Distance estimation to BLE beacons using Raspberry Pi 3 boards for indoor positioning and social tracking applications

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Abstract— **The Raspberry Pi (RPi) boards family is not only a set of versatile devices suitable for quick prototyping, but robust, low-cost systems that can be used in production. For example, RPi 3B and RPi 3B+ models have integrated WiFi/Bluetooth interfaces, so they can be used to interact with Bluetooth Low Energy (BLE) beacons. In particular, distance among beacons and Raspberries can be inferred using the received signal strength indicator of Bluetooth signals. This feature allows to build low-cost indoor positioning systems, that in turn can be used to track people that works closely for disease prevention.**

In this paper we present the results of an empirical study that aims to determine whether RPi 3B and RPi 3B+ models are equally good to be used as receiving stations, and whether their relative orientations with respect to BLE beacons make any difference. Among other findings, in this work we show that the Bluetooth/WiFi antenna design of the RPi 3B+ receives different RSSI values depending on their orientation, thus being a poor choice for this application domain.

Keywords—**BLE, Bluetooth, Raspberry Pi, beacons, indoor positioning**

I. Introduction

The Raspberry Pi (RPi) platform [1] is a robust and versatile computer that can be used as a building block of more complex systems. Thanks to its extended connectivity (Ethernet, WiFi and Bluetooth interfaces), its computing capabilities, its low cost and the use of the GNU/Linux operating, the RPi platform is a versatile candidate for Edge Computing applications.

Using RPis as building blocks, our research group has developed XtremeLoc, a low-cost indoor localization system that allows persons and goods to be tracked in situations where GPS is not a cost-effective or feasible solution. The solution consists of the use of Bluetooth Low Energy (BLE) [2] emitters, called beacons, that are carried by the persons or goods that should be tracked. Note that this use of beacons is the opposite of their mainstream use: In our case, beacons are not installed at fixed locations. A set of low-cost, receiving stations based on RPi platform located at fixed places receives the signals emitted by the beacons using their in-board WiFi/Bluetooth antenna. RPi Bluetooth interface not only captures the Bluetooth packet received, but also returns their RSSI (received signal strength indicator) value [3]. These values are used to calculate the distances to each beacon, and these distances are sent to a cloud-based server. This server uses a trilateration algorithm to determine the position of the elements to be tracked, and draws the position at real time in a web browser.

XtremeLoc is a cost-effective solution for tracking persons and goods. However, it offers a limited precision, of around two to three meters. The reason is that the distance between each beacon and the receiving stations built with RPis is estimated using their RSSI value, that can be affected by different factors, including attenuations due to the presence of obstacles, and the relative orientation of beacons and receiving antennas. By its nature, the first factor is difficult to handle, although it can be mitigated by collecting several, consecutive measures and use a Kalman filter to reduce noise [4], thus obtaining a more representative result. The second factor (the influence of the relative orientation of antennas and beacons), can be better study in controlled experiments.

In this paper we present the results of an empirical study consisting on the use of two sets of different RPi boards (3B and 3B+) to estimate the distances to a set of Bluetooth beacons located at known distances. Our study aims to answer to different questions: (a) how the relative orientation of RPi 3B boards affects the RSSI value associated to a particular Bluetooth signal; (b) how the relative orientation of RPi 3B+ boards affects the RSSI value associated to a particular Bluetooth signal; (c) how the relative orientation of beacons does affect their RSSI values; and (d) whether the expected propagation model of Bluetooth signals corresponds with the experimental results obtained using both RPi models.

Our experimental results shows an important difference between the behavior of RPi 3B and 3B+ when used for this purpose. We believe that the results of this experimental study would save efforts to the community, and would foster the use of these low-cost technologies for indoor positioning.

The rest of the paper is organized as follows: Section II describes our environment setup. Section III analyzes how different orientations of RPi 3B affects the RSSI values associated to received Bluetooth packets. Section IV performs the same analysis using RPi 3B+ boards. Section V discusses how the relative orientation of Bluetooth beacons affects

