Evaluating the Impact of Anchors Deployment for an AoA-based Indoor Localization System

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***Abstract*—Indoor localization techniques are rapidly moving toward the combination of multiple source of information. Among these, RSS, Time of Flight (ToF), Angle of Arrival (AoA) and of Departure (AoD) represent effective solutions for indoor environments. In this work, we propose an on-going activity investigating the performance of an indoor localization system based on the AoA-Bluetooth 5.1 specification, namely Direction Finding. We evaluate the effect of two anchor deployments and we test our localization algorithm by varying the orientation of the target according to four postures: North, West, South and East. From our study, we observe that anchor nodes deployed on the ceiling provide the best performance in terms of localization error. We conclude this work with a discussion of two further lines of investigation potentially increasing the performance of AoA-based indoor localization systems.**

***Index Terms*—Bluetooth 5.1, Angle of Arrival, Indoor Localization, Proximity**

I. Introduction

Indoor localization techniques have increased their diffusion and accuracy in the last decade, as many IoT scenarios require the existence of a location-based service estimating the location both indoor and outdoor. We observed an interesting technological trend [1] moving toward the adoption of RF-based technologies, combined with the adoption of different techniques, such as RSS (Received Signal Strength), AoA or AoD (Angle of Arrival and Departure), ToF (Time of Flight) and PDoA (Phase Difference of Arrival). We are interested in further exploring the potentialities of Bluetooth-based AoA estimation, available with devices adhering to the Bluetooth 5.1 Direction Finding specification [2]. Such specification enables a device, e.g. an anchor deployed indoor, to estimate the AoA of messages received by a target, e.g. a moving tag. Similarly, the BT 5.1 specification also enables a target to estimate the AoD by analyzing the phase difference of messages sent by anchors. Given the estimate AoA, anchors can determine the location of a target by implementing different algorithms according to the topology of the wireless network. In particular, the triangulation method is commonly adopted when K anchor nodes are present. In this case, the location of the target corresponds to the intersection point of K circumferences of radius $r_k, k \in K$ [3].

A crucial aspect of the effectiveness of AoA-based solutions is where deploying the anchors in the monitored environment. Indeed, the location of anchors affects the accuracy of the AoA estimations which, in turn, reflects with the resulting localization error. In this work, we study the performance of an indoor localization system based on AoA by varying the location of anchors indoor. More specifically, we detail the results of a rigorous indoor data collection campaign in which we consider 2 possible locations: wall-mounted and ceiling-mounted. These layouts represent common deployments for the considered hardware, but with different performance issues. Furthermore, we study for each of the 2 layouts, the impact of the body orientation to the localization system. To this purpose, we test our system with a person resting in 28 locations, but assuming 4 different postures: North, West, South and East. From our analysis, we observe that such postures have a great impact on the AoA estimation reflecting with different ranges of the localization error. This study allows us to determine the coverage of a single anchor node indoor, and to better understand which postures mostly affect the AoA estimation. From our results, we observe that the anchor ceiling-mounted provides the best performance in terms of the localization error for all 4 orientations. More specifically, the mean localization error is 1.87 meters (with $50th$ and $75th$ percentile of 1.67 and 2.92 respectively).

At the current stage, many BT5.1 studies available in the current literature are based on simulative settings and only few of them detail real-world experiments based on AoA estimation. Authors of [4] describe a scenario with 2 fixed anchors based on Software Defined Radios (SDR), reproducing the Constant Tone Extension (CTE) packets required for BT5.1 Direction Finding. The proposed solution calculates the position of a tag by taking into account both the AoA of the received packets and the spatial position of the receiving antennas. Authors found that as the frequency of the used channels increases, the AoA average absolute error decreases. In the indoor settings, the absolute AoA error is contained within 5° considering the 15° to 90° range, while the positioning errors are below 85cm for more than 95% of the tested positions. Authors of [5] present a mixed solution, based on the SLWSTK6006A hardware kit which provides both AoA and the RSSI values. The experiment is carried out in a real scenario of 25x15m laboratory with four receiving anchors. The obtained results show an average error of 70cm, computed on 8 distinct locations.

The rest of this work is structured as follows, Section II describes how the AoA techniques and some background and the adopted BT5.1 hardware, Section III reports our experimental settings. In particular, we describe the testing environment, the indoor location algorithms and the experimental results. Section IV frames the direction of our ongoing work and further lines of investigation.

