Experimental Demonstration of BLE Transmitter Positioning Based on AOA Estimation

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***Abstract*—The introduction of the Bluetooth Low Energy (BLE) standard significantly streamlines the development of the Internet of Things (IoT) applications. These applications often require the sensor positioning to link the measurements with its location. Therefore, it is essential to conduct studies on BLE transmitter positioning methods. Power fingerprinting transmitter positioning approaches are commonly used in BLE network. However, these methods have their own limitations in terms of practical use and ease of implementation. The purpose is to develop a simple BLE transmitter positioning of high accuracy. In this paper, a BLE transmitter positioning method is proposed based on Angle of Arrival (AOA) estimation. Multiple Signal Classification (MUSIC) algorithm is used for angle estimation due to the high angular resolution and sensitivity. Several experiments have been conducted in an indoor environment and the results compared with simulation results. Experimental results show that our proposed BLE transmitter positioning method achieves a promising positioning accuracy.**

I. Introduction

Internet of Things (IoT) plays an important role in the deployment of the fifth generation (5G) of mobile communication services [1]. Besides communication technology, IoT devices could greatly benefit from localization [2]. Traditional outdoor positioning method like Global Positioning System (GPS) cannot be used effectively in an indoor environment. Different wireless technologies have been used to improve the efficiency of indoor localization methods. BLE is the most widely used wireless technology thanks to its low power consumption, low cost, high availability and high accuracy [3]. In [4], the accuracy of the BLE transmitter positioning is compared with that of WiFi transmitter positioning by Received Signal Strength Indicator (RSSI) measurements. The results show that the BLE transmitter positioning can outperform WiFi transmitter positioning in a point-to-point trial with a 27% improvement. Accordingly, there has been considerable interest in the development of the BLE transmitter positioning techniques. To the best of authors knowledge, RSSI fingerprint methods have been used commonly in literature and commercial systems for BLE transmitter positioning and their accuracies are ranged between 20 centimeters and about 3 meters depending on the experimental setup. The accuracy of RSSI can be seriously affected by power control and multi-path interference [5]. In [6], the impact of multi-path is evaluated on power fingerprint transmitter positioning from BLE beacons and is shown that channel scattering reduces the positioning accuracy.

Moreover, papers [7] and [8] presented a BLE transmitter positioning method based on the RSSI approach. In the former paper, nineteen BLE beacons are distributed around a 600 m^2 testbed to find the position of a device. They achieved less 2.6 meters error for a dense BLE network (1 beacon per 30 m^2). In the latter paper, the localization was done in a testbed with 12 subareas around 40 m^2 each and the localization error is between 3-5 meters. Paper [9] proposed an indoor navigation system based on BLE beacons fingerprinting and three machine learning techniques were used to improve power fingerprinting accuracy within the testbed of 30 beacons. The proposed algorithm can estimate the location of multiple users with room-level accuracy 91% of the time. The BLE transmitter positioning technique in [10] is an improved Least Square Estimation (LSE) by processing RSSI for distance estimation. The testbed environment is a grid area of 5×5 meters with four beacons at fixed positions. The experimental results show that the proposed approach has an accuracy of positioning within 20 to 35 cm.

The aim is to experimentally demonstrate and assess an enhanced BLE transmitter positioning technique in an indoor environment. AOA estimation is a prominent method for improving the estimated position accuracy. AOA determines the direction of an incoming signal from a target to a base station. It doesn't need the clock synchronization between the target and the base stations and just requires two stations for 2D positioning. The most widely investigated method in AOA estimation is MUSIC thanks to the high angular resolution and good estimation at low signal to noise ratio (SNR) levels [11]–[13]. The position of the beacon can be estimated using known positions of the anchors and measured AOAs at each anchor by conducting some geometric calculations.

The rest of the paper is organized as follows. Section II gives a short overview on BLE. Section III describes the AOA estimation techniques. In section IV, the experimental setup and results are shown for BLE transmitter positioning using MUSIC. Section V presents the conclusion.

