A COMPREHENSIVE STUDY OF BLUETOOTH SIGNAL PARAMETERS FOR LOCALIZATION

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ABSTRACT

We provide an elaborate discussion on Bluetooth signal parameters with respect to localization, whereby we collectively designate all types of Bluetooth specification parameters that are related to signal strength – such as RSSI, Link Quality, Received and Transmit Power Level – as *Bluetooth signal parameters*. According to our analysis and experimental results, "RSSI" and "Transmit Power Level" turn out to be poor candidates for localization, while "Link Quality" has its limitations. On the other hand, "Received Power Level" correlates nicely with distance, which makes it the most desirable Bluetooth signal parameter to be used in location systems. We contend that it is vital to choose the appropriate signal parameter in Bluetooth location systems, and we expect our work to provide useful pointers in any future design of such systems. Existing systems can also benefit by adopting the appropriate Bluetooth signal parameter in their systems, and thereby, improve their location accuracy.

I INTRODUCTION

The future ubiquitous computing environment will consist of various types of gadgets, of which many will be equipped with wireless networking capabilities. The current popularity of Bluetooth wireless protocol – due to its short-range, low power consumption, and ease of integration – makes it a strong candidate to be incorporated into these mobile devices. With ubiquity, location awareness is expected to become a basic necessity for many applications. For example, a mobile user may require location-aware services in order to find the nearest points-of-interest, or to get around an exhibition center based on multimedia-guided tours. As a result, there is a keen interest to design positioning technologies that work indoors.

The current research efforts for indoor localization systems can largely be divided into two main categories:

- Those that rely on specialized hardware (e.g., IR or RF tags, ultrasound receiver) and extensive deployment of infrastructure solely for localization purpose [1, 2].
- Those that try to build localization systems on top of existing infrastructure (e.g., Wi-Fi networks) [3–5], and thereby, eliminating the need for any special modification at both the client and the infrastructure.

Between these two categories, the latter has a brighter prospect at achieving cost-effectiveness and deployability. Since Bluetooth is increasingly becoming popular in a wide variety of devices, and that a localization system built upon Bluetooth falls under the preferred category above, such a system would likely gain wide acceptance in the near future.

To the best of our knowledge, previous research on Bluetooth location system either provides discouraging results when considered alone, or requires the aid of additional wireless technologies [4, 5]. These unconvincing results thus far were often used to declare that Bluetooth is ill-suited for localization.

In this paper, we provide an elaborate discussion on all Bluetooth signal parameters, and discuss their potentials and pitfalls. To our knowledge, no previous work has delved into inspecting Bluetooth signal parameters in such great detail. In the remaining of this paper, we first provide in Section II an overview of these parameters, and then analyze in Section III their effects on location systems. In Section IV, we support these analyses with our experimental findings, and finally, we present in Section V the conclusions drawn, and future work.

II OVERVIEW OF BLUETOOTH SIGNAL PARAMETERS

We use the term *Bluetooth signal parameters* to denote all the status parameters of a Bluetooth connection together with any other signal strength values made available in Bluetooth Core Specification [6]. The Host Controller Interface (HCI) provides access to three such connection status parameters, namely, Link Quality (LQ), Received Signal Strength Indicator (RSSI), and Transmit Power Level (TPL). All these status parameters require the establishment of an active Bluetooth connection in order to be measured. From Bluetooth 1.2 onwards, another signal parameter, "Inquiry Result with RSSI", is made accessible. This is a special inquiry procedure which perceives RSSI from the responses sent by its nearby devices. To date, these are the 4 signal-related parameters made available by Bluetooth Core Specification. In the following, we briefly discuss each.

A *Link Quality (LQ)*

LQ is an 8-bit unsigned integer that evaluates the perceived link quality at the receiver. It ranges from 0 to 255; the larger the value, the better the link's state. For most Bluetooth modules, it is derived from the average bit error rate (BER) seen at the receiver, and is constantly updated as packets are received. However, the exact mapping from BER to LQ is device-specific. LQ is used mainly for adapting to changes in the link's state, notably to support CQDDR (Channel Quality Driven Data Rate).

