Performance Evaluation of Device Discovery in Bluetooth LE with Probabilistic Model Checking

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***Abstract*—The device discovery in Bluetooth is needed before establishing data communications. Almost all Bluetooth slaves are battery-powered so that they should connect with a master through the device discovery for a short time. To prevent the worst case scenario with long device discovery in Bluetooth, the events with long device discovery should be estimated in advance. However, it is intractable to estimate the exact longest device discovery time with Monte Carlo simulations or mathematical analysis because of the probabilistic behavior. In this paper, we reveal the longest device discovery time and the maximum energy consumption in Bluetooth Low Energy (LE) with a probabilistic model checking tool, PRISM. The results show that some parameters in Bluetooth LE will largely affect the energy consumption so that their design criteria will be desired to reduce the energy consumption.**

I. Introduction

Recently, Bluetooth has been widely used as a short-range wireless network standard. Bluetooth is mainly mounted in battery-powered mobile terminals so that the available energy will be limited. The proper network design should be required in Bluetooth to reduce the energy consumption. In Bluetooth, slaves attempt to connect with a master before establishing data communications, where slave and master are called peripheral and central, respectively. This process called device discovery significantly affects the energy consumption so that its elapsed time and consumed energy should be estimated in advance. Especially the exact longest device discovery time and maximum energy consumption will be estimated to avoid the worst case scenarios. However, the device discovery of Bluetooth contains some probabilistic behavior so that an exhaustive search should be required to estimate the worst case events. As a result, Monte Carlo simulations or theoretical analysis could not be suitable for the exhaustive search whereas the probabilistic model checking will be useful.

Duflot *et al.* have evaluated the longest device discovery time of Bluetooth Basic Rate (BR) with a probabilistic model checking tool, PRISM [1]. The results showed that it was infeasible to use battery-powered wireless sensors with Bluetooth BR for a long time. Bluetooth Low Energy (LE) has been developed to resolve the energy shortage problem of Bluetooth BR. Bluetooth LE has an inherent different technology with Bluetooth in the medium access control (MAC) and physical (PHY) layers through the reconsideration from the viewpoint of low energy consumption. Recently, Liu *et al.* have analyzed the energy consumption on the device discovery of Bluetooth LE in the stable and deterministic region that the scan window is larger than the advertising interval [2]. It will be effective in low energy to enlarge the advertising interval but may be unstable and probabilistic.

In this paper, we analyze the longest device discovery time and the maximum energy consumption on the device discovery of Bluetooth LE in some probabilistic but energy-effective region. The analysis in Bluetooth LE is conducted with PRISM for some advertising start time and interval parameters, showing that some interval parameter set will be critical in elapsed time and consumed energy. This paper contributes to the modeling of the Bluetooth LE networks and finding of their worst case events with PRISM.

II. Device Discovery in Bluetooth LE

In Bluetooth LE, a central manages one or more peripherals. To join some central, peripherals exploit the advertising mode in Bluetooth LE. A non-associated peripheral broadcasts packets in the advertising mode for device discovery. After associating with some central, the peripheral moves to the data communication mode. The device discovery process will be described in this section.

A. Advertising Channel

Bluetooth LE has the total of 40 channels in the 2.4 GHz band and only 3 channels in them are exploited for device discovery. These channels are called advertising channels and have the frequency IDs of 37, 38, and 39. In 2.4 GHz wireless LAN, non-overlapping 1st, 6th, and 11th channels are often utilized. Advertising channels in Bluetooth LE are located in the gaps among these wireless LAN channels so that they may not interfere from wireless LAN signals. In an advertising event, the non-associated peripheral will send the advertising packets on three advertising channels in ascending order if any packet would not be received from some central.

B. Advertising and Scan

In Bluetooth LE, a peripheral is associated with a central via a negotiation with advertising and scan. Figure 1 illustrates the timing chart of advertising by a peripheral. The advertising event is repeated every an advertising interval plus a random

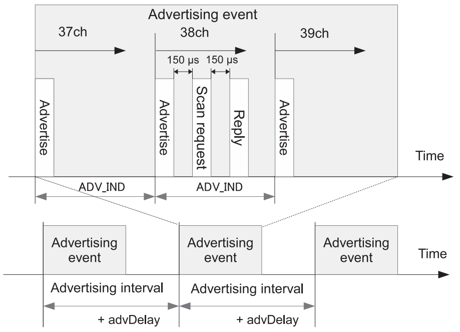

Fig. 1. The timing chart of advertising by a peripheral.

