RESEARCH ARTICLE

Performance evaluation of bluetooth low energy in indoor positioning systems

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ABSTRACT

Local positioning systems (LPS) are attracting much attention, both commercially and scientifically, as they represent a natural extension of global positioning systems to indoor scenarios. Amongst all the viable wireless technologies used in this context, WiFi and Bluetooth are the most widely extended. These technologies are also chosen for their simplicity, low cost and integration into mobile devices. The appearance of the new Bluetooth specification, named Bluetooth low energy (BLE), and the emergence of new popular devices that incorporate it, opens the door to new LPS wireless solutions based on BLE. Here, we evaluate the viability of BLE for indoor positioning scenarios. In addition, we develop a framework to analyse, understand and help migrate previous LPS systems, based on other technologies, to BLE. We show experimentally that, with proper configuration of the BLE devices, great performance can be obtained in terms of discovery time and energy consumption. Copyright © 2014 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Current technology, mainly because of their interconnection capabilities, is reaching an unprecedented level of penetration in society. Communication, not just amongst final users but also from autonomous devices (the so-called Internet of things) is exceeding the most optimistic forecasts [1]. However, there is one area where human–machine communication is not reaching such expectations: local positioning systems (LPS) in indoor scenarios. Thus, getting precise directions to an specific store in a mall or creating a reliable guidance system for people with visual disabilities in a large city underground network, is simple contexts in which traditional global positioning systems cannot fulfil their specific requirements. The emergence of new communication technologies such as bluetooth low energy (BLE) should help to close this gap and offer these solutions with a minimum guaranteed functionality. BLE evolved from the classic Bluetooth wireless technology, and much effort has been put to reduce energy consumption and response times, thus introducing profound changes in the original specification. These changes had in mind the drastic increase of the autonomy of these devices with specific applications in mind as biomedical sensors, door locks, wearable solutions and so on.

Many LPSs are based on existing wireless technologies such as Bluetooth, Zigbee, Wi-Fi or Ultra-wide band (UWB). This article aims to analyse and evaluate the operation and performance of BLE for these systems and also provide quantitative criteria to help to migrate old systems to BLE. The remainder of the article is organised as follows. In Section 2, BLE specification is briefly summarised. In Section 3, we provide a brief review of the existing positioning systems based on wireless technologies, in general, and based on the previous specifications of Bluetooth, in particular. In Section 4, we present novel results obtained experimentally and their main implications are discussed. Finally, the conclusions of the article are highlighted in Section 5.
2.2. The advertising state

more thoroughly in the following sections. Devices search: advertising and scanning that we discuss most interesting states are those involved in the process of coming for the need of sending sporadic sensor information. This feature comes for the lifetime of the devices and shorter discovery times. BLE allows basic actions such as packet reception and request for basic information used by the network. This feature comes for the need of sending sporadic sensor information.

Bluetooth low energy technology is characterised by five states in the link layer (Figure 1): standby, scanning, advertising, initiating and connection. Furthermore, BLE allows basic actions such as packet reception and request for basic information without establishing a connection. This feature comes for the sending sporadic sensor information.

In the case of indoor positioning scenarios, the two most interesting states are those involved in the process of devices search: advertising and scanning that we discuss more thoroughly in the following sections.

2.2. The advertising state

The main function of this state is to let a device (the scanner) detect other devices (the advertiser). There are four types of advertising packages depending on the type of search. The device with the role of advertiser sends a packet every \( T_{\text{adv}} \) seconds (Figure 2). At each advertising cycle, these packets are sent using one to three channels reserved for this purpose (37, 38 and/or 39). In order to avoid interference with other advertisers that could be spontaneously synchronised, a random time is added at the end of each advertising event. This time should not exceed 10 ms.

The types of packets that can be sent by an advertiser are the following:

- **ADV_IND** (Connectable undirected advertising event). Once the advertiser has sent a packet, it receives another packet of type SCAN_REQ from the scanner, requesting additional information. This packet is replied with another type of packet called SCAN_RSP using the same advertising channel. Finally, the scanner can request a new connection with a packet of type CONNECT_REQ.
- **ADV_DIRECT_IND** (Connectable directed advertising event). When the advertiser sends this packet, it receives a CONNECT_REQ packet from the scanner.
- **ADV_NONCONN_IND** (Non-connectable undirected advertising event). When the advertiser sends this packet, it no longer accepts connections.
- **ADV_SCAN_IND** (Scannable undirected advertising event). It has the same function as the packet ADV_IND, but in this case, it does not accept any connections.

