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Performance Evaluation of Bluetooth Low Energy Communication

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Abstract

Bluetooth Low Energy (BLE), also known as Bluetooth Smart is the new power efficient version of Bluetooth. With the massive increase in the use of IoT devices, their compatibility and suitability for use with BLE, it has become an important protocol for communication.

The performance of the protocol in terms of throughput, however, remains untested. Several parameters like connection interval, packet size per connection interval, data length extension and others constitute the implementation of the BLE protocol on a device. These parameters directly or indirectly effect the throughput of devices communicating over BLE. In this paper, we evaluated BLE performance by performing experiments to calculate throughput with varying values of connection interval and MTU size of application payload. We provide experimental values of throughput and compare it with the theoretically expected results and discuss the pattern and aberration found.

Keywords: BLE; Throughput; Performance.

1. Introduction

Bluetooth Low Energy (BLE), also known as Bluetooth Smart is the power efficient version of Bluetooth. There has been a large increase in the number of Internet of Things (IoT) devices deployed in the market. These devices are usually resource constrained in terms of processing power, memory, and energy. When deployed, these devices are expected to run for long periods on coin cell batteries or energy harvesting devices like a low capacity solar panel.

The Internet of Things along with cloud computing is driving the innovation and expansion of technology into our daily life. New "smart" devices are being introduced in the market every day. There has been explosive growth in smartphones and wearable devices. New domains for IoT have been explored by new innovations. Sensors and actuators are being deployed in homes, streets for various purposes.

IoT devices are increasingly using IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) for internet connectivity. 6LoWPAN runs on an adaption layer between network layer and data link layer and provides internet connectivity to these devices on significantly low energy consumption. It has traditionally been running over IEEE 802.15.4 in the link layer. However, with the advances in BLE technology, there has been a shift towards using 6LoWPAN over BLE [1].

BLE is the low power version of the original Bluetooth protocol and has been specifically designed for the Internet of Things. Familiarisation and native support for Bluetooth in all major operating systems have made it a popular protocol choice for communicating with these “smart” devices. From listening to music to turning on the lights, from measuring the heart rate to controlling the TV all can be done using Bluetooth enabled devices.

In this paper, we perform experiments to test the effectiveness of BLE protocol. We perform experiments on devices communicating over BLE while varying different configurable parameters such as connection interval, packet size per connection interval, Data Length Extension (DLE) and Maximum Transmission Unit (MTU). These parameters usually vary in different implementation and are up to the designer to specify.

Our contribution is establishing the results for BLE throughput variation by varying connection interval and MTU payload size with enabled data length extension. As per the best of our knowledge work done so far in this field doesn’t provide these two results.

This paper is structured as follows: Section II gives an overview of work done relate to BLE performance evaluation. Section III provides an overview of Bluetooth low energy stack with the parameters affecting throughput. Section IV provides the details for the methodology used in the evaluation. Section IV presents the results obtained from the experiments followed by future work and a short conclusion.

2. Related Work

Due to large scale adaptation of BLE, there has been significant work done in this area. Low power consumption in BLE communication is one of the key factors for its adaptation. Work done in [2] provides an overview of BLE and analysis of the performance of BLE node in terms of energy consumption, latency and piconet size. The results in [2] show how the lifetime of a BLE device varies with the BLE operation parameters such as connection interval, connection slave latency, connection supervision timeout.

In [3], evaluation results for an implementation based on [1] has been provided. It evaluates the energy consumption and throughput in different L2CAP modes and header compression by varying size of IPV6 datagram payload. Two modes were considered in the evaluation, the streaming mode and the basic L2CAP mode. For the remaining modes, the authors have established a theoretical model rather than an experimental one.

A significant amount of work has been done for the comparison of BLE with another link layer technology called ZigBee [4]. Authors have analysed the energy consumption with increase connection interval and packets per connection event and did a comparative measurement with ZigBee (IEEE 802.15.4).

