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Performance analysis of device discovery of Bluetooth Low Energy (BLE) networks

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ABSTRACT

Bluetooth Low Energy (BLE) technology has opened a whole new dimension of single-hop wireless communication technology due to its inexpensive and low-power properties. This technology makes it possible for a large number of devices to be connected to the Internet of Things. The BLE mechanism is clearly defined by the standard, however, there is room for improvements in some aspects of the technology such as the discovery process. Although the discovery process of traditional Bluetooth architecture has been intensively investigated through analytical and simulation models over the years, it cannot be applied to the BLE technology because of many changes introduced in the design of the BLE. Recently, there have been several works for performance evaluation of BLE discovery process, but they are not still thorough enough in providing a holistic analysis of the BLE. This has motivated our study for more accurate modeling of the BLE discovery process. Our work focuses on developing an analytical model and carrying out intensive simulations to investigate discovery probability and quantitative examination of the influence of parameter settings on the discovery latency and the energy performance metric of the discovery process.

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1. Introduction

Internet of things (IoT) is a concept that has been introduced through the competitions of access technologies which aim at fulfilling the internet and data requirement of mobile users. IoT is still a very new concept and, therefore, much time is required before it can be standardized and implemented. IoT includes both short and long range communication services. The traditional wireless technologies such as WiFi and LTE provide excellent service for long range communication, but they are not ideal in the case of IoT since they consume much energy and time in short range communication. Short-range communication technologies are employed in various IoT applications like smart home, health and fitness service, medical service, etc.

Bluetooth is considered as one of the technologies that can be used to handle short-range communications in the IoT systems. The traditional versions 2.0 and 3.0 are developed for high data rate communications, thus it cannot be used in low-power and low data rate systems. Bluetooth Low Energy (BLE) is an enhanced feature of Bluetooth standard and it is published as Bluetooth Version 4.0. First of all, the BLE provides a fast and energy-efficient discovery process handling hundreds or thousands of devices for short-range wireless applications. The BLE standard defines various parameters used for the discovery process to be appropriately set to various applications. Moreover, the BLE is capable of balancing and optimizing the performance metrics such as energy consumption and latency for device discovery by selecting an appropriate parameter set to meet the need of practical use. Similarly, having a wide range of parameter options provides the opportunity for BLE devices to customize performance in specific applications [1–4]. The BLE networking provides the bulk transmission capability of previously stored data to support different type of sensors. It also offers more robust connectivity by automatically re-establishing connection when devices rejoin the network within a communication range. These capabilities can be best utilized for integrating BLE into wearable devices. The IoT technology can be used in synergy with the BLE to provide a variety of services to exchange information for healthcare, medical service, smart home, smart car, emergency services, etc.

The device discovery of classical Bluetooth protocols has been intensively investigated through experimental, simulation and formal modeling schemes. The Classical Bluetooth device discovery cannot be applicable to BLE because of some fundamental design and conceptual changes in the discovery mechanism of the BLE. As a result, only just a handful of research works has been introduced in the performance evaluation of the BLE discovery process.

In the last couple of years several approaches have been proposed to enhance the working of the BLE discovery process. In this regard, J. Liu et al. proposed a 3-channel-based analytical model for neighbor discovery in the BLE networks and validated through an NS-2 BLE

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extension [5]. Their study could provide a beneficial guidance to customize the advertising or scanning behavior to obtain the required performance. The model could be used to determine mean latency or mean energy consumption during the course of neighbor discovery. They also presented a model for analyzing the neighbor discovery energy in the BLE networks which were built upon measurement results of CC2540 mini-development kit. They presented an interesting conclusion that the parameter used by the device was one of the biggest factors contributing to the performance tradeoff between the energy consumption and the latency [6]. In addition, they introduced an idea based on classical pure ALOHA algorithm, which could allow the BLE devices to adjust dynamically their parameters after receiving the report [7]. A general model for device discovery on multi-channel at first, and then simplified and tailored the model for the BLE network with three broadcasting channels have been proposed in [8]. They presented three parameter setting strategies to enhance the latency performance and validated their accuracy and effectiveness.

Kamath [9] described the setup and procedures to measure power consumption on a CC2541 device operating as a peripheral in a BLE connection. The current consumption measurements were presented, and the battery life time was calculated for an application scenario. They also showed that a variety of factors would influence the battery life time calculation and final measurements.

Gomez et al. [10] investigated the lifetime of the BLE device in a data collection application. Their research represented a trade-off between energy consumption, latency, the piconet size as well as throughput depending on major parameters like ConnSalveLatency and ConnInterval. Their theoretical results revealed that the lifetime of a BLE device powered by a coin cell battery ranged between 2 days and 14.1 years for the whole range of valid connection interval values (i.e., from 7.5 ms to 4 s). They pointed out implementation constraints that might reduce BLE performance in a real scenario.

Sedov et al. [11] introduced a discovery mechanism using the inquiry procedure focusing on the time and energy consumption. They showed that the proposed mechanism was consuming less time and energy than the traditional mechanisms. However, this mechanism assumed that all nodes were within each other's range.

Zanella et al. [12] presented a simple mathematical model for point-to-point Bluetooth link, which was based on the finite state Markov chain. The theory of renewal reward processes was applied to derive the performance of the system in terms of throughput and energy efficiency. They investigated the potential performance tradeoff between the average traffic rate and various packet formats and examined the impact of the receiver correlator margin on the system performance. Although the analysis focused on a piconet with just two units, their mathematical model could be extended to accommodate more complex piconet structures to design energy–efficient algorithms for the piconet management.

Cho et al. [13] presented an analytical model to investigate discovery latency, as well as the probability of the successful discovery with a wide variety of parameter settings. They examined to what extent parameter setting affected the discovery latency through modeling and simulations for practical BLE networks. Similarly, they considered a realistic situation where many collisions caused by the contention among the BLE devices during discovery process.

Previous works for performance evaluation of BLE discovery process are not still thorough enough to provide a complete analysis of the BLE. Our study is motivated by the need to develop a new, accurate latency and energy model for BLE device discovery to analyze quantitatively latency and energy performance consumed for the discovery process. In this paper, we build analytical models for the discovery probability as well as expected discovery latency and energy performance with various parameter settings, which are then validated via extensive simulations and experiments.

The rest of this paper is organized as follows. BLE discovery overview and two performance criteria are presented in Section 2. An analytical model of the BLE discovery process is presented in Section 3. Section 4 validates our latency and energy model, and finally the conclusion is given in Section 5.

2. BLE discovery process and performance criterion

2.1. Overview of discovery process

BLE operates in the same spectrum range (2.4 GHz–2.4835 GHz ISM band) as the classical Bluetooth technology. As previously explained, the advertising channel index is 37, 38, 39 and the rest are data channel indexes. In Fig. 1(a), an example topology of BLE network is shown that demonstrates a number of the architectural features of BLE device [3]. $A_1(S_1)$ is a master in a piconet with $S_1(A_1)$ and $S_2(A_2)$ as slaves. Each slave communicates on a separate physical channel with the master. The $A_1(S_1)$ and $S_1(A_1)$ are using one physical channel. Similarly, $S_1(A_1)$ and $S_2(A_2)$ are using another piconet physical channel. In broadcast group G_3 and $S_3(A_3)$ is advertising using a connectable event on the advertising physical channel, and device $A_1(S_1)$ acts is an initiator. $A_1(S_1)$ can form a connection with $S_3(A_3)$ and add the device to piconet G_1 [3].

A BLE device operates in either of three modes, namely advertising, scanning and initiating, to provide the required functionality as illustrated in Fig. 1. A device in advertising mode transmits advertising information in three advertising channels indexed by 37, 38 and 39 as shown in Fig. 1(b). It continuously and sequentially sends Packet Data Units, called ADV_IND PDUs, via each of the three advertising channels during an advertisement interval. It then keeps listening to the same advertising channel to respond to the SCAN_REQ from the scanner. Each advertising interval is composed of a fixed AdvInterval (τ_{AI}) and a pseudo-random AdvDelay (δ). The pseudo-random AdvDelay is generated by the link layer and is used to separate the advertising intervals when two or more advertisers are getting close [5,6]. When all advertisers are set with the same advertising interval, then collisions on the first channel will pass to the second and the third channels [5,8].

In the scanning mode, a BLE device scans the advertising channels periodically to listen to the advertising information from advertisers as shown in Fig. 1(c) [6]. The scanner sends back a SCAN_REQ to request additional information of the advertiser whenever it receives an ADV_IND PDU. When the advertiser receives a SCAN_REQ from a scanner, it sends a reply with SCAN_RSP PDU on the same advertising channel [5,6]. In addition, since multiple scanners may respond to an advertiser simultaneously, back-off procedures are used by each scanner to minimize collision [4]. The scanner scans a different advertising channel for a duration of ScanWindow (τ_{SW}) during each ScanInterval (τ_{SI}). The ScanInterval and ScanWindow should be less than or equal to 10.24 s.

In the initiating mode, a BLE device shares a similar process with the scanner while the only exception is that it can only respond to a specific type of advertising packets.

2.2. Performance criterion

The BLE link Layer is composed of four components namely, the preamble, the access, PDU and the cyclic redundancy check (CRC). PDU has varying types and is further made up of a header and a payload. The length of the payload determines the length of the packet, ranging from 0 octets to 37 octets.

The transmission time of the ADV_IND, SCAN_REQ, and SCAN_RSP are denoted by $T_{\mathrm{ADV-IND}}$, $T_{\mathrm{SCAN-REQ}}$, respectively. The time needed to exchange control messages in the scanning procedure is given by T_S ($= T_{\mathrm{SCAN-REQ}} + T_{\mathrm{SCAN-RSP}} + 2T_{\mathrm{IFS}}$) as shown in Fig. 2. The list of major timing parameters specified in BLE standard is shown in Table 1.