2.3. The scanning state

This state complements the advertising state during the discovery process. The device enters this mode (becoming a scanner) and will start listening to advertising packets during \( T_{\text{scanWindow}} \) in each channel defined for this purpose. This process will be repeated each \( T_{\text{scanInterval}} \) (Figure 3). This interval cannot exceed 10.24 s.

There are two scanning modes in this state:

- **Passive scanning**: The scanner only receives packets but it will not reply to any of them.
- **Active scanning**: Depending on the type of packet sent by the advertiser, the scanner will answer to the device in the advertiser state.

An advantage of BLE is that inside the advertiser packets of type ADV_IND, ADV_NONCONN or ADV_SCAN_IND, up to 31 bytes of data can be embedded. There we see an opportunity to configure BLE devices for LPS scenarios where the beacons, for example, can be used to send basic information used by the network. This is a great improvement with respect to the previous Bluetooth specifications because it allows the sharing of information (for instance, data captured by a sensor) without requiring the previous connection between devices.

Figure 4 shows the matching that exists between the packet sending rate by the advertiser (at times given by

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**Table 1.** Comparison of some transmission parameters between standard Bluetooth specifications (versions 3.0) and the new Bluetooth low energy. Relative energy consumption refers to the consumption with respect to the standard specification.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bluetooth (3.0)</th>
<th>BLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective velocity</td>
<td>2.1 Mbps</td>
<td>0.26 Mbps</td>
</tr>
<tr>
<td>Relative energy consumption</td>
<td>100 per cent</td>
<td>1–5 per cent</td>
</tr>
<tr>
<td>Latency in data transmission</td>
<td>100 ms</td>
<td>3 ms</td>
</tr>
</tbody>
</table>

BLE, Bluetooth low energy.
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Figure 1. Sketch of the states defined in BLE and its interrelationship. The state advertising allows the transmission of packets that can be discovered by any device in the scanning mode.

Figure 2. Diagram showing the main parameters and events occurring in the advertising state.

Figure 3. Diagram showing the main parameters and events occurring in the advertising state.

3. RELATED WORKS

Recently, many studies have been devoted to solve the problem of indoor location using different existing wireless technologies. Here, we have classified and summarised some of the most important contributions to the field.
One of the first systems used in LPS, called active badge system [2], was based on infrared technology. The Cricket system [3], introduced by MIT, was another pioneering work in LPS systems. In the case of Cricket, the system is based on the so-called pingers (ultrasound and radio frequency emitters). LandMarc [4] is based on RFID and is one of the first works that identified the problems of positioning based on the measurement of the signal strength. Finally, MoteTrack [5] is another approach also based on radio frequency and was developed by Harvard University.

Virtually, all those systems present large positioning errors when trying to discriminate ranges of about 2 or 3 m. This explains the complexity of the LPS problem, where the signal can be distorted by different mechanisms as multipath, signal reflection, refraction and so on.

One of the solutions that have been proposed to reduce these problems by supplementing the acquisition of data with different signal post-processing techniques to eliminate, for instance, multipath effects or the use of filtering methods to reduce the problem of cross-correlation, in which the strongest signals need to be removed in favour of the weaker ones [6–8]. From a practical perspective, most of the systems use an observable that measures the signal strength called received signal strength indicator (RSSI). After this value has been measured in a specific device, different approaches that deal with information extraction typically fall into two categories: range-based or range-free.

Range-based methods require an initial training phase in which RSSI values are previously measured at different locations, so those values can be reproduced afterwards in real-time. It is also customary to use a technique called fingerprinting [9] that also requires the participation of special devices (as access points). It is based on the use of the RSSI of each access points in order to create a map of the entire infrastructure. These techniques are often combined with other types of sensors (for instance, accelerometers) and the application of signal filters (for instance, Kalman filters) to increase the signal-to-noise ratio and, hence, to predict the motion of an object to improve its tracking. Other post-processing techniques such as artificial neural networks, particle-based filters, Monte Carlo methods [10], Butterworth [11] or Chebyshev filters, statistical Markov models [12] or Bayesian models [13] have also been used.

On the other hand, range-free system does not require a training phase (to, as mentioned, store data collected in different locations) what gives them higher flexibility. The main drawback of this technology is that an accurate estimation of the location of each device is unattainable and it is only able to provide a proximity area [14].

