Regular paper

Journal of the KIECS. pp. 9-16, vol. 11, no. 1, Jan. 31 2016, t. 69, pISSN 1975-8170 | eISSN 2288-2189
http://dx.doi.org/10.13067/JKIECS.2016.11.1.9

IEEE 802.15.4 저속 WPAN에서 듀티 사이클과 비콘 추적의 통합 제어

박성우[*]

Joint Control of Duty Cycle and Beacon Tracking in IEEE 802.15.4 LR-WPAN

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요 약

IEEE 802.15.4 LR-WPAN에서 대부분의 디바이스는 배터리에 의존해 동작하기 때문에 효율적인 에너지 소비 기능을 갖추도록 설계되어야 한다. 본 논문은 LR-WPAN에서 에너지 절약을 위한 두 개의 알고리즘, DDC (Dynamic Duty Cycle)와 DBT(: Dynamic Beacon Tracking)를 제안한다. DDC 알고리즘은 채널 상태에 따라 듀티 사이클을 동적으로 조정한다. DBT 알고리즘은 트래픽 조건에 따라 비콘 트래킹 모드를 적응적으로 제어한다. 또한, DDC와 DBT 알고리즘을 결합함으로써 프레임 전달률과 평균 지연 시간을 만족할 만한 수준으로 유지하면서 광범위한 입력 부하에 대해 효과적으로 에너지를 절약할 수 있다.

ABSTRACT

Since most of devices in the IEEE 802.15.4 LR-WPAN are expected to operate on batteries, they must be designed to consume energy in a very conservative way. Two energy conservation algorithms are proposed for the LR-WPAN: DDC (Dynamic Duty Cycle) and DBT (Dynamic Beacon Tracking). The DDC algorithm adjusts duty cycle dynamically depending on channel conditions. The DBT algorithm switches beacon tracking mode on and off adaptively depending on traffic conditions. Combining the two algorithms reduces energy consumption more efficiently for a wide range of input loads, while maintaining frame delivery ratio and average delay at satisfactory levels.

키워드

IEEE 802.15.4, LR-WPAN, Duty Cycle, Beacon Tracking
IEEE 802.15.4, 저속 WPAN, 듀티 사이클, 비콘 추적

Ⅰ. Introduction

The IEEE 802.15.4 LR-WPAN is a low-rate, wireless network that can be applied for ubiquitous computing systems such as home automation, environmental monitoring, and telematics etc[1-2]. Standardization of the LR-WPAN is conducted by Zigbee Alliance and IEEE 802.15 WG. The Zigbee Alliance is building an overall protocol architecture, leaving the details of MAC and PHY to be defined by the IEEE 802.15.4. The MAC/PHY layers have been implemented by several companies as their

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• 접 수 일 : 2015. 10. 27
• 수정완료일 : 2016. 01. 13
• 게재확정일 : 2016. 01. 24

• Received : Oct. 27, 2015, Revised : Jan. 13, 2016, Accepted : Jan. 24, 2016

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commercial products[1][2].

The LR-WPAN, where most devices operate on batteries, prefers to have devices with a longer lifetime that can last from several months to years without replacing batteries. In the IEEE 802.15.4 MAC, duty cycle and beacon tracking mode play important roles in energy management. The duty cycle must be carefully chosen so that energy can be conserved more efficiently. Otherwise, energy would be unnecessarily wasted due to excessive frame collisions or prolonged idle states. Selective use of beacon tracking mode also causes devices to consume less energy by enabling them to be active only when needed. Thus, a well-controlled duty cycle or beacon tracking may lead to a considerable amount of reduction in energy consumption. Several related works have been made to conserve energy in the LR-WPAN[3-5].

With the same objective to enhance energy efficiency, two algorithms are proposed: DDC(: Dynamic Duty Cycle) and DBT(: Dynamic Beacon Tracking). The DDC algorithm adjusts duty cycle dynamically depending on channel conditions. The DBT algorithm turns beacon tracking mode on and off adaptively depending on traffic conditions. The combination of two algorithms reduce further energy consumption in the LR-WPAN.