The discovery latency is defined as the interval for the advertiser from entering into the first advertising event by sending an ADV_IND

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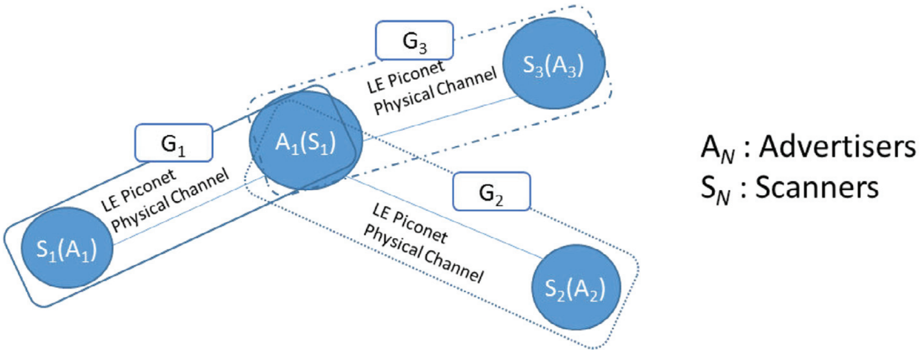
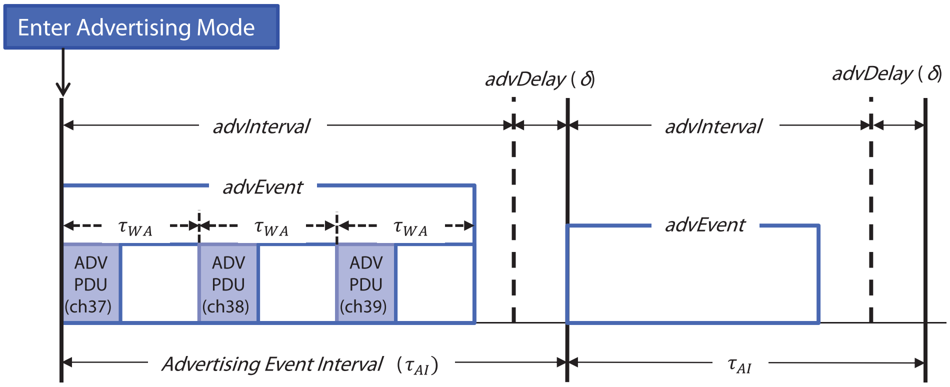
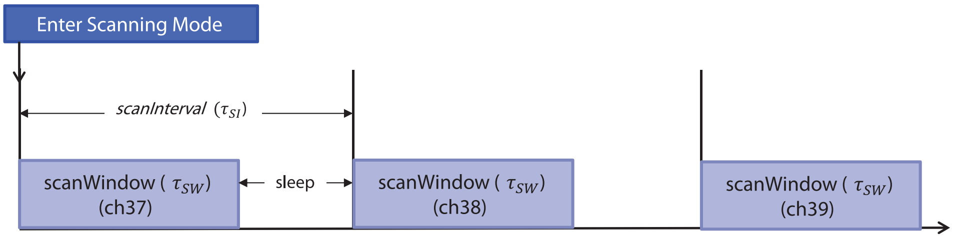


(a) Example of BLE topology



(b) Advertising process



(c) Scanning process

Fig. 1. Example of BLE network and device discovery.

Table 1
List of major timing parameters.

Notation	Meaning	Recommended specification
τ_{AI}	advertising interval for three advertising channels	Integer multiple of 0.625 ms in [20∼10240] ms
τ_{WA}	Advertising period per channel (Max allowable listening time for SCAN_REQ after sending ADV_IND on each channel)	$\leq$ 10 ms
τ_{SI}	ScanInterval	Integer multiple of 0.625 ms in [2.5∼10240] ms
τ_{SW}	ScanWindow	Integer multiple of 0.625 ms in [2.5∼10240] ms ($\tau_{SW} \leq \tau_{SI}$)
$\delta_{\max}$	Upper bound to choose a random delay δ	$\leq$ 10 ms

until it successfully receives a SCAN_REQ from the scanner as illustrated in Fig. 2. Similarly, the discovery energy is defined as the energy consumed during the interval for the advertiser from entering into the first advertising event by sending an ADV_IND until it successfully receives a SCAN_REQ from the scanner.

J. Liu et al. [7] have defined some states and operations related to energy consumption based on the current consumption of CC2541. Timing, current, and energy in each state are listed in Table 2, where the energy is simply obtained by the time duration multiplying the current. In Fig. 3, six consecutive Tx and Rx peaks can be observed, which shows the transmission of the advertising PDUs (marked by ②). The consequent listening actions is marked by ⑥, over the three advertising channels. The listening interval duration varies depending on whether the device discovery process succeeds in the current advertising or not. Similarly, as the BLE device goes through several different states of sleeping (⑨ or ⑩), post-processing (⑧), and channel switching (⑦),we can observe that the current draw changes before or after the advertising event.

A device goes through states ②→⑤→③→⑤→④→⑤→⑥ when it succeeds in discovering an advertisement (τ_{WA}) after

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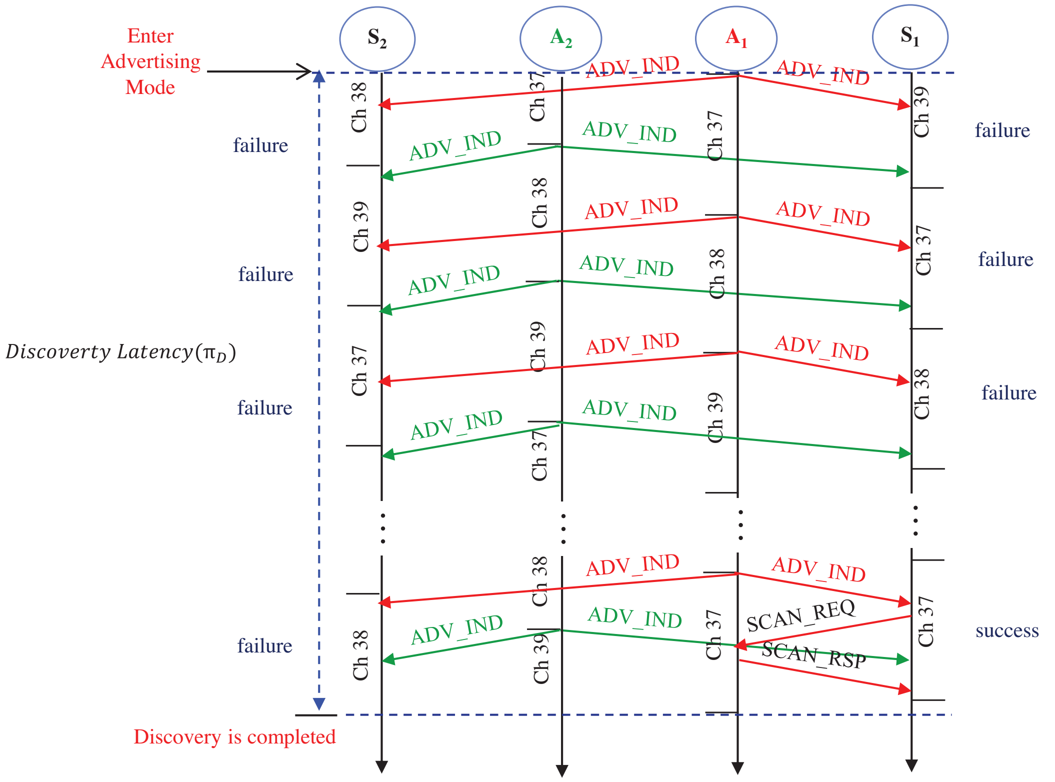
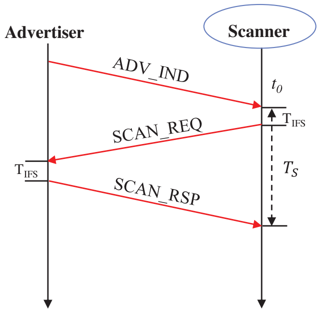


(a) Discovery latency



t_0 : Time instance at which the scanner receives an ADV_IND

(b) Control messages exchanged for discovery process

Fig. 2. Discovery latency and control messages exchanged for discovery process.

Table 2
States defined for energy analysis during device discovery process.

States	Meaning	Amount of current in each state	Time duration of each state	Energy consumed in each state
① INIT	Wake-up, pre-process to prepare radio and turn on radio in preparation of Tx and Rx	i_{in}	τ_{in}	$\epsilon_{in} = i_{in}\tau_{in}$
② TADV	Send an ADV_IND on an advertising channel	i_{tx}	T_{ADV_IND}	$\epsilon_{ta} = i_{tx}T_{ADV\_IND}$
③ RSCAN	Receive a SCAN_REQ	i_{rx}	T_{SCAN_REQ}	$\epsilon_{rs} = i_{rx}T_{SCAN\_REQ}$
④ TSCAN	Send a SCAN_RSP on an advertising channel	i_{tx}	T_{SCAN_RSP}	$\epsilon_{ts} = i_{tx}T_{SCAN\_RSP}$
⑤ CONVERT	Convert Tx-mode to Rx-mode, or vice-versa	i_{co}	τ_{co}	$\epsilon_{co} = i_{co}\tau_{co}$
⑥ LISTEN	Listen a SCAN_REQ until completion of τ_{WA}	i_{rx}	τ_{li}	$\epsilon_{li} = i_{rx}\tau_{li}$
⑦ TRANS	Tx and Rx on one advertising channel are done, and it takes some transition time (or waiting time) to continue operating on the next channel (identical to interframe space)	i_{ch}	τ_{ch}	$\epsilon_{ch} = i_{ch}\tau_{ch}$
⑧ POST	Set up the sleep timer in preparation for the next advertising event	i_{po}	τ_{po}	$\epsilon_{po} = i_{po}\tau_{po}$
⑨ SLEEP	Sleep by turning off irrelative components so as to save energy	i_{sl}	τ_{sl}	$\epsilon_{sl} = i_{sl}\tau_{sl}$
⑩ DELAY	A random delay (AdvDelay) chosen from $[0, \delta_{max}]$ to determine advertising interval	i_{sl}	δ	$\epsilon_{\delta} = (\frac{\delta_{max}}{2})i_{sl}$

