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# A discovery scheme based on carrier sensing in self-organizing Bluetooth Low Energy networks

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ABSTRACT

Bluetooth Low Energy (BLE) gets lots of attention from researchers as one of the most prominent solutions for short range communications. But, the BLE still has many challenging issues which must be resolved before deploying it for the technologies. In this paper, an enhanced discovery mechanism is proposed for BLE devices to avoid collisions during advertisement process, so as to achieve lower latency as well as energy consumption. The proposed scheme is modeled and validated via analytical and simulation methods. The proposed mechanism has shown its effectiveness in avoiding unexpected long latency and much energy consumption by carrier sensing during discovery process in crowded BLE networks.



## 1. Introduction

Recently, various wireless access technologies have been introduced to fulfill the internet and data requirement of mobile users. The competition of these access technologies gives birth to a new concept called Internet of Things (IoT) (Holler et al., 2014). IoT includes both short and long range communication services. With the introduction of 4G technology, it is now easy to use IoT in a mobile environment like vehicles and fast moving trains. The traditional wireless technologies can provide better services for long range communication, but it can consume more power and hence it is not an ideal technology for the short range communication.

Bluetooth Low Energy (BLE) is considered one of the solutions for providing wireless and data services which can be used to provide enhanced services for short-range communications in IoT. The IoT technology can be used in concatenation with BLE for providing different services like home devices and, police systems, and emergency services, medical services, etc.

BLE is designed to enable devices low power consumption. Devices with peripheral and central roles have different power requirements. BLE devices normally operate on very low-energy profile and hence the battery power can be used for months and even years with a 1000 mAh coin cell battery. Also, the BLE architecture supports the novel re-establishing service, i.e. when a mobile sensor node comes back in a network it automatically reconnects to an IoT system.

The fundamental structure of communication system of BLE is clearly defined in the Bluetooth standard, but there are still many other issues that can be addressed before using this technology for IoT systems. Researchers have proposed some ideas to improve functionalities of BLE for IoT systems, but none of them is able to be used as a generic model for IoT (Shrestha et al., 2013).

The BLE technology operates in the same spectrum range (the 2.400–2.4835 GHz ISM band) as the classic Bluetooth but uses a different set of channels. Instead of the classic Bluetooth 79 1-MHz channels, BLE only uses 39 channels. Channels number 37, 38 and 39 are reserved for broadcasting and discovering of devices. BLE uses frequency hopping to counteract narrowband interference problems in the ISM band.

When one or more BLE devices simultaneously begin advertising on the same advertising channel in a crowded BLE network, there will be a collision. When this happens, the advertising packets from both BLE devices will be distorted and not received successfully, which results in significant performance degradation. To resolve this problem, BLE standard introduces a random delay called advDelay to separate the advertising events over times. But, that is not good enough to avoid the collision in crowded BLE networks.

In this paper, we propose a discovery scheme based on carrier sensing during advertisement period to avoid collisions in crowded BLE networks. Our scheme makes use of a simple carrier sense (CS) algorithm before initiating advertisement. The working of the CS is illustrated in Fig. 2, for example if a device wants to find some neighboring devices, it first listens to each advertising channel

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before sending ADV_IND. If the channel is idle, the device may transmit; otherwise the device must back off for some random time before advertising. With our scheme, there will be no collision for those advertising packets because other devices are now aware of the advertisement.

Section 2 deals with related works. Section 3 explains the background of BLE operation and PDU types. Section 4 proposes the advertising scheme based on carrier sensing for BLE device discovery. Then, Section 5 presents an analytical model of the proposed scheme, and Section 6 validates the analytical model and evaluates the scheme via simulation. Finally, Section 7 contains the conclusion.

## 2. Related works

The device discovery performance of classical Bluetooth protocols has been intensively investigated using experimental and formal methods (Drula et al., 2007; Basagni et al., 2002; Duflot et al., 2006; Scott et al., 2005; Liberatore et al., 2006).

The study by Drula et al. (2007) discovered that it was possible to reduce the expected power consumption of Bluetooth devices by adaptive parameter settings depending on a mobility context. They performed comprehensive experiments on real devices, exploring the parameter space to determine the relationship between parameter settings and mean discovery time or power consumption.

Another simulation-based study on Bluetooth Device Discovery was presented by Basagni et al. (2002), who investigated device discovery in multi-hop Bluetooth networks, i.e. Bluetooth Scatternet, by means of classical Bluetooth inquiry procedures. Simulation results were taken to find that even if it required a long time for each node to become aware of all its neighbors, the Bluetooth topologies could be obtained about 6 s after the connection through those discovered devices.

