On the Impact of Intra-System Interference for Ranging and Positioning with Bluetooth Low Energy

Pedro Figueiredo e Silva
Dpt. of Electronics and Comm. Eng.
Tampere University of Technology
Tampere, Finland
pedro.silva@tut.fi

Anahid Basiri
The University of Nottingham,
The United Kingdom
anahid.basiri@nottingham.ac.uk

Elena Simona Lohan
Dpt. of Electronics and Comm. Eng.
Tampere University of Technology
Tampere, Finland
elena-simona.lohan@tut.fi

James Pinchin
The University of Nottingham,
The United Kingdom
james.pinchin@nottingham.ac.uk

Chris Hill
The University of Nottingham,
The United Kingdom
chris.hill@nottingham.ac.uk

Terry Moore
The University of Nottingham,
The United Kingdom
terry.moore@nottingham.ac.uk

ABSTRACT

This paper focuses on the study of intra-system interference for ranging and positioning applications using Bluetooth Low Energy (BLE). While BLE tries to avoid interference with other protocols in the same frequency band, such as Wi-Fi, the intra-system interference is unavoidable, either due to multipath or simultaneous transmissions in the same channel. This study shows that intra-system interference contributes with a deviation of approximately 5 dBm in the Received Signal Strength (RSS) and by taking this into account the ranging and positioning accuracy can be significantly improved. The study uses data collected from two different environments.

Categories and Subject Descriptors

D.2.1.3 [**Reusable Software**]: Reuse models

Keywords

Bluetooth Low Energy (BLE), Received Signal Strength (RSS), Interference, Indoor Positioning

1. INTRODUCTION

The Global Navigation Satellite System (GNSS) is the most widely-used positioning technology for outdoor use, however in deep urban canyons and indoor environments GNSS may fail to provide the positioning service due to stronger multipath, signal attenuation and blockage [7, 8]. In these environments other opportunistic signals, such as Wi-Fi are commonly used for positioning. However, in addition to the privacy concerns and the high power consumption, the positioning accuracy provided by Wi-Fi is highly correlated with the density of Wi-Fi access points. Hence, indoor localization is still a big challenge for many Location Based Services (LBS) applications, such as emergency and safety, navigation and tracking [3].

Lately, BLE has been enabling several indoor LBS applications thanks to its low power consumption and cheap hardware. Its popularity is growing, particularly where beacons are being deployed throughout the environment, to broadcast location specific information. These beacons are the BLE devices, most of the times, operating with batteries with a life span of months or even years, depending on its duty cycle. However, the major disadvantage of the BLE is the operation in the crowded 2.4 GHz band [2], where other systems, such as Wi-Fi, interfere with the BLE signals. Besides the interference from other systems, the number of available channels for the operation of BLE signals is limited. This limit is particularly small when the devices are operating in the advertisement mode, where 3 channels are available for broadcasting the advertisement packets. This is the case for BLE beacons. For that reason, this study investigates the interference caused by other beacons and its impact on received signal strength applications.

2. BLUETOOTH LOW ENERGY

BLE is designed for lower power operation, low complexity and cost. BLE devices operate according to several profiles defined by the Bluetooth SIG. These define how a device behaves in a particular application, e.g. the heart rate monitor or the battery level indicator. The Generic Attribute Profile (GATT) is a common profile adopted by the majority of BLE applications allowing them to receive and send short pieces of data, known as attributes, over a BLE link. These profiles are used to define specific protocols on top of it, such as Apple's iBeacon [1, 2].

For medium access, BLE relies on Adaptive Frequency Hopping (AFH) to avoid interference from other systems, for example, Wi-Fi, operating in the same frequency band [1].

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BLE operates over forty channels, with a 2 MHz bandwidth, three of which are being reserved for advertisement packets, for device discovery and connection establishment purposes. While a BLE device can operate under several modes, however this paper is focus on the unconnected mode. In this mode, the BLE devices are operating, exclusively, over three advertisement channels. While in a connected mode, the devices would use the advertisement channel for discovery and to establish connection, with the remaining channels being used for data exchange.

Even though AFH minimises the interference to other systems, it cannot guarantee the lack of interference from other Bluetooth devices. This would be more critical if the BLE devices operate solely in advertisement mode, as the number of channels is reduced to three, as it increases the likelihood of picking a channel where another beacon is already sending an advertisement packet. These three channels are located at 2.402, 2.426 and 2.480 GHz.