The remainder of this paper proceeds as follows. Section 2 introduces the IEEE 802.15.4 standard. Two energy saving algorithms are described in Section 3. Simulation results are discussed in Section 4. Finally, Section 5 concludes this paper.

Ⅱ. IEEE 802.15.4 Overview

2.1 Network Topology

As shown in Fig. 1, the IEEE 802.15.4 LR-WPAN may have two types of topology: star and peer-to-peer. The standard mainly deals with frame transmission on a single-hop basis[6]. The star topology allows frames to be exchanged only between the PAN coordinator and the devices. Issues related to multi-hop transmission such as routing and beacon scheduling are discussed separately in the Zigbee Alliance.

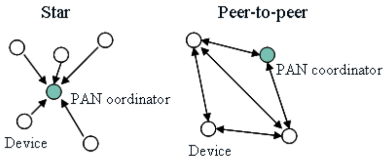

Fig. 1 Topologies in the LR-WPAN

2.2 Superframe Structure

In the beacon-enabled LR-WPAN, network synchronization is maintained by beacon frames sent periodically by the PAN coordinator. Frame transfer between the PAN coordinator and the devices must conform to the superframe structure, shown in Fig. 2. The nonbeacon-enabled LR-WPAN allows the devices to operate without the beacon frames. We restrict our focus on the beacon-enabled LR-WPAN only.

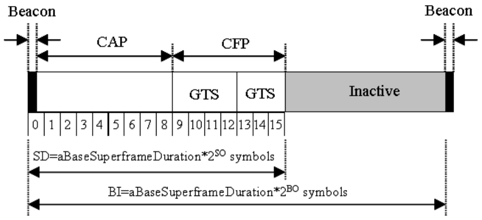

Fig. 2 Superframe structure

A superframe starts with the reception of beacon frame from the PAN coordinator. The superframe is divided into two parts: the active and inactive periods. Devices are allowed to exchange frames only during the active period, and sleep during the inactive period to save energy consumption. Being

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[1] http://www.atmel.com

[2] http://www.ti.com

composed of 16 equally-spaced time slots, the active period again consists of three sub-periods: beacon, CAP(: Contention Access Period), and CFP(: Collision Free Period). The GTS(: Guaranteed Time Slot) is used to deliver delay-sensitive frames within the CFP[7].

2.3 Data Transmission

A device that wants to transmit data frames to the PAN coordinator must first receive a beacon frame and understand the structure of superframe. If the device is assigned the GTS, it transmits data frames during the CFP. Otherwise, data frames are transmitted using the slotted CSMA-CA during the CAP beginning just after the reception of the beacon frame.

2.4 Duty Cycle

Shown in Fig. 2 are BO(: Beacon Order) and SO(: Superframe Order) that are directly related to BI(: Beacon Interval) and SD(: Superframe Duration), respectively. The MAC constant, *aBaseSuperframeDuration* defined in the standard takes 960 symbols as default. One symbol corresponds to 16μs when data rate is 250Kbps at 2.4GHz. Both BO and SO ranges from 0 (15ms) to 14 (245s). The duty cycle is defined as the ratio of active period to the beacon interval: $2^{SO}/2^{BO}$. Considering energy consumption as well as channel interference, the duty cycle of less than 1% would be used in most applications.

The duty cycle may take a default value or, if necessary, vary according to the circumstances. In the latter case, the duty cycle needs to be managed dynamically by the PAN coordinator in a centralized way. The PAN coordinator determines the proper duty cycle in consideration of network conditions and broadcasts the latest value via the BO and the SO fields in the beacon frames.

2.5 Beacon Tracking

In the beacon-enabled LR-WPAN, the PAN coordinator broadcasts the beacon frames periodically to inform other devices of the intended superframe structure. Before sending data frames, devices must receive a beacon frame and synchronize with the PAN coordinator first. There are two ways of synchronization: tracking mode and non-tracking mode.

