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Energy-Efficient BLE Device Discovery for Internet of Things

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***Abstract*—As a short-range and peer-to-peer wireless communication technology, Bluetooth low energy (BLE) receives lots of attentions recently. By enabling discover devices in the proximity, BLE could support various mobile Internet of Things (IoT) applications. Obviously, device discovery plays an essential role on the trade-off between the number of devices discovered and the energy consumption for a mobile IoT device with a constrained resource. This paper subsequently proposes a smart device discovery mechanism, named sDiscovery, to adaptively adjust scan window and scan interval according to the variant of the environment. In particular, we record the identities of devices discovered during each scan window and find out the redundant ones. Intuitively, a larger number of redundant devices encountered implies a more stable environment. In this case, the number of unknown devices encountered becomes smaller and the scan window can be shortened as well as the scan interval can be enlarged to preserve energy. The simulation results show that sDiscovery outperforms the existing solution and conventional BLE mechanism from the perspective of power saving. Moreover, we verify the correctness of simulation model through experiments in TI CC2540 development board, where a prototype of the protocol is implemented.**

***Index Terms*—Bluetooth Low Energy, CC2540, Device Discovery, Energy Efficiency, Internet of Things**

I. Introduction

Bluetooth Low Energy (BLE) has received attentions recently due to low power consumption, the small amount of data transmission, and infrequent communications [1]. BLE has been widely applied to broad range of devices, including smartphones and household equipment, wearable computer, medical, and wellness devices. The device-to-device (D2D) feature of BLE is of major interest to the development of the Internet of Things (IoT) since direct interoperation between devices is achieved [2], [3]. Comparing with the conventional Bluetooth audio and data streaming applications, where significant amounts of data transmission and frequent interaction between two devices are needed, BLE is more suitable for the control message delivery among mobile IoT devices.

In an environment with numerous mobile IoT devices, device discovery becomes a must of achieving successful data exchange and link establishment among IoT devices. In order to discover peers in the vinicity, a device periodically listens on the spectrum with duration of ScanWindow and the interval ScanInterval. If we spend more efforts on scanning, such as decrease the scan interval or increase the scan window, we can observe more candidate devices for connections. It unfortunately consumes more power, which might be unnecessary if the current environment is stable, i.e., no new devices will be encountered. How to detect enough number of IoT devices so that discovery latency is constrained without incurring unnecessary waste on energy is a critical issue [4], [5].

The current literature [6]–[11] focus on analyzing the performance of device discovery in Bluetooth and BLE from the perspective of either discovery latency or power consumption. Among them, Han, *et al.* [11] first proposed a eDiscovery protocol considering the number of scanned peers to adjust the scanning interval and window in Bluetooth. Inspired by the idea of [11], this paper further investigates the environment of BLE and considers the number of "repeated peers" scanned, since it reflects the stability of environment more precisely. In the proposed smart discovery (named as sDiscovery) protocol, if the number of repeated devices in the successive scannings is larger than a threshold, a static environment is implied. In this case, we can enlarge the scan interval and shorten the scan window since a small number of new devices are expected to be discovered, and a frequent scanning is unnecessary, thereby decreasing the power consumption.

In order to evaluate the performance of sDiscovery, we follow the analtyical model of neighbor discover process [12], [13] and further conduct extensive simulation experiments on discovery protocol of BLE device. Moreover, we practically implement sDiscovery on the famous BLE development board, TI CC2540 [14], to validate the correctness of the simulation. The simulation results show that comparing with the device discovery protocol with constant scan interval and conventional BLE device discovery, sDiscovery could consume less energy by paying the price of discovering fewer peers for connection. In the case of the stable environment, a smaller number of peers discovered is acceptable while much smaller power consumption is more beneficial.

The rest of this paper is organized as follows. Section II describes the discovery protocol and the related works. The proposed sDiscovery mechanism is described in the following section. Section IV presents the simulation and experimental results. Finally, we conclude this work in Section V.

II. Background and Related Work

Typically, the establishment of a connection between two BLE-enabled devices is regarded as an asymmetric procedure by which an advertiser announces that it is a connectable device, while a scanner listens for such advertisements. As

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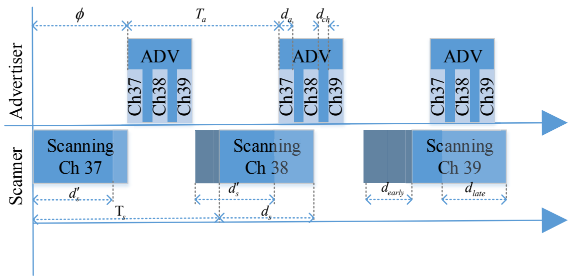

Fig. 1: Advertising and scanning in BLE

shown in Figure 1, an advertising node periodically sends out advertising packets and a group of consecutive packets. In each of these advertising events, advertising packet is sent sequentially via three dedicated adverting channels.