Bluetooth Low Energy Overview

2.1 BLE Layer

Bluetooth protocol stack consists of two main components: The Controller and the Host. The controller takes care of physical layer and link layer of BLE stack and is typically implemented in the form of System-on-a-Chip (SoC) with an integrated radio. The host runs on application processor and includes application-level functionality. A short description of all the layers (Figure 1) is mentioned below:

1. **Attribute Protocol (ATT)**: Defines the communication between two devices playing server and client role.
2. **Generic ATT (GATT):** Defines the framework that uses the ATT for discovery services and exchange of characteristic from one device to another.
3. **Generic Access Profile (GAP):** Defines the device role, modes and procedure for device discovery and services.
4. **Logical Link Control and Adaptation Layer Protocol (L2CAP):** the main function of L2CAP is to multiplex the data of three higher layer protocol, ATT, SMP and Link layer control signalling.

Communication between host and controller takes place using a host controller interface (HCI).

A. Communication Paradigm

To broadcast or advertise data a device has 3 advertising channels which are referred as channel 37, 38 and 39 which are spread out to avoid interference (Figure 2). When the central device is advertising data to the peripheral device, the central device connects to the peripheral using the address which each BLE device has, these addresses can be random, further subdivided into static or private. Static address never changes, whereas a private address is resolvable where it can change after a given interval. The public address is unique and is obtained from IEEE and it identifies the chip vendor.

In addition, application of the device must be identified which is done by the help of UUID which stands for universal unique identifiers. UUIDs can be 16-bit defined by Bluetooth Special interest group supporting the list of applications defined by the BLE device moreover, if the application is custom, then 128-bit UUID is used.

B. Topology

BLE defines four roles in its topology which are broadcaster, observer, peripheral and central.

1. **Broadcaster**: transmits data known as advertising packets. Devices like beacons and sensors cannot connect to the broadcaster during the advertisement. The purpose is to let other devices know of its presence.

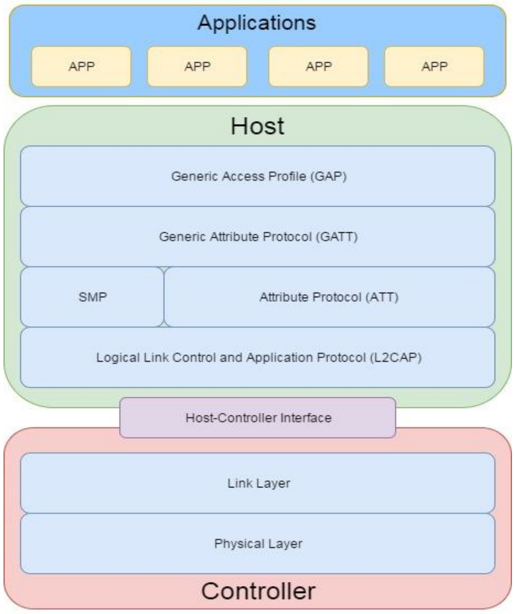

Figure 1: Bluetooth Low Energy stack

2. **Observers**: These are receivers which can receive advertising packets from broadcasters and peripheral devices.
3. **Peripherals**: These are devices that connect in a slave role. They first broadcast their presence so that the central device knows of its presence and then chose to connect to the device.
4. **Central**: These are complex devices and support multiple connections. It initiates connections to peripherals. This device can be central and peripherals at the same time.

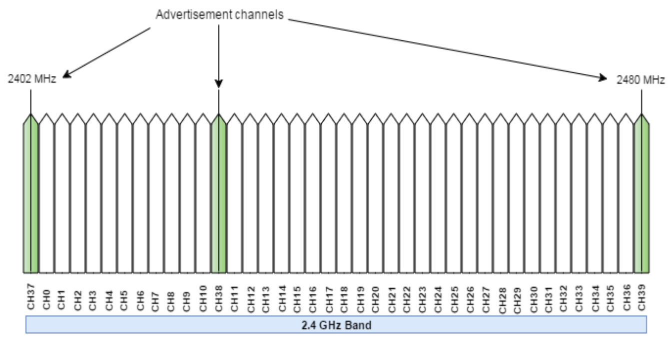

Figure 2: Bluetooth Low Energy Connection Channel

C. Connectivity

If a central device wants to initiate the connection, it transmits the connect request packets to the peripheral in RX period (the advertising device can receive a scan request or connect request). When peripheral device receives connect request it stops advertising and turns on its receiver, hence, becoming a slave device. It then waits for the packet from the master, once received it responds with another packet and then the connection is then established and exchange of data can begin.