B *Received Signal Strength Indicator (RSSI)*

RSSI is an 8-bit signed integer that denotes whether the received (RX) power level is within or above/below the Golden Receiver Power Range (GRPR), which is regarded as the ideal

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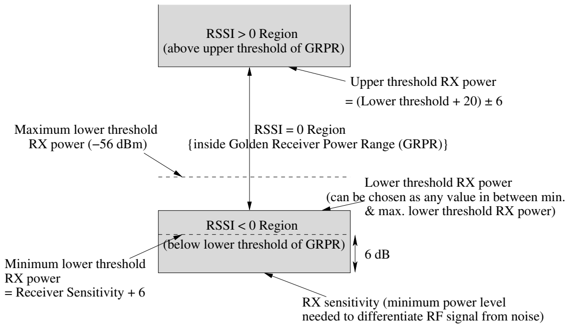


Figure 1: Relationship between GRPR and RSSI.

RX power range. Fig. 1 illustrates the relationship between GRPR and RSSI, as defined in Bluetooth specification. A positive or negative RSSI (in dB) means the RX power level is above or below the GRPR, respectively, while a zero implies that it is ideal (i.e., within GRPR). The lower and upper thresholds of GRPR are loosely bound, leaving them to be device-specific. This, in turn, affects the RSSI, since it is merely a relative parameter. In fact, its absolute accuracy is not mandated in the specification; the only requirement is to be able to indicate whether it is within, above, or below the GRPR. The RSSI status parameter of Bluetooth is particularly intended to be used for power control purpose [6]. The receiver sends "increase" or "decrease" TPL request to the transmitting side, depending on whether the perceived RSSI at its side is negative or positive, respectively.

C Transmit Power Level (TPL)

TPL is an 8-bit signed integer which specifies the Bluetooth module's transmit power level (in dBm). Although there are instances when a transmitter will use its device-specific default power setting to instigate or answer inquiries, its TPL may vary *during a connection* due to possible power control. For Class 1 devices, which have a maximum output power of $+20$ dBm, power control is mandatory when the TPL is between $+4$ and $+20$ dBm. In Bluetooth specification, power control is optional for TPL under $+4$ dBm. Therefore, Class 2 (maximum output power $+4$ dBm) and Class 3 (maximum output power 0 dBm) devices need not support power control, although their manufacturers may choose to implement it.

D Inquiry Result with RSSI

"Inquiry Result with RSSI" works in a similar manner as a typical inquiry. In addition to the other parameters (e.g., Bluetooth device address, clock offset) generally retrieved by a normal inquiry, it also provides the RSSI value. Since it requires no active connection, the radio layer simply monitors the RX power level of the current inquiry response from a nearby device, and infers the corresponding RSSI.

III Analysis

In this section, we analyze the various signal parameters' effects on location systems, as well as the different challenges posed by their inherent characteristics.

Table 1: LQ Conversion Algorithm of CSR Chipsets

BER, β (%)	LQ conversion equation	LQ value, l
$0 \leq \beta \leq 0.1$	$l = \lfloor 255 - \frac{\beta}{0.0025} \rfloor$	$255 \geq l \geq 215$
$0.108 \leq \beta \leq 10.1$	$l = \lfloor 215 - \frac{\beta - 0.1}{0.08} \rfloor$	$214 \geq l \geq 90$
$10.74 \leq \beta \leq 67.7$	$l = \lfloor 90 - \frac{\beta - 10.1}{0.64} \rfloor$	$89 \geq l \geq 0$

A Effect of LQ

As previously mentioned, the mapping from BER to LQ is device-specific. For our experiments, we have chosen Ranger's BT-2100 Bluetooth USB adapters, which use BlueCore4-ROM chips from Cambridge Silicon Radio (CSR). Table 1 shows the LQ approximation algorithm that they use. Since LQ is an 8-bit integer, it can only assume 256 different values to represent various BER conditions. From Table 1, we can see that LQ does not always decrease at the same rate when BER increases. For example, when we consider LQ between 255 and 215, each consecutive LQ value denotes an additional 0.0025% BER, whereas between 214 and 90, each consecutive value means an additional 0.08% BER. In other words, CSR chips report LQ with finer BER resolution when BER is small, but as the BER increases, the resolution becomes coarser. According to Bluetooth specification, a link is only considered workable if its BER is at most 0.1%. Therefore, it makes sense for LQ values below 215 to be mapped with a coarser BER resolution, as the link is already considered undesirable.

