NUMERICAL ANALYSIS OF THE IDLE LISTENING PROBLEM IN IEEE 802.15.4 BEACON-ENABLE MODE

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ABSTRACT

In the wireless communication, a major source of energy consumption is the idle listening problem. The IEEE 802.15.4 beacon-enable mode is designed to consume less energy, but it still has a serious idle listening because of its fixed active period. In this paper, we analyze the idle listening of IEEE 802.15.4 beacon-enable mode and evaluate its energy consumptions with various factors such as the data traffic, super-frame duration and data frame sizes.

1. INTRODUCTION

The IEEE 802.15.4 standard [1] addresses a simple, low-cost and low-rate communication network that allows a wireless connectivity between devices with limited resources and battery. The scope of standard is to define the physical layer (PHY) and medium access control (MAC). We expect that it can be applied to various applications such as industrial automation, home networks, body networks and wireless sensor networks. The IEEE 802.15.4 MAC protocol supports two network management models according to the periodic beacon generation: the non beacon-enabled mode and the beacon-enabled mode. The non beacon-enabled mode utilizes non-slotted CSMA/CA mechanism and does not support a periodic energy saving mechanisms. However, the beacon-enabled mode permits wireless devices to turn off their radio transceiver in the specific duration (inactive period). Such a state of turning off is known as 'sleep' or 'power down' state in which neither packet transmission nor reception is allowed, and therefore very little energy is consumed. To support the mechanism, a coordinator periodically transmits the beacon frame and manages the active/inactive period of its network. The general devices try to associate with the coordinator and track the schedule of the beacon frame.

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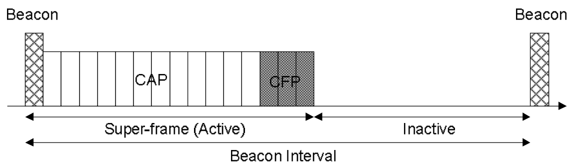


Fig.1 Super-frame structure in beacon-enable mode [1]

In the research of a power limited wireless network, it is very important to achieve minimum communication energy consumption. Measurements of [2] have shown that idle listening problem consumes the most of the energy and it is the major source of energy waste in the wireless communication. Since a node does not know when the data traffic is generated from other nodes, its transceiver continuously stays in the receiving mode even when there is no data traffic. We call this problem as the idle listening. The problem can be reduced by the periodic RF sleep mechanism, and there are many MAC protocols [2-4] proposed to solve it.

The IEEE 802.15.4 beacon-enable mode is also designed to reduce the idle listening problem by using the periodic RF sleep mechanism based on the active/inactive period. However, it still has the idle listen problem and consumes much energy because of its fixed active period. In this paper, we analyze the energy consumption of the idle listening problem. Through a numeric analysis, we show that the idle listen problem is still a main energy consumption factor and a serious in the IEEE 802.15.4 beacon-enable mode. Many researches [5-7] have analyzed the performance of IEEE 802.15.4. However, none of them specifically address the idle listening problem in the IEEE 802.15.4 beacon-enable mode. To our knowledge, this is the first analytical study of the idle listen problem in IEEE 802.15.4 beacon-enable mode.

2. OVERVIEW OF BEACON-ENABLE MODE

In the beacon-enable mode, the coordinator periodically generates a beacon and bounds its super-frame structure. Beacon interval begins with a beacon frame and it consists of the active and inactive period, as shown in Fig. 1.

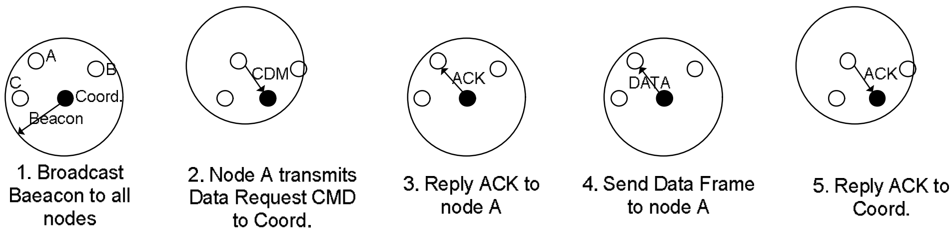


Fig.2. Indirect Transmission: Coordinator tries to transmit its pending data to node A.

