Energy optimization for upstream data transfer in 802.15.4 beacon-enabled star formulation

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ABSTRACT

Energy saving is one of the major concerns for low rate personal area networks. This paper models energy consumption for beacon-enabled time-slotted media accessing control cooperated with sleeping scheduling in a star network formulation for IEEE 802.15.4 standard. We investigate two different upstream (data transfer from devices to a network coordinator) strategies: a) tracking strategy: the devices wake up and check status (track the beacon) in each time slot; b) non-tracking strategy: nodes only wake-up upon data arriving and stay awake till data transmitted to the coordinator. We consider the tradeoff between energy cost and average data transmission delay for both strategies. Both scenarios are formulated as optimization problems and the optimal solutions are discussed. Our results show that different data arrival rate and system parameters (such as contention access period interval, upstream speed etc.) result in different strategies in terms of energy optimization with maximum delay constraints. Hence, according to different applications and system settings, different strategies might be chosen by each node to achieve energy optimization for both self-interested view and system view. We give the relation among the tunable parameters by formulas and plots to illustrate which strategy is better under corresponding parameters. There are two main points emphasized in our results with delay constraints: on one hand, when the system setting is fixed by coordinator, nodes in the network can intelligently change their strategies according to corresponding application data arrival rate; on the other hand, when the nodes' applications are known by the coordinator, the coordinator can tune the system parameters to achieve optimal system energy consumption.

Keywords: 802.15.4, Low Rate Personal Area Network, Energy Optimization, MAC sublayer beacon-enabled

1. INTRODUCTION

With consideration of low cost, low power, short range wireless devices, the low rate personal area networks have emerged with widely used applications. For example, the low rate wireless personal area networks (LR-WPANs) can be applied to light control, security alarms, motion sensors, thermostats, smoke detectors and personal health monitor system etc [1] .

The IEEE 802.15.4 standard focuses on low rate WPAN physical layer and MAC sublayer specification. Based on the IEEE 802.15.4-2006 [2] standard, we consider a star topology WPAN consists of one PAN coordinator and some application devices. The PAN coordinator sends out beacons periodically, to synchronize devices and specify the structure of the superframe. The goal of this study is to find a method to minimize the total system energy cost (i.e., summation of energy consumption through all the application devices) in unit time.

The main contribution of this work is to investigate when to use two application specific strategies (namely, tracking beacon strategy and non-tracking strategy) to reduce energy consumption. We derive the expression for the network devices to determine the appropriate strategy according to different superframe interval lengths. We also investigate how the network coordinator can calculate the superframe interval length to minimize the network power consumption.

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The paper is organized as follows. In section 2, we talk about related works and compare the difference between our work and other works. The network configurations and reasonable assumptions are presented in section 3. With the network configuration, we formulate and solve the energy optimization problem mathematically in section 4. The advantages and disadvantages of our formulation are discussed in section 5. Finally, we conclude the work in section 6.

2. RELATED WORKS

The power saving problem had been widely studied in the wireless network literature [3] [4] [5] [6] [7]. In 2002, Ye *et al.*[6] proposed S-MAC, a medium access control (MAC) protocol designed for wireless sensor networks. The most important technique employed by S-MAC to reduce energy consumption is the sleep schedule. Different with S-MAC, instead of using a fixed duty cycle, Dam *et al.*[7] proposed T-MAC with adaptive active time to further reducing idle listening. However, these works are not specifically on low rate personal area networks as specified in IEEE 802.15.4. Compared other wireless networks which aim to provide high-throughput, low-latency data transfer services, the required data rate for LR-WPAN applications is expected to be only on the order of tens of kbps. The objective of IEEE 802.15.4 standard is to provide a guidance to form a network with ultra-low complexity, cost, and power for low-data-rate wireless connectivity among cheap fixed devices. With these new characteristics for LR-WPAN, new performance evaluation needs to be conducted and new strategies to lower the power consumption needs to be considered. Several works have been done specifically on IEEE 802.15.4 standard power consumption problem [8] [9] [10] [11] [12] [13] [14] [15] since the first version of this standard was published in 2003.

Huang and Pang[15] provided a thorough study via simulations with NS2 simulator energy to evaluate the power saving mechanism for IEEE 802.15.4-2003 standard by changing the traffic load, beacon order and super-frame order parameter. Lee *et al.*[11] conducted a series of real experiment on IEEE-802.15.4-2003 standard to show that the standard perform in energy consumption.