4. RESULTS

4.1. Methods

As discussed in the preceding section, many works have introduced different communication technologies and processing techniques to reduce mismatches in the RSSI. Here, we present a systematic assessment of BLE as a technology that, potentially, can improve the existing ones in the context of local positioning solutions (LPS). This assessment is based on massive experiments with the following hardware and software:

- Four dongles Bluegiga BLED112 with chip TI C2540.
- Two dongles Texas Instruments C2540.
- One sniffer TI BLE.

In order to acquire all the relevant information needed for the calculation and processing of packet delays, we have also embedded custom software, written in C, within the BLE Bluegiga dongles. This software based on the BGLib library (provided by the manufacturer) allows to manage the reception of packets received on the scanner.
Amongst all the possible discovery modes and packet types described in Section 3, we will use those that simplify the process so there is no need of establishing a new connection.

In Figure 5, we show schematically the experimental setup used in the present work. As shown in panel (a), one computer (playing the role of a mobile device) will act as scanner listening to advertising packets during a long period from the other computers configured as advertisers (playing the role of beacons). The scanner will log all packets received in the computer, that will allow us to convert between the RSSI and the distance (see succeeding text for a more detailed explanation). In the case of two-dimensional scenarios, the trilateration technique (a method of determining the relative positions of three or more points by treating these points as vertices of a triangle or triangles of which the angles and sides can be measured) is mandatory in order to estimate the location of the scanner.

Embedded in every advertising packets, the value of the RSSI is included, so we remove the need to force the devices to enter into the connection state, and consequently, we avoid the need to create the network and the related delays. Note that changing to the connection state would require higher response times and also higher energy consumption. It is also worth mentioning that we make use of the three channels available (37, 38 and 39) reserved for advertising, as described in Section 2.2.

In order to remove fluctuations from experiment to experiment, we have averaged our results over many realisations of the same conditions (topology) and parameters.

In order to evaluate the process of searching for BLE, the impact of the following parameters defined in the specification will be considered: $T_{\text{adv}}$, $T_{\text{scanInterval}}$, $T_{\text{scanWindow}}$. We will assess the performance of every condition with two metrics: the time needed to find a specific device (through the reception of the corresponding beacon) and the associated cost in terms of energy consumption. In both cases, the lower the better.

### 4.2. Assessment of the advertising state

To assess the impact of advertising in the discovery state, we have modified the default value of the advertising interval ($T_{\text{adv}}$). In this first analysis, we have configured the device to listen continuously during a time $T_{\text{scanWindow}} = T_{\text{scanInterval}}$ set to 1000 ms. As shown in Figure 6, the scanner discovery time is proportional to the frequency of generation of advertising packages but only down to a
certain threshold. Below that threshold, for $T_{adv} < 200\text{ms}$, the discovery time is constant at a value of 191 ms. The reason behind this saturation effect is that the BLE stack implemented in our dongles supports only the reception of the first five packets received (the dongle buffer), dropping the rest. For this reason, the discovery time saturates around 200 ms, namely,

$$T_{saturation} = \frac{T_{scanWindow}}{N} \Rightarrow \frac{1000\text{ms}}{5 \text{ packets}} = 200\text{ms} \quad (1)$$

The existence of this limitation in the buffer size, $N$, is because, in general, applications that make use of this stack are only interested in the presence/absence of a device during the scanning window time but not on the frequency with which that device is detected. In Figure 6 (dashed straight line), we show the theoretical (linear) dependence of the discovery time with $T_{adv}$.

### 4.3. Assessment of the scanning state

Given the mandatory synchronisation amongst devices in the search process in BLE, the optimal interval advertising time ($T_{adv}$) should be adjusted depending on the listening window of the advertising packages, determined by the scanning window ($T_{scanWindow}$). In the last set of experiments (Figure 6), the scanner was listening continuously. Of course, this continuous activity is detrimental for consumption. To diminish this energy consumption, we have changed the value of $T_{scanWindow}$ in the range 0 to 1000 ms, whilst keeping constant the value of $T_{scanInterval} = 1000$ ms. In addition, $T_{adv}$ was set to 200 ms. As shown in Figure 7, for a value of $T_{scanWindow} = 1000$ ms, an average discovery time of 191 ms is obtained, confirming the validity of the experiment. We find it interesting that the delay in the search process grows exponentially as the ratio of $T_{scanInterval}$ and $T_{scanWindow}$ is lower, thus making those combinations of parameters clearly unsuitable for LPS scenarios.

### 4.4. Impact of independent values of the parameters

After analysing the aforementioned results and knowing the restrictions in the BLE stack devices (the buffer size), the choice of $T_{scanInterval}$ and $T_{scanWindow}$ is critical for LPS solutions.

