LETTER

An Energy-Efficient Sleep Mode in IEEE 802.15.4 by Considering Sensor Device Mobility*

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SUMMARY The current version of IEEE 802.15.4 MAC protocol does not support energy-efficient mobility for the low-power device. In this paper, we propose an energy-efficient sleep mode as part of the IEEE 802.15.4 that can conserve energy by considering mobility of mobile sensor devices. The proposed energy-efficient sleep mode dynamically extends the sleep interval if there is no data to transmit from the device or receive from corresponding nodes.

key words: *IEEE 802.15.4, sleep mode, sensor device mobility*

1. Introduction

IEEE 802.15.4 [1] provides low-cost and low-speed communications between devices, allowing simple wireless connectivity in applications with limited power. The IEEE 802.15.4 defines fundamental lower network layers that include both physical and media access control (MAC) protocols. It is suitable for small sensor devices with low energy consumption in wireless sensor networks. The MAC protocol in the IEEE 802.15.4 is able to operate in either non-beacon or beacon-enabled modes. In the non-beacon mode, the protocol uses the simple carrier sense multiple access with collision avoidance (CSMA-CA) scheme. This requires continuous reception of possible incoming data. On the other hand, the power saving features that are critical within wireless sensor network applications are provided by the beacon-enabled mode. This paper considers only the beacon-enabled mode.

All communications in the beacon-enabled mode are performed within a superframe structure, which is presented in Fig. 1. The superframe is bounded via periodically transmitted beacon frames, which allow devices to synchronize with the network. An active part of the superframe is divided into 16 contiguous time slots that form three parts, as follows: the beacon, contention access period (CAP), and contention-free period (CFP). At the end of the superframe is an inactive period, allowing devices enter into power saving mode. The beacon interval (BI) and the active super-

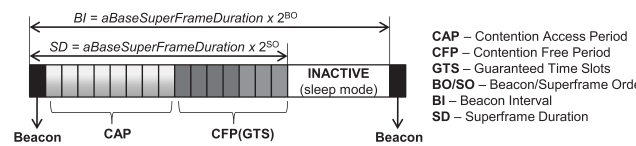

Fig. 1 Superframe structure of IEEE 802.15.4.

frame duration (SD) are adjustable by the beacon order (BO) parameters as follows:

$$BI = aBaseSuperframeDuration \times 2^{BO} \quad (1)$$

$$SD = aBaseSuperframeDuration \times 2^{SO} \quad (2)$$

where $aBaseSuperframeDuration = aBaseSlotDuration \times aNumSuperframeSlots$, and $0 \leq SO \leq BO \leq 14$.

In the IEEE 802.15.4-based sensor network, coordinators periodically transmit the superframe beacons to synchronize with their child-devices in predetermined intervals. According to the superframe beacon, the device sleeps the majority of the time for saving battery power during the inactive period, and then wakes up for listening to the next beacon frame. However, even though the device has no data to send or receive, it should continuously attempt to listen to the beacon frame by switching from the inactive to the active mode. This is a needless waste of energy given the low traffic rate of the wireless sensor networks.

In order to solve this inefficiency problem, a lot of work has been studied to reduce energy consumption for IEEE 802.15.4, such as beacon order adaptation [2], duty-cycle adaptation [3], and energy-efficient wakeup scheduling algorithm [4]. Additionally, various algorithms for power saving in IEEE 802.15.4 have evaluated by analysis and experiments [5]. However, no study has proposed the IEEE 802.15.4 MAC protocol considering sensor device mobility. In the previous algorithms, sufficient energy efficiency cannot be achieved when the sensor devices move to a new sensor network.

In this paper, we propose an energy-efficient sleep mode, which is able to extend the sleep interval dynamically, if no data is transmitted. For further enhancement of the extendable sleep mode, especially, we consider that the sensor device is possible to move between the sensor networks. The proposed scheme supports that the mobile sensor device can continually keep extending the sleep interval, which is uninitialized, by exchanging the current sleep interval value with a new coordinator.