In the tracking mode, a device is forced to receive every beacon frame sent from the PAN coordinator. Even if the device has no frame to be sent, it cannot but consume energy to receive the beacon frames and figure out the superframe structure. Fortunately, since the beacon arrival times are known a priori, the device can save some energy by activating its receiver for a short time only when it receives the beacon frames.

In the non-tracking mode, a device does not keep track of the beacon frames unless it has some data frames to be sent. Therefore, the device is not aware of when the next beacon frame arrives. As soon as data frames to be sent are generated, the device should turn on its receiver instantly and wait for the beacon frame in the idle state.

III. Energy Saving Algorithms

3.1 DDC(: Dynamic Duty Cycle)

Energy consumption in a device may become very inefficient when the duty cycle is not chosen appropriately. The smaller duty cycle shrinks the portion of active period relative to the beacon interval. This may cause some reduction in energy consumption. However, if the duty cycle is excessively small, the collision rate increases and the energy consumption normalized to the throughput may get even worse. When the duty cycle is too large, energy can be wasted due to the prolonged idle state during the active period. Besides, the duty cycle affects the network throughput, delay, and the channel interference and so on. Thus, the duty cycle needs to be carefully chosen by considering the network conditions as well as its effects to other performance indexes.

The DDC algorithm controls the duty cycle adaptively based on the measurements of channel conditions. The basic idea of the DDC algorithm is simple: increase the duty cycle when the channel condition is favorable and, otherwise, decrease it. The channel conditions during the CAP are characterized by channel utilization and collision rate at hand. The low channel utilization is usually followed by the small collision rate. However, this is not always the case. If the traffic is bursty over a specific time period, the collision rate may go higher even with the low channel utilization.

The DDC algorithm reduces the duty cycle only when both channel utilization and collision rate are sufficiently low together. On the contrary, if both are high, then the DDC algorithm increases the duty cycle. Besides the above two cases, if those two parameters show a controversial result against each other, the duty cycle remains unchanged. The DDC algorithm shown in Fig. 3 is performed every beacon interval at the PAN coordinator, just before the beacon frame is transmitted.

```
if ($N_r$ = 0)
    increase $C_i$ by one
else{
    compute $C_{avg}$
    if ($N_c/N_r > T_c$ and $C_{avg} > T_u$){
        increase $DC$        // duty cycle
        reset $C_{avg}$
    }
    else if ($N_c/N_r < T_c$ and $C_{avg} < T_u$){
        decrease $DC$        // duty cycle
        reset $C_{avg}$
    }
    else
        do nothing
    reset $C_i$
}
```

Fig. 3 Pseudo code of DDC algorithm

In Fig. 3, N_r and N_c represent the number of frames received from the devices and the number of frame collisions occurred during the current beacon interval, respectively. Both C_i and C_{avg} are the parameters related to the channel utilization. C_i is the cumulative number of beacon intervals passed with no data frames exchanged. C_{avg} represents the exponentially weighted moving average of C_i and is calculated by equation (1).

$$C_{avg} = \alpha \cdot C_{avg} + (1-\alpha) \cdot C_i \tag{1}$$

Here, α is an empirical constant and takes the value of 0.98. Since the DDC algorithm resets C_{avg} to 0 whenever the duty cycle is updated, α affects the update interval of duty cycle. That is, with the larger value of α, the duty cycle would be updated less frequently. DC represents the value of duty cycle. DC can be updated by changing either BO or SO. Lastly, T_c and T_u represent the thresholds for channel utilization and collision rate whose values are assigned 10 and 1, respectively.

3.2 DBT(: Dynamic Beacon Tracking)

As pointed out in [8], there is a trade-off between tracking mode and non-tracking mode from the viewpoint of energy management. In the tracking mode, energy can be wasted, due to power consumption for receiving unnecessary beacon frames. In the non-tracking mode, each device receives beacon frames only when required. Once the device decides to receive the beacon frame, however, it should wait until the beacon frame arrives, consuming energy in the idle state.

