 symbols and $aNumSuperframeSlots$ is equal to 16 in the standard. In Table II-A, we list some BO and SO values with their corresponding durations measured in seconds when using various frequency bands defined in the standard.

B. The CSMA-CA Mechanism

The IEEE 802.15.4 MAC uses the slotted carrier sense multiple access with collision avoidance (CSMA-CA) mechanism for contention-based channel access in a beacon-enabled network. The time during a CAP is slotted and each slot is named *aUnitBackoffPeriod*. A backlogged node starts with a backoff, the length of which (measured in slots) is uniformly chosen in the range of $[0, 2^{BE} - 1]$, where the integer-valued parameter BE represents the *backoff exponent* and takes an initial value given by *macMinBE*. At the end of the backoff period, the node performs clear channel assessment (CCA) to monitor the channel status. If the channel is idle, it performs a second CCA at the boundary of the next slot. The node starts to transmit its packet if the channel is continuously sensed idle for CW times (where CW denotes the *contention window*). After the transmission, the node will immediately go back to sleep to save energy. In a network that requires acknowledgment for a successful packet transmission, the node will wait for an acknowledgment frame from the coordinator. The acknowledgment mode is optional in the standard.

If the channel is detected to be busy, the node increases its BE by one and performs another random backoff. In response

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BO, SO		0	1	2	3	4	5	6	7	8	9	...
duration (s)	868 MHz	0.048	0.096	0.192	0.384	0.768	1.536	3.072	6.144	12.288	24.576	...
	915 MHz	0.024	0.048	0.096	0.192	0.384	0.768	1.536	3.072	6.144	12.288	...
	2.4 GHz	0.0154	0.0307	0.0614	0.1229	0.2458	0.4915	0.9830	1.9661	3.9322	7.8643	...

TABLE I

BO AND SO WITH THEIR CORRESPONDING DURATIONS UNDER VARIOUS FREQUENCY BANDS.

$$E_{sum}(n) = \underbrace{P_{act}S_{sd} + P_{sleep}(S_{bi} - S_{sd})}_{\text{for coordinator}} + \underbrace{N_{all}E_0}_{\text{for all nodes}} + \underbrace{m_{cca}E_{cca} + m_{tx}E_t + n(P_{idle}S_{nip} + P_{sleep}S_{nsp})}_{\text{for backlogged nodes}} + \underbrace{(N_{all} - n)P_{sleep}(S_{bi} - S_{bn})}_{\text{for non-backlogged nodes}}. \quad (1)$$

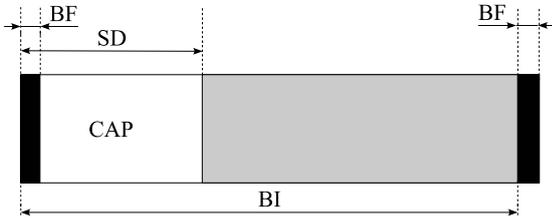


Fig. 1. IEEE 802.15.4 MAC superframe structure.

to repeated backoff periods ending in busy detections, the value of BE increases up to a maximum value $aMaxBE$, where it remains for the remainder of the attempts. The packet is discarded after a maximum number of attempts, $macMaxCSMABackoffs$, is reached.

III. OUR METHOD

We consider a network with N_{all} nodes (excluding the coordinator). Let N denote a random variable representing the number of backlogged nodes at the beginning of a BI and n denote an outcome of N . We also allow the requirement for the number of successful packets k to vary as a function of n , and we capture this dependence through the notation $k(n)$. We define a generic function $k(n) = \min(\alpha_1 n, \alpha_2 N_{all})$, where $\alpha_1, \alpha_2 \in (0, 1)$ and $\alpha_1 \geq \alpha_2$. This function typically allows k to increase proportionally with n until it hits the upper bound $\alpha_2 N_{all}$ when n is close to N_{all} . In addition, we introduce the following notation.

- p_N : probability mass function of N .
- D_{max} : maximum delay constraint, [s].
- $W_{k(n)}$: probability of at least k successes out of n nodes.
- $\eta_{k(n)}$: a user-specific QoS requirement for $W_{k(n)}$.
- S_{bn} : slot duration for the BF, [s].
- S_{sd} : length of SD, [s].
- S_{bi} : length of BI, [s].
- S_{nip} : average node idle time spent in backoff state, [s].
- S_{nsp} : average node sleep time, [s].
- m_{cca} : average number of CCA operations in one BI.
- m_{tx} : average number of packet transmissions in one BI.

- P_{act} : average coordinator power consumption in SD, [mW].
- P_{idle} : node power consumption in idle period, [mW].
- P_{sleep} : node power consumption in sleep period, [mW].
- E_{sum} : overall energy consumption in one BI, [mJ].
- E_0 : node energy consumption to wake up and listen to the BF, [mJ].
- E_t : node energy consumption to transmit a packet, [mJ].
- E_{cca} : energy consumption to perform a CCA, [mJ].

A. Traffic Model

In the scenario we consider, a node becomes backlogged if during the previous BI one or more packets have been generated for transmission. The random variable N is generally distributed and this distribution is denoted as $p_N(n)$.

In our setup, we assume that when a node generates a new packet, it will be accommodated into the transmission buffer if the buffer is empty. When there is already a packet in the node's buffer, the action taken depends on the status of the node. If the node is active, it means the buffered packet is attempting to transmit, so the new packet will wait to transmit in the next BI. If the node is sleeping, the new packet will replace the old one, which will be discarded.

B. Energy Model

A typical sensor node is comprised of several sub-systems such as a microcontroller unit, a radio and a sensing device, each of which consumes energy when a node works [5]. In our energy model, we only investigate the energy consumption of the radio unit, which is closely related to the design of MAC protocols. To simplify the energy model, we use the non-acknowledgment mode of the standard and assume an ideal channel such that every transmitted packet that does not suffer a collision is successfully received. The overall energy consumption in a network during one BI consists of several components.