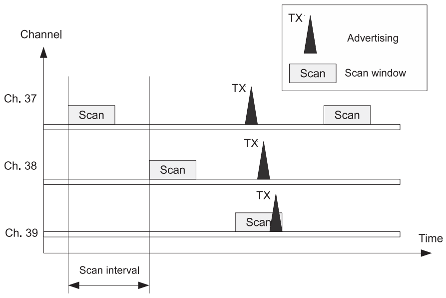

Fig. 2. The timing chart of scan by a central.

delay, advDelay. The random variable, advDelay, is uniformly-distributed in the range of 0 to 10 ms. The interval each channel for advertising, ADV_IND, is equal to or less than 10 ms. On the other hand, a central scans three advertising channels sequentially in ascending order and the scan is repeated by the central. Figure 2 illustrates the timing chart of scan by a central. The interval each channel for scan is called scan interval and the scan time each channel is called scan window. If a central receives an advertising packet sent from a peripheral, then the central sends the scan request packet after 150 μs and the peripheral replies the scan response packet after 150 μs of the reception of the scan request packet as shown in Fig. 1.

III. Modeling in PRISM

In this section, let us describe the modeling of the device discovery in PRISM.

A. Probabilistic Model Checker PRISM

PRISM is a probabilistic model check tool, and targets the model which combines time and probabilistic factors. It can estimate system performance reliability and stability with probabilistic behavior. Discrete-time Markov chain (DTMC), continuous-time Markov chain (CTSC), Markov decision process (MDP), probabilistic automata (PA), and probabilistic timed automata (PTA) can be provided to PRISM. Models on PRISM are described by PRISM language based on states. In the device discovery of Bluetooth LE, PRISM is useful to evaluate exhaustively probabilistic events such as the longest device discovery time and the maximum energy consumption.

TABLE I

Model check parameters for performance tests, where $[a, b]$ stands for integers no less than a and no more than b.

Properties	Rmax = ? [F rec = max_reply]
Init. freq. ID (Peripheral)	37
Init. freq. ID (Central)	37, 38, 39
ADV_IND	0.5 ms
Advertising interval	1.28 – 10.24 s
Scan window	1.28 s
Scan interval	2.56 s (test 1), 10.24 s (test 2)
advDelay	$0.5 \cdot [0, 20]$ ms

B. Modules of the Model

The device discovery behavior in Bluetooh LE is modeled on PRISM. The model consists of three modules, which are the peripheral module, the central module, and the random number module. In this paper, the minimum unit time is set to 10 μs in the model. The details of the respective modules are described as follows:

1) Peripheral module: This module models the time behavior in a peripheral. The peripheral broadcasts an advertising packet with a specified frequency according to the timing chart shown in Fig. 1. If the start time transmitting an advertising packet with a frequency ID is included in the scan window with the same frequency ID, the central module will finish the device discovery. If the peripheral cannot be discovered by the central in an advertising event, it sleeps until the start of the next advertising interval.

2) Central module: This module models the time behavior in a central. The central scans a specified frequency in a scan window according to the timing chart shown in Fig. 2. If the central cannot detect an advertising packet with the same frequency ID in the scan window, it sleeps until the start of the next scan interval with the next frequency ID. Otherwise, the central module finishes the device discovery process.

3) Random number module: This module generates a random number uniformly-distributed from 0 to 10 ms by 0.5 ms interval for advDelay.

IV. Performance Evaluation

In this section, it attempts to find the longest device discovery time and the maximum energy consumption with PRISM especially when the advertising interval is equal to or larger than the scan window because this region will be unstable but energy-efficient for peripherals.