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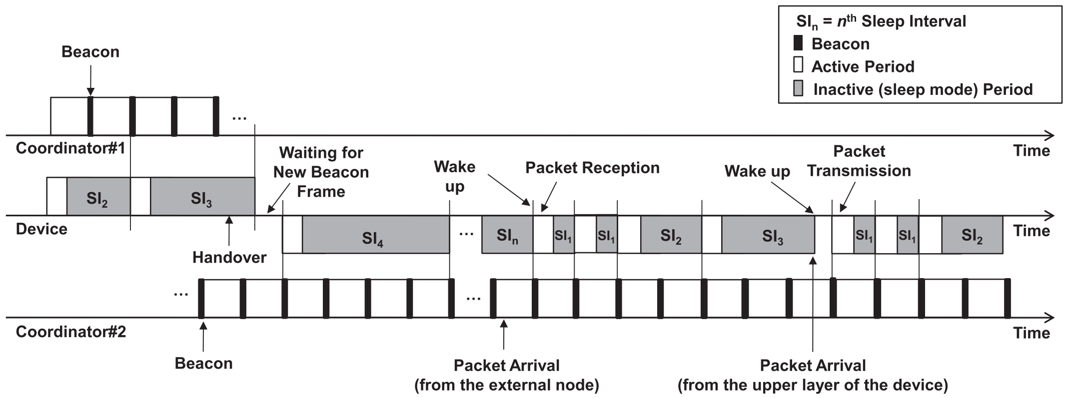

Fig. 2 The change of sleep intervals and timing relationship between the coordinators and the mobile sensor device.

2. Proposed Energy-Efficient Sleep Mode Scheme

In this section, we describe the proposed energy-efficient sleep mode scheme using a reference scenario. Figure 2 illustrates the change of sleep intervals in the mobile sensor device according to various events, such as movement between wireless sensor networks that have different beacon timings of the coordinators, packet reception from the corresponding node, and packet transmission. Figure 3 shows the signaling flow of the proposed sleep mode through the reference scenario.

The mobile sensor device initially starts up at a current sensor network, which is managed by a coordinator#1. We propose the inclusion of sleep interval request (SI_REQ) and sleep interval acknowledgement (SI_ACK) messages for every active period. The proposed new messages enable to exchange information on the duration of the current sleep interval and the indication of the packet arrival between the coordinator and the mobile sensor device.

Let SI_n denote the duration time for the nth sleep interval. If there is no data to transmit from the mobile sensor device or receive from the coordinator for a while, the mobile sensor device requests the sleep mode using the proposed SI_REQ message with the first sleep interval (SI_1). Upon receipt of the SI_REQ message from the mobile sensor device, the coordinator#1 replies to the SI_ACK message. The mobile sensor device then goes into sleep mode during the inactive period in the beacon interval.

For the next beacon interval, the mobile sensor device wakes up and sends the SI_REQ message with a second sleep interval (SI_2) if there is no data to transmit. In the beacon enabled mode, all packets that are sent to the mobile sensor device from the corresponding node should be forwarded via the coordinator. Hence, the proposed SI_ACK message can be used for indication whether the packet towards to the mobile sensor device has arrived from the corresponding node with a positive flag, or not by setting a negative flag. In this paper, the coordinator is able to recognize whether the status of the mobile sensor device is active or inactive, and manages a list of all mobile sensor devices'

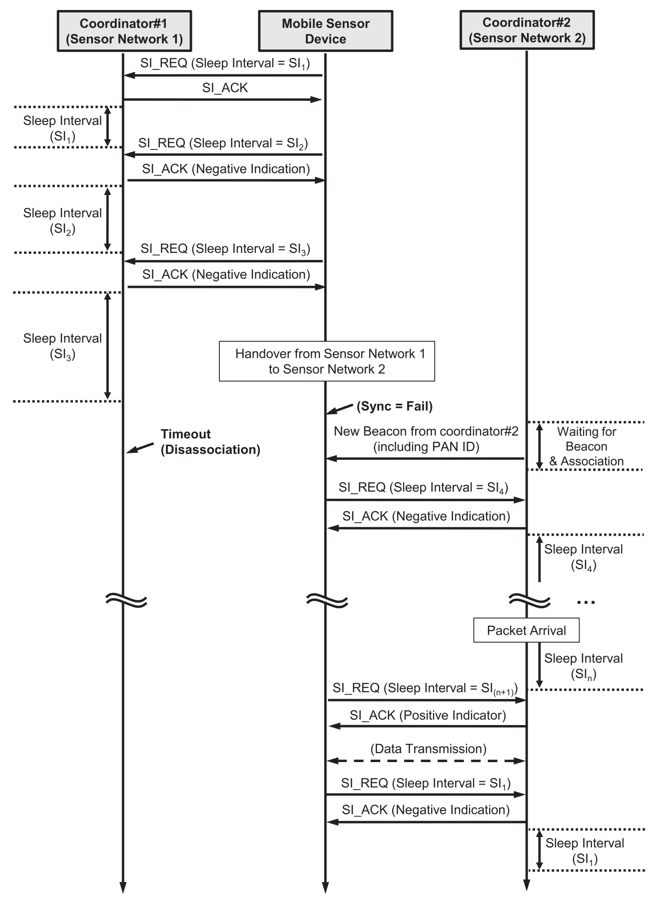

Fig. 3 Signaling flow of the proposed sleep mode.

sleep interval information by receiving the SI_REQ message. Upon receipt of the packet from the corresponding node, the coordinator first checks the status of the mobile sensor device. If the status of the mobile sensor device is active, the coordinator can immediately forward the packet to the mobile sensor device after sending the SI_ACK message with a positive indication flag. On the other hand, if the status of the mobile sensor device is inactive, the coordinator should wait for a specified time until the mobile sensor device wakes up. In this scenario, the coordinator#1 replies to the SI_ACK message with the negative flag, and the mobile sensor device then goes into the sleep mode, which is extended to SI_2.