Assume that a device generates frames at a constant rate and denote their generation interval by I_F. If the frame interval is smaller than the beacon interval, that is, $I_F < BI$, at least one frame is generated during a beacon interval. Then the energy consumption in tracking mode is always less than that of non-tracking mode. The difference arises from the power consumption in the idle state of non-tracking mode. However, if the frame interval is larger than the beacon interval, $I_F > BI$, comparing the energy consumption wasted to receive the unnecessary beacon frames(tracking mode) and that wasted in idle states(non-tracking mode) becomes necessary to decide which mode runs in a more energy-efficient manner.

Let us denote the transmission time for the beacon frame by T_b and the power consumed for receiving the beacon frame by P_r. Then the energy dissipated by unnecessary reception of beacon frames in the tracking mode, denoted by E_{TR}, is given by equation (2).

$$E_{TR} = \lfloor \frac{I_F}{BI} \rfloor \cdot P_r \cdot T_b \tag{2}$$

Let P_i also denote power consumption during the idle state in the non-tracking mode. If we assume that frames arrive in the middle of beacon interval on average, then the energy wasted in the idle state before the arrival of beacon frame, denoted by E_{nTR}, can be calculated by equation (3).

$$E_{nTR} = P_i \cdot \frac{BI}{2} \tag{3}$$

According to equations (2) and (3), E_{TR} becomes low, with low data rate and large BI. On the other hand, E_{nTR} is favored by small BI. Fig. 4 shows the variations of E_{TR} and E_{nTR}, for some values of R, assuming that TI's CC2420 transceiver is used[9]. R represents the frame generation rate and equals to the inverse of frame interval. Power consumptions for frame reception and in idle state are given as $P_r = 35.5mW$ and $P_i = 0.77mW$, respectively. As shown in the Fig. 4, E_{nTR} is less than E_{TR} when the BO is small and, vice versa, with the larger BO. We also observe that the cross points move to the left as R becomes larger.

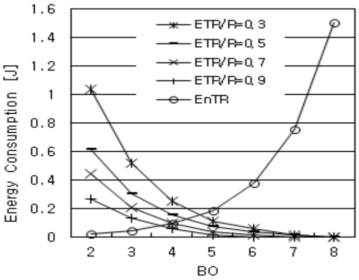

Fig. 4 E_{TR} vs. E_{nTR}

The DBT algorithm, described in Fig. 5, lets devices select alternatively between the tracking mode and the non-tracking mode in consideration of frame arrival rate and beacon interval. After comparing E_{TR} and E_{nTR}, the device decides to stay in the tracking mode if E_{TR} is less than E_{nTR}. Otherwise, the device operates in the non-tracking mode.

```
// tracking = 1: tracking mode
// tracking = 0: non-tracking mode
update $I_{avg}$
if (tracking and $E_{TR} > \gamma \cdot E_{nTR}$)
        tracking = 0
else if (!tracking and $E_{nTR} > \gamma \cdot E_{TR}$)
        tracking = 1
else
        do nothing
```

Fig. 5 Pseudo code of DBT algorithm

The DBT algorithm is triggered by the frame generation at each device. If the rate of frame generation is variable, I_F would be replaced by I_{avg}, which is the exponentially weighted average of I_F. I_{avg} is updated whenever frames are generated. The empirical constant $\gamma = 1.2$ is introduced to lessen the effects of oscillations between the two modes. In addition, if the DBT algorithm is combined with the DCC algorithm, the BI delivered from the PAN coordinator changes by the integer multiples, and thus needs to be smoothened out again by taking an exponentially weighted moving average.