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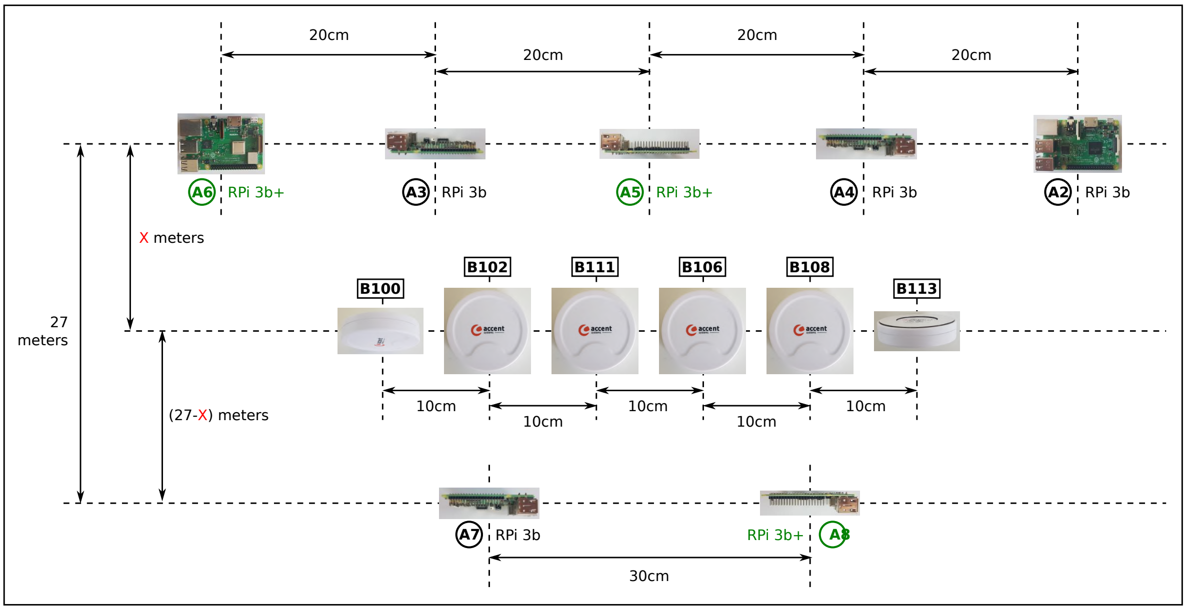


Fig. 1: Setup of our experiment. Both rows of RPi boards were 27 meters apart. We have moved the bench of beacons between them. The drawing is not at scale.

their RSSI value. Section VI makes some considerations on the propagation model used to estimate distance with respect to RSSI values for our experimental setup. Finally, Sect. VII concludes our paper.

II. Environment setup

We have built an installation composed by two benchs of RPi boards, arranged in two lines 27 meters apart from each other, and a mobile bench of six Bluetooth beacons. The distance among beacons are fixed. In our experiment, we have moved the entire mobile bench of beacons back and forth between both benchs of Raspberries, to different positions. See Fig. 1. In this figure, all the equipment is seen from above, in order to appreciate their orientation. RPis A2, A3, A4 and A7 are RPi 3B models, while A5, A6 and A8 are RPi 3B+. All beacons are iBKS-105, manufactured by Accent Systems, and emitting at +4dB. All three benches are coplanar, 1.5m above the floor. In our experiment, the RPis report the RSSI values obtained to a cloud-based server, using a WiFi connection. We have found that the Bluetooth RSSI values returned by RPi boards are affected by the simultaneous use of the on-board WiFi interface, because both WiFi and Bluetooth interfaces share the same antenna. To avoid these interferences, we have used external WiFi USB sticks attached to each RPi for WiFi communications, disabling the on-board WiFi interface.

We have collected data setting the beacon bench in 22 different positions, all of them parallel to both RPi benchs, and acquiring data during ten-minutes intervals. Each beacon emits one signal per second and was captured by each one of the seven RPis, generating around $(60 \times 10 \times 6 \text{ beacons} \times 7 \text{ RPis}) = 25\,200$ measures per interval distributed into $(6 \text{ beacons} \times 7 \times RPis \times 22 \text{ positions}) = 924$ series of data.

III. Effects of RPi 3B orientation on the RSSI of Bluetooth signals

Our first study was to determine how the relative orientation of RPi 3B boards affects to the RSSI value of the same Bluetooth signal. To do so, we have compared the series of data collected by three RPi 3B boards (namely, A2, A3, and A4) with respect to the same beacon (labeled 108) at 12.83m. As can be seen in Fig. 1, these boards have different orientations with respect to this beacon. Table I shows the results obtained when analyzed the data collected, while Fig. 2 shows the histograms represented the number of signals perceived at different RSSI levels.

As can be seen, all three boards behave approximately in the same way, regardless of their orientation. Average values and median values are similar, the standard deviation with respect to the average is equal to or less than 5%, and the kurtosis (that is, the "tailedness" of the probability distribution)[1], indicates that this distribution produces more values near the media than a normal distribution [5] This makes the RPi 3B a good device for capturing Bluetooth signals and estimating distances to beacons using the RSSI values. As we will see in the following section, this is not the case for the other candidate.

IV. Effects of RPi 3B+ orientation on the RSSI of Bluetooth signals

Our second study was to determine how the relative orientation of RPi 3B+ boards affects to the perceived intensity of the same Bluetooth signal. The RPi 3B+ uses a Proant PCB antenna similar to the antenna used in the ZeroW board [6]. The RPi 3B, on the contrary, uses a chip antenna soldered to the board. See Fig. 4. We have compared the series of

[1]In this paper, we show as kurtosis the calculations of the estimator of the sample excess kurtosis.