If the mobile sensor device is in the sleep mode, it probably maintains a sleep state even after moving to a new sensor network. When the mobile sensor device moves to the new sensor network area while in the sleep mode (SI_3) and wakes up after finishing the sleep period, the mobile sensor device may not receive the previous beacon frame since the synchronization with the previous beacon frame has failed. Therefore, the mobile sensor device should wait or request a new beacon frame in order to synchronize with a new coordinator#2. The detailed procedure for the establishment of a new connection and association with the coordinator#2 is out of the scope in this paper. If the mobile sensor device detects movement within the new sensor network, the mobile sensor device tries to send the SI_REQ message to the coordinator#2 with a request to continue the extended sleep interval (SI_4). Upon receipt of the SI_ACK message from the coordinator#2, the mobile sensor device maintains the uninitialized sleep interval (SI_4), even if the mobile sensor device moves to the new sensor network area.

The mobile sensor device extends the interval of the sleep mode until the packet is transmitted or received so that the mobile sensor device is able to conserve energy most of the time. Hence, we can define the nth sleep interval (SI_n) as follows:

$$SI_n = \begin{cases} SI_1 + (n-1) \times BI & n < n_{max} \\ SI_1 + (n_{max-1}) \times BI & n > n_{max} \end{cases} \tag{3}$$

where n_{max} is the maximum sleep interval.

If the packet arrives via the coordinator#2 while the mobile sensor device is in the sleep state, then the coordinator#2 replies to the SI_ACK message with the positive indication flag. If the channel is idle, the coordinator#2 transmits the arrival packet to the mobile sensor device. After completing data transmission, if no data is to be received from the coordinator#2 for a while, the mobile sensor returns to the sleep mode in order to conserve energy. If the mobile sensor has data to be sent to the coordinator#2, it wakes up immediately and joins the active period.

3. Analytical Model

This section presents an analytical model to evaluate packet transmission delay and energy consumption of the proposed energy-efficient sleep mode scheme.

3.1 Packet Transmission Delay

As we described in Sect. 2, when the coordinator receives a data packet towards the mobile sensor device from the corresponding node, the packet transmission delay is caused by the sleep interval of the mobile sensor device. If the mobile sensor device is put into sleep mode, the coordinator cannot immediately transmit the packet and should wait to forward the packet until the mobile sensor device wakes up. In this paper, we define that the packet transmission delay is a time between the arrival of the packet at the MAC transmit buffer of the coordinator and the time that this packet is completely delivered to the mobile sensor device.

We assume that the packet arrival rate follows a Poisson distribution [6] with a mean rate of λ (packets per unit time), and that the inter-packet arrival time follows an exponential distribution with a mean of $\frac{1}{\lambda}$. Hence, the number of arrival packets during the sleep time of the mobile sensor device is $N_n = \frac{\lambda SI_n}{1-e^{-\lambda SI_n}}$, and we can obtain the average packet transmission delay [7], [8] during sleep time using $W_n = \frac{SI_n}{2}$.

The Poisson distribution is a discrete probability distribution in which all events occur with a known average rate that is independent of the time since the last event. P_n represents the packet arrival probability at the coordinator from the corresponding node when the mobile sensor device sleep interval is nth.

$$P_n = 1 - e^{-\lambda \times SI_n} \times \prod_{i=1}^{n-1} e^{-\lambda \times SI_i} \tag{4}$$

Let $P_n N_n W_n$ denote the waiting time of the packets in the nth sleep interval, and $P_n N_n$ denote the total number of packets. When the mobile sensor device is in sleep mode, the average packet transmission delay from the coordinator to the mobile sensor device, therefore, can be

$$E[d] = \frac{\sum_{n=1}^{\infty} P_n N_n W_n}{\sum_{n=1}^{\infty} P_n N_n}. \tag{5}$$

3.2 Energy Consumption

If the packets arriving at the device have a Poisson distribution, then we can calculate the total energy consumption [9] of the mobile sensor device as follows:

$$E_n = E_{active} \times T_n^{active} + E_{inactive} \times T_n^{inactive} \tag{6}$$

where E_{active} and $E_{inactive}$ denote energy consumption per time (sec) for an active and inactive period, respectively. T_n^{active} represents the total time of the active period given by (7), and $T_n^{inactive}$ is the total time of the inactive period for the nth sleep interval which can be denoted by (8).

