AoA Estimates for LPWAN Technologies: *Indoor Experimental Analysis*

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***Abstract*—In this paper, we present an experimental analysis of the Angle of Arrival (AoA) estimation accuracy in an indoor environment. We utilized an AoA estimation system that is suitable for Low Power Wide Area Network (LPWAN) technologies. The AoA estimation system constituted 8 antenna elements that are distributed as Uniform Linear Array (ULA) antenna. Both Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) conditions were considered. The conventional beamformer, MUISC, Root MUSIC, ESPRIT and SAGE algorithms were employed to provide the AoA estimates. The experimental results reveal that the AoA estimation algorithms provide a very poor AoA estimation accuracy for signals that were originated within the endfire region of the ULA. Furthermore, the signals that were originated within the ULA broadside region have a maximum estimation error equals 10 and 15 degrees for the LoS and NLoS conditions, respectively.**

***Index Terms*—Angel of Arrival, AoA, Direction of Arrival, DoA, IoT, LPWAN, indoor experimental analysis, ULA, Uniform Linear Array, Conventional Beamformer, MUSIC, Root MUSIC, ESPRIT and SAGE.**

I. Introduction

The Angle of Arrival (AoA) estimation technique is a well established technology. It estimates the angle between the transmitter and the receiver by measuring the phase of the received signal at different points in space using array antennas [1]. Over the years, the AoA information were utilized in various applications (e.g. noise and interference cancellation, spatial diversity, localization, etc) for indoor and outdoor environments. Lately, and due to the increased demands for accurate localization systems, AoA estimation technique has been utilized for positioning purposes by many communication technologies. WiFi, Ultra-Wideband (UWB) and Bluetooth are few examples where the AoA estimation technique has been deployed in localization systems [2]–[4].

Recently, due to the rapid increase of Internet of Things (IoT) applications, Low Power Wide Area Network (LPWAN) technologies have gained a great industrial interest. LPWAN technologies have emerged to provide the internet connectivity to vastly distributed sensors and devices [5]. This massive deployment of the LPWAN transceivers can be attributed to the low production cost and the minimal transmission power. Furthermore, an LPWAN transceiver is expected to operate for a long period of time using a small battery. This is possible due to the fact that IoT messages are usually very short (e.g. temperature data, motion information, etc), thus, a narrowband transmission is sufficient for this purpose [6]. Consequently, the AoA estimation technique is a very promising approach that can be utilized to provide a localization solution for LPWAN technologies. This is because the AoA estimation technique can exploit accurately the narrow operating bandwidth of the LPWAN signal to provide a unique phase response, hence, achieving an accurate AoA estimation. Moreover, the AoA estimation approach does not depend directly on the Received Signal Strength (RSS), thus, the effect of the wireless communication channel fading, relative to the RSS-based localization solution, is minimal. Furthermore, unlike the time-based localization systems, the AoA-based localization system does not require a synchronization process among the various gateways.

In this paper, we provide an experimental analysis of the AoA estimation technique in an indoor environment. Both Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) conditions were studied and analyzed. We utilized a DASH7 transceiver as the transmitting device. DASH7 is an open source mid-range communication standard for IoT applications. Its physical layer exploits the Gaussian Frequency Shift Keying GFSK modulation scheme and it operates in the unlicensed sub-1 GHz bands. The physical layer of DASH7 signals is comparable to the physical layer of typical LPWAN signals that are operating in the sub-1 GHz bands.

The remainder of the paper is structured as follows: In Sections II the deployed AoA estimation system is introduced. The experimental environment is presented in section III. In section IV the experimental results and analysis are presented. Finally, in Section V, the conclusions are drawn.