As reported in [4], for s BLE devices operating solely in the advertisement mode and sharing n advertisement channels, the probability that at a given time t the given channel will be occupied will be given by,

$$\mathrm{P} = 1 - \left(\frac{n-1}{n}\right)^{(s-1)}. \tag{1}$$

For $n = 3$ there is a 56% chance of picking a channel that is occupied by another BLE beacon and with $n = 8$ the probability increases to 94%. However, this assumes a simplified scenario where the devices are synchronised with each other and the time between jumps is considered to be the same. however in real world applications, the random delays in the hopping structure can reduce this probability, but in a massive deployment of such devices, interference between each other will inevitability happen.

3. PATH LOSS MODELS

This study uses two path loss models, the ITU-R model defined as,

$$\mathrm{P_r}(d) = \mathrm{P_t} + \mathrm{C} - 20\log_{10}\left(\frac{4\pi f}{c}\right) - 20\eta\log_{10}(d) + v \tag{2}$$

and the log distance model described by,

$$\mathrm{P_r}(d) = \mathrm{P_r}(\mathrm{d_0}) - 10\eta\log_{10}\left(\frac{d}{\mathrm{d_0}}\right) + w, \tag{3}$$

where $\mathrm{P_r}(d)$ is the RSS at a given distance d in meters, $\mathrm{P_t}$ the transmission power, f the operating frequency in Hertz, η is a constant that models additional losses in the path of the signal, $v, w \sim \log(\mathrm{N}(0, \sigma^2))$, are log-normal distributed random variable which model the slow fading phenomenon.

Both models offer an equivalent interpretation to the expected RSS at a given distance, but the ITU-R tries to take into account all the losses in the signal's path, while the log distance model, assumes an apparent transmission power, $\mathrm{P_r}(\mathrm{d_0})$, at a reference distance, $\mathrm{d_0}$. For that reason, the meaning of η differs in both models. For the ITU-R model, this parameter must be bigger than 1, since that represents the free space propagation. For the log distance model, this value has to be bigger than 0. Therefore, C is a constant that models additional system losses for the ITU-R model, while in the log distance model, it is lumped together with the apparent power.

Both models are used to fit measurement data obtained at Tampere University of Technology in Finland and at University of Nottingham in the UK. The beacons were deployed on regular grids over a corridor and over a table in a closed office room. For the first one, 8 beacons were deployed every 1.5 m from each other and from the floor, while for the later one, a single beacon was deployed at several distances from the receiver; 0.10, 0.5, 1, 1.5, 2, 2.5 and 3 meters from the receiver. The data from the beacons were captured using a laptop running Ubuntu 14.04. The beacons were manufactured by Kontakt.io and left at their default transmission power (-12 dBm) [5].

Using the models (2) and (3), tables 1 and 2 show the root mean square error (RMSE) for each environment and model. The RMSE is defined as,

$$\mathrm{RMSE} = \sqrt{\frac{\sum\limits_{i=0}^{N}\left(y^{(i)}_{\mathrm{observed}} - y^{(i)}_{\mathrm{expected}}\right)^2}{N}}, \; N > 0 \tag{4}$$

where $y^{(i)}_{\mathrm{observed}}$ is taken as the mean of the measurements and $y^{(i)}_{\mathrm{expected}}$ the value obtained through the fitted path loss model.

In both tables the columns contain the RMSE for the log distance model and the ITU-R model. However, since the BLE beacons report the apparent power, the log distance column is divide in two. In the first column, the reported apparent power of -77 dBm is used in (3), while the second column shows the results when the apparent power in (3) is set to -79.73 dBm. This value is the measured mean RSS value, over 1 hour, for a single beacon (beacon 3) at 1 meter distance.