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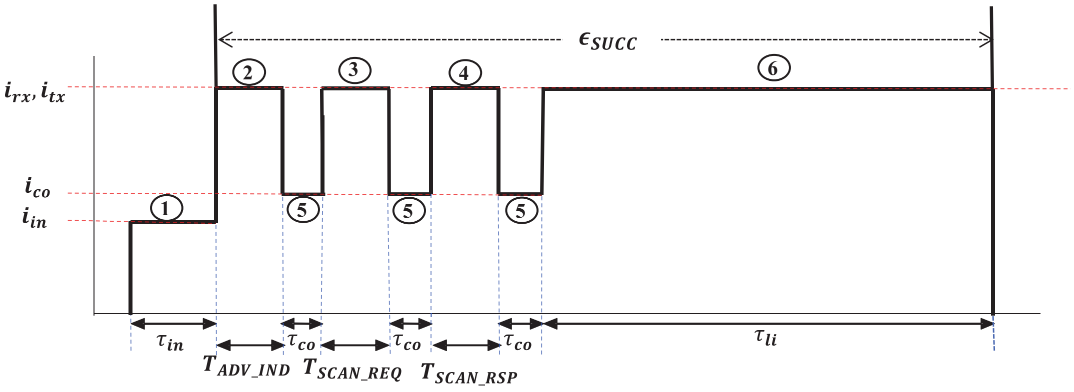
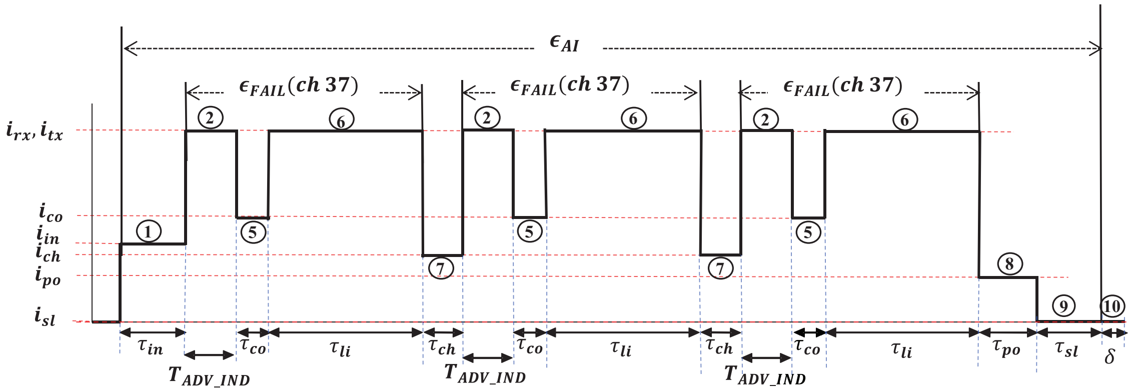
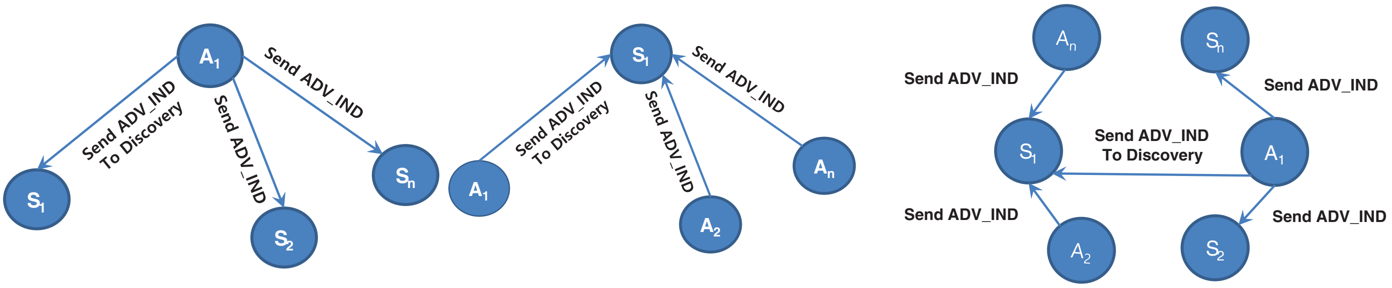


(a) Consumed energy in case of successful discovery



(b) Consumed energy in case of discovery failure

Fig. 3. Consumed energy in case of discovery success and failure.



(a) 1:N network (b) M:1 network (c) M:N network

Fig. 4. Configurations of BLE networks used for our analysis.

initialization as illustrated in Fig. 3(a), However, when the discovery process fails on an advertisement, the BLE device goes through states ②→⑤→⑥ after initialization, as illustrated in Fig. 3(b).

3. Analytical model

In this section, we inspect energy performance of the BLE device discovery from the perspective of a theoretical model that fully accords with the BLE specification. In our prior study [13], we have presented an analytical model for discovery latency considering a realistic situation where there are many collisions caused by contention among BLE devices during the discovery process. The analysis for energy performance evaluation is also based on [13].

We investigate the performance of the BLE device discovery from the perspective of the theoretical model in full accordance with the BLE specification to investigate performance metrics. We first present an analytical model for the probability of device discovery, which lay an important basis to derive an analytical model for latency and energy cost spent on device discovery.

3.1. Probability of successful discovery

Our analysis is derived from focusing on investigating under what conditions a particular pair of advertiser and scanner (called A_1 and S_1) successfully discover each other among them. In our analysis, we consider three configurations of BLE network as shown in Fig. 4. Fig. 4(a) illustrates a network with (N+1) BLE devices, where only A_1 acts as an advertiser and other N devices (S_1, S_2,..., S_N) work as scanners. On the contrary, Fig. 4(b) illustrates a network with (M + 1) BLE devices, where only S_1 acts as scanner and other M devices (A_1, A_2,..., A_M) work as advertisers. Fig. 4(c) depicts a more general configuration consisting of (M + N) BLE devices where M devices (A_1, A_2,..., A_M) work as advertisers and N devices (S_1, S_2,..., S_N) work as

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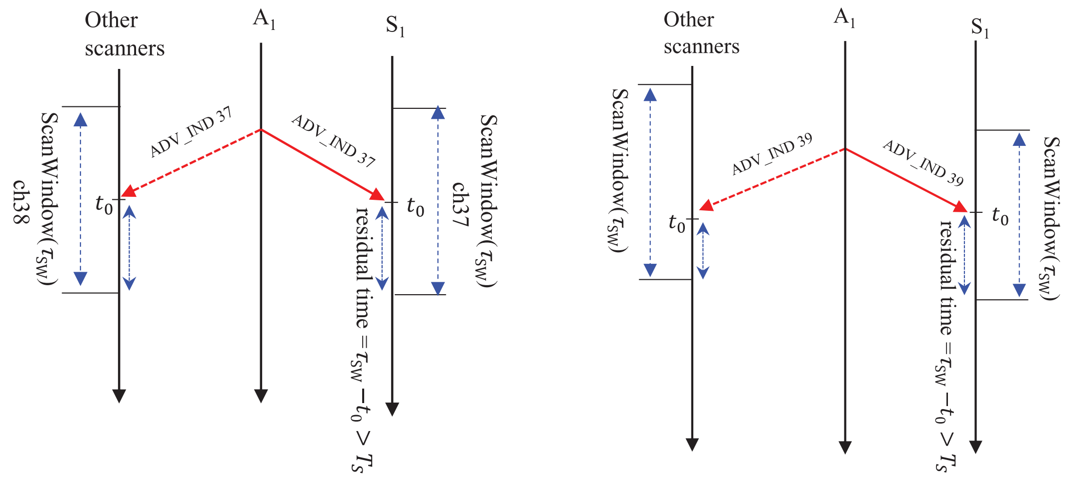
Table 3
Events used for analysis of device discovery process.

Event	Meaning
E1	S_1 is synchronous with A_1.
E2	One or more of S_2, S_3,... and S_N are synchronous with A_1.
E3	One or more of A_2, A_3,... and A_M are synchronous with S_1.
E4	S_1 has enough time to reply to ADV_IND until ScanWindow is finished.
E5	Synchronous scanners of S_2, S_3,... and S_N are sleeping or cannot reply to ADV_IND within their current ScanWindows.
E6	S_1 does not receive ADV_IND from A_2, A_3..., and A_M in an interval [t_1-T_s, t_1+T_s].



(a) Case 1 : $(\mathrm{E1} \cap \overline{\mathrm{E2}} \cap \mathrm{E4})$ (b) Case 2 $(\mathrm{E1} \cap \mathrm{E2} \cap \mathrm{E4} \cap \mathrm{E5})$

Fig. 5. Cases for successful discovery in 1:N network.

scanners. We define six events to express clearly under what conditions A_1 can successfully discover S_1, as listed in Table 3.

1) 1:N network

Consider a network with (N + 1) BLE devices, where In this network, A_1 can successfully discover S_1 if () or () is true, where $\overline{\mathrm{E2}}$ is the complementary event of E2 indicating "none of S_2,S_3,... and S_N is synchronous with A_1". The former case means that only S_1 is synchronous with A_1 AND S_1 has enough time to reply to ADV_IND until the current ScanWindow is finished. The latter case means S_1 and one or more scanners of S_2,S_3,..., and S_N are synchronous with A_1 AND only S_1 has enough time to reply to ADV_IND until the current ScanWindow is finished.

The probability that S_1 is synchronous with A_1 on receipt of the ADV_IND on channel 37 is given by . ${}_3C_1$ represents the probability of selecting a specific channel out of three channels (37, 38 and 39). Assuming that S_1 receives an ADV_IND from A_1 at an arbitrary time instance of t_0, the residual time until completion of ScanWindow is given by $(\tau_{SW} - t_0)$. For successful discovery, S_1 should reply to ADV_IND with a SCAN_REQ message and then should receive a SCAN_RSP from A_1 within the residual time. In other words, S_1 should have a sufficient residual time greater than T_S $(= T_{SCAN\_REQ} + T_{SCAN\_RSP} + 2T_{IFS})$ until completion of ScanWindow to reply to ADV_IND. The probability that S_1 has sufficient residual time is given by $\frac{\tau_{SW} - T_S}{\tau_{SI}}$. So, we have the probability of successful discovery on channel 37 by

$$\mathrm{PROB}(\mathrm{E1} \cap \overline{\mathrm{E2}} \cap \mathrm{E4}) = 3\mathrm{C}1\left(\frac{1}{3}\right)^2\left(\frac{2}{3}\right)^{N-1}\left(\frac{\tau_{SW} - T_S}{\tau_{SI}}\right)$$
$$= \left(\frac{1}{3}\right)\left(\frac{2}{3}\right)^{N-1}\left(\rho - \frac{T_S}{\tau_{SI}}\right) \quad (1)$$

where $= \frac{\tau_{SW}}{\tau_{SI}}$, which means duty cycle defined as the proportion of time to express how long a BLE device spends time on scanning process during a given ScanInterval. There is no doubt that $0 \le \rho \le 1$. In particular, ρ becomes equal to one in the continuous scanning mode