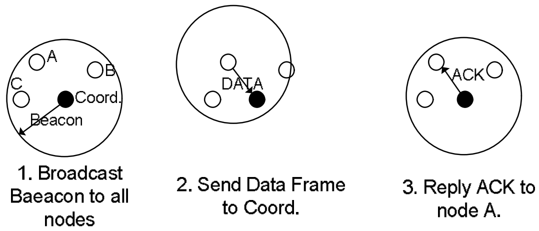


Fig.3. Direct Transmission: Node A tries to transmit its data to coordinator.

All devices synchronize the super-frame schedule of the coordinator and try to communicate based on the slotted CSMA/CA mechanism during the active period. In the inactive period, nodes are allowed to enter the sleep mode to conserve energy. The length of the beacon interval (BI) and super-frame duration (SD) are defined as follows:

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

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

where *aBaseSuperframeDuration* is defined as *base slot duration × a number of super-frame slots (60×16=960 symbols)* in IEEE 802.15.4 standard. The parameters BO and SO indicate the beacon order and the super-frame order which are determined by a coordinator and included in beacon frame. Their ranges are $0 \leq SO \leq BO \leq 14$, and SO should not be bigger than BO. By both two parameters, performances of energy consumptions and data latencies are decided in beacon-enable mode.

The super-frame duration is re-divided two parts: a contention access period (CAP) and a contention free period (CFP). The communication in CAP use a general slotted CSMA/CA mechanism, but the communication in CFP is scheduled TDMA mechanism by the coordinator. General data traffic or control messages are transmitted during CAP, and some specific QoS traffics are managed in the CFP. However, CFP is the optional mechanism and it needs permission from coordinator. In this paper, we consider the general data and command traffic only.

3. NUMERIC ANALYSIS

The core contribution of this paper is the analytical evaluation of the idle listening problem in IEEE 802.15.4 beacon-enable mode. We assume that there is number N of devices (including a coordinator) and the general devices are already associated with the coordinator. Data packets are assumed to be fixed sizes and the packet arrival rate at a node during a beacon interval is expressed as λ. There are several papers [6, 7] proposed the analysis of the transmission probability and channel access models in IEEE 802.15.4 beacon-enable mode. However, since this paper focuses on the analysis of idle listening problem in the energy consumption aspect, we simply define the probability $P_s(N)$ as the data transmission success by attempting Carrier Channel Assessment (CCA) [1] twice among N devices. We define the probability $P_{ti}(N)$ that there is a packet to be transmitted at node i during a beacon interval among N devices

$$P_{ti}(N) = P_s(N) \times \lambda \quad (3)$$

Our analyses are distinguished two parts according to the transmission mechanisms: Indirect transmission (from a coordinator to a general device) and direct transmission (from a general device to a coordinator). When the coordinator wishes to transfer data to a device, it piggybacks the pending data information into a beacon frame and sends it to the network at the starting beacon interval. If the device finds the pending information related from the beacon frame, it transmits a data request command to the coordinator as mean to permit the communication. After receiving the command and reply its ACK, the coordinator tries to send the pending data frame to the device. Both command and data are transmitted using slotted CSMA/CA. This sequence is illustrated in Fig. 2. The

[1] Under the slotted CSMA/CA in IEEE 802.15.4, CCA is performed twice before a data transmission.

indirect transmission traffic at the coordinator during a beacon interval can be given as:

$$P_{tc}(N) \times (O_c + T_{comm} + T_{comm\_ack} + O_c + T_{coord\_data} + T_{coord\_ack}) \quad (4)$$

where T_{comm}, T_{coord_data}, two T_{ack} and O_c mean the length of data request command, data frame in the coordinator, ACK frame and average contention overhead, respectively. The direct data transmission is simpler than the indirect transmission. When a device wishes to transfer some data frame to a coordinator, it first synchronizes the beacon interval through the beacon frame and then tries to transmit the data frame based on the slotted CSMA/CA. This sequence is illustrated in Fig. 3. The direct transmission at the general device *i* can be also expressed as:

$$P_{ti}(N) \times (O_c + T_{device\_data} + T_{device\_ack}) \quad (5)$$

where T_{device_data} and T_{device_ack} mean the length of data frame in the general device and its ACK frame. By referring equation (4) and (5), we can present the transmitting duration of the coordinator and the device. We assume the data rate of devices as 250kbps in 2.4GHz of IEEE 802.15.4 standard [1]. If there are number of *N* devices in the network, the transmitting duration (Ψ_c) of a coordinator can be expressed as:

$$\Psi_c(N) = [T_{beacon} + P_{tc}(N) \times (T_{coor\_data} + T_{comm\_ack}) + \sum_{i=1}^{N-1} P_{ti}(N) \times (T_{device\_ack})] / (250 \times 10^3 / 8) \quad (6)$$

where the T_{comm_ack} and T_{device_ack} are responses of a data request command and a data frame of a device (T_{device_data}). T_{beacon} means the length of the beacon frame. As one device's transmitting duration is not affected by the number of other nodes, the transmitting duration (Ψ_d) of the device *i* can be expressed as:

$$\Psi_d(N) = [P_{tc}(N) \times (T_{comm} + T_{coord\_ack}) / (N-1) + P_{ti}(N) \times (T_{device\_data})] / (250 \times 10^3 / 8) \quad (7)$$

where T_{coord_ack} are a response of a data frame of the coordinator (T_{coord_data}).

The receiving duration of the coordinator and devices can be expressed by referring equation (6) and (7). The receiving duration of the coordinator with number *N* devices can be derived to be:

$$\Phi_c(N) = [P_{tc}(N) \times (T_{comm} + T_{coor\_ack}) + \sum_{i=1}^{N-1} P_{ti}(N) \times (T_{device\_data})] / (250 \times 10^3 / 8) + T_{CCA} \quad (8)$$

where the T_{CCA} indicates the total contention overhead durations for transmitting. In the receiving duration of all devices, we should consider the data traffics of coordinator as well as data traffics of other devices because all devices are included in one coordinator network and can overhear other traffics. The receiving duration of all devices can be expressed as:

$$\Phi_d(N) = [(N-1) \times (T_{beacon} + P_{tc}(N) \times (T_{coord\_data} + T_{comm\_ack}) + \sum_{i=1}^{N-1} P_{ti}(N) \times T_{device\_ack}) + (N-1) \times \sum_{i=1}^{N-2} (P_{ti}(N) \times (T_{comm} + T_{coor\_ack}) + P_{ti}(N) \times T_{device\_data})\ ] / (250 \times 10^3 / 8) + T_{CCA} \quad (9)$$

The idle listening duration can be calculated by the super-frame duration and equation (6)-(9). If the total transmitting durations $\Psi_c(N)+\Psi_d(N)$ is smaller than the super-frame duration, sum of idle listening duration (δ) of *N* devices can be expressed as:

$$\delta(N) = N \times SD \times T_{symbol} - \Psi_c(N) - \Psi_d(N) - \Phi_c(N) - \Phi_d(N) \quad (10)$$

where *SD* and T_{symbol} mean the super-frame duration and one symbol duration[2] respectively. *SD* is defined by *SO*, with their ranges are $BS \leq SD \leq BS \times 2^{SO}$ and SO=1, 2,…14.

Finally, the transition time of the power down mode is easily calculated by using the super-frame and beacon-frame durations. Sum of power down duration (Γ) of N devices can be expressed as

$$\Gamma(N) = N \times (BI - SD) \times T_{symbol} \quad (11)$$

where *BI* means the beacon-frame interval, which their ranges are same with super-frame duration. However, the beacon-frame duration should not be smaller than SD in IEEE 802.15.4 beacon-enable mode.

In order to analyze energy consumptions in detail, we should need to identify the radio states and their power drains. For these purposes, we refer the Chipcon CC2420 datasheet [8] which includes the IEEE 802.15.4 physical characteristics. The CC2420 RF transceiver supports the following four states:

- Power Down mode: In this mode, CC2420's crystal oscillator is turned off for consuming low energy. It can not transmit or receive packet, but it maintains RF configurations.