Table 1: Fit of the two models for the measurement data obtained in Finland

Distance (m)	**RMSE (dBm)**		
	log dist		**ITU-R**
	$\mathrm{P_r}(\mathrm{d_0}) = \mathbf{-77dBm}$ $\eta = \mathbf{1.02}$	$\mathrm{P_r}(\mathrm{d_0}) = \mathbf{-79.73dBm}$ $\eta = \mathbf{0.98}$	$\mathbf{C = -24.76}$ $\eta = \mathbf{1.08}$
0.50	0.95	1.87	4.60
1.00	3.59	0.87	3.78
1.50	8.57	5.91	6.74
2.00	7.69	5.07	4.42
2.50	8.95	6.37	4.58
3.00	5.33	2.78	0.05
Mean	**5.85**	**3.81**	**4.03**

Table 2: Fit of the two models for the measurement data obtained in the UK.

Distance (m)	**RMSE (dBm)**					
	log dist				**ITU-R**	
	$\mathrm{P_r}(\mathrm{d_0})$ = **-77 dBm**		$\mathrm{P_r}(\mathrm{d_0})$ = **-79.73 dBm**		$\mathbf{C = -15.96}$	$\mathbf{C = -19.28}$
	$\eta = \mathbf{0.99}$	$\eta = \mathbf{0.97}$	$\eta = \mathbf{0.94}$	$\eta = \mathbf{0.96}$	$\eta = \mathbf{1.09}$	$\eta = \mathbf{1.00}$
	beacons = 8	**beacons = 1**	**beacons = 8**	**beacons = 1**	**beacons = 8**	**beacons = 1**
1.39	1.15	2.48	1.40	5.04	4.05	2.06
1.90	3.19	3.08	5.87	5.76	4.07	1.09
3.22	2.23	2.06	0.39	4.70	7.87	0.71
Mean	**2.19**	**2.54**	**2.55**	**5.17**	**5.33**	**1.29**

Table 1 compares the fit of the log distance model and ITU-R model for the office room, where a single beacon (beacon 3) RSS was measured at several distances for periods of 30 minutes. The overall RMSE is the smallest for the log distance model with the estimated apparent power. With the ITU-R the overall RMSE is approximately the same and the worst fit happens when the apparent power is set to the reported value.

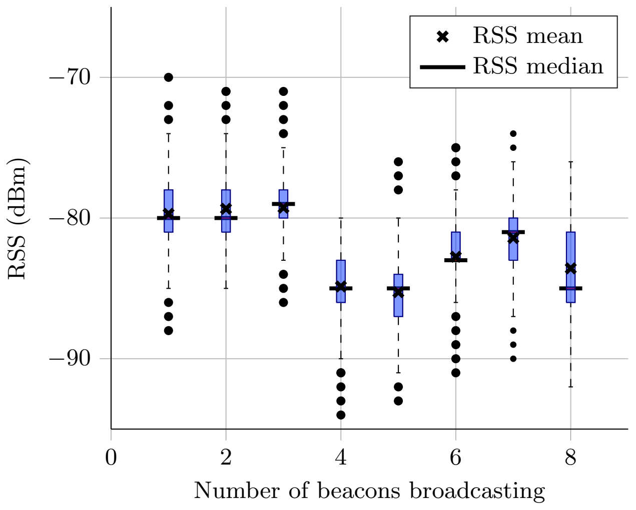

Figure 1: RSS values for beacon 3 at 1 meter versus the number of beacons broadcasting.

Table 2 shows the results in the office corridor, where data was collected for periods of 15 minutes in three different points. The acquisition was done with 1 and 8 beacons in advertisement mode. In contrast with office scenario, here, the log distance model with the reported apparent power is now the one with the lowest overall RMSE. While the fit with the log distance still offers an accurate fit for the case where 8 beacons are transmitting, it is quite poor when solely one is transmitting. On the other hand the ITU-R error for only one beacon is low, approximately 1 dBm error.

To understand the impact of other beacons on the RSS value of a single beacon, Fig. 1 shows the statistics for the RSS of beacon 3 when up to 7 other beacons are spread around it. The 7 other beacons are regularly spaced on a half meter grid around it and the observations lasted over 3 hours.

From Fig. 1 there seems to be no relevant degradation of the signal up to the presence of three beacons. Above this number, i.e. 3, the mean value drops by 4 dBm. With 4, 5 and 8 beacons broadcasting simultaneously, the mean and median values are approximately 5 dBm lower than for cases 1, 2 and 3. With 6 and 7 beacons broadcasting there are changes of 3 dBm and 1 dBm in the metrics, respectively. More interestingly, with 3 simultaneous beacons, the value is increased by 1 dBm, which is probably due to channel phenomena specific to that observation period. Therefore, with more than 3 beacons on advertisement mode, there is a degradation of the RSS that can reach up to 5 dBm.