II. BLE System Characteristic

Bluetooth Low Energy (BLE), also called Bluetooth Smart, was introduced in the 4.0 specification of the IEEE 802.15.1 standard by the Bluetooth Special Interest Group. It is classified as a Wireless Personal Area Network (WPAN) with low power consumption, low latency, low cost, and support for high connection numbers of devices [3].

At physical layer, BLE operates in the 2.4 GHz Industrial Scientific Medical (ISM) band and uses 40 Radio Frequency (RF) channels with 2 MHz channel spacing. The BLE RF channels are categorized into two types of advertising channels (beacons) and data channels. The three channels are advertising channels that responsible for device discovery, connection setup, and broadcasting advertisements. Each advertising packet is repeated on all three advertising channels. These are labeled 37, 38 and 39 at the corresponding center frequencies 2.402 GHz, 2.426 GHz and 2.48 GHz [14], while the remaining 37 channels are used for data exchanges. Frequency Hopping Spread Spectrum (FHSS) technique is implemented in data channels to mitigate interference with Wireless Local Area Network (WLAN), which operates also in the same band. The simple formula, $f_{n+1} = (f_n + hop)\ mod\ 37$ provides the working way for frequency hopping. f_{n+1} is the next channel that will be used, f_n is the current channel and hop is a random number between 5 and 16 [14].

BLE link layer has only one packet format used for both advertising and data channel packets. The channel Packet Data Unit (PDU) contains a 2 bytes header and a payload size up to 255 bytes and advertising PDU has a 2 bytes header and a maximum payload size of 37 bytes. The hardware enters a deep sleep mode between advertisements to spare energy. An advertising interval is a time between two packet transfer events and theoretically can be configured between 20 ms to 10.24 s [3].

The BLE modulation is the Gaussian Frequency Shift Keying (GFSK) with a data rate of 1 Mbps and fixed bandwidth-bit period product of 0.5. The modulation index is ranged between 0.45 to 0.55, which allows reduced peak power consumption. The transmission power of a BLE transmitter can be varied between 0.01 mW (-20 dBm) and 10 mW (+10 dBm), which is 10 to 20 times less energy than classic Bluetooth technology to locate nodes. The coverage range is typically over tens of meters [3].

III. AOA Estimation Techniques

The information about AOA can be measured in two different ways. The first way is Switched Beam System (SBS) which uses a fixed number of beams to scan the azimuth plane and find the highest received power or signal strength. The second way is Adaptive Array System (AAS) that can steer the beam in any required direction by setting the weights across the M antenna array elements. The AOA techniques that use AAS can operate at lower SNRs than the SBS techniques but have higher hardware and computational complexities [12]. Among these techniques, MUSIC algorithm is widely used because of the high angular resolution and sensitivity [13].

MUSIC algorithm is based on separation of the observation space into the source and noise subspaces. In order to estimate these subspaces, the input covariance matrix is decomposed in eigenvectors that form a basis of both signal and noise subspaces. The waveforms received at the M array elements are linear combinations of the signals from S sources and additive white Gaussian noise (AWGN). These antennas are separated by a fixed separation distance d. The $M \times 1$ received vector $\boldsymbol{x}$ is defined as:

$$\boldsymbol{x} = \boldsymbol{A}(\boldsymbol{\theta})\boldsymbol{s} + \boldsymbol{n}, \tag{1}$$

where $\boldsymbol{s}$ is the $S \times 1$ signal vector, and $\boldsymbol{n}$ is the $M \times 1$ noise vector. The ith columns of the $M \times S$ matrix $\boldsymbol{A}(\boldsymbol{\theta})$ is known as steering vectors and defined as:

$$\boldsymbol{a}(\theta_i) = [1, e^{\beta d cos(\theta_i)}, ..., e^{\beta(M-1)d cos(\theta_i)}]^T, \tag{2}$$

where θ_i is the azimuth angle of source $\boldsymbol{s}$ and varies between $-90°$ and $+90°$. Moreover, $\beta = 2\pi/\lambda$ is the wave number and λ is the wavelength. The auto-covariance function of the received signal is denoted by $\boldsymbol{R_{xx}}$ matrix of size $M \times M$. After an eigenvalue decomposition, it can be written as [13]