Ⅳ. Performance Evaluation

4.1 Simulation Environments

NS-2 has been used to evaluate the performance of the proposed algorithms[3]. The star topology consists of one PAN coordinator and 15 devices, as shown in Fig. 6. The data rate is 250Kbps at 2.4GHz. Transmission powers used by the PAN coordinator and devices are equally set to 1mW. Devices are close enough so that the hidden terminal problems are eliminated.

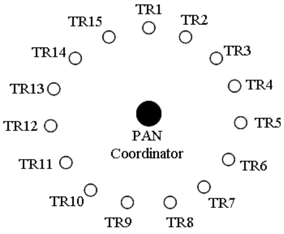

Fig. 6 Network topology for simulation

The PAN coordinator broadcasts the beacon frames periodically. Each device sends data frames, with a fixed length of 25 bytes, to the PAN coordinator in a CBR(: Constant Bit Rate) pattern. Data frames are sent using the CSMA-CA only during the CAP, without relying on the GTS. The simulation duration is 20,000 seconds for all cases.

The duty cycle in the DDC algorithm can be updated by changing either BO or SO. For the sake of simplicity, only BO is permitted to change; SO is set to 0, and BO is initialized to 8. Given the same duty cycle, frame delay can be minimized when the smallest value of SO is used.

4.2 Simulation Results

From Fig. 7 to Fig. 9, simulation results of the DDC algorithm in the tracking mode(DDC/TR) are shown in comparison with the cases when the beacon intervals are fixed (BO=n/TR). The letter n represents the value of BO and TR means that the tracking mode is activated. The x-axis indicates the data rate per device in bps as the input load.

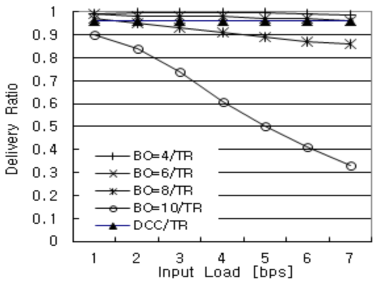

Fig. 7 Delivery ratio in tracking mode

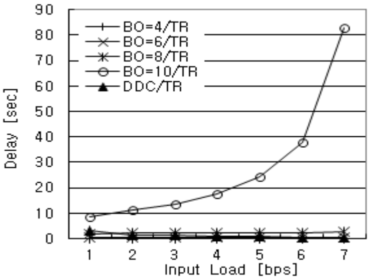

Fig. 8 Average delay in tracking mode

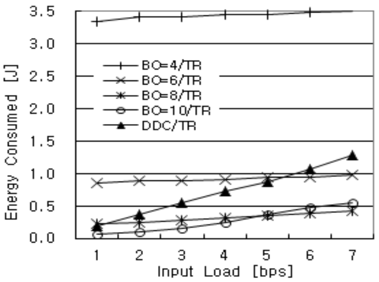

Fig. 9 Energy consumption in tracking mode

In Fig. 7 and 8, the DDC/TR achieves the satisfactory performance results comparable to the case of $BO=6/TR$, in terms of delivery ratio and average delay. In Fig. 9, energy consumption of the DDC/TR lies in between $BO=6/TR$ and $BO=8/TR$. The DDC/TR nears $BO=8/TR$ when input load is low. With lower input load, the DDC/TR tends to have the smaller duty cycle, and,

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[3] http://www.isi.edu/nsnam/ns/

accordingly, power consumption in beacon reception gets reduced. On the other hand, if the input load becomes higher, the DDC/TR approaches to $BO=6/TR$ to accommodate the increased traffic, consuming more energy. This implies that the DDC/TR controls the duty cycle dynamically depending on the traffic conditions and provides an efficient way of energy consumption.

From Fig. 10 to Fig. 12, the simulation results of the DDC algorithm(DDC/nTR) are shown in comparison with the cases when the beacon intervals are fixed(BO=n/nTR), both in the non-tracking mode.