II. AoA estimation system

AoA estimation systems consist of hardware and software components. The hardware component constitutes

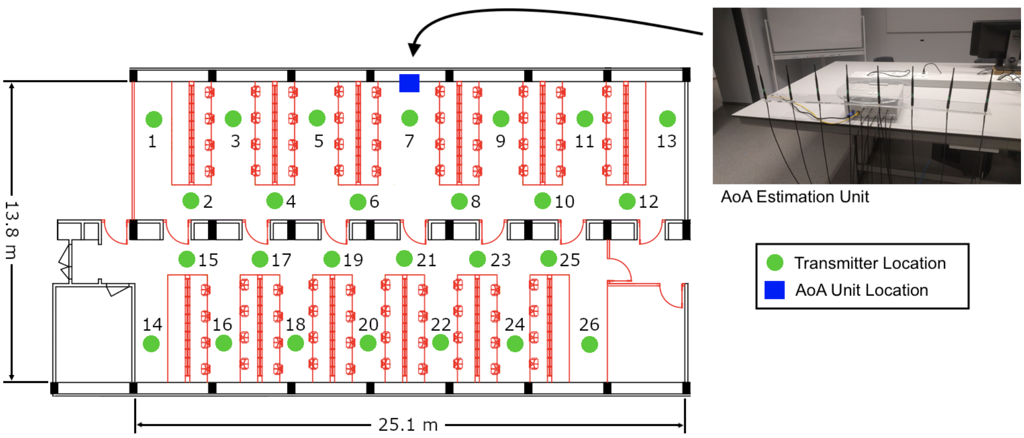

Fig. 1: The experimental setup. It constitutes two parallel computer classrooms of dimensions $25.1\mathbf{m}\times6.9\mathbf{m}$ each. 780 DASH7 signals were transmitted from 26 different locations in both rooms (30 signals per location). The two parallel classrooms were full with computer screens, therefore, this environment can be considered a rich multipath environment. Furthermore, the wall (that is separating the two classrooms) provides a physical barrier between the two rooms.

array antenna frontend. The software component, on the other hand, constitutes AoA estimation algorithm. In the following subsections, we will provide brief descriptions of the deployed AoA estimation system's components.

A. *Array Antenna Frontend*

In the literature, several array antenna systems, that can provide AoA estimations for LPWAN technologies, have been proposed [7]–[11]. These array antennas utilize either hardware or software solutions to reduce the cost and the complexity of the array antenna system. Steckel et al. [8], Avitabile et al. [10] and Bnilam et al. [11] introduced practical hardware implementations for array antenna frontend. These hardware solutions have great merits, nonetheless, they have been tested in highly controlled environments where only direct paths were considered. BniLam et al. [7] and Baik et al. [9] have provided a software solution using Software Defined Radio (SDR), they demonstrate the AoA estimation accuracy in an outdoor environments with minimal multipath effect.

Recently, we introduced the RTL-Array as an AoA estimation unit for IoT applications [12] . The RTL-Array is a low cost hardware solution based on converting multiple individual low cost SDR (called RTL-SDR [13]) into a single SDR with multiple coherent RF-channels (i.e. the RF-channels are synchronized in time and frequency, and coherent in phase). The RTL-Array unit captures the received signals in an In-phase and Quadrature (I/Q) complex data format. The I/Q data can be utilized for estimating the AoA of the received signals. The angular estimation accuracy of the RTL-Array was verified in an anechoic chamber. The estimated AoA accuracy, for a Uniform Linear Array (ULA) consists of 6 antenna elements, was below 1 degree in the 868 MHz frequency band. The RTL-Array has a limited receiving bandwidth, it can only provide a maximum receiving bandwidth of around 2.5 MHz. Nevertheless, for LPWAN technologies, this bandwidth limitation will suffice.

In this paper, we utlized the RTL-Array to estimate the AoA of the received signals in an indoor environment. Both LoS and NLoS locations were studied and analyzed. The RTL-Array was connected to an ULA antenna that consists of 8 half wave length dipole elements with inter-element spacing equal to a half wavelength, as shown in figure 1. The operating frequency and the sampling rate were 863 MHz and 1M sps, respectively.

