Energy Analysis of Neighbor Discovery in Bluetooth Low Energy Networks

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Abstract:
This technical report presents a model for analyzing the neighbor discovery energy in Bluetooth Low Energy (BLE) networks. The archival model, built upon measurement results of CC2540 Mini-Development Kit, has been validated quite accurate via extensive experiments. Several interesting results have been found during the investigation of the archival energy model, which not only provide better understanding to the important energy metric, but also offer valuable guides for the parameter setting in practical applications.

Index Terms:
Bluetooth Low Energy
Performance Evaluation
Quality of Service
Modeling

1. Introduction
Recently, products with the support of Bluetooth Low Energy (BLE) [1] appeared in consumer market. BLE is an extended version of Classic Bluetooth (BR\EDR), designed as a low-power, low-complexity, and low-cost short-range radio enabling for devices that powered by coin-cell battery to operate for months to even several years.

This technical report sets the focus on BLE’s energy metric spend in neighbor discovery. An analytical model is proposed to analyze the energy consumption expectation for BLE neighbor discovery process, which is then validated via measurement based experiments. In BLE networks, since intermittent device discoveries are frequent, it is important to understand this vital metric to provide guide for the configuration of the parameters.

The rest of the report is organized as follows: Section 2 presents the preliminary of BLE neighbor discovery. Section 3 proposes the analytical model for BLE neighbor discovery. Section 4 validates the model before the whole report is finally concluded in Section 5.
2. Preliminary

2.1. BLE Standard Definition

This section describes standard contents related to BLE advertising.

According to the Bluetooth Core Spec. V4.0, a BLE device in scanning or initiating mode, called scanner or initiator, periodically scans advertising channels (index = 37, 38, 39) and listens to advertising information of others. The persistent duration of scanning, $T_s$, is bounded within 10.24s; the interval between two consecutive scanning, $T$, should be equal or large than $T_s$, while also being bounded within 10.24s.

![Figure 1 Advertising events perturbed in time using advDelay](image1.png)

![Figure 2 Connectable undirected advertising event with only advertising PDUs](image2.png)

Other BLE devices operating in advertising mode, named advertiser, periodically transmit advertising information in three advertising channels. Once the advertising packets are received by the initiator/scanner, it is considered the peer device discovers the advertiser; the peer will also respond accordingly to further establish the connection or perform other operations. Altogether there defined 4 types of Advertising Event for BLE, which can be categorized into two types, i.e., Undirected Advertising Event Type and Directed Advertising Event Type. In the vast number of cases, Undirected Advertising Events are adapted for unknown device detection;
while Directed Advertising Events are used to establish connections with already known devices. This report will be limited in discussion of undirected advertising events only.

As shown in figure 1, the time between the start of two consecutive advertising events ($T_{\text{advEvent}}$, or $T_a$) is computed by $T_a = \text{advInterval} + \text{advDelay}$. The $\text{advInterval}$ is an integer multiple of 0.625ms ranging from 20ms to 10.24s; the $\text{advDelay}$ is a pseudo-random value ranging from 0ms to 10ms, generated by the Link Layer for each advertising event. Being in Advertising Event, an advertiser keeps in active state, the energy consumption is decided by the specific transmission, reception, and idle state.

Taking ADV_IND for instance, as shown in figure 2, an Advertising Event contains three ADV_IND PDUs that sent on channel 37, 38 and 39, iteratively. After each sending of the advertising packets, the advertiser will be listening on the same channel for a while to check if there is response coming from any initiator/scanner. Here we denote $A$ as the length of the advertising packet transmission time, and $b$ as the time between the beginnings of two consecutive advertising packets. According to the specification, $A + b$ shall be less than or equal to 10ms.

### 2.2. Measurement and Analysis

![Figure 3 Capture of waveform during an Advertising Event](image)

To better evaluate the BLE advertising process, we present the captured current waveform during an Advertising Event on Texas Instruments CC2540 [2][3].