The scanner periodically and sequentially scans three advertising channels with duration of ScanWindow and interval ScanInterval. Once the scanner finds the advertiser at a specific advertising channel, the role of scanner becomes an initiator, who initialize a connection between the advertiser by transmitting a Connection Request message containing its information. The advertiser expects a response on the same advertising channels to achieve two-way signaling communications. Obviously, the performance of making a connection highly depends on the frequency and latency of the scanning. How to adjust the scanning interval and window so that enough number of devices in the nearby will be detected with constained discovery latency and acceptable energy consumption has been widely investiaged from the perspectives of Bluetooth [6], [11] and BLE [7]–[10], [12], [13]. Drula et al. [6] adjust device discovery parameters according to recent activity level and the location of previous contacts. In [11], the historical information about discovered peers is leveraged to change the duration so that the unnecessary energy consumption is avoided.

The analytical models are proposed to derive discovery latency [7] and energy consumption [9] for BLE devices. The analytical model in [10] analyze the performance for multiple BLE device pairs (i.e., advertiser and scanner). Kindt et al. [12] concentrate on derive a precise model to analyze the power consumption of BLE devices. Authors in [13] provide a practical guideline in selecting the initial or default device discovery parameter values for the best trade-off between discovery latency and energy consumption. In [8], an adaptive algorithm is proposed where the scanner adjusts its parameters according to the reports from already discovered advertisers, which might consume extra energy. An adpative algorithm considering both energy consumption and discovery latency for BLE devices is necessay, which motivates this work.

III. sDiscovery

This section proposes a Smart Discovery mechanism, sDiscovery, to adaptively change the ScanInterval and ScanWindow to achieve energy efficiency. The primary design concept of sDiscovery is to reduce energy consumption, while maintaining discover acceptable peers for possible connection. Comparing with eDiscovery [11] which leverages the number of discovered peers as the metric, sDiscovery further considers the peers discovered repeatedly, i.e., redundant neighbors. As a result, the key parameters in this algorithm are the threshold of the number of discovered peer N, the threshold of the number of discovered redundant peers $redundantN$, and the increment/decrement of ScanInterval I. Please note that the presentation of this paper follows the style of eDiscovery [11] for the easier understanding.

Algorithm 1 Dynamically device discovery protocol

1: ScanWindow = $BaseW$, ScanInterval = $BaseI$
2: **while** (TRUE) **do**
3: StartDiscovery (ScanWindow)
4: identify $peers$ and $redundantpeers$
5: **if** ($redundantpeers > redundantN$) **then**
6: ScanWindow = $SmallW$
7: ScanInterval = $q \times BaseI$
8: **else**
9: **if** ($peers > N$) **then**
10: ScanWindow = $BaseW$
11: **else**
12: ScanWindow = $SmallW$
13: **end if**
14: **if** ($peers == 0$ and $LastPeers == 0$) **then**
15: ScanInterval = $q \times BaseI$
16: **else if** ($peers <> 0$ and $LastPeers == 0$) **then**
17: ScanInterval = $BaseI + r$
18: **else if** ($peers > LastPeers$) **then**
19: ScanInterval $- = I$
20: **else if** ($peers < LastPeers$) **then**
21: ScanInterval $+ = I$
22: **end if**
23: **end if**
24: $LastPeers = peers$
25: sleep (ScanInterval - ScanWindow)
26: **end while**

The basic idea is to adjust those thresholds to determine ScanWindow and ScanInterval, and thus to affect the duration and interval of BLE scanning. The main body of this algorithm is a while loop that performs BLE discovery for period of ScanWindow and then sleeps for period of ScanInterval - ScanWindow. The values of ScanWindow is adjusted at each round according to the number of discovered redundant peers. From lines 5-7, we exploit parameter $redundantN$ to determine the variety of environment. Obviously, when the number of discovered redundant peers is smaller than $redundantN$, the network is more static, and we increase ScanInterval as well as decrease ScanWindow to reduce power consumption. By changing the values of N and I, we can achieve the different tradeoff between the number of discovered peers and BLE energy consumption. Smaller N and I lead to more aggressive BLE scanning, which may discover more peers but also consumes more energy on the BLE device.