A. Model Check Parameters

Model check parameters are shown in Table I. A query

$$\text{Rmax} = ?\ [\text{F rec} = \text{max\_reply}]$$

is provided to PRISM. The variable ‘rec’ indicates the number of replies received by the central and ‘max_reply’ indicates the largest number of replies which the central should receive. ‘Rmax = ?’ outputs the accumulation costs when the query succeeds. All the interval parameters of Bluetooth LE can be arbitrarily configured as needed by users. The scan intervals 2.56 s and 10.24 s are set to test 1 and test 2, respectively. The

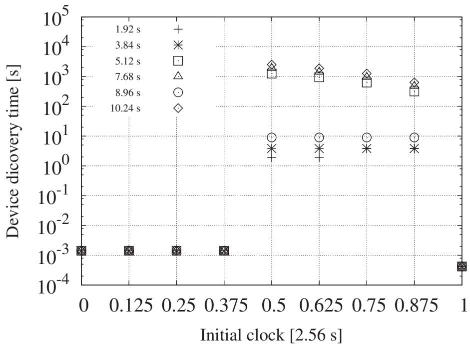

Fig. 3. Longest device discovery time vs. initial clock for test 1.

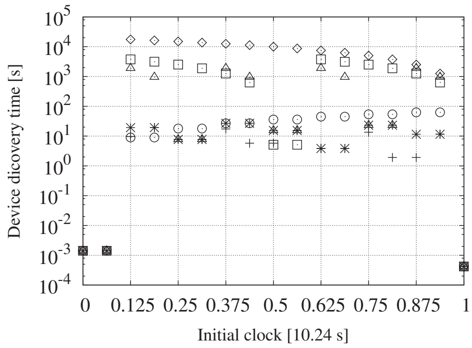

Fig. 5. Longest device discovery time vs. initial clock for test 2.

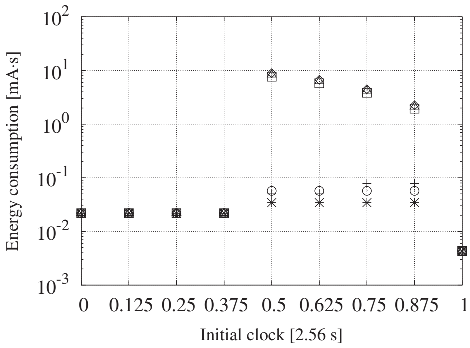

Fig. 4. Maximum energy consumption vs. initial clock for test 1.

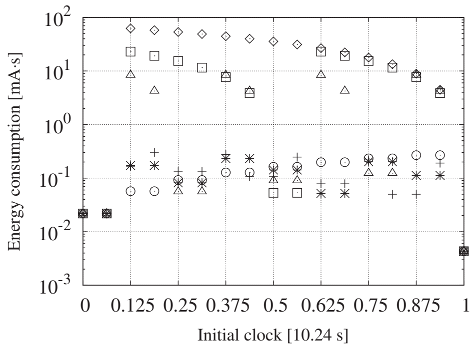

Fig. 6. Maximum energy consumption vs. initial clock for test 2.

device discovery properties in Bluetooth LE will depend on the interval parameters and initial state in the unstable region, where the initial state means the time and frequency of the central when the peripheral begins a discovery process.

B. Model Check Results

The device discovery properties are clarified in the unstable region. Let us define the initial clock and initial frequency ID as the time normalized by scan interval and the frequency ID at the central when a peripheral begins a device discovery process respectively, where the start frequency ID at the peripheral is 37. Let us assume that the initial frequency ID at the central is 39 because its performance is slightly worse than those in the other frequency IDs.

Figures 3 and 4 illustrate the longest device discovery time and the maximum energy consumption in test 1 with probabilistic model checking for some given advertising intervals, respectively. Figures 5 and 6 also illustrate the performances in test 2. These figures show us that the performances largely vary with the initial clock and advertising interval in the unstable region. Note that the initial clock is not controllable for the peripheral in the current Bluetooth LE before the device discovery is complete. The advertising interval of 10.24 s provides the maximal values averaged over initial clocks in longest device discovery time and the maximum energy consumption for both test 1 and test 2. These values are also high in the case of the advertising intervals of 2.56, 5.12, and 7.68 s. These advertising intervals are integer multiples of the scan window 1.28 s so that the integer-multiplied advertising intervals should be avoided. The device discovery time will be 135 s and the energy consumption will be 5.24×10^{-1} mA·s even in the worst scenario if non-integer-multiplied advertising intervals are exploited for test 1 and test 2.

V. Conclusion

In this paper, we have evaluated the performances on device discovery of Bluetooth LE by a probabilistic model checker, PRISM. It reveals the longest device discovery time and the maximum energy consumption even in the unstable and probabilistic region. The results provide us a design criterion that the advertising intervals should not be the integer multiples of the scan window when the advertising interval is equal to or larger than the scan window.

Acknowledgment

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