B. *AoA Estimation Algorithms*

Over the years, several AoA estimation algorithms have been proposed. These algorithms, in general, can be classified into four main kinds of algorithms; algorithms that are based on an beamforming technique, algorithms that rely on signal and noise subspaces' decomposition, algorithms that employs a parametric search using maximum likelihood estimator, and algorithms that apply the sparse representation of the space [1]. In this paper we deployed and tested five AoA estimation algorithms, as follows:

1) The Conventional Beamformer (CBF) algorithm; also known as Bartlett beamformer or delay and sum beamformer. The CBF has a very poor angular resolution which is considered its major short come.
2) The MUltiple SIgnal Classification (MUSIC) [14], Root-MUSIC [15], and Estimation of Signal Parameters via Rotational Invariance Technique (ESPRIT) [16] algorithms. They deploy the signal subspace decomposition operation to estimate the AoA of the received signals. These algorithms have been proposed as super resolution AoA estimation techniques. Nevertheless, their performance deteriorates

in the presence of the multipath effect. To overcome the multipath problem, a spatial smoothing technique [17] can be employed. The spatial smoothing technique decorrelates the received signals spatially, causing a decrease in the array antenna degrees of freedom (i.e. the number of AoA estimates is less than the number of the array antenna elements).

3) The Space Alternating Generalized Expectation-maximization (SAGE) algorithm [18]. The SAGE algorithm deploys the Maximum Likelihood Estimator (MLE) to estimate the received signals parameters. The SAGE algorithm can estimate the AoA of correlated signals efficiently based on few received signals' samples, making it suitable for estimating the AoA of both the direct and the reflected paths of the received signal.

The first 4 algorithms have been implemented and optimized in MATLAB's phased array antenna toolbox [19]. The SAGE algorithm, on the other hand, has been implemented as presented in [18].

III. Experimental Setup

We conducted a measurement campaign to study the AoA estimation accuracy in an indoor environment for LPWAN technologies. The experimental environment constitutes two parallel computer classrooms of dimensions 25.1m×6.9m each. 780 DASH7 signals were transmitted from 26 different locations (30 signals per location), these locations were distributed equally between the two rooms. During the experiment, the RTL-Array has been installed in one room as shown in Fig. 1. The RTL-Array constituted 8 antenna elements that are distributed as ULA antenna. The two parallel classrooms were full with computer screens, therefore, this environment can be considered a rich multipath environment. Furthermore, the wall (that is separating the two classrooms) provides a physical barrier between the two rooms. Therefore, the majority of the location in the second classroom (i.e. location 14 to 26) were within the NLoS region relative to the AoA estimation unit, as shown in Fig. 1.

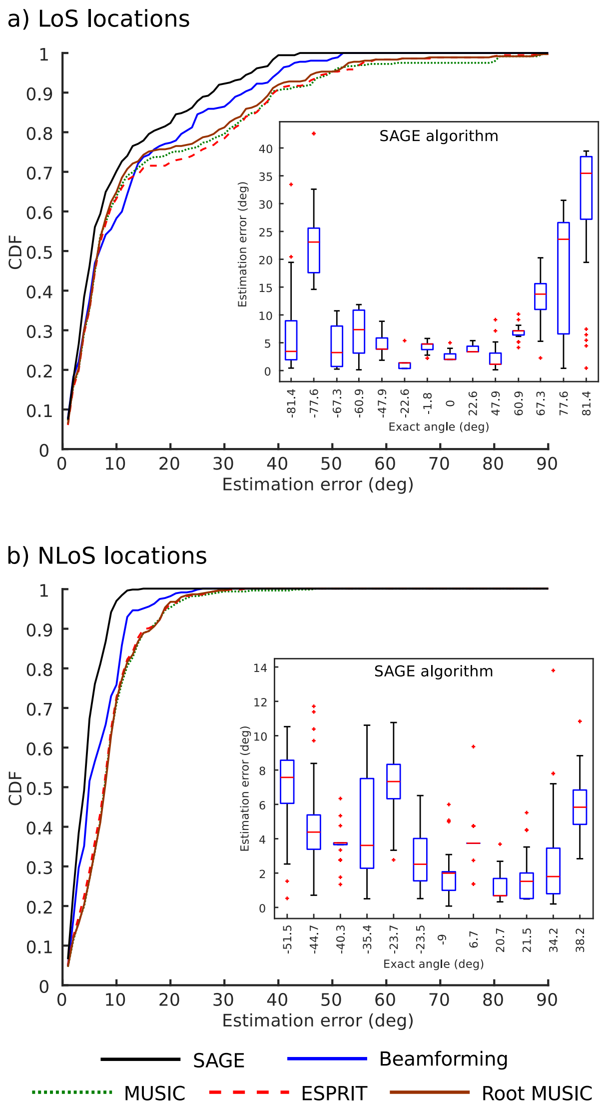

Fig. 2: The CDF and the boxplot (inner figures) graphs for the AoA estimation error of all the received signals from the LoS and the NLoS locations, respectively. The CDF figures show the AoA estimation error as estimated from all the deployed AoA estimation algorithms. The boxplot figures, on the other hand, provide the AoA estimation error from the SAGE algorithm only. Every boxplot represents the estimation error from a specific location (i.e. 26 boxplot graphs in total).