$$\boldsymbol{R_{xx}} = \boldsymbol{U_s}\boldsymbol{\Lambda_s}\boldsymbol{U_s} + \boldsymbol{U_n}\boldsymbol{\Lambda_n}\boldsymbol{U_n}, \tag{3}$$

where $\boldsymbol{U_s}$ and $\boldsymbol{U_n}$ are the signal and noise subspaces unitary matrices and $\boldsymbol{\Lambda_s}$ and $\boldsymbol{\Lambda_n}$ are diagonal matrices of the eigenvalues of the signal and noise. The spatial power spectrum is represented by:

$$\boldsymbol{P}_{MUSIC}(\boldsymbol{\theta}) = \frac{1}{\boldsymbol{A}^H(\boldsymbol{\theta})\boldsymbol{U_n}\boldsymbol{U_n}^H\boldsymbol{A}(\boldsymbol{\theta})}, \tag{4}$$

where $(.)^H$ denotes the Hermitian matrix operation. The spectrum peaks indicate the angles of arrival. The accuracy of the algorithm depends on the number of array elements (M), number of incoming signals (S), array element spacing (d) and number of data samples ($Snapshot$) used to estimate the covariance matrix [13].

IV. Indoor BLE transmitter positioning

Several experiments are set up to evaluate the performance of BLE transmitter positioning where an advertising channel is used. As a suitable positioning method, MUSIC algorithm is used to estimate the AOA of BLE beacon and deduce the device position.

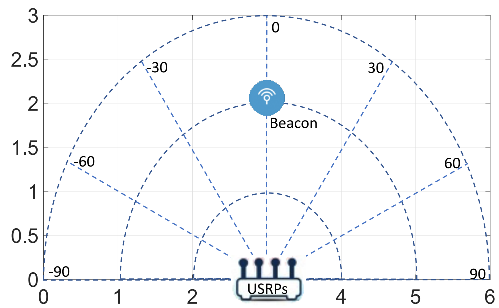

Fig. 1. Testbed setup.

A. Experimental Setup

All experiments are conducted in the testbed located in the OPERA-Wireless Communications lab at Université libre de Bruxelles. Fig. 1 shows the testbed environment for the experiments which is a room of about 6×3 meters. It is assumed that the beacon is static and radio frequency interferences are negligible. The positioning process detects the position of the beacon using the known positions of the anchors and estimated AOA at each anchor. Before performing a measurement, a phase calibration has to be applied since USRPs introduce a hardware phase difference during the acquisition of signals. The phase calibration defines the reference direction. Moreover, to compute the Root Mean Square Error (RMSE) of the predefined angles for a chosen SNR, predefined angle firstly has to be calibrated at high SNR near the initial assumed point.

During the experiments, two models of Universal Software Radio Peripheral (USRP) devices are used: USRP X310 and USRP B205mini-i (manufactured by Ettus). Two anchors are placed at the fixed positions. For each anchor, we use two USRPs X310 with two antennas each, sharing a clock. The antenna array has a size $M = 4$. The four antennas are vertical dipoles formed in a uniform linear configuration with array spacing of $d = 6$ cm. All USRPs are connected to a host computer via the Gigabit Ethernet cables. The host computer commands the USRPs by GNU Radio Companion [15]. USRP B205mini-i with a vertical dipole antenna is used to build a beacon. The BLE beacon will send out advertising packets on a regular basis. A baseband BLE signal is generated as defined in IEEE 802.15.1 standard. The data rate of transmission is 1 Mb/s. In the GFSK modulation part, a Gaussian filter with $BT = 0.5$ is applied and the modulation index is set to 0.45, so the maximum frequency will be $f_d = 225$ kHz. At the receiver, the sampling frequency is assumed to be equal to twice of the maximum frequency and is therefore 450 kHz. Minimum and maximum advertising PDU sizes of 2 bytes and 39 bytes are transmitted with advertising interval of 1 s.