Application for ranging and positioning

Many applications of the indoor positioning, such as creation of probabilistic fingerprint databases, can benefit from accurate path loss models. Since BLE, unlike Wi-Fi, can report the transmit power, rather than a manufacturer dependent indicator, such models can calculate the distance by solving (2) and (3) with the values of the observed RSS. Fig. 2 shows the distance from the beacon to the receiver in the closed office environment, using (2) and (3). The input to the model is an averaged RSS value with the last observed 2 seconds. With the addition of more beacons there is a

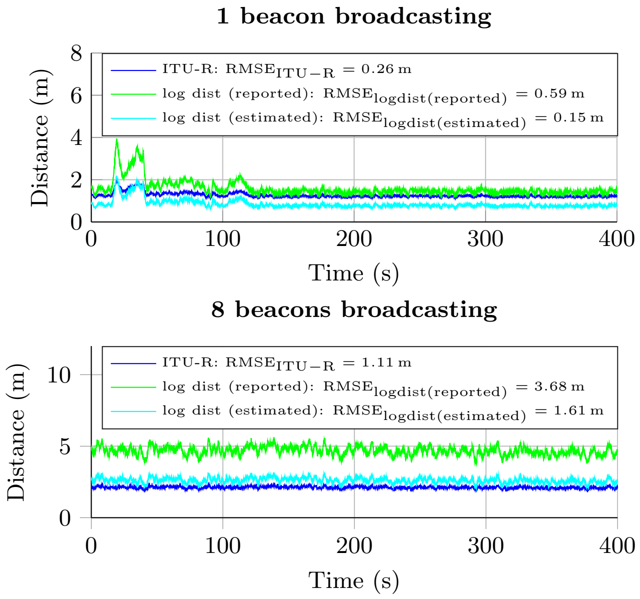

Figure 2: Ranging to beacon 3 with 1 and 8 beacons broadcasting.

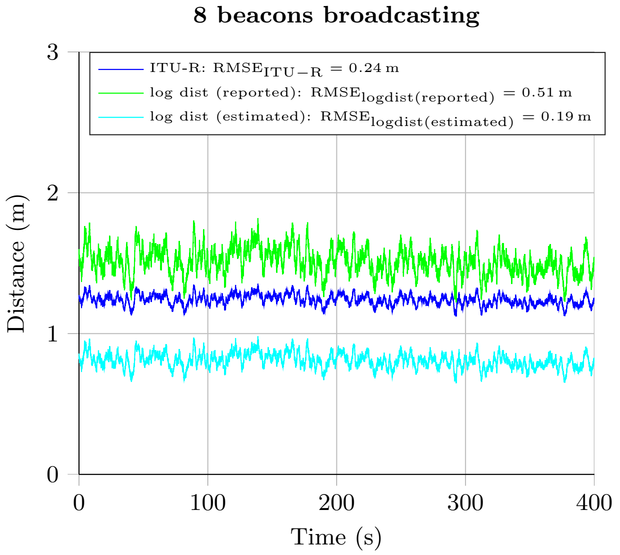

Figure 3: Ranging to beacon 3 with 8 beacons broadcasting and interference offset added to model.

significant impact in the RMSE for each model. With a single beacon broadcasting all the models achieve a sub meter level accuracy, while the opposite is true when all 8 beacons are broadcasting, increasing the RMSE significantly. Of particular interest is the degradation of the RMSE of the log distance model with the reported apparent power level by the beacons. Its RMSE increases by more than 3 m while the RMSE for the other models increases, approximately, by one meter.

However, if the interference contribution is taken into account by summing to the left side of (2) and (3) an addition term I = -5 dBm, the accuracy of the ranging approximates the one observed when a single beacon is broadcasting, as seen in Fig. 3.