Beacon 108	RSSI A2	RSSI A3	RSSI A4
Average	-77.09	-74.16	-73.79
Real distance (m)	12.83	12.83	12.83
Median	-77	-74	-74
Mode	-76	-74	-71
Variance	12.53	12.95	6.10
Std Dev.	3.54	3.60	2.47
%Std Dev vs average	5%	5%	3%
Maximum	-67	-66	-69
Minimum	-91	-85	-84
Range (Min-Max)	24	19	15
% Range vs average	31%	26%	20%
kurtosis	0.48	-0.01	0.15

Table I: Data analysis of RSSI values collected by RPis A2, A3, and A4 with respect to beacon 108 at 12.83m.

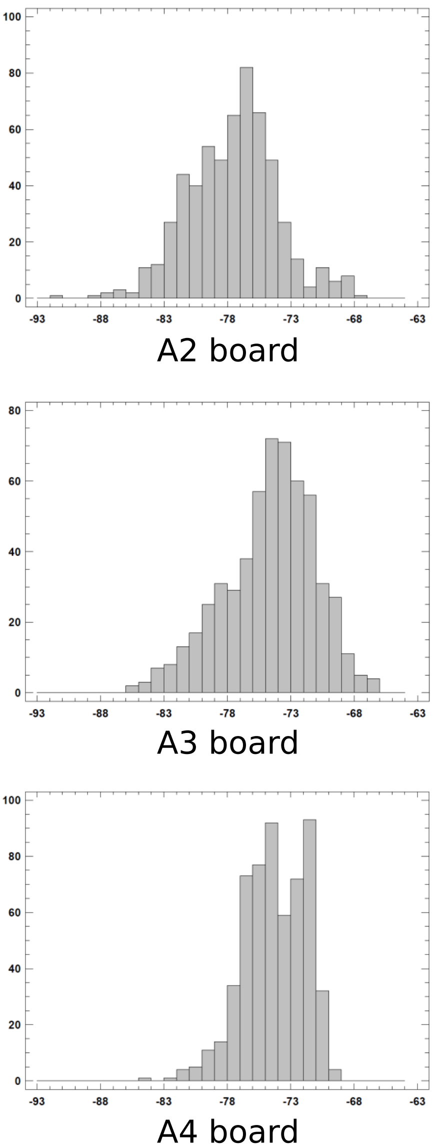


Fig. 2: Histograms that represent the distribution of measures with different RSSI values, received by RPi 3B boards with different orientations.

data collected by two RPi 3B+ boards (namely, A5, and A6) with respect to the same beacon (labeled 102) at 12.83m. Recall that these boards have different orientations with respect to that beacon.

Table II shows the results obtained when analyzed the data collected, while Fig. 3 shows the histograms represented the number of signals perceived with different RSSI values.

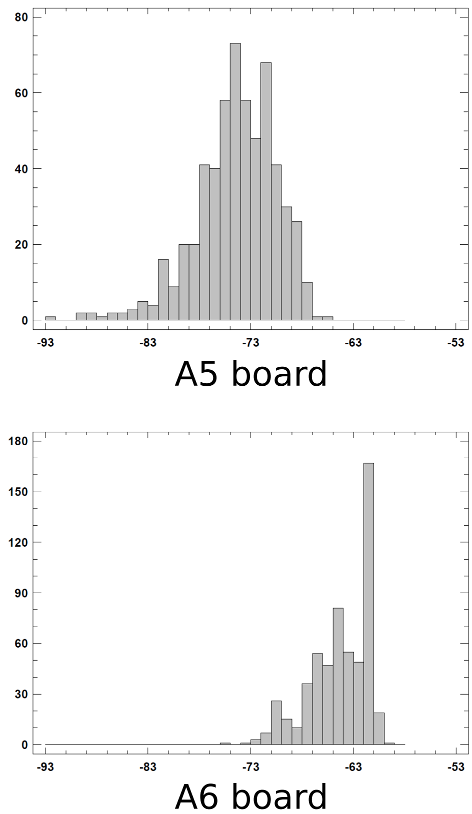
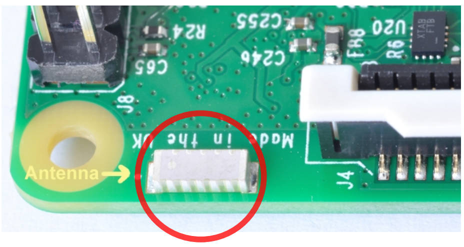


Fig. 3: Histograms that represent the distribution of measures with different signal strengths, received by RPi 3B+ boards with different orientations.