[2] IEEE 802.15.4 utilizes *a symbol* as a unit time duration and it is defined as 16μs in 250kbps data rate.

Table 1. Energy States of CC2420 RF Transceiver

States	Power Drains (Current)
Power Down mode (RF Sleep)	20μA
Idle mode (RF Sleep)	426μA
Receive mode	19.7mA
Transmit mode	17.4mA (0dBm)

- Idle mode: Since CC2420's crystal oscillator is turned on, device's CPU can access to CC2420 RF transceiver. But, its RF function is continuously disabled.
- Receive mode: CC2420 RF transceiver can detect and receive a frame from the wireless medium.
- Transmit mode: CC2420 RF transceiver is transmitting a frame to the wireless medium.

Table 1 lists the states and their current drains referred from CC2420 RF transceiver, which are used in the following analysis. Since the CC2420 is supplied 1.8V as regular power, each state's energy consumption (mW) can be calculated as:

$$TransitionTime \times PowerDranins \times 1.8V \quad (12)$$

With previous equations, we can describe the energy consumptions of Tx, Rx, idle listening and sleep states within N devices. Table 2 shows the equations of them. E_{tx}, E_{rx} and E_{sleep} indicate the power consumed when nodes are in transmitting, receiving and sleep modes. Note that, power drain of idle listening is not the drain of idle mode in table 1. It should refer the receive mode drain in table1 because idle listening means the continuous RF detecting problem.

4. NUMERICAL RESULTS

In this section, we present the numerical results on the energy consumptions aspects in IEEE 802.15.4 beacon-enable mode. The results are obtained from our mathematic analysis frameworks and the CC2420 RF transceiver information in table 1. For the analysis, we fix a beacon frame is 38 bytes, a data request command is 25 bytes, an ACK frame is 11 bytes and a data frame is 133[3] bytes as referring 802.15.4 standard [1]. These sizes include MPDU (MAC Protocol Data Unit) as well as physical headers such as preamble sequence and start of frame delimiter. For simplifying analysis, we omit the switch delay between states and contention overheads. Number of nodes in the network are 10 (one is a coordinator and others are general devices). SO and BO are set to 1 and 2, so the super-frame duration is 1920 symbols and a beacon frame duration is 3840 symbols.

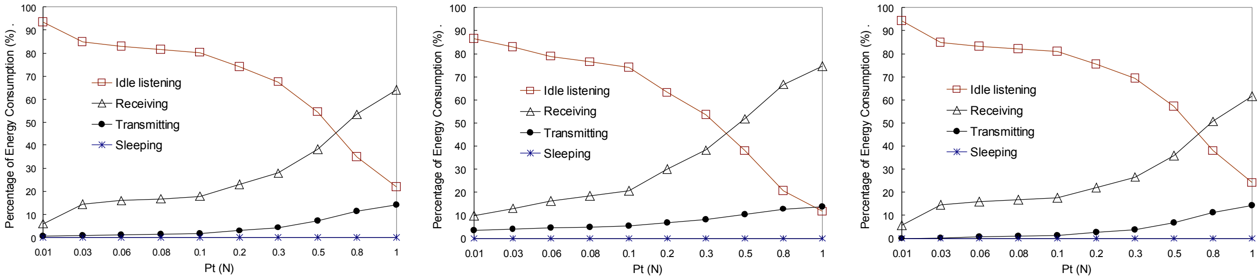
Table 2. Energy Consumptions of Tx, Rx, Idle listening and Sleep states

Descriptions	Energy Consumption
Coord. Tx	$E_{tx} \times \Psi_c (N)$
Coord. Rx	$E_{rx} \times \Phi_c (N)$
Coord. Idle listening	$E_{rx} \times \delta(N)/N$
Coord. Sleep	$E_{sleep} \times \Gamma(N)/N$
Device Average Tx	$E_{tx} \times \Psi_d (N)/(N-1)$
Device Ave. Rx	$E_{rx} \times \Phi_d (N)/(N-1)$
Device Ave. Idle listening	$E_{rx} \times \delta(N)/N$
Device Ave. Sleep	$E_{sleep} \times \Gamma(N)/N$
Total Tx	$E_{tx} \times (\Psi_c (N) + \Psi_d (N))$
Total Rx	$E_{rx} \times (\Phi_c (N) + \Phi_d (N))$
Total Idle listening	$E_{rx} \times \delta(N)$
Total Sleep	$E_{sleep} \times \Gamma(N)$