Firstly, the network coordinator is active for S_{sd} and inactive for $(S_{bi} - S_{sd})$. Secondly, every node spends energy E_0 in waking up and listening to the BF. When a node wakes up, it switches from the sleep mode to receive mode and turns on its radio. Thirdly, for the backlogged nodes, they on average

Parameter	Value
Voltage (V)	3
Transmit current (mA)	20
Receive current (mA)	15
Idle current (mA)	10
Avg. current (coord. active) (mA)	16
Sleep current (mA)	0.03
Initialize radio and time (mA, s)	$6, 3.5 \times 10^{-4}$
Turn on radio and time (mA, s)	$1, 1.3 \times 10^{-3}$
Sleep to RX and time (mA, s)	$15, 2.5 \times 10^{-4}$

TABLE II
ELECTRICAL SPECIFICATIONS.

perform m_{cca} CCA operations in one BI and m_{tx} of the nodes eventually transmit their packets using the slotted CSMA-CA mechanism. The CCA mode we choose for our energy model is “carrier sense only”, in which a busy medium is reported only when a signal with the modulation and spreading characteristics of IEEE 802.15.4 is detected [1]. Moreover, a backlogged node on average spends S_{nip} in the backoff state and goes back to sleep for S_{nsp} , i.e., the rest of the current BI. Finally, non-backlogged nodes immediately go to sleep after the BF and expend $P_{sleep}(S_{bi} - S_{bn})$ amount of energy.

In summary, given that there are N_{all} nodes in a network and n of them are backlogged, the overall energy consumption in a BI, E_{sum} , is given by (1).

C. Energy Consumption Minimization

Our aim is to minimize the expectation of the overall energy consumption per unit time in one BI. To this end, we formulate an optimization problem as follows:

$$\begin{aligned}
\min : & \frac{1}{S_{bi}} \sum_{n=0}^{N_{all}} p_N(n) E_{sum}(n) \\
s.t. & W_{k(n)} \geq \eta_{k(n)} \\
& S_{bi} + S_{sd} - S_{bn} \leq D_{max} \\
& 0 \leq SO \leq BO \leq 14
\end{aligned} \quad (2)$$

where $n = 0, 1, \dots, N_{all}$. The decision variables are SO and BO . Note that S_{sd} and S_{bi} are one-to-one functions of SO and BO , respectively. The first constraint is to satisfy that at least k out of n nodes are successful with probability no less than $\eta_{k(n)}$, and the second constraint is to meet the maximum delay requirement. The worst case packet delay we consider is equal to $S_{bi} + S_{sd} - S_{bn}$. The third constraint $0 \leq SO \leq BO \leq 14$ is imposed by the standard.

IV. NUMERICAL RESULTS

We adopted the electrical specifications used in [6] (reproduced in Table 2), which are based on the CC1000 transceiver [7]. We assume that the locations of the nodes remain unchanged once they are deployed, and thus we can use constant transmit and receive power levels. We chose Poisson processes for packet generation of the nodes, which means that for each node, the probability to become backlogged at the beginning of a BI is given by $p_{nd} = 1 - e^{-\lambda t}$, where $t = S_{bi}$

Parameter	Value
Data packet size (PHY) (bytes)	25
Beacon frame size (bytes)	25
Maximum packet delay D_{max} , (s)	5
Packet arrival rate λ , (pkts/s)	0.5
QoS requirement $\eta_{k(n)}$	variable

TABLE III
SYSTEM PARAMETERS.

N_{all}	$\eta_{k(n)} = 0.7$		$\eta_{k(n)} = 0.9$	
	SO	BO	SO	BO
5	0	7	0	7
10	0	7	0	7
15	0	7	1	7
20	1	7	1	7
25	1	7	1	7
30	1	7	1	7
35	1	7	2	7

TABLE IV
OPTIMAL SOLUTIONS IN THE 2.4 GHz FREQUENCY BAND.

and λ is the packet arrival rate. Given a network with N_{all} sensor nodes, the probability mass function of N is given by $p_N(n) = \binom{N_{all}}{n} p_{nd}^n (1 - p_{nd})^{N_{all} - n}$. We set $\alpha_1 = 0.8$ and $\alpha_2 = 0.7$ in $k(n)$, which requires that most of the packets need to be transmitted successfully.

We implemented a C-based simulator for the IEEE 802.15.4 MAC. Some system parameters used in our simulations are shown in Table 3. For each set of parameters (i.e., SO , BO , n and N_{all}), we ran a simulation to obtain the proportion of successful packet transmissions $W_{k(n)}$ and the other parameters (m_{cca} and m_{tx}) required to compute the energy consumption based on (1). We have repeated the process a sufficient number of times such that the radius of the 95% confidence interval based on student-t distribution is within 5% of the energy consumption value. Since SO , BO are both integer-valued and their ranges are limited by D_{max} , we were able to use exhaustive search to solve (2). Optimal solutions for the 2.4 GHz frequency band are shown in Table 4 for various user-specific QoS parameters. Similar results can be found for other frequency bands.

V. CONCLUSIONS

We have formulated an optimization problem to determine the optimal MAC attributes *macBeaconOrder* and *macSuperframeOrder* for an IEEE 802.15.4 beacon-enabled star network. This problem is to minimize the energy consumption per unit time of the network and constrained by some user-specific QoS requirements, such as proportion of successful packet transmissions and maximum delay constraint. Optimal solutions can be found using a simple exhaustive search method through the simulation of the IEEE 802.15.4 MAC.

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