Lu *et al.*[14] conducted one of the first simulation-based performance evaluations on IEEE 802.15.4-2003, focusing on its beacon-enabled mode for a star topology network. The authors also provide a preliminary analysis comparing the energy costs of beacon tracking and non-tracking modes for synchronization by simulation. Extending their work, we mathematically form and solve the energy optimization problem from both a self-interested perspective (strategy decided by devices) and system view (parameters optimized by PAN coordinator) based on IEEE 802.15.4-2006 configuration.

3. BASIC NETWORK CONFIGURATIONS AND ASSUMPTIONS

Before we go further to the problem formulation, we introduce the basic network configurations and the corresponding assumptions of our formulation in this section. The network topology used in our formulation is specified in section 3.1, which is followed by a brief introduction to the MAC layer data transmission in LR-WPAN star topology. Four different kinds of energy consumption for a battery powered network devices in each duty circle are described in section 3.3. At the end of this section, we depict the two different communication strategies a network device can choose to transmit data with the network coordinator.

3.1 The Network Topology

In IEEE 802.14.5 LR-WPAN standard specification, there are two typical operating network topologies that are mentioned with respect to different application requirements: the star topology and the peer-to-peer topology. In this formulation, we only consider the star topology as shown in figure 1. In this topology, the network communication is established between devices and a single central controller, called the PAN coordinator. A device typically has some associated application and is either the initiation point or the termination point for network communication. A PAN coordinator may also have a specific application, but it can be used to initiate, terminate, or route communication around the network.In the real world, the PAN coordinator might often be mains-powered, while the devices will most likely be battery-powered. Hence, in our formulation, we focus on the energy consumption of the devices in the network.

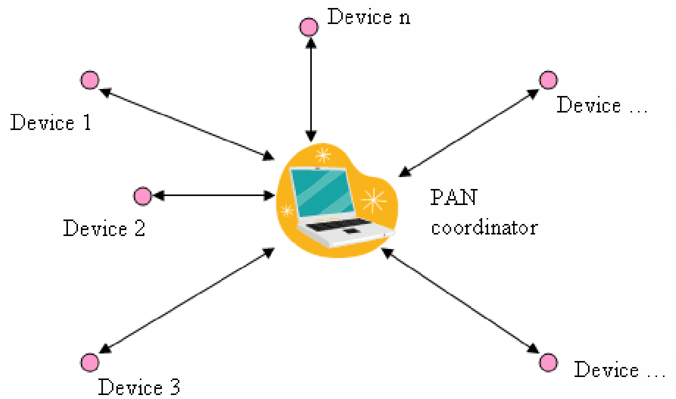

Figure 1. An illustration of the star network topology.

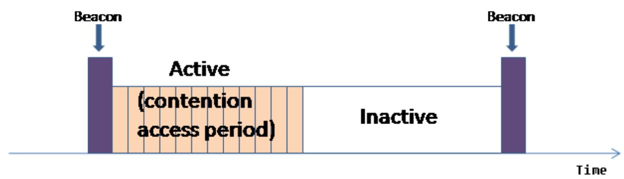

Figure 2. An illustration of superframe defined by the PAN coordinator.

3.2 MAC Sublayer Data Transfer to Coordinator

In this paper, we focus on a beacon-enabled MAC sublayer structure. As described in the standard, the beacon frame is a control frame that is transmitted in the first slot of each superframe. The beacons are used to specify the structure of a superframe. All transactions between the devices and coordinators are completed between two adjacent beacons. In this formulation, we consider a superframe that contains both an active period and an inactive period besides beacon for a coordinator. The active period only contains contention access period (CAP), and the corresponding beacon describes the time interval of the active period and inactive period, as shown in figure 2. Any device attempting to communicate during the CAP between two beacons competes with other devices using a slotted CSMA-CA mechanism in coordinator active period.

There are two types of data transfer transaction that exist in a star topology PAN. The first one is the data transfer to a coordinator in which a device transmits the pending data. The second transaction is the data transfer from a coordinator in which the device receives the data. We consider the power consumption of the first case (i.e. the upstream data transfer) in this work.

When a device wishes to transfer pending data to a coordinator in a beacon-enabled PAN, it first listens for the network beacon. When the beacon is found, the devices synchronize to the superframe structure. At the appropriate time, the device transmits its data frame, using slotted CSMA-CA to the coordinator. The coordinator may acknowledge the successful reception of the data by transmitting and optional acknowledgement frame. Note that we assume there is no acknowledgement from the coordinator in our problem formulation.

In the problem we consider, the PAN coordinator can configure the lengths of active period and inactive period according to the packet arrival rates for all the devices in the network. The goal of the PAN coordinator is to minimize the system energy consumption when considering the maximum average delay constraints.