Although any other scanner of S_2, S_3,..., and S_N is synchronized with A_1, it cannot send any message if its residual time is shorter than T_{IFS} until completion of ScanWindow or it receives ADV_IND during the sleeping period. So, the probability that one or more scanners of S_2, S_3,..., and S_N are synchronous with A_1, but they cannot reply to ADV_IND is given by $\sum_{k=1}^{N-1} \mathrm{N-1Ck}(\frac{1}{3})^k(\frac{\tau_{SI} - \tau_{SW} + T_{IFS}}{\tau_{SI}})^k(\frac{2}{3})^{N-1-k}$. Using algebra $(a+b)^N = \sum_{k=0}^{N} \mathrm{NCk}a^k b^{N-k}$, we have

$$\mathrm{PROB}(\mathrm{E1} \cap \mathrm{E2} \cap \mathrm{E4} \cap \mathrm{E5})$$
$$= 3\mathrm{C}1\left(\frac{1}{3}\right)^2\left(\frac{\tau_{SW} - T_S}{\tau_{SI}}\right)\left\{\sum_{k=1}^{N-1} \mathrm{N-1Ck}\left(\frac{1}{3}\right)^k \right.$$
$$\left. \times\left(\frac{\tau_{SI} - \tau_{SW} + T_{IFS}}{\tau_{SI}}\right)^k\left(\frac{2}{3}\right)^{N-1-k}\right\}$$
$$= \left(\frac{1}{3}\right)\left(\rho - \frac{T_S}{\tau_{SI}}\right)\left[\left\{\left(\frac{1}{3}\right)\left(1 - \rho + \frac{T_{IFS}}{\tau_{SI}}\right) + \frac{2}{3}\right\}^{N-1} - \left(\frac{2}{3}\right)^{N-1}\right] \quad (2)$$

Summing (10) and (11), we get the probability of successful discovery on channel 37, denoted by P_1, by

$$P_1 = \left(\frac{1}{3}\right)^N\left(\rho - \frac{T_S}{\tau_{SI}}\right)\left(3 - \rho + \frac{T_{IFS}}{\tau_{SI}}\right)^{N-1} \quad (3)$$

Since A_1 sends another ADV_IND on the next advertising channel (channel 38) after a duration of τ_{WA}, S_1 receives the second ADV_IND at $t_0 + \tau_{WA}$. So, the residual time for the second ADV_IND until completion of ScanWindow is $(\tau_{SW} - t_0 - \tau_{WA})$ assuming that τ_{SI} is sufficiently longer than τ_{WA} as shown in Fig. 5.

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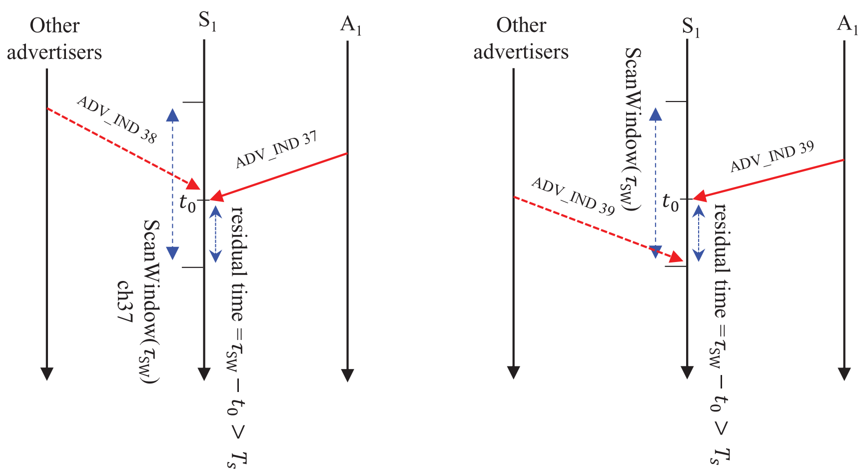

(a) Case 3 : $\mathrm{E1} \cap \overline{\mathrm{E3}} \cap \mathrm{E4}$ (b) Case 4 : $\mathrm{E1} \cap \mathrm{E3} \cap \mathrm{E4} \cap \mathrm{E6}$

Fig. 6. Cases for successful discovery in M:1 network.

The probability that S_1 has enough time for handshaking control messages for the second ADV_IND until completion of ScanWindow is given by $(\frac{\tau_{SW}-\tau_{WA}-T_S}{\tau_{SI}})$. Since the probability that S_1 is synchronous with A_1 on receipt of the second ADV_IND is given by $3C1(\frac{1}{3})^2$, we have the probability of discovery successful on channel 38 by

$$P_2 = \left(\frac{1}{3}\right)^{N-1}\left(\rho - \frac{\tau_{WA}}{\tau_{SI}} - \frac{T_S}{\tau_{SI}}\right)\left(3 - \rho + \frac{T_{IFS}}{\tau_{SI}}\right)^{N-1} \tag{4}$$

Similarly, the arrival time of the third ADV_IND at S_1 is $t_0 + 2\tau_{WA}$, and thus the residual time for the third ADV_IND until completion of the ScanWindow is given by $(\tau_{SW} - t_0 - 2\tau_{WA})$. Thus, we have the probability of successful discovery on channel 39 by

$$P_3 = \left(\frac{1}{3}\right)^{N-1}\left(\rho - 2\frac{\tau_{WA}}{\tau_{SI}} - \frac{T_S}{\tau_{SI}}\right)\left(3 - \rho + \frac{T_{IFS}}{\tau_{SI}}\right)^{N-1} \tag{5}$$

2) M:1 network

Next, we consider a BLE network with (M + 1) BLE devices as shown in Fig. 6. In this configuration, A_1 can successfully discover S_1 if $(\mathrm{E1} \cap \mathrm{E2} \cap \mathrm{E4})$ or $(\mathrm{E1} \cap \overline{\mathrm{E2}} \cap \mathrm{E4} \cap \mathrm{E6})$ is true. In the same way as previously, we get

$$\begin{aligned}\mathrm{PROB}\left(\mathrm{E1} \cap \overline{\mathrm{E3}} \cap \mathrm{E4}\right) &= 3C1\left(\frac{1}{3}\right)^2\left(\frac{2}{3}\right)^{M-1}\left(\frac{\tau_{SW} - T_S}{\tau_{SI}}\right)\\ &= \left(\frac{1}{3}\right)\left(\frac{2}{3}\right)^{M-1}\left(\rho - \frac{T_S}{\tau_{SI}}\right)\end{aligned} \tag{6}$$

$$\begin{aligned}&\mathrm{PROB}(\mathrm{E1} \cap \mathrm{E3} \cap \mathrm{E4} \cap \mathrm{E6})\\ &= 3C1\left(\frac{1}{3}\right)^2\left(\frac{\tau_{SW} - T_S}{\tau_{SI}}\right)\left[\sum_{k=1}^{M-1} N - 1Ck\left(\frac{1}{3}\right)^k\right.\\ &\quad\left.\times\left(\frac{\tau_{SI} - 2T_S}{\tau_{SI}}\right)^k\left(\frac{2}{3}\right)^{M-1-k}\right]\\ &= \frac{1}{3}\left(\rho - \frac{T_S}{\tau_{SI}}\right)\left[\left\{\frac{1}{3}\left(1 - \frac{2T_S}{\tau_{SI}}\right) + \frac{2}{3}\right\}^{M-1} - \left(\frac{2}{3}\right)^{M-1}\right]\end{aligned} \tag{7}$$

So, we have the probability of successful discovery on channel 37 by

$$P_1 = \left(\frac{1}{3}\right)^{M}\left(\rho - \frac{T_S}{\tau_{SI}}\right)\left(3 - \frac{2T_S}{\tau_{SI}}\right)^{M-1} \tag{8}$$

Similarly, the probability of successful discovery on channel 38 and 39, can be computed as follows:

$$P_2 = \left(\frac{1}{3}\right)^{M}\left(\rho - \frac{\tau_{WA}}{\tau_{SI}} - \frac{T_S}{\tau_{SI}}\right)\left(3 - \frac{2T_S}{\tau_{SI}}\right)^{M-1} \tag{9}$$

$$P_3 = \left(\frac{1}{3}\right)^{M}\left(\rho - \frac{2\,\tau_{WA}}{\tau_{SI}} - \frac{T_S}{\tau_{SI}}\right)\left(3 - \frac{2T_S}{\tau_{SI}}\right)^{M-1} \tag{10}$$

3) M:N network

Using the events listed in Table 3, we can derive four cases where A1 can successfully discover S1 as shown in Fig. 7. For example, the first case means the situation where only S_1 is synchronous with A_1 and at the same time S_1 has enough time to reply to ADV_IND until the current ScanWindow is finished. This case can be expressed by $\mathrm{E1} \cap \mathrm{E4}$ using events in Table 3. Similarly, we can express the other three cases as follows:

1. Case 5: $\mathrm{E1} \cap \overline{\mathrm{E2}} \cap \overline{\mathrm{E3}} \cap \mathrm{E4}$
2. Case 6: $\mathrm{E1} \cap \mathrm{E2} \cap \overline{\mathrm{E3}} \cap \mathrm{E4} \cap \mathrm{E5}$
3. Case 7: $\mathrm{E1} \cap \overline{\mathrm{E2}} \cap \mathrm{E3} \cap \mathrm{E4} \cap \mathrm{E6}$
4. Case 8: $\mathrm{E1} \cap \mathrm{E2} \cap \mathrm{E3} \cap \mathrm{E4} \cap \mathrm{E5} \cap \mathrm{E6}$

where $\overline{\mathrm{E2}}$ and $\overline{\mathrm{E3}}$ mean the complementary events of E2 and E3, respectively.

$$\begin{aligned}P\left(\mathrm{E1} \cap \overline{\mathrm{E2}} \cap \overline{\mathrm{E3}} \cap \mathrm{E4}\right) &= 3C1\left(\frac{1}{3}\right)^2\left(\frac{2}{3}\right)^{M+N-2}\left(\frac{\tau_{SW} - T_S}{\tau_{SI}}\right)\\ &= \left(\frac{1}{3}\right)\left(\frac{2}{3}\right)^{M+N-2}\left(\rho - \frac{T_S}{\tau_{SI}}\right)\end{aligned} \tag{11}$$

$$\begin{aligned}&P\left(\mathrm{E1} \cap \mathrm{E2} \cap \overline{\mathrm{E3}} \cap \mathrm{E4} \cap \mathrm{E5}\right)\\ &= 3C1\left(\frac{1}{3}\right)^2\left(\frac{2}{3}\right)^{M-1}\left(\frac{\tau_{SW} - T_S}{\tau_{SI}}\right)\left\{\sum_{k=1}^{N-1} N - 1Ck\left(\frac{1}{3}\right)^k\right.\\ &\quad\left.\times\left(\frac{\tau_{SI} - \tau_{SW} + T_{IFS}}{\tau_{SI}}\right)^k\left(\frac{2}{3}\right)^{N-1-k}\right\}\\ &= \left(\frac{1}{3}\right)^N\left(\frac{2}{3}\right)^{M-1}\left(\rho - \frac{T_S}{\tau_{SI}}\right)\left[\left(3 - \rho + \frac{T_{IFS}}{\tau_{SI}}\right)^{N-1} - 2^{N-1}\right]\end{aligned} \tag{12}$$

$$\begin{aligned}&P\left(\mathrm{E1} \cap \overline{\mathrm{E2}} \cap \mathrm{E3} \cap \mathrm{E4} \cap \mathrm{E6}\right)\\ &= 3C1\left(\frac{1}{3}\right)^2\left(\frac{2}{3}\right)^{N-1}\left(\frac{\tau_{SW} - T_S}{\tau_{SI}}\right)\left\{\sum_{k=1}^{M-1} N - 1Ck\left(\frac{1}{3}\right)^k\right.\end{aligned}$$