Regarding lines 9-23, we follows the suggestions from eDiscovery, where $peers$ is leveraged as the metric. In particular,

TABLE I: Simulation parameters set up

Scan Interval	$3.12s$
Scan Window	$2.56s$
Advertising Interval	$(0, 10]s$
Duration of an advertising packet	$446us$
Duration of wake up and preprocessing phase	$0.700ms$
Current wake up and preprocessing phase	$7.087mA$
Duration of postprocessing phase	$0.816ms$
Current consumed of postprocessing phase	$8.012mA$
Duration of reception phase	$d_{rx,s} = d_s$
Current consumed of reception phase	$26.339mA$
$redundantN$	1
N	3
I	1s
$BaseW$	2.56s
$BaseI$	3.12s
$SmallW$	$BaseW/2$ s
r	0

if the number of discovered peers is larger than N, ScanWindow remains as the initial value $BaseW$ so that more peers are expected to be discovered in the following rounds. If not, we set the next ScanWindow as $SmallW + r$, where r is defined in eDiscovery [11]. In this case, ScanWindow is reduced and energy is saved. In a similar way, we adapt the value of ScanInterval according to the trend on the number of discovered peers. For example, if the current number of discovered peers is larger than the previous one, we decrease ScanInterval by I, and vice versa.

IV. Performance Evaluation

This section conducts simulation experiments to investigate the performance of the algorithm from the perspective of the number of devices discovered and power consumption. We use C language to implement Algorithm 1 and simulate BLE network. The simulation area is a $1,800 \times 20$ meters^2 rectangle, where the scanning BLE devices move from $(0, 10)$ to $(1,800, 10)$ with a constant speed 1 meter/sec. We distribute 100 scanning BLE devices in the simulation area uniformly. The setup of simulation parameters is described in Table I. We are interested in the effects of $BaseW$, $BaseI$, $SmallW$, and r on the *ratio of discovered peers* and *energy consumption*. By applying the power model from [12], the energy consumption of a BLE device can be easily estimated.

A. Verification of Simulation

In order to validate the simulation results, this subsection implements a realistic experiment by using TI CC2540. First, we consider a simple case where only one advertiser-scanner pair exists. In this experiment, ScanWindow is set as 3.12 secs, ScanInterval is set as 1.28 sec, and AdvertisingInterval is set as $[0, 3]$ sec. As shown in Figure 2, we can observe that the trend of experimental results match that of simulation result. This figure also shows that as advertising interval increases, the expected discovery latency increases. It is due to that as advertising interval increases, the scanner has smaller probability to find out the existence of advertisor, which leads

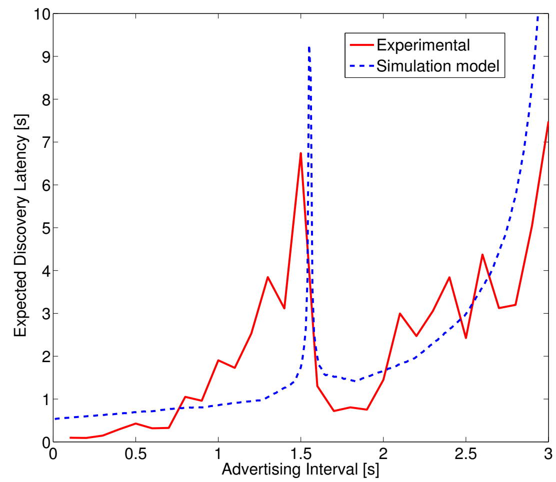

Fig. 2: Measured discovery latency compared to simulation values for one advertiser

a higher discovery latency. The peaks here is regarded as *Coupling Phenomena*. It occurs where scan interval is multiple time of advertising interval. In this case, scanner will have a very small probability to observe the advertisor, which incurs a large discovery latency.

We consider at most 11 BLE devices in the experimental environment, where one of them is set as the scanner, and all the others are set as the advertisers. In this experiment, ScanWindow is set as 5 secs, ScanInterval is set as 1 sec, and AdvertisingInterval is set as 1 sec. Figure 3 shows the effects of number of advertisers on the latency of discovering all devices. We can easily observe that the simulation and expermental results are matched in all cases. The figure also shows an intuitive result that when more advertisers exist, the scanner will spend much more time to discover all of them.

B. Simulation Results

1) Power Saving: This subsection compares the performance of sDiscovery, eDiscovery in BLE (please note that eDiscovery is originally proposed on Bluetooth [11], and we implement it in BLE), original scheme in specification [1], and constant scheme (i.e., the scanning interval is equals to scan window, that is, the scanner scan constantly). Figure 4 discusses the effects of advertising interval on number of discovered peers. An intuitive result is that as the advertising interval increases, the number of discovered peers decreases. It is due to that when the advertising interval increases, the scanner has smaller probability to find the nearby devices.