To this aim, one natural question that arises is that what is the mean discovery time if we change independently the three main parameters: $T_{scanInterval}$, $T_{adv}$ and $T_{scanWindow}$? Figure 8 shows that, although $T_{scanWindow} = T_{scanInterval}$, the fact that the scanner is listening requests during the whole interval is the main parameter that affects the discovery time.

### 4.5. Impact of the number of channels

As we discussed in Section 2, the process of advertising up to three channels (37, 38 and 39) can be used to that aim. They are strategically located at the beginning, middle and end of frequency ranges and, in all cases, outside the WiFi channel 11. Figure 9 shows that discovery time is reduced in proportion to the number of used channels (for instance, for $T_{scanWindow} = 1100$ ms the discovery time is 3364 for one channel and 1131 for three channels). This needs to be considered for the specific problem in hand.

### 4.6. Impact of the number of advertisers

Finally, to complete the study of what factors determine the discovery time, in Figure 10, we show the deterioration of the discovery time due to the buffering effect. Specifically, the fact that the scanner buffer is fixed independently of the origin of the packet produces an amplification (because of the interaction amongst advertisers) of the saturation effect, both by shifting the critical value of $T_{advertising}$ and, ultimately, the discovery time itself.
4.7. Energy consumption

As previously shown by Liu and Chen [9], the energy consumption of the radio module during the send/receive state is twice that in the standby state. Therefore, setting a configuration that fits the needs at each stage can be critical. To that aim, here, we propose three performance profiles, defined according to the delay requirements of the application and that are aimed to help in the designing process of specific LPS applications. We summarise the main parameters for each profile in Table II.

In the relative consumption column, we show the relative energy consumption with respect to the exhaustive mode. As shown, an almost linear relation exists between energy consumption and discovery time. For instance, the relaxed profile consumes 12.5 times less energy than the exhaustive profile, at the expenses of the discovery delay about 10 times higher.

Our results predict an optimistic scenario in the use of BLE in indoor positioning systems. Using range-free approaches, with the exhaustive profile, we obtain the discovery around 56 ms, which is well below the results offered by other wireless technologies. Classic Bluetooth, for example, provides discovery times between 3 and 10 s depending on the number of devices in range and energy consumption of the order of 20 times higher. The energy saving is even more pronounced in the relaxed state, and the discovery times are still only 550 ms.

To assess the viability of LPS BLE in other contexts, such as range-based approaches using RSSI as the main indicator for positioning, more detailed information needs to be collected, and it is the aim of the following section.

4.8. Computing RSSI in BLE

As we discussed in Section 3, RSSI is one of the most widely used indicators in indoor positioning scenarios [6, 15, 16] but, at the same time, RSSI is one of the most controversial parameters because of the low precision that it provides indoor positioning [9]. Besides, it has also been shown that beyond 3 m (approx.), the accuracy drops dramatically. Thus, in this work, we will focus exclusively in ranges below 3 m [17].

In Figure 11, the average values of the signal intensity at different distances are plotted. There, an (almost) linear trend between the RSSI and the distance can be recognised (correlation coefficient 0.96) that allows to map between decibel-milliwatts (dBm) and meters

\[
\text{RSSI} = -17.2 \pm 1.9 \text{ (dBm/m)} \times d - 44.0 \pm 2.0 \text{ (dBm)} \tag{2}
\]

This linearity means that there is a reasonable relation between both parameters and that there are no discontinuities in that relation, so we can use that prediction to convert from RSSI to distance and the reverse. However note that there is some fluctuations in the value of RSSI.

To be more concrete on the implications of the RSSI-distance mapping, let us consider an example. Suppose that we have obtained an RSSI in the range [–67 dBm, –77 dBm]. The mapping would provide an estimated range of [1.2 m, 1.65 m]. Note how these fluctuations can produce an error in the location estimation of 45 cm, as shown schematically with the red arrow in Figure 11. This positioning uncertainty can still be too large to be acceptable depending on the specific scenario.
The origin of this uncertainty in the value of RSSI can be seen in Figure 12. There, we show a typical time series of measured RSSI values (in decibel-milliwatts) at a distance 1.4 m from the source (main panel). Note the high variability of this observable, plotted with a solid black line. The fluctuations around the mean ($\approx -70$ dBm) have standard deviation $SD = 4.63$ dBm but there are some bursts that can be as large as 20 dBm.