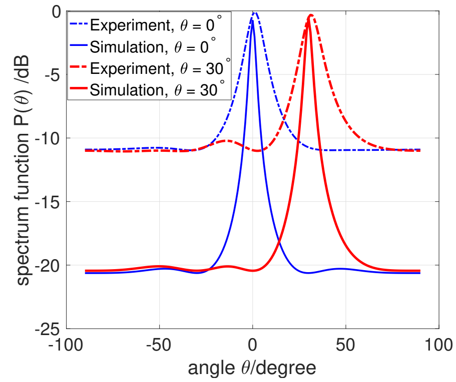

Fig. 2. Spatial power spectra versus AOA at $SNR = 0$ dB with minimum advertising PDU size of 2 bytes.

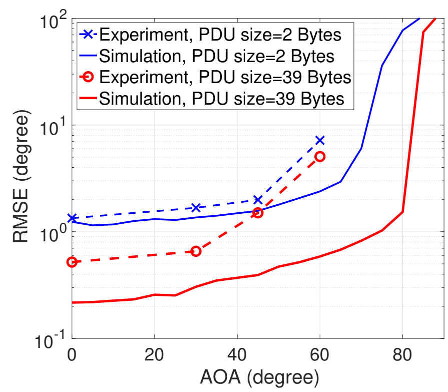

Fig. 3. RMSE of the estimated AOA versus predefined AOA at $SNR = 0$ dB.

B. Results

In order to evaluate the proposed positioning approach, the experiments are compared with simulations in MATLAB over 100 simulation runs.

Fig. 2 presents a comparison between the spatial power spectra observed at the output of the MUSIC algorithm for two different direction of arrivals $\theta_1 = 0°$ and $\theta_2 = 30°$ at $SNR = 0$ dB. In MUSIC spectra obtained from experiments, the effect of multi-path and hardware imperfections (i.e., quantization, antenna mismatch, inter-array distance, etc.) can be seen clearly since the peaks are less sharp and accurate than simulations.

In Fig. 3, the Root Mean Square Error (RMSE) of proposed positioning algorithm is illustrated as a function of the AOA $0° \leq \theta \leq 90°$ for $SNR = 0$ dB. In experiments, we conducted the tests for predefined angles of $\theta = 0°, 30°, 45°, 60°$. RMSE is below $2°$ for AOA $\theta \leq 45°$. Fig. 4 shows the RMSE of the estimated AOA as a function of SNR at AOA $\theta = 0°$. The proposed estimator presents an improved performance when SNR increases and can achieve an RMSE below $1°$ for SNRs higher than 5 dB. From last two figures, it can be noticed that the RMSE is significantly improved by increasing

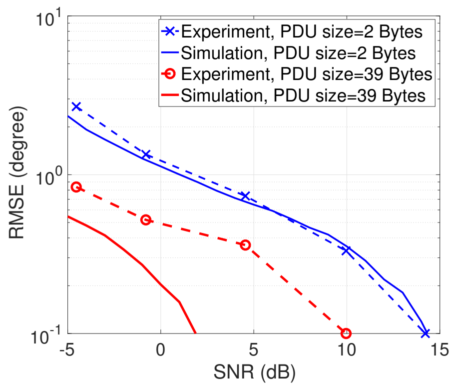

Fig. 4. RMSE of the estimated AOA versus predefined SNR at AOA $\theta = 0°$.

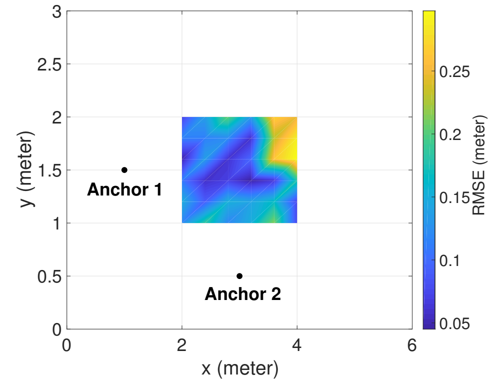

Fig. 5. RMSE of the estimated beacon position with minimum PDU size of 2 bytes.

the advertising packet size as the accuracy of MUSIC algorithm depends on the number of data samples. In addition, the accuracy of experimental results is less than that of simulation results because of multi-path effects and hardware imperfections.