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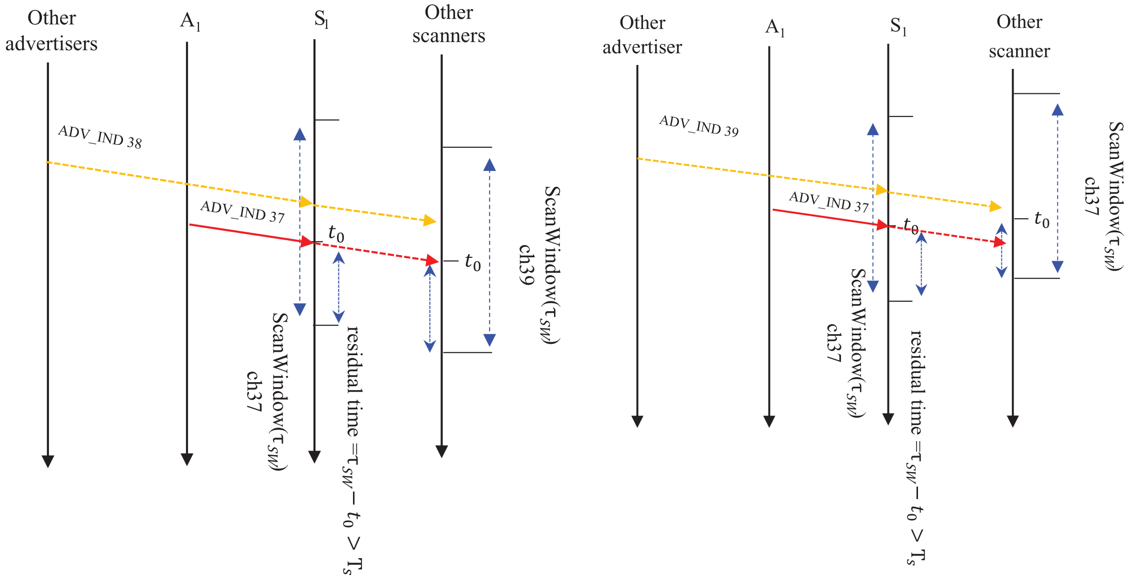
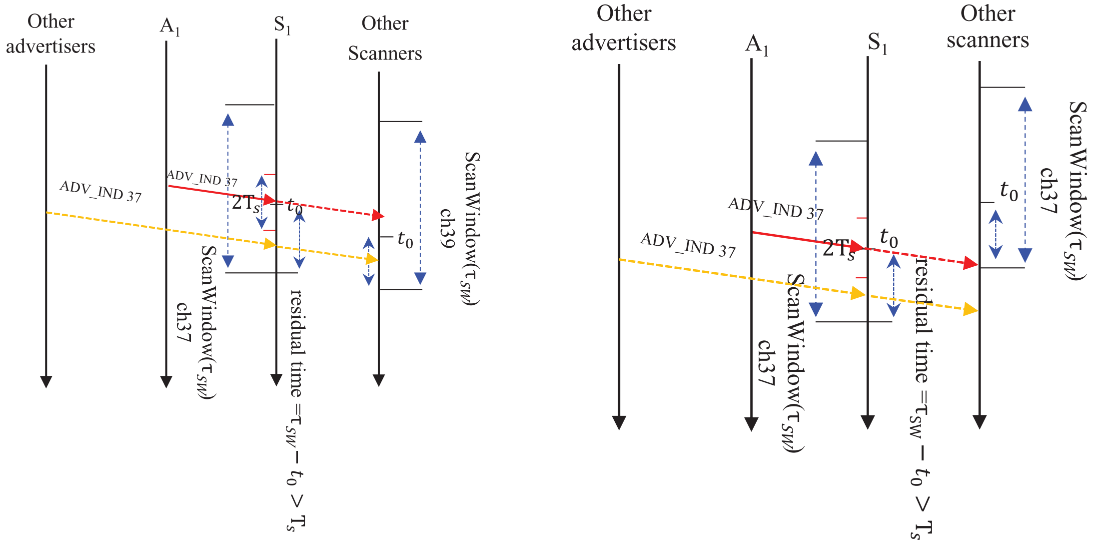


(a) Case 5: $(E1 \cap \overline{E2} \cap \overline{E3} \cap E4)$ (b) Case 6 : $(E1 \cap E2 \cap \overline{E3} \cap E4 \cap E5)$



(c) Case 7 : $(E1 \cap \overline{E2} \cap E3 \cap E4 \cap E6)$ (d) Case 8 : $(E1 \cap E2 \cap E3 \cap E4 \cap E5 \cap E6)$

Fig. 7. Cases for successful discovery in M:N network.

$$\times \left(\frac{\tau_{SI} - 2T_S}{\tau_{SI}}\right)^k \left(\frac{2}{3}\right)^{M-1-k} \Bigg\}$$

$$= \left(\frac{1}{3}\right)^M \left(\frac{2}{3}\right)^{N-1} \left(\rho - \frac{T_S}{\tau_{SI}}\right) \left[\left(3 - \frac{2T_S}{\tau_{SI}}\right)^{M-1} - 2^{M-1}\right] \tag{13}$$

$P(E1 \cap E2 \cap E3 \cap E4 \cap E5 \cap E6$

$$= 3C1 \left(\frac{1}{3}\right)^2 \left(\frac{\tau_{SW} - T_S}{\tau_{SI}}\right) \left\{\sum_{k=1}^{M-1} N - 1Ck \left(\frac{1}{3}\right)^k \left(\frac{\tau_{SI} - 2T_S}{\tau_{SI}}\right)^k\right.$$

$$\left. \times \left(\frac{2}{3}\right)^{M-1-k} \right\}$$

$$\times \left\{\sum_{k=1}^{N-1} N - 1Ck \left(\frac{1}{3}\right)^k \left(\frac{\tau_{SI} - \tau_{SW} + T_{IFS}}{\tau_{SI}}\right)^k \left(\frac{2}{3}\right)^{N-1-k}\right\}$$

$$= \left(\frac{1}{3}\right)^{M+N-1} \left(\rho - \frac{T_S}{\tau_{SI}}\right) \left[\left(3 - \frac{2T_S}{\tau_{SI}}\right)^{M-1} - 2^{M-1}\right]$$

$$\times \left[\left(3 - \rho + \frac{T_{IFS}}{\tau_{SI}}\right)^{N-1} - 2^{N-1}\right] \tag{14}$$

Summing (11)–(14), we have the probability of successful discovery on the first advertising channel by

$$P_1 = \left(\frac{1}{3}\right)^{M+N-1} \left(\rho - \frac{T_S}{\tau_{SI}}\right) \left(3 - \frac{2T_S}{\tau_{SI}}\right)^{M-1} \left(3 - \rho + \frac{T_{IFS}}{\tau_{SI}}\right)^{N-1} \tag{15}$$

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Table 4
Latency and consumed energy for successful discovery and the corresponding probability.

AdvInterval	Channel ID	Probability of successful discovery	Latency to successful discovery	Consumed energy for successful discovery
1	37	P_1	τ_{WA}	$\epsilon_{in} + \epsilon_{SUCC}$
	38	$(1-\mathrm{P}_1)\mathrm{P}_2$	$2\tau_{WA}$	$\epsilon_{in} + \epsilon_{FAIL} + \epsilon_{SUCC}$
	39	$(1-\mathrm{P}_1)(1-\mathrm{P}_2)\mathrm{P}_3$	$3\tau_{WA}$	$\epsilon_{in} + 2\epsilon_{FAIL} + \epsilon_{SUCC}$
2	37	$(1-\mathrm{P}_1)(1-\mathrm{P}_2)(1-\mathrm{P}_3)\mathrm{P}_1$	$(\tau_{AI} + \frac{\delta_{max}}{2}) + \tau_{WA}$	$\epsilon_{AI} + \epsilon_{\delta} + \epsilon_{in} + \epsilon_{SUCC}$
	38	$(1-\mathrm{P}_1)^2(1-\mathrm{P}_2)(1-\mathrm{P}_3)\mathrm{P}_2$	$(\tau_{AI} + \frac{\delta_{max}}{2}) + 2\tau_{WA}$	$\epsilon_{AI} + \epsilon_{\delta} + \epsilon_{in} + \epsilon_{FAIL} + \epsilon_{SUCC}$
	39	$(1-\mathrm{P}_1)^2\,(1-\mathrm{P}_2)^2(1-\mathrm{P}_3)\,\mathrm{P}_3$	$(\tau_{AI} + \frac{\delta_{max}}{2}) + 3\tau_{WA}$	$\epsilon_{AI} + \epsilon_{\delta} + \epsilon_{in} + 2\epsilon_{FAIL} + \epsilon_{SUCC}$
…		…	…	
i	37	$(1-\mathrm{P}_1)^{i-1}\,(1-\mathrm{P}_2)^{i-1}(1-\mathrm{P}_3)^{i-1}\mathrm{P}_1$	$(i-1)(\tau_{AI} + \frac{\delta_{max}}{2}) + \tau_{WA}$	$(i-1)(\epsilon_{AI} + \epsilon_{\delta}) + \epsilon_{in} + \epsilon_{SUCC}$
	38	$(1-\mathrm{P}_1)^{i}\,(1-\mathrm{P}_2)^{i-1}(1-\mathrm{P}_3)^{i-1}\mathrm{P}_2$	$(i-1)(\tau_{AI} + \frac{\delta_{max}}{2}) + 2\tau_{WA}$	$(i-1)(\epsilon_{AI} + \epsilon_{\delta}) + \epsilon_{in} + \epsilon_{FAIL} + \epsilon_{SUCC}$
	39	$(1-\mathrm{P}_1)^{i}\,(1-\mathrm{P}_2)^{i}(1-\mathrm{P}_3)^{i-1}\mathrm{P}_3$	$(i-1)(\tau_{AI} + \frac{\delta_{max}}{2}) + 3\tau_{WA}$	$(i-1)(\epsilon_{AI} + \epsilon_{\delta}) + \epsilon_{in} + 2\epsilon_{FAIL} + \epsilon_{SUCC}$

$$\mathrm{P}_2=\left(\frac{1}{3}\right)^{M+N-1}\left(\rho-\frac{\tau_{WA}}{\tau_{SI}}-\frac{\mathrm{T}_S}{\tau_{SI}}\right)\left(3-\frac{2\mathrm{T}_S}{\tau_{SI}}\right)^{M-1}\left(3-\rho+\frac{\mathrm{T}_{IFS}}{\tau_{SI}}\right)^{N-1} \tag{16}$$

$$\mathrm{P}_3=\left(\frac{1}{3}\right)^{M+N-1}\left(\rho-2\frac{\tau_{WA}}{\tau_{SI}}-\frac{\mathrm{T}_S}{\tau_{SI}}\right)\left(3-\frac{2\mathrm{T}_S}{\tau_{SI}}\right)^{M-1}\left(3-\rho+\frac{\mathrm{T}_{IFS}}{\tau_{SI}}\right)^{N-1} \tag{17}$$