For positioning applications there are more challenges to tackle, since the lack of line of sight will reduce the RSS further, for example due to people and environment objects [6]. For example, in this study, the data was collected in the UK during off hours, with the receiver set at the beginning of corridor (A), middle of the corridor (B) and end of the corridor (C). The position of the receiver is obtained by solving and minimizing the following non linear equation for each beacon,

$$\sqrt{(x^{(i)}_{\text{beacon}} - \hat{x})^2 + (y^{(i)}_{\text{beacon}} - \hat{y}) + (z^{(i)}_{\text{beacon}} - \hat{z})} - L^{(i)}_{\text{beacon}} = 0 \quad (5)$$

where $(x^{(i)}_{\text{beacon}}, y^{(i)}_{\text{beacon}}, z^{(i)}_{\text{beacon}})$ are the known coordinates to the i-th beacon, $(\hat{x}, \hat{y}, \hat{z})$ the unknown receiver position and $L^{(i)}_{\text{beacon}}$ the distance to the i-th beacon obtained through the path loss model.

Table 3 contains the RMSE of the positioning in 2D (assuming the height is known) and 3D of the receiver's location, using ranges to the 8 available beacons. These results are a mean over 1000 observations. With no surprise, the RMSE values are better in most cases for the 2D positioning, however the difference between them is almost none in some cases, for example, at point B the results are quite the same in both scenarios. The overall performance, mean of the three points, (last column) for 3D is quite similar for the ITU-R model and the log distance using the estimated apparent power. With the log distance model using the reported apparent power, the performance increases by 70%, with the RMSE decreasing from 1.7 m to 1 m. For the 2D case, the best performance is still achieved by the log distance model using the reported apparent power, but now the performance is slightly worse when using the ITU-R model.

With the introduction of the interference offset in the models, the overall accuracy improves significantly by more than 50% in some cases, for either a positioning in 3D or 2D. This also shows, that the estimated interference offset can be calibrated in a different scenario from where it is used.

Table 3: RMSE (m) values for 2D and 3D positioning in the office corridor at the UK.

	Model	RMSE_{A} (m)	RMSE_{B} (m)	RMSE_{C} (m)	$\text{RMSE}_{\text{Modelmean}}$ (m)
3D	ITU-R	1.82	2.14	1.30	1.75
	log $\text{dist}_{\text{rep.}}$	1.35	1.18	0.60	1.04
	log $\text{dist}_{\text{est.}}$	1.95	2.18	0.95	1.69
2D	ITU-R	1.75	2.07	1.19	1.67
	log $\text{dist}_{\text{rep.}}$	1.52	1.24	0.22	0.99
	log $\text{dist}_{\text{est.}}$	1.61	2.01	0.67	1.43
3D (interf. corrected)	ITU-R	1.20	1.21	1.35	1.25
	log $\text{dist}_{\text{rep.}}$	0.47	0.57	0.57	0.54
	log $\text{dist}_{\text{est.}}$	0.79	1.05	1.32	1.05
2D (interf. corrected)	ITU-R	1.21	1.20	1.31	1.25
	log $\text{dist}_{\text{rep.}}$	0.47	0.57	0.57	0.53
	log $\text{dist}_{\text{est.}}$	0.79	1.06	1.32	1.06

4. CONCLUSION

This paper focuses on the study of the signal behaviour for BLE devices, under two office environments. The study focuses on the interference caused between beacons in advertisement mode, where more than three beacons cause a deviation on the RSS of, approximately, 5 dBm.

In addition, this paper compares two path loss models to identify the best fit to the measured data. It was seen that the log distance model, using an apparent power equal to the one reported to the beacons, was performing better in most situations than the log distance model with an estimated apparent power and the ITU-R model. When applying the models for ranging purposes, it was possible to see that the ITU-R and the log distance model using an estimated apparent power were indeed performing better in a closed office scenario, particularly when all the 8 beacons were broadcasting. In the office corridor, where the ranges were used to position the reader, all the three models performed in a similar manner, but the log distance model using the reported apparent power, did manage to outperform the other two. It was also seen, that taking the 5 dBm offset into account leads to a better positioning and ranging performance in either of the scenarios.

In the end, this paper shows that intra-system interference has a negative effect in the observed RSS and path-loss dependent applications, such as ranging and positioning. This effect can be removed by taking it into account in the path loss models, which should hold across different scenarios. Future studies should focus on mechanisms to monitor and compensate for intra-system interference.

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Open Access

The data and scripts used for this study are available at https://goo.gl/GHlSbK, under a CC 4.0 license.

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