II. Determining the Angle Of Arrival

In order to estimate the AoA of messages sent by a mobile tag, anchor nodes must be equipped with an antenna array and RF radiogoniometry techniques [5]. In particular, AoA can be obtained by measuring the phase difference γ between signals received at each pair of neighboring antennas, as the wavelength of the signal λ and the geometry of the antenna, such as the distance d, are known. Generally, it is possible to consider two planes for estimating the AoA between an anchor and a tag, namely the azimuth ϕ and elevation δ planes. Given a Cartesian plane, the azimuth refers to the angle on the XY plane (azimuth plane), while elevation angle is computed on a plane orthogonal to the azimuth plane and passing through Z axis. More specifically, given ϕ the estimated AoA on the azimuth plane, it can be obtained as follows: $\phi = \arccos(\frac{\lambda\gamma}{2\pi d})$, as reported in Fig. 1. The figure shows 2 antennas at distance d, and the wave front propagating from the right-side with angle θ with respect to the antenna's reference plane. The BT5.1 specification

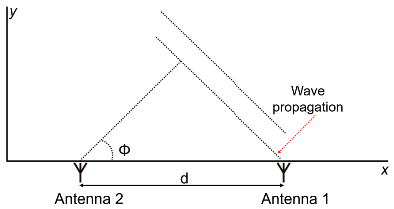

Fig. 1: AoA computation based on the geometry of the antenna array.

allows determining the AoA by extending the PDU format of Bluetooth messages with the CTE. The CTE consists of a sequence of unwhitened 1-valued bits with variable length between $[16-160]\mu s$, so that to guarantee a constant frequency for this part of of the Bluetooth signal. In turn, the receiver node equipped with an antenna array can collect In-Phase and Quadrature (IQ) samples of the signal for every array's antenna. Finally, given the IQ samples the anchor estimates the information about the received signal, such as wavelength and frequency, from which computing the AoA on the azimuth and elevation.

In this work, we adopt the XPLR-AOA kit produced by ublox adhering to the BT5.1 specification. The kit is composed by a set of anchor nodes and a set of tags. Anchor nodes are 11.5x11.5 cm boards equipped with an array of 5 square-shape C211 antennas and NINA-B411[1] BLE module. Anchors have an USB I/0 and can be plugged to a Raspberry PI board. Tags are based on the NINA-B406[2] BLE module. They can be powered via a USB port and they simply advertise BLE beacons with an interval in the range: $1, 10, 50$ Hz, and a power of emission in the range: $-40dBm$ to $8dBm$, as shown in Fig. 2.

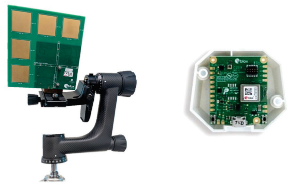

Fig. 2: The XPLR-AOA kit with anchor node and tag.

III. Experimental Settings and Results

A. The Testing Environment

Our scenario is characterized by a rectangular wide-empty room located at ISTI-CNR in Pisa. The room covers $110m^2$ with the ceiling at $3.06m$ from the ground. The room is characterized by a regular floor composed of 60x60 tiles. We consider two layouts for the deployment of anchors:

- layout 1: anchor deployed on the ceiling at $Z_A = 311cm$ parallel with respect to the floor and centered in the middle of the room;
- layout 2: anchor deployed on the wall at $Z_A = 266cm$ from the ground and with $\alpha = 32°$ inclination with respect to the floor, in a way that it points to the room center.

Concerning the location of the tag, we consider 28 distinct locations in the room for evaluating the localization system described in Section III-B. More specifically, the testing location reproduces a regular grid spaced of $180cm$, in which an actor assumes 4 possible postures: North, West, South and East. For each location and for each orientation, the actor rests for 2 minutes with the tag held around the neck. The Bluetooth tag advertises beacon messages at $50Hz$, resulting with 6000 samples for each posture, and a total of 672.000 expected samples. Fig. 3 depicts the 2 anchor layouts and the sampling locations.

B. The Indoor Positioning System

Our localization system is based on the analysis of the estimated AoA to determine the location of the tag at different locations and postures. Our localization algorithm differs according to the two experimental layouts previously described.

Layout 1: Concerning layout 1 the anchor is positioned on the ceiling parallel with respect to the floor, as shown in Fig. 4. In the figure, we show the position of anchor A and the position of tag T with respect to the azimuth plane (ϕ), and elevation (δ). Concerning the azimuth plane, the angle ϕ is used to determine $x = (Z_A - Z_T) \cdot \tan(\phi)$ given the