One of the first things that one may notice in the capture is the three consecutive Tx and Rx peaks, which reflect the transmission of the advertising PDUs and the consequent listening over the three advertising channels. In addition to these peaks, it is noticed that the current draw
changes as the CC2540 goes through several different states before or after the Advertising Event. Based on [4], each state represents some kind of operation that is interpreted as follows:

- **Sleep** – the sleep state; irrelative components are turned off so as to save energy
- **MCU wake-up** – upon waking up, the current level drops slightly
- **Pre-processing** – the BLE protocol stack prepares the radio for sending and receiving data
- **Pre-Tx** – the CC2540 radio turns on in preparation of Tx and Rx
- **Tx** – the radio transmits a packet on the advertising channel
- **Tx-to-Rx transition** – the sending stops, and the radio prepares to receive a packet from the initiator/scanner
- **Rx** – the radio receiver listens for a packet on the advertising channel
- **Inter-channel transition** – the Tx and Rx on one advertising channel is done, and it takes some transition time (or waiting time) to continue operating on the next channel
- **Post-processing** – the BLE protocol stack sets up the sleep timer in preparation for the next advertising event.

![Figure 4 Current waveform split into sections](image)

In sleep state, the current consumption of CC2540, $I_{sleep}$, is about $1 \mu A$ [2]; accurate timing and current for other states can be measured by means of the oscilloscope cursors, as shown in figure 4. For some states, such as State 1, the current draw is not steady. However exploiting the divisions shown and guessing an average current value should provide enough accurate estimates. The total active time $T_{active}$ ranging from State 1 to 15 is $4.25 ms$. Table 1 below shows the measurements of the specific state in figure 4:
### Table I Time & current measurements of each state

<table>
<thead>
<tr>
<th>NO.</th>
<th>Explanation</th>
<th>Time (μs)</th>
<th>Current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>wake-up</td>
<td>400</td>
<td>6.0</td>
</tr>
<tr>
<td>2</td>
<td>pre- processing</td>
<td>600</td>
<td>7.4</td>
</tr>
<tr>
<td>3</td>
<td>pre-Tx</td>
<td>200</td>
<td>10.0</td>
</tr>
<tr>
<td>4</td>
<td>Tx on ch37</td>
<td>380</td>
<td>17.5</td>
</tr>
<tr>
<td>5</td>
<td>Rx-to-Tx</td>
<td>105</td>
<td>7.4</td>
</tr>
<tr>
<td>6</td>
<td>Rx on ch37</td>
<td>115</td>
<td>17.5</td>
</tr>
<tr>
<td>7</td>
<td>Inter-ch37 &amp; 38</td>
<td>150</td>
<td>7.4</td>
</tr>
<tr>
<td>8</td>
<td>Tx on ch38</td>
<td>380</td>
<td>17.5</td>
</tr>
<tr>
<td>9</td>
<td>Rx-to-Tx</td>
<td>105</td>
<td>7.4</td>
</tr>
<tr>
<td>10</td>
<td>Rx on ch38</td>
<td>115</td>
<td>17.5</td>
</tr>
<tr>
<td>11</td>
<td>Inter-ch38 &amp; 39</td>
<td>150</td>
<td>7.4</td>
</tr>
<tr>
<td>12</td>
<td>Tx on ch39</td>
<td>380</td>
<td>17.5</td>
</tr>
<tr>
<td>13</td>
<td>Rx-to-Tx</td>
<td>105</td>
<td>7.4</td>
</tr>
<tr>
<td>14</td>
<td>Rx on ch39</td>
<td>115</td>
<td>17.5</td>
</tr>
<tr>
<td>15</td>
<td>post-processing</td>
<td>950</td>
<td>7.4</td>
</tr>
</tbody>
</table>

### 3. Energy Consumption Model

![Figure 5](image)