First, we evaluate the percentage of energy consumption in transmitting, receiving, idle listening and sleeping according to the probability $P_t(N)$ in a beacon interval among N devices. Fig. 4(a) shows the percentage of total energy consumption of all nodes with various $P_t(N)$ factors from 0.01 to 1. The idle listening consumes up to 90% energies in the low data traffic. Since a high $P_t(N)$ factor means the high data traffic generated in nodes, the percentage of transmitting and receiving should increase and the percentage of idle listening decrease when $P_t(N)$ value is high. Nevertheless, the idle listening problem is continuously a main energy consumption factor up to 25% in the high data traffic. Fig. 4(b) and (c) show the percentages of average energy consumption in a coordinator and a device. Since the coordinator periodically generate a beacon frame and manage the network, its energy percentages of transmitting and receiving are larger than a device. However, its idle listening also consumes much energy as a device.

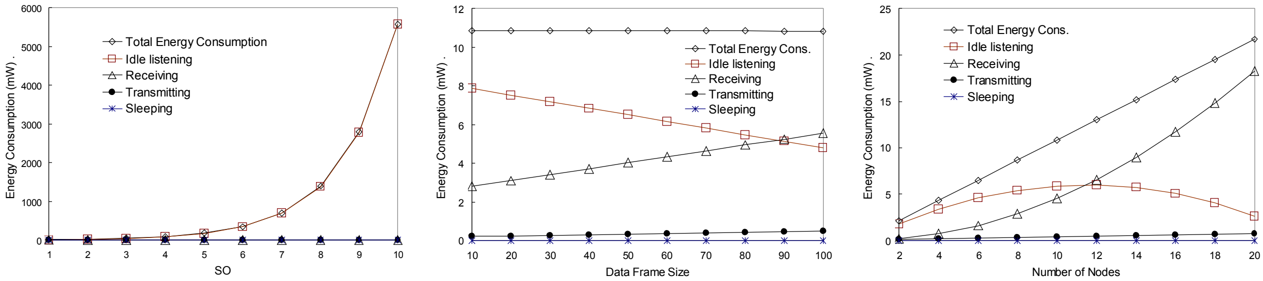
Next, we observe the idle listening problem in energy consumptions (mW) according to the SO, data frame sizes and number of nodes. In this case, we fix the probability $P_t(N)$ as 0.3. The SO value affects the super-frame duration. As the longer super-frame duration, the idle listening problem dynamically increases and is the most energy consumption factor, as shown in Fig. 5(a). Then, we evaluate energy consumption with changing the data frame size from 0 to 100 bytes. As the larger data frame, energy of receiving and transmitting slightly increase, but the idle listening is still serious as shown in Fig. 5(b).

[3] Maximum size of IEEE 802.15.4 is 133 bytes: 127 MPDU + PHY header (6 bytes)



(a) All Nodes including Coordinator and Devices (b) A Coordinator (c) A Device

Fig. 4. Percentage of Energy consumptions in four RF states (all nodes, a coordinator and a device)



(a) Super-frame Durations (b) Data Frame Sizes (c) Number of Nodes

Fig. 5. Energy consumption according to the super-frame duration, data frame sizes and number of nodes

Finally, we vary a number of nodes from 2 to 20. As increasing number of nodes, data traffics and receiving durations are dynamically increased. Therefore, in the large number of node, energy consumptions of receiving can be larger than that of the idle listening as shown in Fig. 5(c).

5. CONCLUSION

In this paper, we present the analysis of the idle listening problem in IEEE 802.15.4 beacon-enable mode. By using the RF sleep mechanism and periodic synchronization, the beacon-enable mode seems to well design for saving communication. However, our analysis and results show that the idle listening problem is still a serious energy consumption factor in IEEE 802.15.4 beacon-enable mode and need some algorithm to reduce the problem. As a part of our future work, we will study on how to reduce the idle listening problem for the further improvement of energy saving in IEEE 802.15.4 standard.

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