[1]https://www.u-blox.com/en/docs/UBX-20035327

[2]https://www.u-blox.com/en/docs/UBX-19049405

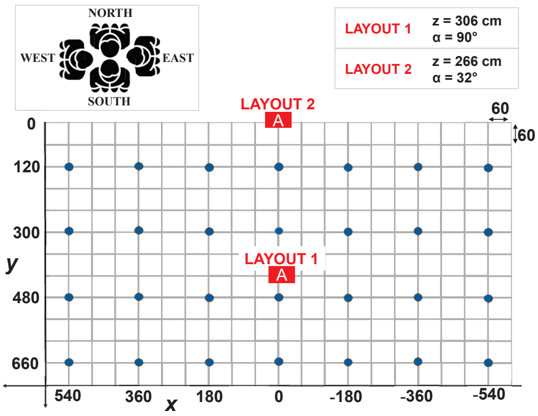

Fig. 3: Experimental layouts of anchors and locations.

tag's height $Z_T = 1.11m$ and the anchor's height $Z_A = 3.06m$. While the elevation angle δ , is used to determine $y = \sqrt{(Z_A - Z_T)^2 + x^2} \cdot \tan(\delta)$.

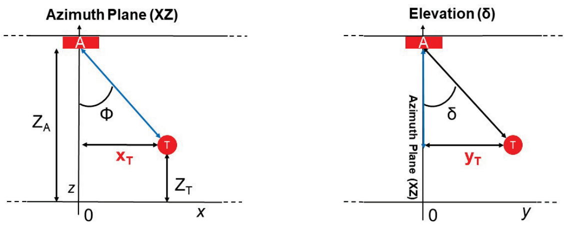

Fig. 4: Computing the coordinates of the tag T in layout 1.

Layout 2: Concerning layout 2, the anchor is positioned on the wall at $Z_A = 266cm$ from the ground and with $\alpha = 32°$ inclination, as shown in Fig. 5. Concerning the azimuth plane, the azimuth angle ϕ is used to determinate $x = y \cdot tan(\phi)$. The y-coordinate can be obtained computing the tangent of the angle $\theta = \beta - \delta$, where δ is elevation angle and β is the angle of a point (x, y) on the anchor plane with α°inclination from the ceiling, as follows[6]:

$$y = \overline{\text{AC}} = \frac{\overline{\text{CT}}}{\tan(\theta)} = \frac{Z_A - Z_T}{\tan(\beta - \delta)} \tag{1}$$

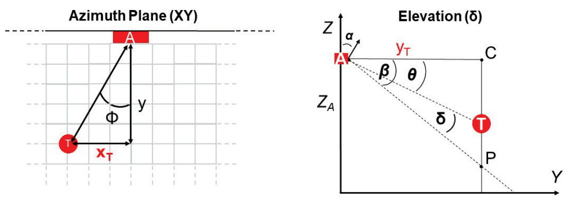

Fig. 5: Computing the coordinates of the tag T in layout 2.

C. Analysis of the Results

In order to evaluate the proposed algorithms with the previously described layouts, we compute the localization error ρ as the absolute error of the difference between the estimated tag's position and the actual tag's position $\hat{\rho}$.

Figure 6 reports the localization error ρ for layouts 1 and 2 and with 4 postures. The gradient color ranges from 0 to 10 meters. We observe that body's orientations influence the accuracy of the estimated position for both layouts. Concerning layout 1, ρ is generally lower than layout 2. In particular, we observe errors lower than 1 meter for those locations close to the anchor's location (see Fig. 3) and without the human body's obstacle, i.e. tag in line-of-sight with the anchor. This aspect can be observed from the contours map in Fig. 6. In particular, the central part of the map results with the darkest gradient, indicating a lower estimated error with respect to layout 2. In this last case, the darkest gradient is generally bounded only close to the anchor's location (see Fig. 3).

Furthermore, as a general trend and similarly for all the postures, ρ increases with the distance from the anchor, reaching its maximum value (approximately $\rho \simeq 3.5m$) on the room's corners. Concerning layout 2, we measure ρ values generally higher with respect to those measured with layout 1. The North orientation provides the best performance, as the anchor node and the tag lie in the same line-of-sight. Conversely, the South orientation provides the worst results caused by human body attenuation, while the East and West orientations provide intermediate results.

IV. Conclusions and Future Directions

Indoor localization techniques are increasing their accuracy with the improvement of sensing technologies also available with commercial devices. Under this respect, the Bluetooth 5.1 specification introduces AoA estimation with hardware units equipped with an antenna array and a micro-controller able to analyze Bluetooth raw signals. In this work, we study the performance of an indoor localization system based on AoA in two layouts, in which we vary the location of the anchor and the orientation of the emitting Bluetooth tag: North, West, South and Est.

The results presented in this work can be used to drive the deployment in a more complex indoor localization system based on the AoA technique. In particular, by showing the performance of a single antenna in a wide indoor room, we are able to identify those regions in which the localization error decreases deriving three considerations: i) in both of the layouts the localization error increases as the tag moves towards peripheral areas of the room (far from the anchor), e.g. left-down corner ii) it is possible to identify a bounding box surrounding the anchor in which the estimated position provides consistent results and iii) deploying the anchor according to layout 1 (ceiling-mounted, see Fig. 4) results with a general reduction of localization errors and, at the same time, with a more simple algorithm to compute the location of the target.