Figure 5 The model of neighbor discovery for BLE

Considering that an initiator is scanning periodically on channel 37, 38, and 39, as shown in figure 5, it can be inferred that an advertising packet may send at a random starting point in the three consecutive scanning intervals. To accurately classify these points, we partition the circulation time of three channel scanning, \(3T\), into region I, I, and III, bearing the length that

\[
R_1 = T + 2A + 2b
\]

\[
R_2 = R_3 = T - A - b
\]

Here, \(A\) is the length of sending an advertising packet, and \(b\) is the gap between two consecutive advertising packets (see figure 2). Within each region, the starting points are further categorized into different bins: bin 0 has a length of \(T_s - A\), and other bins have the same length of \(T_a\) (the last bin can be short than \(T_a\) due to not exact division by this region).
In region III, for example, if the advertising event starts somewhere in bin 0, the initiator will receive the advertising packet on channel 39 right after time $3A + 2b$. Otherwise, if it starts in the $i$th bin ($i = 1, 2, ..., k_3 + 1$), it will be expected to take $i$ times of $T_a$, for the advertiser, to meet the initiator’s scanning window before taking an additional $3A + 2b$ time to get the packet received. This can be easily verified also in region I and II.

In order to establish the energy model, we next propose following energy constants according to Table 1:

- $E_{ext}$: Extra energy consumption outsides the Advertising Event, including pre-energy in State 1, 2, and 3 and post-energy in state 15
- $E_{TR}$: Tx, Tx-to-Rx, and Rx energy consumption in State 4, 5, and 6 (or 8, 9, and 10; or 12, 13, and 14)
- $E_{int}$: Inter-channel energy consumption in State 7 (or 8)

Therefore, the energy consumption when the Advertising Event stops by the end of the $n$th time of advertising, is

$$E_n = n \cdot E_{TR} + (n - 1)E_{int} + E_{ext} \quad n = 1,2,3$$

Since the energy consumption in sleep state can be given as

$$E_{sleep} = I_{sleep} \cdot (T_a - T_{active})$$

where $I_{sleep}$ and $T_a - T_{active}$ represent the current and the time being in the sleep state, respectively, the energy consumption for the whole duration of $T_a$ will be

$$E_{T_a} = E_{active} + E_{sleep} = E_3 + I_{sleep} \cdot (T_a - T_{active})$$

It then comes to the conclusion that, if any advertiser begins advertising in the $i$th bin within region $n$ ($i = 0,1, ..., k_n + 1$, $n = 1,2,3$), the energy consumption will be equal to $i \cdot E_{T_a} + E_n$.

Now that the probability of being in bin $i$ equals to the length of all three scanning intervals divided by the length of that bin, the probabilities of energy consumption $E$ are given by following equations:

$$\begin{aligned}
P_n(E = E_n) &= \frac{T_2 - A}{3T} \\
P_n(E = i \cdot E_{T_a} + E_n) &= \frac{T_a}{3T} \\
P_n(E = (k_n + 1)E_{T_a} + E_n) &= \frac{R_n - (T_2 - A) - k_n \cdot T_a}{3T}
\end{aligned}$$

where $k_n = \lfloor (R_n - (T_2 - A))/T_a \rfloor, n = 1,2,3$.

Through some calculation, the average energy consumption, according to $E = \sum_{n=1}^{3} P_n \cdot E$, is derivable:
\[
E = \frac{(E_1 + E_2 + E_3) (T_s - A)}{3T} + \frac{1}{6T} \sum_{n=1}^{3} \epsilon_n \left( 2E_{\text{m}} + E_{\text{r}} + \frac{E_{\text{t}}}{T_a} \epsilon_n \right) + \frac{E_{\text{r}} \cdot T_a}{6T} \sum_{n=1}^{3} \delta_n (1 - \delta_n)
\]

where \(\epsilon_n\) and \(\delta_n\) are to simplify the expression with following definitions:

\[
\epsilon_n = R_n - (T_s - A)
\]

\[
\delta_n = \frac{R_n - (T_s - A)}{T_a} - k_n
\]

It should be pointed out that above model holds only when the condition \(T_s \geq T_a\) is satisfied. This is because the initiator cannot offer the guarantee to receive an advertising PDUs within the region where the advertiser starts the advertising, hence introducing an uncertain latency and accordingly an unexpected energy consumption. This will also be validated by the experiment introduced next.