Prior works [4, 5] generally recorded LQ perceived by the mobile device as location fingerprints during the training phase. But we argue that devices that use chipsets from different vendors other than the one used at the mobile host during the training phase may unfortunately produce quite different LQ readings, because their LQ conversion algorithms may differ.

B Effect of RSSI

The RSSI reported by a Bluetooth device is completely dependent on the device's GRPR and its power control mechanism. The nominal range for GRPR of any Bluetooth device, according to Bluetooth specification, is 20 ± 6 dB. We have earlier seen that RSSI is 0 when the RX power level is within GRPR. Now, let us investigate RSSI's relationship with distance, and consequently, infer how it might affect location systems. Suppose a Bluetooth transmitter's TPL is set to P_t. Let P_{d_1} and P_{d_2} denote the upper and lower GRPR thresholds of the intended receiver, and assume that these power levels are detected at distances d_1 and d_2, respectively, from the transmitter. According to the free-space propagation model,

$$P_{d_1} \propto \frac{1}{{d_1}^2} \text{ and } P_{d_2} \propto \frac{1}{{d_2}^2}, \text{ giving } \frac{P_{d_1}}{P_{d_2}} = \frac{{d_2}^2}{{d_1}^2}. \qquad (1)$$

If we consider 20 dB path loss between these two distances, which is approximately the nominal GRPR range, we get

$$10 \times \log \frac{P_{d_1}}{P_{d_2}} = 20. \tag{2}$$

Combining (1) and (2), we finally obtain

$$\frac{d_2}{d_1} = 10. \tag{3}$$

The above calculation implies that RSSI remains at 0 when the separation ranges between d_1 and d_2, although they differ by a factor of 10. Hence, we may not be able to differentiate over a wide area if we rely on RSSI for localization. To aggravate the problem, Bluetooth devices may request the transmitter to perform power control, so as to keep its RX power level within GRPR. Suppose the devices choose to perform power control over a range of 20 dB (the margin may even be larger according to Bluetooth specification). If we add this quantity to the 20 dB GRPR range, it means we can no longer discriminate path losses of 40 dB. Following the same analysis as before, it can be seen that, a device only 10 cm away may not be distinguishable from one that is 10 m away. This wide range is unacceptable for indoor localization. Hence, RSSI is argued to be a poor candidate for location systems.

C Effect of TPL

The power control feature is introduced into Bluetooth devices in order to facilitate energy conservation, and also to combat interference. The step size for power adjustments ranges between 2 and 8 dB. Upon receipt of a power control request message, the TPL is increased or decreased by a step.

Although according to specification, Class 1 devices are advised to perform power control even below -30 dBm, for the convenience of analysis, we assume here that the minimum selectable power is -30 dBm. In this scenario, Class 1 devices can thus vary its power over a range of 50 dB, since the maximum attainable power for Class 1 devices is $+20$ dBm. If we consider the minimum power control step size of 2 dB, then there can be at most $50 \div 2 = 25$ different TPL values for distinguishing unique locations, which is quite limited.

Our CSR adapters offer updated RSSI measurements once every second. Therefore, if it takes four power control steps to eventually reach a stabilized TPL for a specific location, the overhead can be as long as 4 seconds (ignoring transmission and processing delays), which contributes to the overall latency of such a location system.

D Effect of Inquiry Result with RSSI

Every inquiry that is sent and replied by a device will be transmitted at a device-specific default power setting. As a result, the RSSI fetched through an inquiry is free from the side-effect of power control as explained earlier. Hence, the inquiry-fetched RSSI is expected to provide finer measurements than the connection-based RSSI, although it still suffers from the GRPR-related zero-RSSI problem.