We can summarize the probability of successful discovery on channel 37,38,39 as follows:

Configuration	Probability of successful discovery on channel 37,38,39	
1:N	$P_k = (\frac{1}{3})^{N-1}(\rho - (k-1)\,\frac{\tau_{WA}}{\tau_{SI}} - \frac{\mathrm{T_S}}{\tau_{SI}})(3 - \rho + \frac{\mathrm{T_{IFS}}}{\tau_{SI}})^{N-1}$	(18)
M:1	$P_k = (\frac{1}{3})^{M}(\rho - (k-1)\,\frac{\tau_{WA}}{\tau_{SI}} - \frac{\mathrm{T_S}}{\tau_{SI}})(3 - \frac{2\mathrm{T_S}}{\tau_{SI}})^{M-1}$	(19)
M:N	$P_k = \left(\frac{1}{3}\right)^{M+N-1}\left(\rho - (k-1)\,\frac{\tau_{WA}}{\tau_{SI}} - \frac{\mathrm{T_S}}{\tau_{SI}}\right)\left(3 - \frac{2\mathrm{T_S}}{\tau_{SI}}\right)^{M-1} \times\left(3 - \rho + \frac{\mathrm{T_{IFS}}}{\tau_{SI}}\right)^{N-1}$	(20)

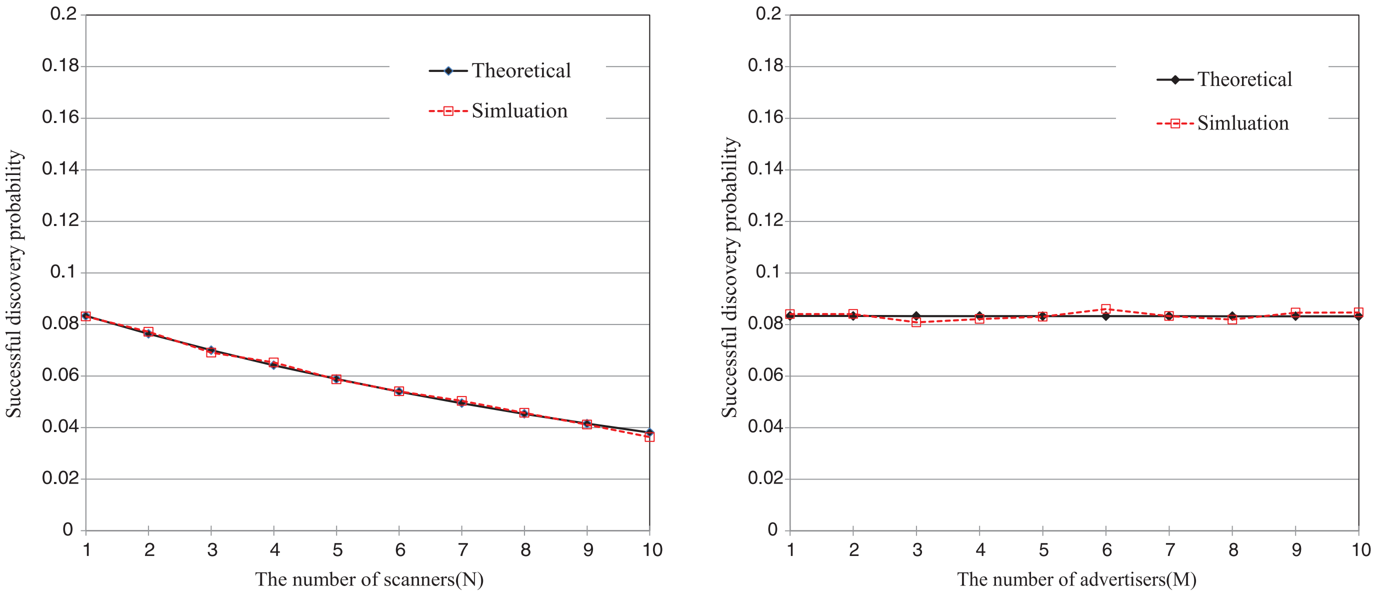
where k = 1,2,3 corresponding to channel 37,38,39, respectively.

Table 5
Simulation parameters and their values.

Parameters	Value	Parameters	Value
Number of advertises (M)	1∼10	τ_{co}	0.105 (ms)
Number of scanners (N)	1∼10	τ_{li}	0.767∼9.767 (ms)
τ_{WA}	1∼10 (ms)	τ_{ch}	0.150 (ms)
τ_{AI}	20∼10240 (ms)	τ_{po}	0.950 (ms)
τ_{SI}	2.5∼10240 (ms)	τ_{sl}	2.46∼10234.55 (ms)
τ_{SW}	2.5∼10240 (ms)	i_{in}	7.36 (mA)
$\mathrm{T_{IFS}}$	0.150 (ms)	i_{co}	7.4 (mA)
$\mathrm{T_S}$	0.604 (ms)	i_{tx}	17.5 (mA)
$\mathrm{T_{ADV\_IND}}$	0.128 (ms)	i_{rx}	17.5 (mA)
$\mathrm{T_{SCAN\_RSP}}$	0.176 (ms)	i_{ch}	7.4 (mA)
$\mathrm{T_{SCAN\_REQ}}$	0.128 (ms)	i_{po}	7.4 (mA)
δ_{max}	10 (ms)	i_{sl}	0.001 (mA)
τ_{in}	1.2 (ms)		

3.2. Expected discovery latency and energy consumption

The energy consumed for successful discovery depends on the number of failures experienced in attempts during the discovery process as shown in Table 4, where P_1, P_2, P_3 mean the probability of successful discovery on the first, the second, and the third advertising channel, respectively, as previously discussed.



(a) Probability of successful discovery as the number of scanners increase (τ_{SI}=10240, τ_{SW}=2560, τ_{WA}=10, τ_{AI}=1280, M=5)

(b) Probability of successful discovery as the number of advertisers increase (τ_{SI}=10240, τ_{SW}=2560, τ_{WA}=10, τ_{AI}=1280, N=5)

Fig. 8. Probability of successful discovery of advertiser as the number of BLE devices increase.

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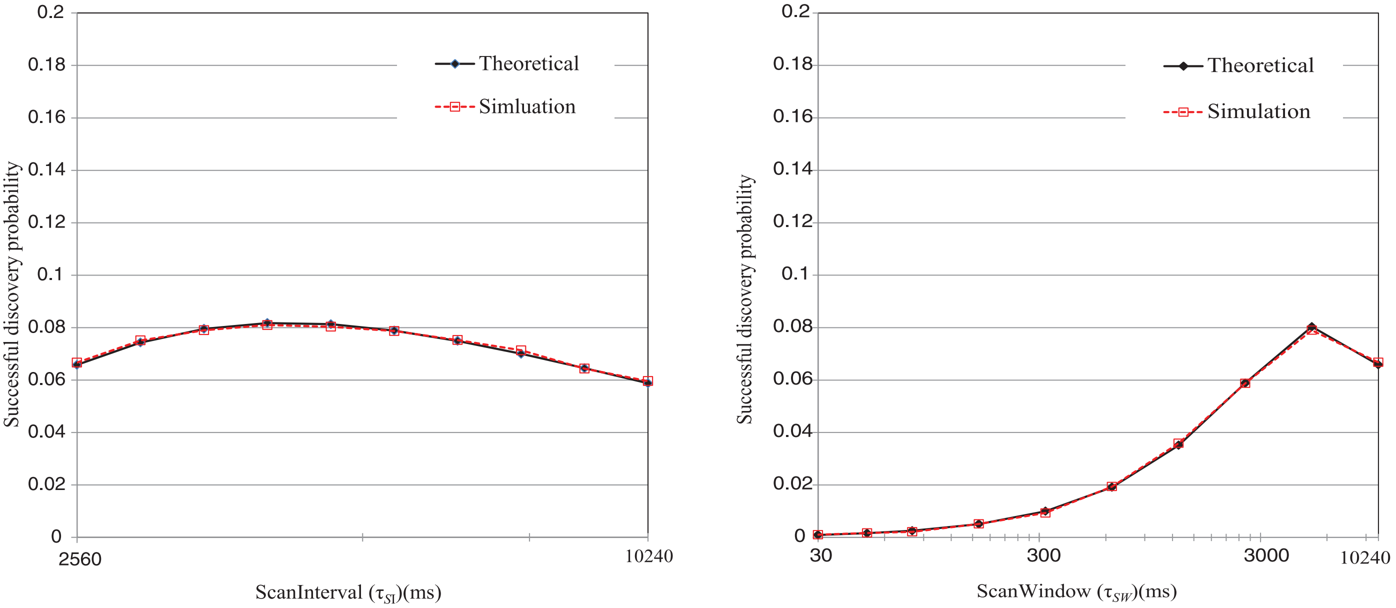
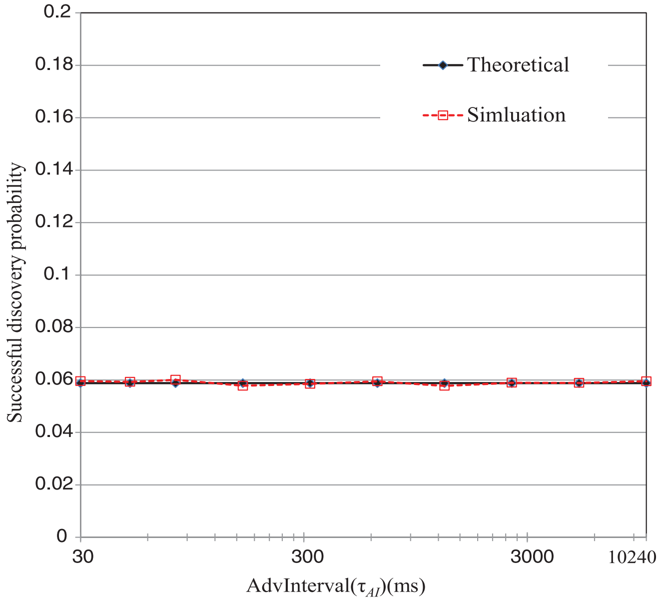


(a) Probability of successful device discovery as ScanInterval(τ_{SI}) is varied (τ_{SW} =2560, τ_{WA}=10, τ_{AI}=1280, M=5, N=5)

(b) Probability of successful device discovery as ScanWindow(τ_{SW}) is varied (τ_{SI} =10240, τ_{WA}=10, τ_{AI}=1280, M=5, N=5)



(c) Probability of successful device discovery as AdvInterval (τ_{AI}) is varied (τ_{SI} =10240, τ_{SW} =2560, τ_{WA}=10, M=5, N=5)

Fig. 9. Probability of successful discovery of advertiser with various parameter settings.