3.3 Duty Cycle and Energy Consumption

As we have mentioned before, in a large portion of applications that use IEEE 802.15.4 standard, devices will be battery powered, and battery replacement or recharging in relatively short intervals is impractical. Therefore, the power consumption is of significant concern in this kind of network. In this case, for battery-powered devices, mechanisms like duty-cycling can make more efficient use of the limited power resources.

Each non-coordinator device has active period and sleep period in a duty cycle. During active period, the device can be at one of the following three status: 1) listening to the channel, looking for a beacon. This happens to the devices that are not tracking or synchronizing with beacons. We will discuss this scenario in more detail in next section; 2) receiving beacon from the PAN coordinator; 3) transmitting pending data to the PAN coordinator using slotted CSMA-CA in coordinator active period.

There are four kinds of different energy consumption in one duty cycle for the devices: transmitting, receiving, idle listening and sleeping. Among them, transmitting data costs most energy and sleeping costs least energy per unit time.

The power supply specification differs with different motes. For example, for CC2420 sensors[16] , transmit mode operates at 8.5 to 17.4 mA; receive mode operates at 18.8 mA; idle mode operates at 426 μA and the power down mode (i.e., sleeping mode) operates at 20 μA.

3.4 Devices Strategies: Tracking VS Non-tracking

There are two options for the non-coordinator nodes* for data transmission: tracking the beacon or not. If a device chooses tracking strategy, it wakes up at the beginning of each superframe and synchronizes with the beacon. If there is pending data in its queue, the device will try to transmit the data to the PAN coordinator in this superframe during PAN coordinator active period. Otherwise, the device will go back to sleep till next beacon from the PAN coordinator.

If a node has fairly low data arrival rate, it might not be willing to wake up every superframe. In this case, a better strategy in terms of energy saving for this node might be not tracking the beacon. Such node only wakes upon data arrival. The node does not synchronize with the PAN coordinator. If a packet arrives at the node, the node will wake up and begin listening to the channel till it hears a beacon. In the corresponding superframe, the node tries to transmit the data to the PAN coordinator and then go back to sleep status again till next data packet arrive. This strategy particularly fits some low data arrival rate applications such as personal weight monitor devices. In these applications, the data might only arrive several times during a day.

4. PROBLEM FORMULATION

In this section, we describe the formulation of the energy consumption for IEEE 802.15.4 MAC sublayer. The energy optimization in a star topology LR-WPAN considers two aspects: 1) from the devices' point of view, we discuss what strategy should the devices pick (tracking beacon or non-tracking) to minimize their energy consumption; 2) from the PAN coordinator's view, we discuss how a coordinator should pick the active period length and inactive period length to minimize the whole network's energy consumption.

We use table 4 to summarize most of the notation we will use in the formulation.

4.1 Energy Optimization

In this section, we formulate the global optimization of energy consumption into two complementary parts. On one hand, devices decide in a distribute fashion whether to track the beacon or not depending on their local traffic and the PAN superframe length. On the other hand, the PAN coordinator determine the superframe length according to the total network traffic to minimize the system power consumption.

4.1.1 Devices: Tracking or Non-tracking

Given B, A and S (note that $B + A + S = I$), the objective of a network device i is to choose an appropriate strategy to minimize its own average energy consumption per unit time according to application packet arrival rate R_i subject to delay constraints. The packet arrival process is modeled as Poission process. Mathematically, we model the optimization problem as linear programming in equations below.

*In the following of this paper, we use devices and nodes inter-changeably. If not specifically pointed out, the PAN coordinator is not referred to as a device.

Notations	Physical Meaning and Units
B	Beacon length (seconds)
A	Coordinator active period (seconds)
S	Coordinator inactive period (seconds)
I	Coordinator superframe length (seconds)
α	Device energy consumption per unit time when transmitting packets (Joule/second)
β	Device energy consumption per unit time when receiving packets (Joule/second)
γ	Device energy consumption per unit time when idle listening (Joule/second)
κ	Device energy consumption per unit time when sleeping (Joule/second)
R_i	Averaged application data arrival rate for device i (packets/second)
λ	Per packet handling time (seconds)
D	the maximum average delay constraints (seconds)
D_i	the maximum average delay for device i (seconds)
P_{d_i}	Averaged power consumption per unit time for device i

Table 1. Notation Table

$$\begin{aligned} min \quad & P_{d_i} \\ subject\ to \quad & D_i \leq D \ \ \forall i \end{aligned} \tag{1}$$

Now we discuss how to calculate P_{d_i} in each scenario. First of all, it is obvious that if $R_i > \frac{1}{I}$, the node is likely to wake up wake up in every superframe. In this case, tracking strategy is more suitable for the application. Hence, we will focus on the case where $R < \frac{1}{I}$ in the rest of this paper.