Since we leverage the number of discovered peers and number of repeated discovered peers nearby, sDiscvoery will adjust the scaning window to prevent unnecessary scanning attempts. As a results, sDiscovery discover less peers than original and constant schemes. We can also observe that sDiscovery has similar performance as eDiscovery in BLE.

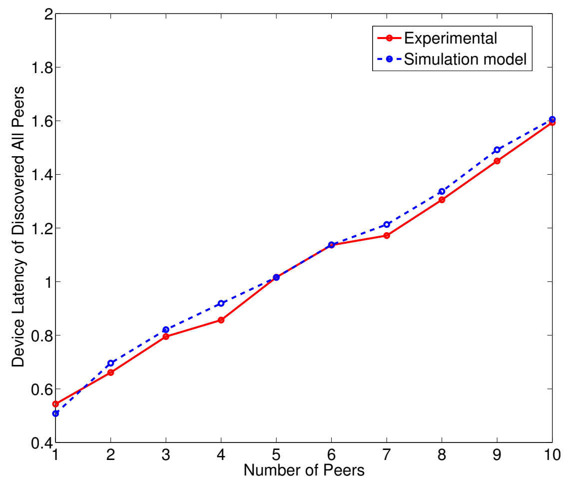

Fig. 3: Measured discovery latency compared to simulation values for multiple advertisers

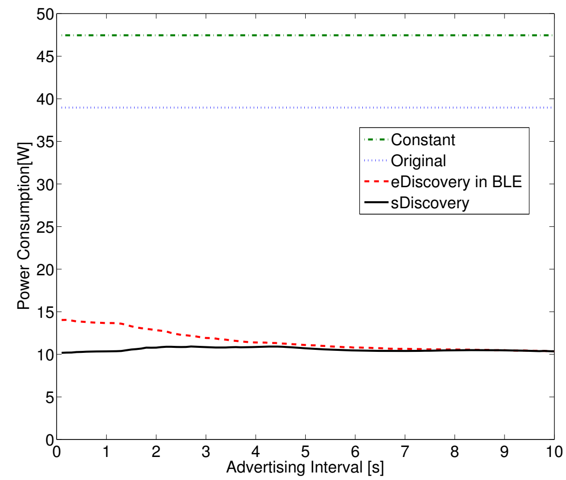

Fig. 5: Power consumption compare

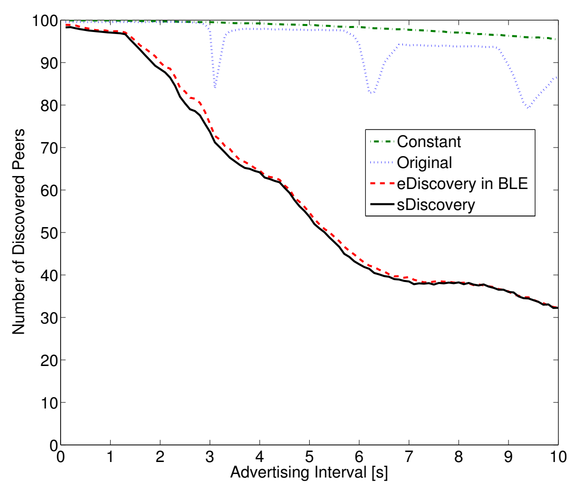

Fig. 4: Number of discovery compare

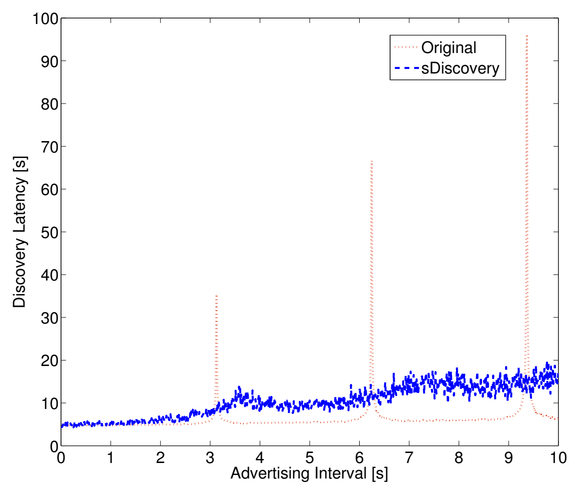

Fig. 6: Coupling Phenomena

Figure 5 discusses the effects of advertising interval on power consumption. We can observe that sDiscovery outperforms the existing solution significantly. Even comparing with eDiscovery in BLE mechanism, sDiscovery performs well when the advertising interval is small. It is due to that when advertising interval is small, the discovered results about the environment might not change so much. As a result, sDiscovery will adjust the scanning interval to prevent unnecessary scanning attempts, which reduces the waste of energy.