The Bluetooth inquiry procedure uses 32 dedicated inquiry hop frequencies (in countries with 79 Bluetooth frequency channels) according to the inquiry hopping sequence as defined in the Bluetooth specification [6]. The inquiry-hopping rate is twice the nominal frequency-hopping rate used by ordinary connections. In other words, an inquiring device switches to a new frequency every 312.5 μs, whereas a typical Bluetooth time slot is 625 μs long. The inquiry hopping sequence is split into two trains, **A** and **B**, of 16 frequencies each (see Fig. 2). In one slot (i.e., 625 μs), the inquiring device sequentially transmits on two different frequencies. In the following slot, it shall listen for any response to the previous two frequency hops, in the same sequence. Consequently, each train comprises 16 alternate transmitting and listening slots, and spans 625 μs $\times$ 16 $=$ 10 ms. According to Bluetooth specification, a single train is repeated for at least $N_{\text{inquiry}} = 256$ times before switching to a new train. In an error-free environment, a Bluetooth device is recommended to perform at least three such switches in order to collect all responses. As a result, the whole inquiry procedure may last for $4 \times (256 \times 10 \text{ ms}) = 10.24$ sec, which can be a major drawback if latency is a prime concern. Nevertheless, the Bluetooth specification allows some flexibility pertaining to this inquiry duration. For example, the inquirer may stop inquiry process if it has collected enough responses.

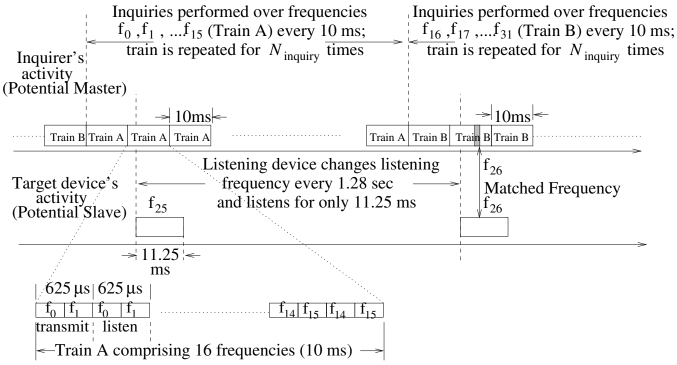


Figure 2: Potential Master's and Slave's frequency scanning during Bluetooth inquiry procedure (in countries with 79 Bluetooth frequency channels) [6].

IV Experiments

In this section, we first describe our experimental testbed. We then elaborate on our data collection procedure, and present the results along with discussions.

A Testbed

Our experimental testbed is located within a research laboratory. It has a dimension of 21.6 m $\times$ 9.56 m, an area of 206.496 m^2, and includes many small cubicles for research students. The whole experimental area is divided into an 11×6 grid, resulting in a unit grid size of 2.16 m $\times$ 1.912 m. We placed three BT-2100 Class 1 Bluetooth adapters in three such grid positions to serve as APs, and connected them to nearby Pentium-based PCs. As Bluetooth APs in an actual location system will invariably be located near ceilings, we raised our Bluetooth adapters with the help of USB cables, and attached them to the roof (2.57 m above the floor). Our mobile host,

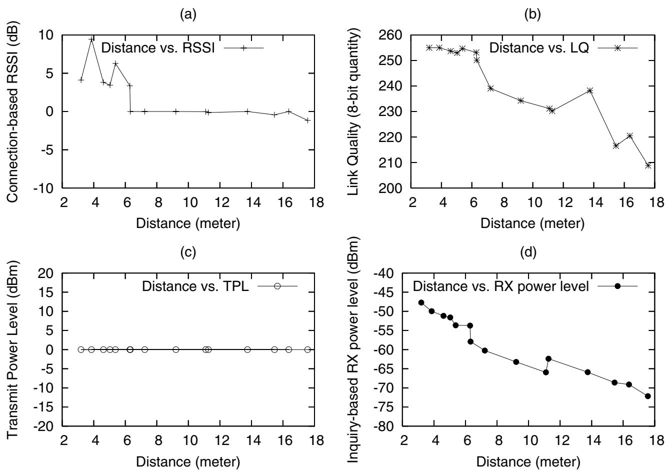


Figure 3: Relationship between various Bluetooth signal parameters & distance.

which is carried by the experimenter, is a Pentium-based Tablet PC. All the desktops (connected to the Bluetooth adapters by USB cables) together with our Tablet PC run Fedora Core 4, with the latest BlueZ protocol stack [7].