### 4. Validation

In this section, we will validate the proposed energy model via experiment. By setting a CC2540 Mini-DK in periodically scanning mode, and letting another advertise ADV_IND PDUs at randomized starting time, we record the time and current of the latter and compare the obtained experimental results with the theoretical ones. The experiment parameters are adopted in conformity with the specification; the power values used in the analytical curves are from those measurements in figure 4. Related details of the parameter settings can be found in Table II. Note that for convenience, the following report will use \(mA \cdot \mu s\) as the unit of energy - it can be also transferred into standard units (e.g. \(mAh\)) when necessary.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textit{advInterval}</td>
<td>20ms~10.24s</td>
<td>\textit{E}_{\text{ext}}</td>
<td>15.870 mA \cdot \mu s</td>
</tr>
<tr>
<td>\textit{advDelay}</td>
<td>r. v [0, 10ms]</td>
<td>\textit{E}_{\text{TR}}</td>
<td>9.4395 mA \cdot \mu s</td>
</tr>
<tr>
<td>\textit{T}</td>
<td>\leq 10.24s</td>
<td>\textit{E}_{\text{int}}</td>
<td>1.110 mA \cdot \mu s</td>
</tr>
<tr>
<td>\textit{T_s}</td>
<td>\leq 10.24s</td>
<td>\textit{E}_1</td>
<td>25.3095 mA \cdot \mu s</td>
</tr>
<tr>
<td>\textit{I_{sleep}}</td>
<td>1 \mu A</td>
<td>\textit{E}_2</td>
<td>35.859 mA \cdot \mu s</td>
</tr>
<tr>
<td>\textit{T_{active}}</td>
<td>4.25 ms</td>
<td>\textit{E}_3</td>
<td>46.4085 mA \cdot \mu s</td>
</tr>
</tbody>
</table>
Figure 6 Average energy comparison with varied $T_a$ ($T_s = 1.28s; T_a \in [20\text{ms}, 10.24s]; T = 10.24s, 5.12s, 2.56s, 1.28s$)

Figure 6 shows the results of average energy versus varied advertising interval $T_a$ ranging from 20ms to 10.24s. To better demonstrate the cut-off effect owing to the size of $T_a$ and $T_s$, we set $T_s$ to a fixed value $1.28s$, and select some typical scanInterval that $T = 10.24s, 5.12s, 2.56s$ and 1.28s. It can be seen that the theoretical and experimental curves are highly accurate when $T_s \geq T_a$, which validates our analysis in last section. In this interval, as $T_a$ increasing, the energy consumption of the advertiser drops quickly. For example given $T = 10.24s$, setting $T_a$ to 20 ms will incur an average of 7280 $mA \cdot ms$ energy for an advertiser to be discovered by the initiator, but if setting $T_a = 1s$, this value drops by 96.7% to 242.9 $mA \cdot ms$. It also holds for the case of $T = 5.12s$ and $T = 2.56s$, the average energy drops by 95.3% and 90.3% for above two values of $T_a$.

In the interval of $T_a > T_s$, experiment results become unstable and increase substantially over the theoretical values. The only exception is the curves with $T = T_s = 1.28s$. Since in such case the initiator actually performs continuous scanning, it provides guarantee of an immediate reception for any advertising event, and thus always introduces the minimal energy consumption for the advertisers, which is about 34 $mA \cdot ms$. 
Figure 7 Average energy comparison with varied $T_s$ ($T_a = 100\text{ms}; T_s \in [20\text{ms}, T]; T = 10.24\text{s}, 5.12\text{s}, 2.56\text{s}, 1.28\text{s}$)