D. Connection parameters affecting BLE Throughput

1. **Connection Interval**: The amount of time during which the central device sends data to its connected peripheral device(s) is considered as connection interval. It is advised to use a connection interval which is not high because if interfered with RF signals the throughput decreases. BLE specification allows setting connection interval ranging from 7.5ms to 4s.
2. **Data Length Extension (DLE)**: The latest Bluetooth specification allows application data of size 251 bytes to be sent in a data packet which is much more than that of the previous specifications, i.e. 27 bytes [5]. In both the cases, stated above there is overhead payload (headers) of size around 7 bytes in L2CAP level. To send application payload more than 23 bytes, DLE support is provided from Bluetooth low energy specification V4.2 onwards hence allowing more time to send the application data and less time on processing the application data overhead.
3. **Number of packets per connection event**: It defines the number packets to send in each connection event. The maximum value for this parameter varies between different vendors of BLE SoC.
4. **Operation type**: To achieve high throughput in BLE-based application, it is necessary to avoid application-level acknowledgements. The use of write command and notifications are significant as these packets are acknowledged at link level instead of application level and hence the packets can be queued.

3. Methodology

Experimental Setup

In our experiment, we used Nordic Semiconductor's nRF52 Development Kit. The platform is powered by a Cortex-M4F processor with 512KB flash and 64KB RAM on chip. The experimental measurements were done in a peer to peer topology wherein one device acted as a central device and another device acted as a slave device. In each experiment, central device sent a total of 1MB data to the slave device over BLE communication channel.

Parameters like connection Interval, the number of packets per connection interval, operation type and Maximum Transmission Unit (MTU) affect the throughput. The number of packets per interval is a parameter that is determined by the implementation of the device. For the device used in our experiments, the Nordic Semiconductor’s nRF52DK, it is fixed at 6 packets per connection interval. We chose the operation type to be the write command for the central device and notifications for the peripheral to avoid sending acknowledgements back and forth which would eventually affect the rate of data transfer. Keeping these two parameters constant, we measured the throughput and its variation with change in connection interval and MTU.

Experiments

We connected two nRF52DK devices over BLE, one of the devices was programmed to act as the central device and the other was programmed as a peripheral device. As described in the previous sections, the peripheral device would advertise its availability which would be scanned by the central. The central would then initiate a connection and send or receive data from the peripherals. For our experiments, we sent 1 MB data from the central to the slave via BLE channel.

Experiment #1: For the first experiment we varied the connection interval while keeping the MTU size fixed at 23 and measured the throughput. Since the selected MTU size was 23 bytes, DLE was not required and hence we kept it disabled. The operation type and packets per connection interval were kept constant for the before mentioned reasons. We did 20 iterations for each connection interval value and we varied the connection interval from 7.5 milliseconds to 400 milliseconds. The data observed in the experiment is presented in the Figure3.

Experiment #2: For the second experiment we varied the size of MTU while keeping the connection interval fixed at 50 milliseconds. The operation type and packets per connection interval were kept constant for the before mentioned reasons. We enabled data length extension in order to use the MTU size greater than 23 bytes. We did 20 iterations for each MTU size and varied the connection interval from 23 bytes to 247 bytes. The result of this experiment is presented in Figure4.

4. Results

This section provides the results for below defined experiments.

1. Throughput Vs. Connection Interval
2. Throughput Vs. MTU size
3.

We used Nordic Semiconductor's nRF52 Development Kit to perform our experiments.