The present work represents a first step toward the exploitation of AoA technique based on the BT5.1 specifi-

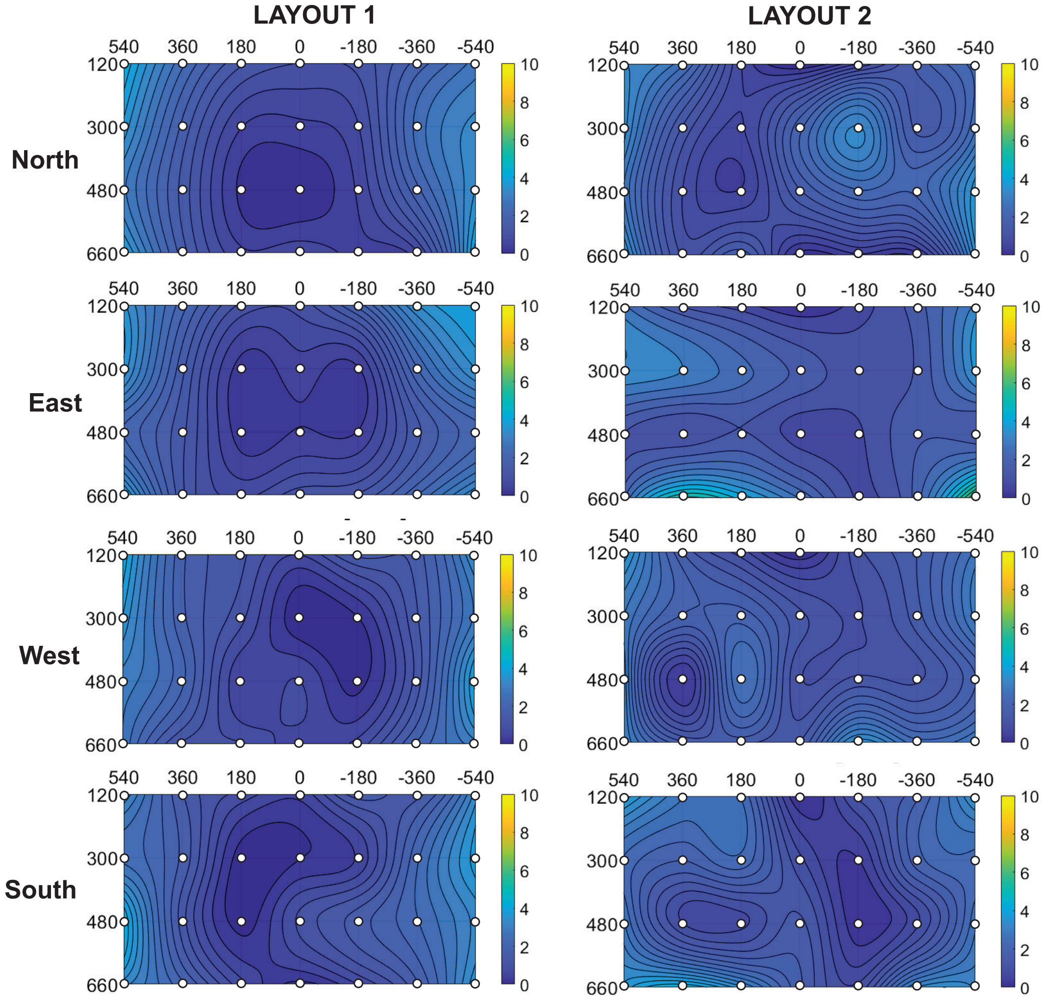

Fig. 6: Localization error ρ expressed in meters for each layout and for different orientations.

cation. On the mid-term, we consider two further lines of investigation. On the one hand, we plan to deploy multiple anchor nodes in the same room, so that to design and evaluate a distributed system merging AoA estimations from multiple sources. More specifically, from this study, we derive that it might be convenient to partition the indoor environment in different regions, in which one anchor node is optimally deployed. The expected results would be reducing the peripheral regions that produce the highest localization errors. On the other hand, our research also moves toward the combination of two localization techniques RSS and AoA estimation. Indeed, RSS has been largely adopted for indoor localization purposes, but not combined with AoA. Our idea is to use the RSS to determine the closest anchor node with respect to a target, and then analyze the respective AoA to estimate the target's location. This approach is suitable for a distributed implementation of the localization system proposed in this work, as RSS might *suggest* which anchor node to consider first for retrieving the AoA values.

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