B Data Collection, Results and Discussion

During the experiments, our mobile host is connected using "SSH" (secure shell) to the desktops controlling the Bluetooth adapters. This facilitated the experimenter to have complete control over the whole system from the mobile host. While standing at a specific grid position, the experimenter could run Bluetooth signal extractor programs at both the mobile host and any AP over the network.

We now present the results from our various experiments:

1) Signal parameters' correlation with distance

For this experiment, we carefully chose five different grid positions where we took readings from each of the 3 APs, thus resulting in 15 data points. We adopted this methodology, rather than choosing 15 distinct distances from a single AP, because we wanted to correlate distance with signals originating from APs that were placed at different locations and surroundings.

In our experiments, we discovered that the Bluetooth wireless signal strengths tend to vary quite significantly depending on the user's orientation. Therefore, for every chosen grid position, we took 30 readings from every AP for each of the four different orientations. We then calculated the average of these 120 readings to obtain the signal parameter's value for that particular AP at the specific grid position. Since we know the distances of all grid positions from any AP, the signal strength values are simply mapped against the corresponding distances to generate Fig. 3.

In order to acquire the connection-based status parameter readings (i.e., RSSI, LQ, and TPL), we maintained connections at the HCI level from the APs to our mobile host.

From Fig. 3, the following observations can be made:

- As anticipated in our earlier analysis, RSSI turns out to correlate poorly with distance, as shown in Fig. 3(a).
- Fig. 3(c) shows a horizontal straight line for TPL values. This is because our Class 2 adapter at the mobile host which uses Broadcom's BCM2035 chip does not support power control feature. As a result, the TPL at the AP remained at its default value, which happens to be 0 dBm for the Bluetooth adapter used.
- From Fig. 3(b), we see that LQ correlates with distance much better than RSSI and TPL, although the LQ readings obtained at smaller distances show very little variation. Note that these readings were taken at the AP side, rather than at the mobile host side, as the LQ perceived at our mobile host was always 255 at any grid position, which is the highest possible LQ value. This is due to our Class 1 APs' large transmit power. The measurements at the AP side, on the other hand, show variations because our mobile host uses a Class 2 adapter.
- Our BT-2100 Class 1 adapters provide absolute RX power level through inquiry, instead of the relative RSSI values as suggested by Bluetooth specification. As the parameter "Inquiry Result with RSSI" also suffers from the GRPR-related zero-RSSI problem (just like the "connection-based RSSI"), we believe that making RX power level available should augur well in terms of distance. Fig. 3(d) certainly establishes this claim since the RX power level shows the best correlation with distance, compared to the other three signal parameters.

2) Effect of GRPR on RSSI

Fig. 5(a) illustrates the adverse effects of wider GRPR on the reported RSSI. From the figure, it is seen that BT-2100's RSSI readings (GRPR $\approx$ 80 dB) showed little variation compared to our Broadcom's adapter, which has a narrower GRPR. Because of the combined effect of large GRPR and power control, BT-2100's RSSI readings always remained at or above 0. On the contrary, Broadcom's adapter gave negative RSSI values at greater distances, although we did not have many such grid positions owing to our testbed's size.

3) TPL Consideration

For this experiment, we recorded the stabilized TPL values as well as the stabilization time periods for each AP's signal at specific grid positions using BT-2100 at the mobile host side. Fig. 4(a) indeed shows very few discrete transmit power levels, in harmony with our analysis in Section C. Moreover, the time periods required to reach these stabilized TPL values are also quite significant, as revealed in Fig. 4(b). Both these attributes make TPL a poor candidate for localization purpose.