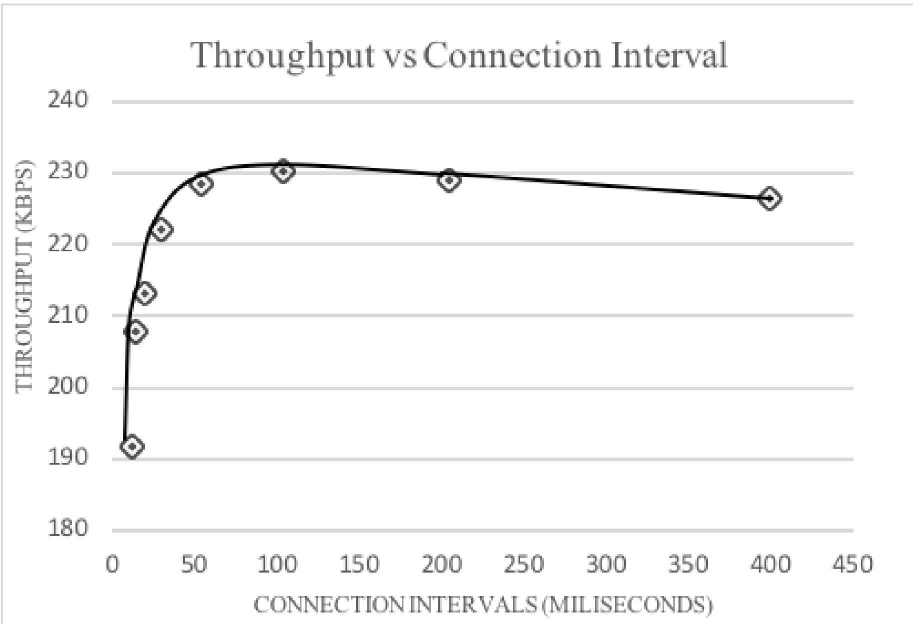

Figure 3 shows the variation of throughput with respect to change in connection interval. It can be seen from the graph that throughput increased with the change in connection interval initially until 50 milliseconds and then remains largely unaffected by the change in connection interval. Higher throughput can be achieved using longer connection intervals. The downside of using higher connection interval is that connection events could be missed due to RF interference which will drastically decrease the throughput. There is a tradeoff between throughput and latency and it is up to the application designer for the best fit of these values.

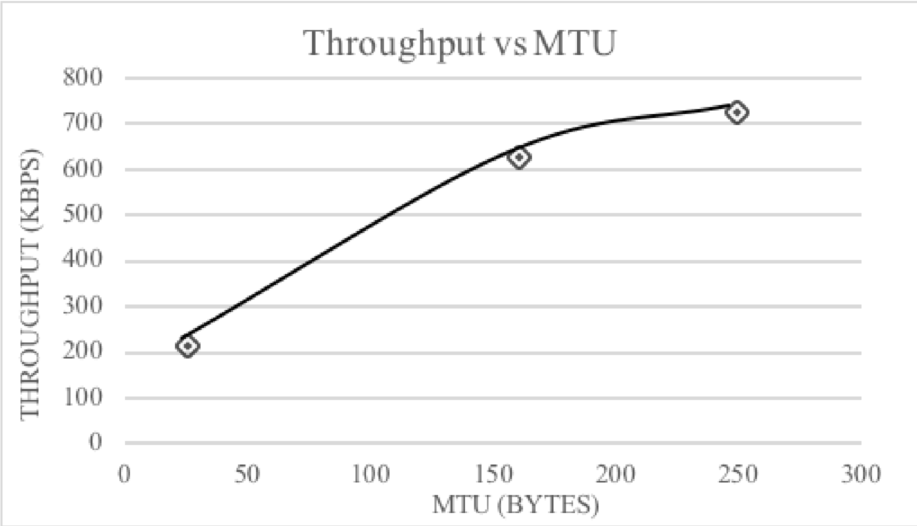

Figure 4 shows the variation of throughput with respect to change in size of MTU. It can be seen from the graph that the throughput increases with the increase of MTU size. The increase in throughput is because with the increase in the size of MTU, the transfer of ATT layer overhead bytes is eliminated and replaced with application data. Use of MTU sizes that is multiple of 23 bytes is ideal.

With the increase in throughput by using larger MTU size, requires less number of BLE packets. Reducing the number of BLE packets will ultimately reduce the power consumption as well.

5. Conclusion

In this paper, we have described our work towards the evaluation of BLE throughput with varying connection interval and MTU size.

In our experiments, we noted that in the case of connection interval variation, throughput increase till connection interval of 50ms and stagnates afterwards. In the case of using MTU parameter, throughput increased with the increase of MTU size.

We noted several interesting areas to work upon in future. First, we will continue our work on establishing a relationship between energy consumption with an increase in throughput by changing the operation parameters of BLE. Next, we will focus on evaluation of performance (throughput, latency and energy consumption) on devices connected in a star topology with 6LoWPAN over BLE [1] under different traffic loads and communication patterns.

6. Acknowledgment

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