IV. Experimental Analyses

In this section, we divide the results into LoS and NLoS AoA estimations. All the deployed algorithms provide several AoA estimations for the direct and reflected paths. Accordingly the AoA estimates from all the algorithms, that are the closest to the exact transmitter location, were considered in our analysis.

Fig. 2(a) and 2(b) show the Cumulative Distribution Function (CDF) and the boxplot (inner figures) for the AoA estimation error of all the received signals from the LoS and the NLoS locations, respectively. The CDF figures show the AoA estimation error as estimated from all the deployed AoA estimation algorithms. The boxplot figures, on the other hand, provide the AoA estimation error from the SAGE algorithm only. Every boxplot represents the estimation error from a specific location (i.e. 26 boxplot graphs in total). The central horizontal red mark, the bottom and top edges of the boxplot indicate the median, the 25th and 75th percentiles, respectively. The whiskers (the horizontal black mark) extend to the most extreme data points not considered the outliers, and

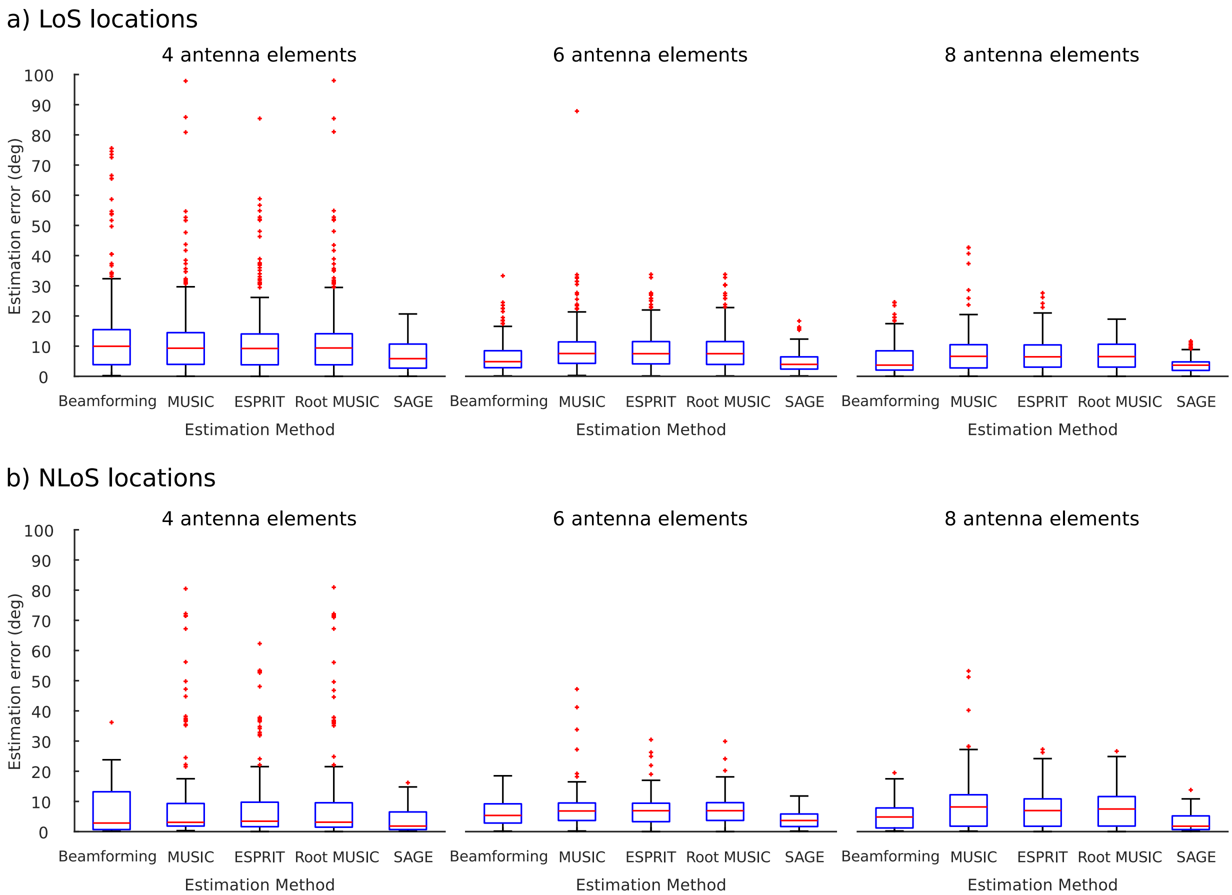

Fig. 3: The boxplot graphs of the AoA estimation error from the various AoA estimation algorithms for different deployed array antenna aperture. Both the LoS and the NLoS locations were considered.

the outliers are plotted individually as red plus signs. The spatial smoothing factor was set to 3 for the MUSIC, Root MUSIC and ESPRIT algorithms. The number of the received signals (from the direct and the reflected paths) for the SAGE algorithm was set to 7. On the other hand, the information theory technique AIC [20] has been deployed to estimate the number of the receive signals for the MUSIC, Root MUSIC and ESPRIT algorithms.

Fig. 2 reveals that the SAGE algorithm performs better than the other algorithms in both LoS and NLoS conditions. Furthermore, the CDF plots shows that the NLoS locations have been estimated with less angular error than the LoS locations. This strange behaviour is attributed to the fact that 8 out of the 14 LoS locations were within the ULA endfire region; as shown in the boxplot figures (also see locations 1 2 3 5 9 11 12 13 in Fig.1). This estimation problem is associated with the ULA antenna structure, therefore, different array antenna structure should be deployed to avoid this estimation problem. Nonetheless, the maximum estimation error for the signals that were originated within the broadside region of the ULA was around 10 and 15 degrees (as shown in the boxplot figures) for the LoS and the NLoS locations, respectively. This estimation error can be attributed to the human error factor while conducting the experiment and the multipath effect on the AoA estimation accuracy.