As described in the previous sections, one of the strengths of BLE is its low discovery time, what allows to obtain a measurement every 56 ms (or, equivalently, around 17 packets per second). This leaves some room for post-processing (for instance, filtering) in order to mitigate the high variability of the signal. Here, we have used a Butterworth algorithm, a bandpass filter that allows to drop high frequency (impulsive) signal fluctuations. This filter needs two parameters, the order of the filter ($n = 2$) and a cutoff frequency [11]. As an illustration of the outcome of this filter, the red line in Figure 12 is the output of a filter with $W_n = 0.007$ Hz. After filtering, we obtained a smoother signal with less dispersion ($mean = -69$ dBm, $SD = 0.76$ dBm), what also allows to reduce the maximum uncertainty from –55 dBm (amplitude of the original RSSI values, black line) to just –5.7 dBm (amplitude of filtered RSSI values, red line). The problem with this choice of the cutoff frequency is that it requires around 143 measurements (see the inset in Figure 12) to obtain reliable stable values, so high performance filtering requires an additional waiting time of $143 \times 56$ ms $\approx 8$ s, assuming a discovery time of 56 ms. Depending of the context, this value can be unacceptable.

Again, using Equation (2), in Figure 13, we show how lower values of the filtering cutoff frequency reduce considerably the uncertainty in the estimation of the device location, labelled as C in the figure. In this case, we have reduced the distance uncertainty from 0.45 m without filtering (highlighted as positioning uncertainty in Figures 13 and Figure 11, $C = 1.65$ m – 1.4 m) to 0.07 meters for $W_n = 0.007$ Hz (labelled as A in Figure 13). Note that
this reduction in the uncertainty comes at the cost of the increased sampling time. So, the optimal situation comes from the trade-off between long filtering times and large position uncertainties.

Thus, for \( W_n = 0.06 \) Hz (B point and vertical blue line in Figure 13), the filter returns a distance uncertainty of 0.1 m, which is a very reasonable value in many situations. In Figure 14, we plot the non-trivial dependence of the filtering time with the choice of the low-pass frequency \( W_n \). In this figure, we show as this selected value of \( W_n = 0.06 \) requires only 1 s of filtering calculation (horizontal red line). For generic human-based interactions, this time might be reasonable enough without the need to filter with lower frequencies. As mentioned, a trade-off between discovery + filtering time and location uncertainty will determine the right value of \( W_n \) for each problem.

5. CONCLUSIONS

In this paper, we have shown experimentally that BLE is a remarkable candidate for indoor positioning scenarios. This claim is supported by the low values of the discovery time, on the one hand, and also the low energy consumption of the devices, on the other. In addition, it provides reliable support for low discovery time (it means a high frequency of received packets), what makes it suitable for post-filtering aimed to minimise distortions in the quantification of RSSI (and, hence, letting this parameter regain relevance). Thus, as many systems have been based on this indicator, our results pushes the migration to BLE whilst maintaining all the complexity layers (based on filtering and/or other post-processing techniques) intact.

One important contribution of this work is the introduction of working profiles (see Table II) that can help in the design process by properly choosing the one that fits the needs of the specific application (as a trade-off between delay and energy consumption). Another important aspect of our contribution is the measured discrepancies between theoretical performance and real (experimental) ones what suggest that careful experimental assessment is mandatory for specific environments. Specifically, as shown in Figures 6 and 9, the buffer size in the specification introduced certain lower bounds in the discovery time, lower times being unattainable.

From a practical viewpoint, we also want to propose increasing the number of advertising channels in the discovery process. As shown, this number greatly impacts the overall performance of the application.

Thus far, we have shown that with the proper modifications and for range-based scenarios where distance to a beacon is enough (one-dimensional problems), BLE is a promising technology for LPS. Our results can be also applicable to other LPS applications that are based on RSSI. In addition, in two dimensions (2D), additional techniques as trilateration or fingerprinting [18], making use of the filtering system proposed earlier, we can improve the quality of signal received from all devices used to calculate the position of the scanner [17, 19]. In the case of the example shown in Figure 5(b), the improvement is applicable to the signal received from three devices. The shaded areas stand for positioning uncertainty to each advertiser, so reducing those areas will improve the estimation of the scanner location.

Finally, we want to emphasise that BLE can be seen as a promising technology in the field of LPS solutions, and that it deserves further a deeper understanding. Also, it would be interesting if some mass consumption devices that have supported BLE (such as iPhone 4S/5/5S) will allow the modification of parameters of the BLE stack (as done in this work). This would help the application programmer to choose between different profiles according to its needs.

REFERENCES