$$T_n^{active} = n \times SD \tag{7}$$

$$T_n^{inactive} = \sum_{i=1}^{n} SI_i \tag{8}$$

Therefore, we derive an equation for the average energy consumption as follows:

$$E[E_c] = \sum_{n=1}^{\infty} \left(P_n \times \sum_{i=1}^{n} E_i \right) \tag{9}$$

4. Simulation Results

We implement the proposed analytical model with a random waypoint mobility of the mobile sensor device using an

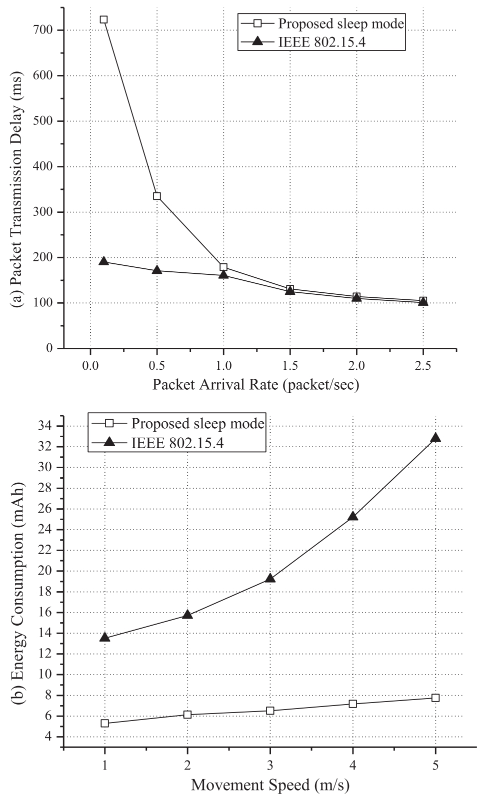

Fig. 4 (a) Packet transmission delay and (b) energy consumption of the mobile sensor device.

objective modular network testbed in a C++ (OMNeT++) [10] simulator, and perform a number of simulation experiments in order to evaluate the average packet transmission delay and energy consumption. We compare the proposed sleep mode scheme with the conventional IEEE 802.15.4 scheme under the assumption that the maximum battery capacity of a mobile sensor device is 3000 mAh. In this simulation, we assume that the power consumptions of the IEEE 802.15.4 radio chip are 17.4 mA while transmitting a 0 dBm, 18.8 mA while in receiving mode, and 20 nA during sleep mode, respectively. The number of BO is set to 5 (i.e., BI = 491.52 ms), and SO is set to 4 (i.e., SD = 245.76 ms). The value of SI is set from minimum of 1 to maximum of 5. We use these values in order to evaluate energy consumption. Five sensor networks are deployed, and each sensor network has ten fixed devices configured with cluster topology. The mobile sensor device is able to move in all sensor network areas following the random waypoint mobility model.

Figure 4(a) shows the results of the average packet transmission delay that is measured by increasing the packet arrival rate with the Poisson distribution. The mobile sensor device receives the packets as the packet arrival rate increases from 0.1 to 2.5. In case of a high packet arrival rate, the average packet transmission delay makes no great difference between the proposed sleep mode scheme and the conventional IEEE 802.15.4. In case of a low packet arrival rate, on the other hand, the average packet transmission delay of the proposed scheme is increased, as compared to the conventional IEEE 802.15.4 scheme. This is because the proposed sleep mode scheme can take a high probability of the long sleep interval.

Figure 4(b) shows the impacts of the mobile sensor device's movement speed on the average energy consumption with different velocities from 1 m/s to 5 m/s and the packet arrival rate set as 1.0. From this simulation result, we can verify that the proposed sleep mode scheme efficiently reduces energy consumption in comparison to the conventional IEEE 802.15.4 MAC scheme. In addition, the proposed sleep mode scheme is not much affected by increasing the movement speed in the energy consumption. This is because the mobile sensor device of the proposed scheme can maintain the sleep interval, which is uninitialized, even when the mobile sensor device moves to the new sensor network. The proposed extendable sleep mode scheme can achieve a significant impact on improving energy efficiency, and it is suitable for non-delay sensitive applications.

5. Conclusions

In this paper, we propose an energy-efficient sleep mode for IEEE 802.15.4 designed to support mobility with minimum energy consumption. Simulation results show that the proposed sleep mode scheme can save more energy regardless of the movement speed of the mobile sensor device, compared to the conventional IEEE 802.15.4 MAC protocol.

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