From Table 4, we can get the expected discovery latency, denoted by π_D, by:

$$\begin{aligned}\pi_D = &\sum_{i=1}^{\infty}(1-\mathrm{P}_1)^{i-1}(1-\mathrm{P}_2)^{i-1}(1-\mathrm{P}_3)^{i-1}\mathrm{P}_1\\ &\times\left\{(i-1)\left(\tau_{AI}+\frac{\delta_{max}}{2}\right)+\tau_{WA}\right\}\\ &+\sum_{i=1}^{\infty}(1-\mathrm{P}_1)^{i}(1-\mathrm{P}_2)^{i-1}(1-\mathrm{P}_3)^{i-1}\mathrm{P}_2\\ &\times\left\{(i-1)\left(\tau_{AI}+\frac{\delta_{max}}{2}\right)+2\tau_{WA}\right\}\\ &+\sum_{i=1}^{\infty}(1-\mathrm{P}_1)^{i}(1-\mathrm{P}_2)^{i}(1-\mathrm{P}_3)^{i-1}\mathrm{P}_3\\ &\times\left\{(i-1)\left(\tau_{AI}+\frac{\delta_{max}}{2}\right)+3\tau_{WA}\right\}\end{aligned} \tag{21}$$

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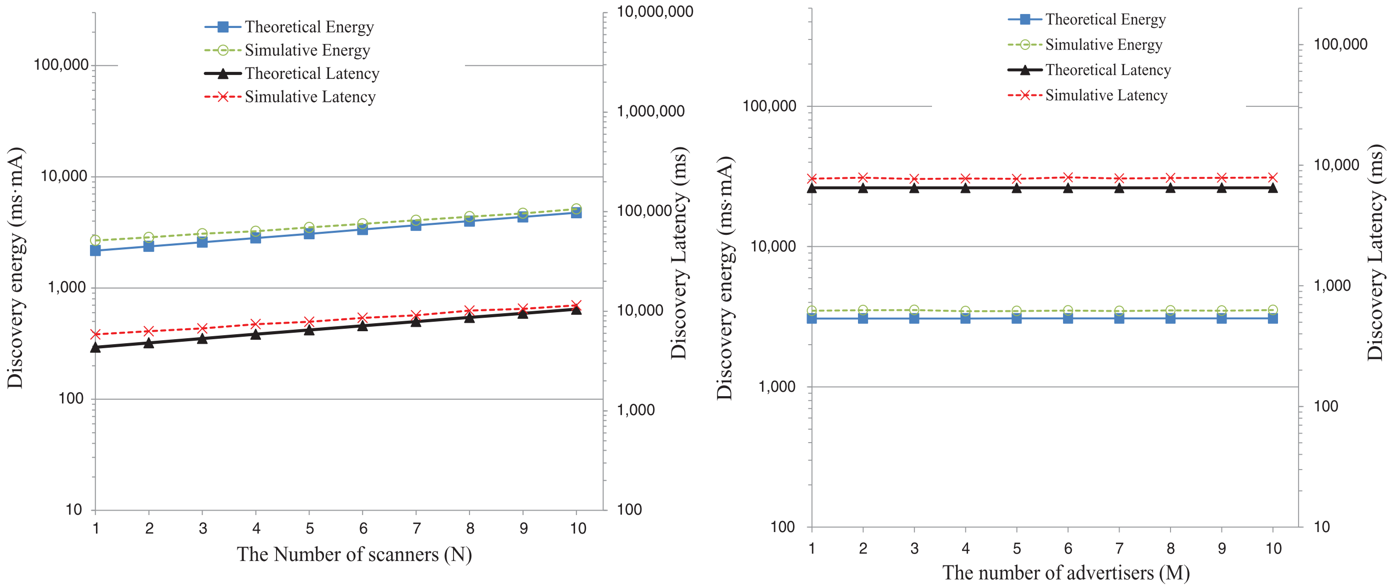

(a) Mean discovery latency and energy as the number of scanners increase (τ_{SI} =10240, τ_{SW} =2560, τ_{WA}=10, τ_{AI}=1280, M=5)

(b) Mean discovery latency and energy as the number of advertiser increase (τ_{SI} =10240, τ_{SW} =2560, τ_{WA}=10, τ_{AI}=1280, N=5)

Fig. 10. Mean discovery latency and energy of advertiser as the number of BLE devices increase.

Using algebra $\sum_{i=0}^{\infty} ix^i = x\frac{d}{dx}(\sum_{i=0}^{\infty} x^i) = \frac{x}{(1-x)^2}$, we get:

$$\pi_D = \left[\frac{(1-P_1)(1-P_2)(1-P_3)}{1-(1-P_1)(1-P_2)(1-P_3)}\right]\left(\tau_{AI}+\frac{\delta_{max}}{2}\right) + \left[\frac{1+(1-P_1)+(1-P_1)(1-P_2)-3(1-P_1)(1-P_2)(1-P_3)}{1-(1-P_1)(1-P_2)(1-P_3)}\right]\tau_{WA} \quad (22)$$

The expected discovery latency of M:N networks can be determined using Eq. (20) respectively, by substituting the corresponding probability of successful discovery in Eq. (22).

The energy consumed for an advertisement on a channel depends on whether the device discovery process succeeds or not. From Fig. 3, we can get the mean energy consumed for successful discovery on a channel by

$$\epsilon_{SUCC} = \epsilon_{ta}+\epsilon_{ts}+\epsilon_{rs}+3\epsilon_{co}+i_{sl} \times\left(\tau_{WA}-T_{ADV_{IND}}-T_{SCAN_{RSP}}-T_{SCAN_{REQ}}-3\tau_{co}\right) \quad (23)$$

Similarly, the mean energy consumed in case of discovery failure on a channel is given by

$$\epsilon_{FAIL} = \epsilon_{ta}+\epsilon_{co}+i_{sl}(\tau_{WA}-T_{ADV_{IND}}-\tau_{co}) \quad (24)$$

When the discovery process fails on all three channels (37, 38 and 39) on an advertising interval (τ_{AI}), the advertiser spends as much energy as

$$\epsilon_{AI} = \epsilon_{in}+3\epsilon_{FAIL}+2\epsilon_{ch}+\epsilon_{po}+\epsilon_{sl}+\epsilon_{\delta} \quad (25)$$

From Table 4, we can get the expected discovery energy, denoted by E_D, by

$$\begin{aligned} E_D = & \sum_{i=1}^{\infty}(1-P_1)^{i-1}(1-P_2)^{i-1}(1-P_3)^{i-1}P_1 \\ & \times\left\{(i-1)(\epsilon_{AI}+\epsilon_{\delta})+\epsilon_{in}+\epsilon_{SUCC}\right\} \\ & +\sum_{i=1}^{\infty}(1-P_1)^{i}(1-P_2)^{i-1}(1-P_3)^{i-1}P_2 \\ & \times\left\{(i-1)(\epsilon_{AI}+\epsilon_{\delta})+\epsilon_{in}+\epsilon_{SUCC}+\epsilon_{FAIL}\right\} \\ & +\sum_{i=1}^{\infty}(1-P_1)^{i}(1-P_2)^{i}(1-P_3)^{i-1}P_3 \\ & \times\left\{(i-1)(\epsilon_{AI}+\epsilon_{\delta})+\epsilon_{in}+\epsilon_{SUCC}+2\epsilon_{FAIL}\right\} \end{aligned} \quad (26)$$

$$E_D = \left[\frac{(1-P_1)(1-P_2)(1-P_3)}{1-(1-P_1)(1-P_2)(1-P_3)}\right](\epsilon_{AI}+\epsilon_{\delta}) + \left[\frac{(1-P_1)(P_2+2P_3-2P_2P_3)}{1-(1-P_1)(1-P_2)(1-P_3)}\right]\epsilon_{FAIL}+\epsilon_{in}+\epsilon_{SUCC} \quad (27)$$

4. Simulation validation

In order to validate the analytical models, we have developed a BLE simulating program which fully complies with the BLE specification. The simulative settings accord with the standard definition

Table 6
Influence factors and their impacts.

Performance criterion Varying factor	Probability of successful device discovery	Mean discovery latency of advertiser	Mean discovery energy of advertiser
As the number of advertisers increases	No significant effect	No effect	No effect
As the number of scanners increases	Decreases slowly in a linear way	Increases slowly	Increases slowly
As ScanInterval is increased	No significant effect	No meaningful effect	No meaningful effect
As ScanWindow is increased	Increases very gradually	Decreases linearly	Decreases linearly
As AdvInterval is increased	No significant impact	Increases linearly	No effect