In addition, an experimental scenario is defined to show the accuracy of proposed BLE transmitter positioning when there are two fixed anchors and one beacon in the room. The location coordinates of the anchors are as followed: $Anchor_1$ $(1, 1.5)$, $Anchor_2$ $(3, 0.5)$ in meters. A grid with 36 points (6×6) is defined in the middle of the room. AOAs are measured at each anchor for 36 different beacon positions when the minimum PDU size is transmitted. In GNU Radio, TX and RX Gains of USRPs are fixed to 30 dB and 20 dB, respectively. Each time, the position of the beacon can be estimated using known positions of the anchors and measured AOAs at each anchor. The intersection of two line of bearings (LOBs) from the beacon to the anchors will give the estimated beacon location. Fig. 5 displays a heat map of the RMSE of the estimated position. The average positioning error is around 14 cm and the maximum error is 30 cm. As can be seen, the RMSE of the estimated position for each point depends on the angle and the distance to each anchor. Therefore, it explains the higher RMSE on the farther edge of the grid.

V. Conclusion

This paper investigates experimentally the positioning of BLE beacons in an indoor environment. The AOA is estimated at two anchors located in a room, equipped with 4 antennas. It is shown that this approach is able to successfully determine the position of a beacon with the average accuracy of 14 cm in the defined scenario.

References

[1] J. M. C. Brito, "Trends in wireless communications towards 5G networks – The influence of e-health and IoT applications," in *International Multidisciplinary Conference on Computer and Energy Science (SpliTech)*, 2016, pp. 1–7.

[2] H. Liu, H. Darabi, P. Banerjee, and J. Liu, "Survey of wireless indoor positioning techniques and systems," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 37, no. 6, pp. 1067–1080, 2007.

[3] SIG Bluetooth, "Specification of the bluetooth system-covered core package version: 4.0," 2010.

[4] X. Zhao, Z. Xiao, A. Markham, N. Trigoni, and Y. Ren, "Does BTLE measure up against WiFi? A comparison of indoor location performance," in *European Wireless 2014; 20th European Wireless Conference*, 2014, pp. 1–6.

[5] A. M. Khalel, "Position location techniques in wireless communication systems," Master's thesis, Blekinge Institute of Technology, School of Engineering, 2010.

[6] J. Powar, C. Gao, and R. Harle, "Assessing the impact of multi-channel BLE beacons on fingerprint-based positioning," in *International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, 2017, pp. 1–8.

[7] R. Faragher and R. Harle, "Location fingerprinting with Bluetooth Low Energy beacons," *IEEE journal on Selected Areas in Communications*, vol. 33, no. 11, pp. 2418–2428, 2015.

[8] X.-Y. Lin, T.-W. Ho, C.-C. Fang, Z.-S. Yen, B.-J. Yang, and F. Lai, "A mobile indoor positioning system based on ibeacon technology," in *37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2015, pp. 4970–4973.

[9] F. Campana, A. Pinargote, F. Domínguez, and E. Peláez, "Towards an indoor navigation system using Bluetooth Low Energy beacons," in *IEEE Second Ecuador Technical Chapters Meeting (ETCM)*, 2017, pp. 1–6.

[10] Q. H. Nguyen, P. Johnson, T. T. Nguyen, and M. Randles, "Optimized indoor positioning for static mode smart devices using BLE," in *IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, 2017, pp. 1–6.

[11] R. O. Schmidt, "A signal subspace approach to multiple emitter location spectral estimation," Ph.D. dissertation, Stanford University, 1981.

[12] A. Badawy, T. Khattab, D. Trinchero, T. E. Fouly, and A. Mohamed, "A simple AoA estimation scheme," *CoRR*, vol. abs/1409.5744, 2014.

[13] H. Tang, "DOA estimation based on MUSIC algorithm," Linnaeus University, Department of Physics and Electrical Engineering, 2014.

[14] R. Faragher and R. Harle, "An analysis of the accuracy of Bluetooth Low Energy for indoor positioning applications," in *Proceedings of the 27th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+'14)*, 2014, pp. 201–210.

[15] GNU Radio, "The gnu software radio," *Available from World Wide Web: https://gnuradio.org*, 2007.