On the other hand, Duflot et al. presented a formal analysis on device discovery performance for classical Bluetooth version 1.1 and 1.2 (Duflot et al., 2006). The probabilistic model checking technique and the tool PRISM were used to compute the performance bounds of device discovery in terms of the expected time and the expected power consumption. Their study proved that a low-level analysis could produce exact results as those derived from simulation techniques, and some innocuous assumptions in simulations could lead to incorrect performance estimations.

There have also been other works that tried to improve the device discovery performance for classical Bluetooth (Scott et al., 2005; Marc Liberatore et al., 2006). For instance, Scott et al. implemented an end-to-end Bluetooth-based mobile service framework (Scott et al., 2005); rather than using the standard Bluetooth device discovery model to detect nearby mobile services, it relied on machine-readable visual tags for out-of-band device and service selection. Their work demonstrated a tag-based connection-establishment technique offering significant improvements over the standard Bluetooth.

Marc Liberatore et al. (2006) have proposed a simple modification to Bluetooth-enabled devices, the addition of a second radio. They found that the dual radio approach and the full-duplex discovery offered longer and more frequent transfer opportunities in a simulated Disruption Tolerant Networks (DTN). In particular they revealed that the dual radio strategy was also more energy efficient than the single radio strategy in the scenarios. Their main contribution was to show how DTN designers could leverage the millions of consumer Bluetooth devices currently deployed with minimal and inexpensive hardware.

Unlike classical Bluetooth protocol studies, there have not been much BLE protocol studies. We review researches dealing with significant subjects of the device discovery, energy problem, and adaptive algorithms in BLE.

In Liu et al. (2012a, b), an analytical model was presented for 3-channel-based discovery process. They built a model that could determine the performance metrics, such as the probability and latency for device discovery depending on the region of the neighbor listening period. Additionally, they proposed an adaptive algorithm to reduce the energy consumption and the latency. Via theoretical analysis and simulation, they showed that the strategies could reduce undesirable latency and effectively improve the efficiency of device discovery in BLE networks.

Liu and Chen (2012) presented a model for analyzing the neighbor discovery energy in BLE networks which was built upon measurement results of CC2540 mini-development kit. The model was validated via extensive experiments. They presented an interesting conclusion that the parameter used by device was one of the biggest factors contributing to the performance tradeoff between the energy consumption and the latency(Liu and Chen, 2012).

Kamath and Lindh (2010) 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 battery life time was calculated for an example application. They also showed that a variety of factors would influence the battery life calculation and final measurements.

Liu et al. (2013) presented an idea based on communication between two devices and piggybacking the report. After receiving the report, devices adaptively adjusted parameters using an algorithm based on the classical pure ALOHA system (Liu et al., 2013).

Bacinoglu et al. (2014) proposed a novel technique to provide efficient operation by adapting BLE protocol in accordance with consumable power limitations. The nub of a novel technique was to observe the decrease of power consumption which could be achieved by augmenting advertisement intervals. According to energy harvesting rates, the scheduling algorithm could be expected to maximize the advertisement throughput as well as the total energy waste (Bacinoglu et al., 2014).

Cho et al. (submitted for publication) presented an analytical model for discovery latency as well as the probability of successful discovery, considering a realistic situation where there are a lot of collisions caused by contention among BLE devices during discovery process.

## 3. BLE overview

### 3.1. Discovery process of BLE

Bluetooth 4.0 defined three different types of BLE devices as advertising, scanning and initiating mode. They are called advertisers, scanners and initiators (Bluetooth, 2010). In scanning or initiating mode, scanner and initiator periodically scans three advertising channels (index=37, 38, 39) and expects to receive an advertising packet. The scanner and initiator operates a similar process excepting response to advertising packet (ADV_IND) (Drula et al., 2007). Scanner or initiator listens to advertiser on a different advertising channel by each ScanInterval (denoted by $\tau_{SI}$) for a duration of ScanWindow (denoted by $\tau_{SW}$). In the BLE standard, it is specified that ScanInterval and ScanWindow should be in the range of 2.5 ms to 10.24 s. In addition, ScanInterval is defined as the interval between the start of two consecutive ScanWindows and should not be less than ScanWindow (Bluetooth, 2010; Drula et al., 2007; Liu et al., 2012a).

In scanning mode, if scanner receives ADV_IND from advertisers, it shall respond scan request (SCAN_REQ) on the same