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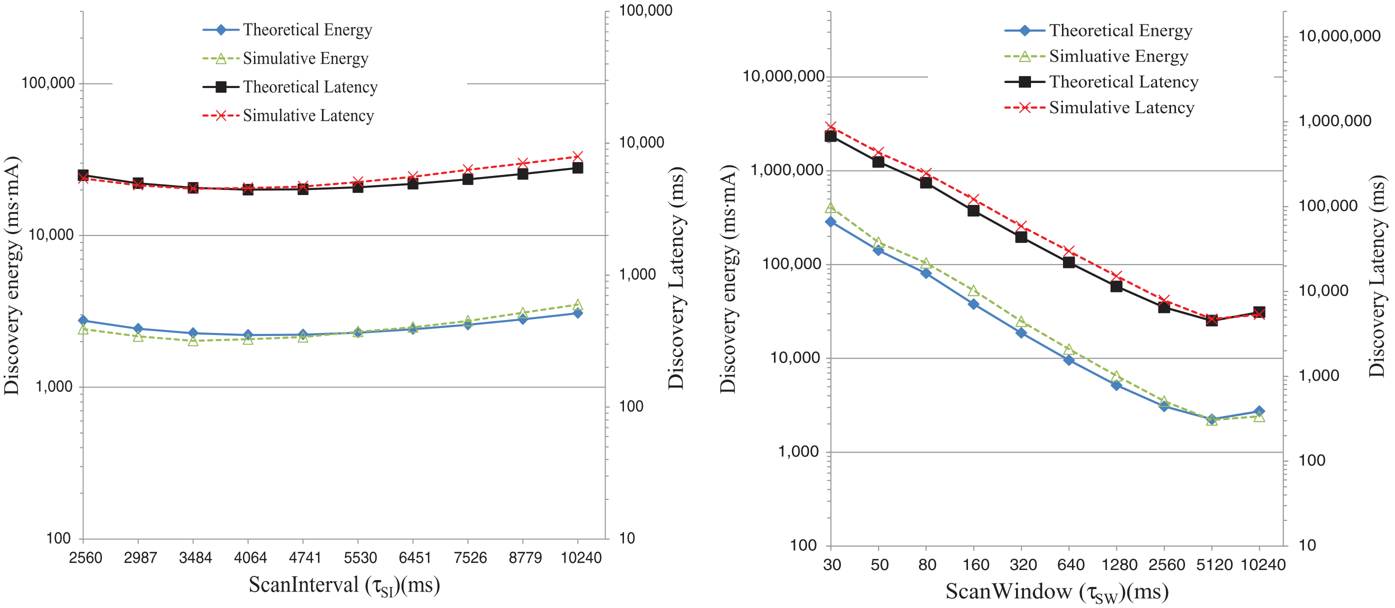
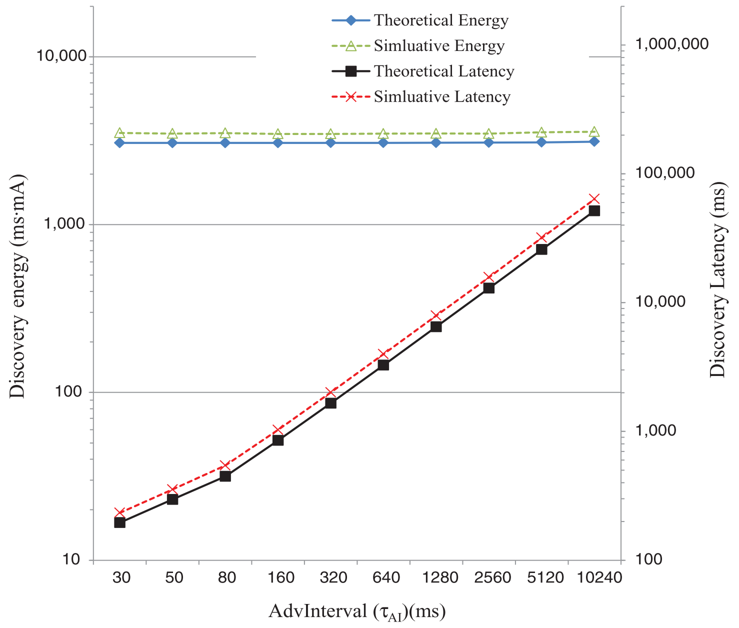


(a) Mean discovery energy and latency as ScanInterval(τ_{SI}) is varied

(τ_{SW} =2560, τ_{WA}=10, τ_{AI}=1280, M=5, N=5)

(b) Mean discovery energy and latency as as ScanWindow(τ_{SW}) is varied

(τ_{SI} =10240, τ_{WA}=10, τ_{AI}=1280, M=5, N=5)



(c) Mean discovery energy and latency as AdvInterval (τ_{AI}) is varied

(τ_{SI}=10240, τ_{SW} =2560, τ_{WA}=10, τ_{AI}=1280, M=5, N=5)

Fig. 11. Mean discovery latency and energy of advertiser with various parameter settings.

as previously described, and we compare the analytical results with those obtained via simulations. We simulate over 10,000 times for each scenario to get the average results, where related details of the experimental settings are listed in Table 5. For the purpose of convenience, we use mA•µs or mA•ms as the unit of energy, which can be easily transferred into standard Ampere hour (e.g. mAh) units whenever necessary.

Fig. 8 shows the probability of successful discovery as the number of BLE devices is increased. It should be noted that the probability indicates A_1 and S_1 successfully discover each other during one τ_{WA} as aforementioned in the previous section. We record experimental results and compare them with the theoretical ones. In Fig. 8, we found that the theoretical curves practically coincide with the simulation. We can see that the discovery probability is very low

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although there are not so many devices in the network. For example, the scanner experiences the success probability of about 0.3 during one τ_{WA} in discovering process in even 1:1 network, which is totally different from the behavior of other wireless networks. This is because BLE devices can be synchronous on one of the three advertising channels with a probability of 1/3 to discover each other. Further, the discovery probability linearly decreases with the number of scanners in the network since the discovery process fails more frequently due to collisions of the abundant control packets such as SCAN_REQ or SCAN_RSP during the discovery process. However, the number of advertisers does not affect the probability of successful discovery. This is because ADV_IND packets from different advertisers are not likely to be collided during a short handshaking time.

Fig. 9 shows results of performance evaluation related to discovery probability in terms of a different set of parameters such as τ_{AI}, τ_{SI} and τ_{SW} in the BLE network. The graphs are obtained by varying one parameter while setting the other two parameters to their default values listed in Table 5. For simulation, we set scanners in periodical scanning mode while letting advertisers begin advertising at the random time. As can be seen in the graph, we cannot observe any meaningful change in the probability of discovery as τ_{SI} is increased. On the contrary, the discovery probability is somewhat comparatively affected by τ_{SW}. The probability of discovery increases very gradually with τ_{SW} when $\tau_{SW} < 5120$ ms. This is because the scanning duration is only dependent on τ_{SW} and the frequency of scans per advertisement is determined by the ratio of τ_{SW} to τ_{SI}. The scanner stays for long time on each channel for scanning despite less frequent scans as τ_{SW} is increased. So, we can say that the scanner loses many chances of device discovery if τ_{SW} becomes shorter than the expectation needed by the advertiser.

On the other hand, the discovery probability is not affected by τ_{AI} since this parameter influences neither scanning duration nor the frequency of scans. Instead, τ_{AI} is only used to determine when the advertiser initiates the next advertisement process.

Fig. 10 shows the mean discovery energy and latency as the number of BLE devices is increased. We record these two performance criteria with two different y-axes in one graph. In this figure, it can be found the theoretical curves coincide with the simulation ones very well. As seen in Fig. 10(a), the mean discovery energy and discovery latency slowly rise with the number of scanners. This is, as explained above, because of collisions of the abundant control packets from different scanners. However, we can observe a different thing in Fig. 10(b). The number of advertisers does not affect the energy consumption and discovery latency since there are few collisions among advertisers, even though, the number of advertisers is increased.

Fig. 11 shows the mean discovery energy and latency in terms of a different set of parameters such as τ_{AI}, τ_{SI} and τ_{SW}. Fig. 11(a) shows the results of average energy and latency versus varied ScanInterval ranging from 2560 ms to 10.24 s where $\tau_{SW} = 2560$ ms and $\tau_{AI} = 1280$ ms, and Fig. 11(b) shows the results of average energy and latency versus varied ScanWinodw τ_{SW} ranging from 30 ms to the maximally available 10.24 s where $\tau_{SI} = 10.24$ s and $\tau_{AI} = 1280$ ms. First, we can see that the theoretical and experimental curves fit quite well over all ranges of parameters which validates our analysis in the previous section.

The mean discovery energy and latency do not change meaningfully on the advertiser side when $\tau_{SI} < 4000$ ms and rises slightly when τ_{SI} exceed 4000 ms as shown in Fig. 11(a). However, tuning the τ_{SW} influences energy expectation of the advertiser in an inverse proportional way as can be seen in Fig. 11(b). We can see that a small τ_{SW} would possibly make the advertiser suffer an undesired high energy and latency waste in advertising, and the average energy and latency of advertiser keeps decreasing with τ_{SW} (even a slight increase of τ_{SW} brings a significant drop in energy consumption). The mean discovery energy and latency approach to the minimal values when $\tau_{SW} \approx \tau_{SI}$, which corresponds to continuous scanning ($\rho \approx 1$). At this time, the scanner makes advertisers minimize their energy and latency. This is because continuous scanning provides a guarantee of an immediate reception for any advertising event, and thus always introduces the minimal energy and latency consumption for the advertisers. However, there is no doubt that for the whole system, continuous scanning quite naturally leads to maximal energy consumption to the scanner. So, for the BLE scanner, the ScanWindow (τ_{SW}) is advisable to set larger than the advertising interval τ_{AI} of the advertiser, to avoid unexpected energy consumption.

We can see that the energy and the latency expectation are different on the advertiser side, even though, the duty cycle remains the same. With the same value of duty cycle, the average energy and latency increase almost linearly with τ_{SI} on the advertiser side. The larger τ_{SI} is selected, the advertiser consumes yet the larger energy and longer latency for its discovery process.

Fig. 11(c) shows the average energy versus advertising interval τ_{AI} ranging from 30 ms to 10.24 s where τ_{SW} is set to a fixed value 2.56 s. This figure depicts that the mean discovery energy remains almost constant with τ_{AI}, but the mean discovery latency increases with τ_{AI} in a linear way. With τ_{AI}, the sleeping period increases in a linear way, but there is little energy consumption during the sleeping period. So, change of τ_{AI} do not bring a significant impact to the discovery energy, while strongly affecting the discovery latency.

In Table 6, we summarize the influence factors their impacts to show what extent these affect the discovery energy and latency.

5. Conclusions

We present analytical models for the discovery probability and the discovery latency and energy consumption on the advertiser side, which are validated through intensive simulations with a wide variety of environments. It is shown the theoretical results well fit the simulation ones. The theoretical and simulations results indicate that a wide range of BLE parameters provide high flexibility for BLE devices to customize efficiently with various applications.

We can see that the mean discovery energy slowly rises with the number of scanners, but the number of advertisers does not significantly affect the energy consumption. We can also see that the advertiser needs more energy with a shorter ScanWindow(τ_{SW}) due to the reduced listening period for receiving the ADU_PDU. Further, when ScanWindow(τ_{SW}) becomes close to ScanInterval(τ_{SI}), the advertiser consumes much less energy. In addition, the average energy and latency increase almost linearly with τ_{SI} on the advertiser side with a fixed value of duty cycle. It can be also seen that AdvInterval(τ_{AI}) does not affect the energy consumption on the advertiser side.

We believe that our work can provide insights regarding the practical usage of BLE and helpful guidelines to the design of fast and energy-efficient applications for BLE.

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