Figure 7 shows the results of average energy versus varied scanWindow $T_s$ ranging from 20ms to $T$, where $T = 10.24\text{s}, 5.12\text{s}, 2.56\text{s}, 1.28\text{s}$, and $T_a = 100\text{ms}$. The theoretical and experimental curves also fit quite well when $T_s \geq T_a$. In this interval, where average energy keeps decreasing with $T_s$ and approaches to the minimal value (about $34 \text{mA} \cdot \text{ms}$, when $T_s = T$). In the interval $T_s < T_a$, gaps turn out between the two curves. A slight increase of $T_s$ brings a significant drop for the practical energy consumption. For example, with $T = 1.28\text{s}$ and $T_a = 100\text{ms}$, if $T_s = 20\text{ms}$ then the average energy consumption by experimental trials reaches as high as $2698 \text{mA} \cdot \text{ms}$; however, when increasing $T_s$ to $60\text{ms}$, the observed result decreases by 74% to $697 \text{mA} \cdot \text{ms}$; if $T_s = 100\text{ms}$, the average energy further drops by 47% to $366.8 \text{mA} \cdot \text{ms}$.

Another important insight from figure 7 is that, with different sets of $T$ and $T_s$, even their proportion keeps the same (that is, the energy consumption in the initiator/scanner keeps unchanged), the energy expectation on the advertiser side will be different. For instance, with $T = 2.56\text{s}$ and $T_s = 100\text{ms}$, which means the duty cycle is about 3.9%, the energy consumption is $657.7 \text{mA} \cdot \text{ms}$. On contrast, with $T = 5.12\text{s}$ and $T_s = 200\text{ms}$, the duty cycle remains the same, but the energy consumption is a different value that $1170 \text{mA} \cdot \text{ms}$. From the figure, it
can be observed that given the same ratio of duty cycle, the large $T$ (or $T_s$) is, the higher energy the advertiser consumes in advertising.

![Figure 8](image)

Figure 8 Average energy comparison with varied $T$ ($T_s = 1.28s; T \in [T_s, 10.24s]; T_a = 20ms, 50ms, 100ms, 500ms$)

At last, figure 8 shows the results of average energy versus varied scanInterval $T$ ranging from $T_s = 1.28s$ to the maximally available 10.24s. We selected 20ms, 50ms, 100ms and 500ms for $T_a$, all of which fall into the criterion that $T_a < T_s$. It is reflected from the figure that the average energy almost increases linearly with $T$; the larger $T$ selected, the smaller duty cycle the initiator takes, yet the higher energy the advertisers consume for their discoveries. Moreover, increasing $T_a$ can effectively lower the energy consumption even the initiator is applying a rather low duty cycle in scanning. Of course, doing so will inevitably increase average accessing delay, hence it must be considered only when specific requirements allowed.

5. Conclusion

In this technical report, an analytical model is proposed for assessing the energy performance of BLE advertiser, and is then verified via a number of experiments. We have drawn several interesting conclusions from the investigation of the model, which are listed as follows:
1. For the neighbor discovery of BLE devices, the scanning interval $T_a$ of the advertiser should be set LESS than the *an*Window $T_s$; otherwise unexpected energy consumption will be introduced.

2. Continuous scanning ($T = T_s$) always gets the minimal energy metrics, despite of $T_a$.

3. For the advertiser, small values of $T_a$ (e.g. $\leq 1000ms$) could consume more than an order of magnitude energy in each of the device discovery than those of lager values. These values should be avoided unless there is definite requirement of discovery delay.

4. For the advertiser, increasing $T_a$ could lower the energy expectation even the initiator/scanner has relative low duty cycle; however, it should be noticed once encountering unexpected long delay, it means the $T_a$ value might have exceeded $T_s$, and energy performance could become worse.

5. For the initiator/scanner, $T_s$ should NOT be set too small (e.g., $\leq 100ms$); otherwise the advertiser might suffer a large portion of energy on advertising.

6. For the initiator/scanner, turning $T$ can lead to proportional changes with the energy expectation; turning $T$ and $T_s$ while keeping their ratio, though own energy almost unchanged, will influence the energy expectation of the advertiser.

**Reference**