If a node chooses tracking mode, the average delay of the packets can be calculated as $D_i = \frac{I}{2} + B + T_{tx}$, where T_{tx} is the expected waiting time in slotted CSMA-CA process before successfully transmission a packet to coordinator. On average, the energy consumption per slot can be calculated as in equation (2).

$$P_{d_i}^{tracking} = \frac{\beta B + R_i I(P_{tx}) + (1 - R_i I)(I - B)\kappa}{I} \tag{2}$$

where P_{tx} presents the expected energy cost to in the superframe of successfully transmitting a packet CSMA-CA, including the power spent in sensing the channel, during the backoff, in transmitting the packet to the PAN coordinator and in the sleeping mode after finishing the transmission till next beacon.

If the device chooses non-tracking strategy, the average delay of the packets remains the same while the average energy consumption in per slot can be calculated as in equation (3).

$$P_{d_i}^{non-tracking} = R_i(\frac{1}{2}I\gamma + \frac{1}{2}I\kappa + P_{tx}) + (1 - R_i I)\kappa \tag{3}$$

In terms of average energy cost, considering equation (2) and (3), we can infer that when

$$R_i \geq \frac{2(\beta - \kappa)B}{I^2(\gamma + \kappa) + BI\kappa}$$

tracking strategy is better for the corresponding application. On the other hand, if

$$R_i \leq \frac{2(\beta - \kappa)B}{I^2(\gamma + \kappa) + BI\kappa}$$

non-tracking strategy is better in terms of energy saving for the device in network.

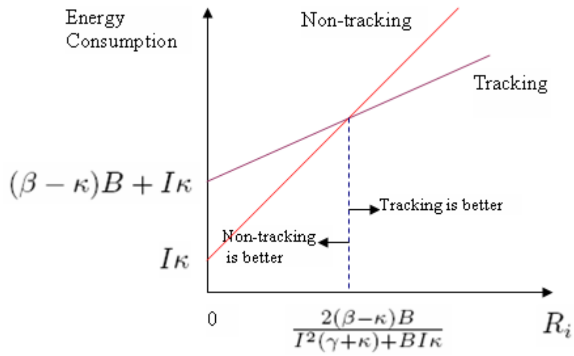

Figure 3. A plot to show better strategy for device i according to R_i,I and B

The appropriate strategy for device i according to the application data arrival rate R_i and system parameters is shown in figure 3.

As we have mentioned in previous sections, each device has different power consumption parameters and these parameters are specified in the device manual. From the above equations, we can infer that the strategies of the network nodes are purely depending on application data arrival rate and network parameters (beacon length B and superframe length I). The superframe length I is a tunable parameter which can be decided by the PAN coordinator.

4.1.2 PAN Coordinator: Minimize the Network Energy Consumption

From the discussion above, we note that the strategy picked by network devices to minimize their energy consumption is based on the announced superframe length I. In this section, we assume that the PAN coordinator knows the arrival rate R_i of the applications in this network before hand. The objective of the PAN coordinator is to decide a superframe length to minimize the power consumption throughout the network subject to the delay constraints.

First of all, we assume the system is stable. That is, the buffer queue for each device will not go to infinity in a long time period. This means that the PAN coordinator active period A should be large enough to handle all the arrived packets in the time period I. Mathematically, I and A need to satisfy

$$\lambda \sum_i R_i I \leq A \tag{4}$$

The equation above describes that the length of active period for PAN coordinator should exceed certain portion of the whole superframe length, according to the applications involved in the network.

We define the system power consumption as the summation of all the devices' (not including the PAN coordinator) power consumption in the network. The objective of the PAN coordinator can be mathematically presented as follows:

$$\begin{aligned} &\textit{minimize} && \sum_{i=1}^{n} P_{d_i} \\ &\textit{subject to} && \lambda \sum_i R_i I \leq A \\ & && D_i \leq D \quad \forall i \end{aligned} \tag{5}$$

where n is the total number of nodes in the network.