2) Coupling Phenomena: This subsection further investigates the coupling phenomena due to some specific parameter setup, i.e., $T_a = nT_s$. In this case, scanning event and advertising event will have smaller probability to meet, which leads high discovery latency. Figure 6 shows the effects of advertising interval on the discovery latency. Obviously, sDiscovery could resolve the problem of coupling phenomenon effectively. In the orignal mechanism, the discovery latency is very large when $T_a = nT_s$. However, sDiscovery adjusts the scanning interval and window so that T_a is not multiple times as long as T_s anymore. In this case, the coupling phenomena is avoided. The reason that the latency of sDiscovery is slightly larger than that of original scheme is that the adjustment of sDiscovery on scan interval and window makes scanner spend more time to find peers.

V. Conclusion

In this paper, an adaptive device discovery protocol, sDiscovery, for reducing the energy consumption of BLE is presented. sDiscovery dynamically changes the BLE scanning duration and interval according to the dynamic environments. We implement an experiment by using CC2540 to validate the correctness of simulation results, and to show that proposed mechanisms are compatible with the existing BLE device, which therefore facilitates the extensive development of BLE. The simulation results show that sDiscovery can save around 75 percent energy at the expense of discovering only about fewer peers, which is very important for energy-constrained IoT devices. Moreover, sDiscovery could effectively avoid coupling phenomena to prevent unnecessary energy waste.

References

[1] B. SIG, "Bluetooth core specification version 4.1," Dec. 2013.

[2] J. Nieminen, C. Gomez, M. Isomaki, T. Savolainen, B. Patil, Z. Shelby, M. Xi, and J. Oller, "Networking solutions for connecting Bluetooth Low Energy enabled machines to the Internet of Things," *IEEE Network*, vol. 28, no. 6, pp. 83–90, Nov. 2014.

[3] A. F. Harris III, V. Khanna, G. Tuncay, R. Want, and R. Kravets, "Bluetooth Low Energy in dense IoT environments," *IEEE Commun. Mag.*, vol. 54, no. 12, pp. 30–36, Dec. 2016.

[4] C. Gomez, J. Oller, and J. Paradells, "Overview and evaluation of Bluetooth Low Energy: An emerging low-power wireless technology," *Sensors*, vol. 12, no. 9, pp. 11 734–11 753, Aug. 2012.

[5] W. Lee, J. Kim, and S.-W. Choi, "New D2D peer discovery scheme based on spatial correlation of wireless channel," *IEEE Trans. Veh. Technol.*, vol. 65, no. 12, pp. 10 120–10 125, Dec. 2016.

[6] C. Drula, C. Amza, F. Rousseau, and A. Duda, "Adaptive energy conserving algorithms for neighbor discovery in opportunistic bluetooth networks," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 1, pp. 96–107, Jan. 2007.

[7] J. Liu, C.-F. Chen, and Y. Ma, "Modeling neighbor discovery in Bluetooth Low Energy networks," *IEEE Commun. Lett.*, vol. 16, no. 9, pp. 1439–1441, Sept. 2012.

[8] J. Liu, C.-F. Chen, Y. Ma, and Y. Xu, "Energy analysis of device discovery for Bluetooth Low Energy," in *Proc. IEEE VTC Fall 2013*, Sept. 2013, pp. 1–5.

[9] ——, "Adaptive device discovery in Bluetooth Low Energy networks," in *Proc. IEEE VTC Spring 2013*, June 2013, pp. 1–5.

[10] K. Cho, W. Park, M. Hong, G. Park, W. Cho, J. Seo, and K. Han, "Analysis of latency performance of Bluetooth Low Energy (BLE) networks," *Sensors*, vol. 15, no. 1, pp. 59–78, Jan. 2015.

[11] B. Han, J. Li, and A. Srinivasan, "On the energy efficiency of device discovery in mobile opportunistic networks: A systematic approach," *IEEE Trans. Mobile Comput.*, vol. 14, no. 4, pp. 786–799, Apr. 2015.

[12] P. Kindt, D. Yunge, R. Diemer, and S. Chakraborty, "Precise energy modeling for the Bluetooth Low Energy protocol," *arXiv preprint arXiv:1403.2919*, Mar. 2014.

[13] W. S. Jeon, M. H. Dwijaksara, and D. G. Jeong, "Performance analysis of neighbor discovery process in Bluetooth Low Energy networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 2, pp. 1865–1871, Feb. 2017.

[14] T. Instruments, "TI CC2540." [Online]. Available: http://www.ti.com/product/CC2540