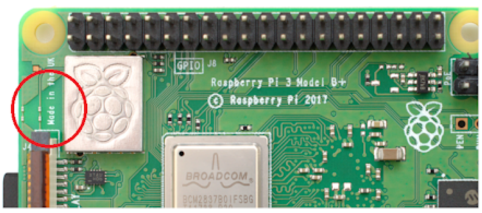
As can be seen in Fig. 3 and Table II, results are now quite different. The average RSSI and the corresponding medians are 15% lower for A6 board. The value for the kurtosis show a very sharp curve for A6. Unlike the RPi 3B, the perceived strength of the signals received by RPi 3B+ boards strongly depends on their orientation, making this board not appropriate for estimating the distance to a set of beacons.

Beacon 102	RSSI A5	RSSI A6
Average	-73.86	-63.81
Real distance (m)	12.83	12.83
Median	-74	-63
Mode	-74	-61
Variance	15.71	8.51
Std Dev.	3.96	2.92
%Std Dev vs average	5%	3%
Maximum	-65	-59
Minimum	-92	-75
Range (Min-Max)	27	16
% Range vs average	37%	25%
kurtosis	1.53	0.11

Table II: Data analysis of RSSI values collected by RPis A5 and A6 with respect to beacon 102 at 12.83m.



(a)



(b)

Fig. 4: Antennas of RPi boards. (a) RPi 3B antenna (source: `raspberrypi.stackexchange.com`). (b) RPi 3B+ antenna (source: `www.proant.se`).

V. Effects of the relative orientation of beacons

Our following question is how the relative orientation of beacons affects to their signals as perceived by the RPis that act as receiving stations. We have calculated the average values for all the diferent distances between the beacon bench and both RPi benchs. The average typical deviation of all Bluetooth signals received with respect to their corresponding mean RSSI values is 5.61% for RPi 3B antennas and 7.01% for RPi 3B+ antennas. This means that the use of RPi 3B+ boards for this purpuse returns a set of measured values that are around 25% more dispersed than using RPi 3B boards, a result that is aligned with the observations carried out in the previous section. Regarding the orientation of beacons itself, we can conclude that their relative orientation at a given moment is not the main source of uncertainty for their distance estimation.

VI. On the expected propagation model of Bluetooth signals

Finally, we aimed to confirm that the propagation model of Bluetooth signals corresponds with the empirical results obtained for both RPi boards. This is indeed the case. Fig. 5(a) shows that the logarithmic function $y = -7.412 \ln(x) - 56.5$ adjust to the RSSI values returned by the RPi 3B board, for Bluetooth beacons emitting at +4dB. The function has an excellent adjustment with respect to the set of measures, with $R^2 = 0.9712$. Regarding the RPi 3B+ model, the corresponding function for beacons emitting at +4dB is $x = -7.069 \ln(x) - 52.199$, with $R^2 = 0.9704$. We have found that both functions, based on experimental data, are better suited for distance estimations than more generic functions found in the manufacturers' datasheets. We encourage the reader to perform a similar experiment with his/her own hardware for improved results.

VII. Conclusions

The joint use of commodity Bluetooth beacons and RPi boards allows the construction of a low-cost indoor positioning system with an acceptable precision for many practical applications. This study aims to compare the usefulness of two RPi boards, namely 3B and 3B+, for this purpose. We have shown that the antenna included in RPi 3B boards is less sensitive to changes in orientation, delivering better results for this purpose in the general case than the one included in RPi 3B+ boards. Regarding beacons orientation, we have shown that their orientation are less critical, allowing the detection of their RSSI values with a typical deviation that is around 5.5% when using RPi 3B boards, and around 7% when using RPi 3B+ boards.

Acknowledgments

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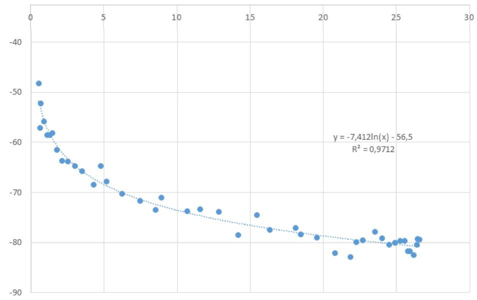
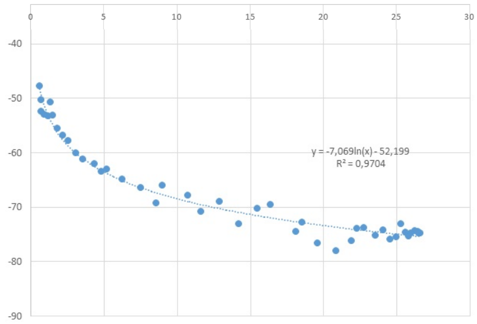


(a) RPi 3B



(b) RPi 3B+

Fig. 5: Obtained RSSI values with respect to real distance for RPi 3B and RPi 3B+ boards, for beacons transmitting at +4dB.

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