We can solve this linear optimization problem numerically in the following steps. First, sort the packet arrival rates in the network in ascending order. Without of loss of generality, we denote the average arrival rates as $R_1 \leq R_2 \leq ... \leq R_n$. According to the discussion in the previous sections, when superframe length I is given, the applications with arrival rate lower than $\frac{2(\beta-\kappa)B}{I^2(\gamma+\kappa)+BI\kappa}$ will choose non-tracking strategy and other devices will choose tracking strategy.

We first discuss the case where the network exists both tracking and non-tracking devices, then compare the average system energy consumption in unit time with the two extreme case where the system only contains tracking devices or non-tracking devices. Suppose there exists a number m $(1 \leq m \leq n)$ $R_m \leq \frac{2(\beta-\kappa)B}{I^2(\gamma+\kappa)+BI\kappa} \leq R_m + 1$, the average network energy cost per unit time can be expressed as follows. Notice that $B < I$ and $\kappa << \gamma$ in practice. We therefore ignore $BI\kappa$ in the denominator comparing to $I^2(\gamma + \kappa)$ in the rest of the paper for simplicity.

$$\sum_{i=1}^{n} P_{d_i} = \sum_{i=1}^{m} P_{d_i}^{non-tracking} + \sum_{i=m+1}^{n} P_{d_i}^{tracking} \tag{6}$$

It is hard to get closed form solution for this problem, but the PAN coordinator can solve this problem numerically. Notice that the second derivative of this objective function is positive definite. Let the first order derivative of the object function to be 0, we have get that the minimum value occurs at the point where

$$I^2 = \frac{2(n-m)\beta B}{\sum_{i=1}^{m} R_i(\gamma+\kappa) - 2\sum_{i=1}^{n} R_i} \tag{7}$$

However, the superframe interval I should also satisfy the condition that

$$\sqrt{\frac{2\beta B}{R_{m+1}(\gamma+\kappa)}} \leq I \leq \sqrt{\frac{2\beta B}{R_m(\gamma+\kappa)}} \tag{8}$$

If I cannot reach the value derived from equation (7), the minimum value of the objective function occurs at one of the boundary points in equation (8).

In order to find the proper superframe length I, the PAN coordinator needs to check $n + 1$ intervals $((0, R_1], (R_1, R_2], ..., (R_k, R_{k+1}], ..., (R_{n-1}, R_n], (R_n, \inf))$ one by one. In each interval, the PAN coordinator calculates the possible minimum value the objective function could reach, considering the delay constraints† and the constraint expressed in equation (8). Among all the possible superframe length in $n + 1$ intervals, the PAN coordinator picks up one that globally minimizes the objective function.

5. DISCUSSION

In this work, we have investigated how to minimize the total energy consumption in a star topology LR-WPAN via MAC layer configuration. The basic configuration follows IEEE 802.15.4 specification. The tunable parameters in this problem are also adjustable options in IEEE 802.15.4 standard.

There are two roles in a star topology LR-WPAN: the coordinator and the application devices. We have assumed that the PAN coordinator has the knowledge of each application's arrival rate in the network and decides how long each superframe last to minimize the total power consumption in the network. Each device reasonably chooses tracking beacon or non-tracking strategies to minimize its own power consumption according to the network superframe interval.

As we have seen, when the superframe interval I is given, it is relatively easy for the devices to choose a proper strategy. However, it is not easy for the coordinator to determine this length I. We cannot give the closed form solution for PAN coordinator to get the optimized I. However, we have pointed out that in a finite network, the problem is efficiently numerically solvable. The superframe length calculation can be performed offline before the coordinator sends out the first beacon.

When a new application joins the network, it stays in idle listening mode till it receives a beacon. In the corresponding superframe, the device sends its application arrival data to the coordinator to invoke a new

†The delay constraints make sure the superframe length I is upper bounded.

calculation of superframe interval. The coordinator will then deliver the new superframe interval with the next beacon to the network.

How to detect a dead or leaving node in this network becomes an open problem. The coordinator does not have the capability to detect when a node uses up its battery unless explicitly informed. This fact may make the power consumption minimization mechanism sometimes sub-optimal.

6. CONCLUSIONS

Energy saving is one of the major concerns for personal area networks. In this paper, we model energy consumption for beacon-enabled time-slotted media accessing control in a star topology for IEEE 802.15.4-2006 standard. For the devices, two different upstream strategies are investigated: tracking beacon strategy (wake-up to receive and synchronize with each beacon) and non-tracking strategy (wake-up upon data arriving and turn to idle listening mode till a beacon is found). Power consumption for both strategies are compared with maximum delay constraint. Our results show that different data arrival rate and system parameters (beacon interval etc.) result in different strategies in terms of energy optimization with maximal delay constraints.

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