4) Effect of Varying Inquiry Time Period

In this experiment, the inquirer, which is the mobile host, is placed at a location where it can hear all 9 Bluetooth devices to be discovered. Since BlueZ's HCI API allows us to vary the inquiry time period in increments of 1.28 sec, we varied it accordingly, and took 50 readings for each distinct inquiry time period. From Fig. 5(b), it is observed that, although the gap between the maximum and the minimum number of discovered

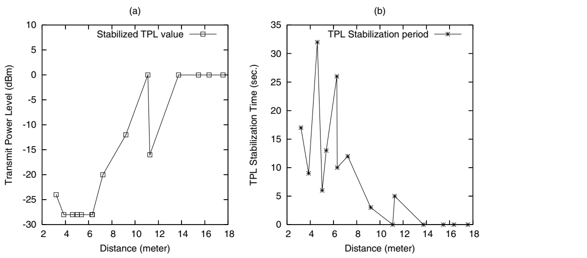


Figure 4: Stabilized TPLs & time periods to attain them.

devices can be quite large when the time periods are small, the average number of discovered devices is actually quite impressive at time period as low as 3.84 sec while the suggested inquiry time period in an error-free environment is 10.24 sec.

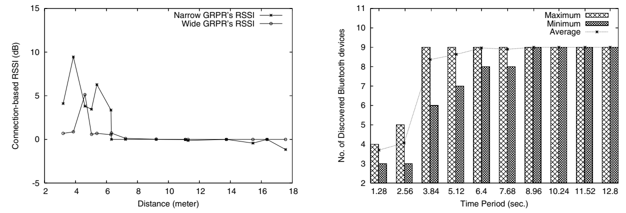
V Conclusion and Future Work

Based on our analysis and experimental results, the following conclusions can be drawn:

- Similar to previous works' verdict, we have shown RSSI's incompatibility for location systems. While previous works based their judgement solely on experimental data, we have also backed it up with proper analysis.
- To the best of our knowledge, no prior Bluetooth localization work has tried to use TPL. From our findings, we conclude that TPL is not suitable for localization.
- Through our experiments, we have shown that the LQ perceived at any location are rather sensitive to the transmitter's Bluetooth class. Therefore, problems would likely arise if LQ measurements were made at the AP side, and the mobile host's Bluetooth class is unknown. On the other hand, if LQ measurements were taken at the mobile host side, the fingerprints would then be sensitive to the BER-to-LQ mapping algorithm used by the mobile host, which is device-specific. Thus, LQ is not suitable for localization. Existing works on LQ-based localization [4, 5] have also reported poor location accuracy so far.
- Location systems that depend on inquiry-based parameters should take into account the latency incurred during the inquiry. Our experimental results show that the default time period for Bluetooth inquiry may be reduced to some extent while still providing acceptable results.
- Because of RX power level's superior correlation with distance, location systems that rely on it would likely outperform any other location systems built upon other Bluetooth signal parameters.

The major contribution of our work is a complete understanding of the Bluetooth signal parameters' issues regarding localization. We contend that it is vital to choose an appropriate signal parameter for a location system. In the following, we list some important future directions that we foresee:

- We have earlier seen that the LQ readings do not vary much at close-range distances. On the other hand, we notice that the RSSI readings tend to change significantly at



(a) Connection-based RSSI for 2 Bluetooth adapters with different GRPR.

(b) Max, min and avg no. of discovered devices during various inquiry periods (Total no. of devices = 9).

Figure 5: RSSI comparison of 2 different Bluetooth adapters and Effect of Inquiry time variation on the number of discovered devices

  close-range distances as well as at distant locations, where the RX power levels are above and below the GRPR, respectively. Therefore, a hybrid location system that combines both LQ and RSSI may be a viable option.
- While the retrieval of inquiry-based signal parameters tends to induce latency to the location system, our results show that most nearby Bluetooth devices are discovered even when the inquiry time period is reduced. Therefore, more extensive analyses are needed in this regard.
- There is no additional latency in obtaining the connection-based signal parameters only if the location system already has pre-established connections to the mobile hosts. On the contrary, if a mobile host needs to be discovered and then subsequently connected when it requests for location service, it will also undergo the latency problem similar to the inquiry-based location systems. The designer of a location system needs to address these issues.
- Finally, if future Bluetooth specification decides to make RX power level available – both as a connection-based status parameter and also through inquiry, it should then instigate new possibilities for Bluetooth localization.

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