Fig. 3 shows the boxplot graphs of the AoA estimation error from the various AoA estimation algorithms for different deployed array antenna apertures. Both the LoS and the NLoS locations were considered. For the LoS locations only 6 locations have been considered (the locations that are within the broadside region of the ULA, see Fig. 2). The spatial smoothing factor for MUSIC, Root MUSIC and ESPRIT was set to 1 and the number of signals for the SAGE algorithm was set to 7. The figure shows that (as expected) the increase of the array antenna aperture will increase the AoA estimation accuracy for all the algorithms. Furthermore, the AoA estimations of the SAGE algorithm was almost independent of the array antenna aperture relative to the other algorithms.

V. Conclusion

In this paper, we presented an experimental analysis of the Angle of Arrival (AoA) estimation accuracy in an indoor environment. We utilized an AoA estimation system that is suitable for Low Power Wide Area Network (LPWAN) technologies. The AoA estimation system constituted 8 antenna elements that are distributed as Uniform Linear Array (ULA) antenna. Both Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) conditions were considered. The conventional beamformer, MUSIC, Root MUSIC, ESPRIT and SAGE algorithms were employed to provide the AoA estimates. The experiment was conducted in two parallel classrooms of dimensions $25.1\text{m}\times6.9\text{m}$ each. 780 signals were transmitted from 26 different locations, these locations were distributed equally between the two rooms. The experimental results reveal the following:

1) The ULA antenna provides a very poor angular response for signals that are originated within the endfire region, hence, the AoA estimation algorithms provided a very poor AoA estimation accuracy for these signals.
2) The signals that were originated within the ULA broadside region had a maximum estimation error equals 10 and 15 degrees for the LoS and NLoS conditions, respectively.
3) The SAGE algorithm provided the best AoA estimation accuracy (with respect to the other deployed algorithms) in all the studied cases. Furthermore, the AoA estimations of the SAGE algorithm was almost independent of the array antenna aperture.

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