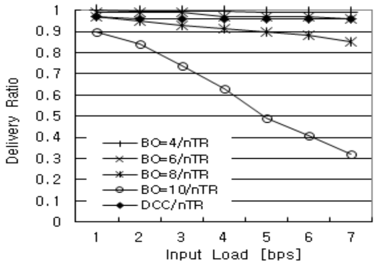

Fig. 10 Delivery ratio in non-tracking mode

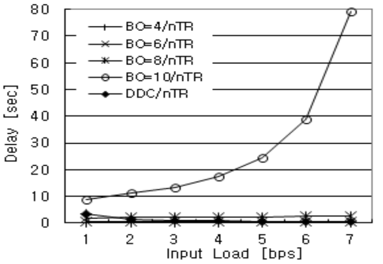

Fig. 11 Average delay in non-tracking mode

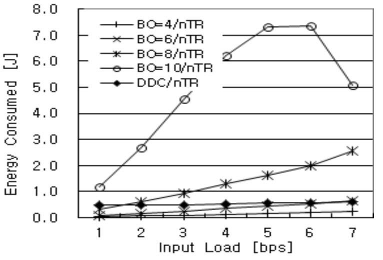

Fig. 12 Energy consumption in non-tracking mode

Like the DDC/TR, in Fig. 10 and 11, the DDC/nTR achieves the similar performance results comparable to the case of $BO=6/TR$, in terms of delivery ratio and delay. In Fig. 12, the energy consumption of the DDC/nTR also lies in between $BO=6/nTR$ and $BO=8/nTR$. However, as the input load increases, the energy consumption of the DDC/nTR does not increase as much as it did in the DDC/TR. If the duty cycle becomes larger with a higher input load, more power will be needed for frame transmission. At the same time, however, the power consumption in the idle states is reduced, compensating for the increased power consumption for frame transmission. The power consumption for the beacon reception is unaffected.

Fig. 13 shows energy consumption of the combined DDC and DBT algorithm(DDC+DBT), compared with the individual cases(DDC/TR and DDC/nTR).

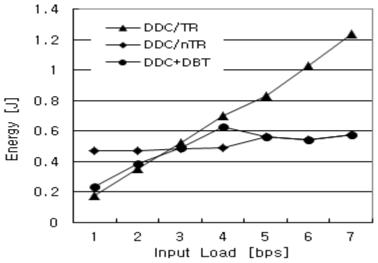

Fig. 13 Comparison of energy consumption for DDC/TR, DDC/nTR, and joint DDC+DBT

Let us assume that a device operates in the tracking mode with very low input load, that is, $E_{TR} < E_{nTR}$. As traffic increases, the PAN coordinator decrements BO (beacon interval) by the DDC algorithm. Then E_{TR} starts to increase while E_{nTR} remains almost constant. When E_{TR} and E_{nTR} cross over, the device changes its synchronization mode to the non-tracking mode.

In the opposite direction, assume that a device now operates in the non-tracking mode with very high input load, that is, $E_{TR} > E_{nTR}$. If the input traffic begins to decrease, then the PAN coordinator increments BO (beacon interval). Now both $E_{TR}$and E_{nTR} start to decrease together, but with E_{TR} changing more rapidly. In this case, the device changes its synchronization mode to the tracking mode when E_{TR} becomes less than E_{nTR}. By switching alternatively between the two modes as the given traffic conditions change, the device enhances the overall energy efficiency.

Ⅴ. Conclusion

Two algorithms have been proposed to provide a way to manage energy consumption more efficiently in the IEEE 802.15.4 LR-WPAN. The first one, known as the DDC algorithm, is performed by the PAN coordinator and the second one, known as the DBT algorithm, is performed by each device. The DDC algorithm controls dynamically over the duty cycle. This is attained by the measurement of channel utilization and collision ratio. The DBT algorithm selects the appropriate mode of beacon tracking, based on the frame rate and the duty cycle determined by the DDC algorithm. With the merits from the two algorithms combined together, the joint DDC and DBT algorithms exhibit better performance results.

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