2.4 GHz Synthetic Linear Antenna Array for Indoor Propagation Measurements in Static Environments

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Abstract—The adoption of beamforming techniques in contemporary communication systems has increased steadily over the past years. Apart from improving link quality, the technology provides opportunities for indoor angle of arrival localization. However, measurement setups for research purposes are mostly complex and provide low flexibility. This paper presents a 2.4 GHz band synthetic linear antenna array for static environments. It consists of a single moving antenna that is sampled at multiple positions, requiring only one receiver channel. Multiple design aspects are discussed, including coax phase stability with flexure and antenna selection. Practical tests are performed for a configuration with a dipole antenna, a shielded dipole antenna and a directional patch antenna. For these configurations, the shapes of the MVDR spatial spectra are evaluated, as well as the angle of arrival estimation accuracy over the complete field of view.

Index Terms—Synthetic antenna array, Indoor localization, Beamforming, Angle of arrival

I. INTRODUCTION

Over the past years, ubiquitous indoor and outdoor wireless communication systems have gained beamforming capabilities. Cellular systems (e.g., WCDMA, LTE, 4G, etc.) and wireless local area networks (e.g., 802.11n, 802.11ac) are now equipped with multi-antenna devices, exploiting the spatial properties of the channel [1]. The use of multipath signal components results in an increased coverage, capacity and link quality of the communication system. Furthermore, spatial information can also be used for localization purposes. Single-antenna communication devices that require positioning usually rely on the Received Signal Strength (RSS), which is related to the distance between two devices [2]. However, with antenna arrays becoming omnipresent in communication systems, Angle of Arrival (AoA) techniques can be used to estimate signal directions [3]. These positioning systems generally consist of a mobile omnidirectional transmitter that is to be localized and multiple fixed antenna arrays (reference nodes), estimating the line-of-sight (LOS) directions to the mobile node. With the help of a triangulation, ray tracing or fingerprinting algorithm, the location of the mobile node can be determined [4]–[6]. Practical applications can be found in guidance and tracking systems, as well as location-based services [7].

The accuracy of indoor radio frequent (RF) localization systems generally depends on system parameters and the environment, which influences propagation characteristics due to reflections, diffraction, scattering and fading. This paper presents a configurable measurement setup for AoA estimation in the 2.4 GHz band. It is depicted in Fig. 1 and consists of two antennas, connected to a vector network analyzer. The transmitting antenna represents a mobile node that is to be localized, while the receiving antenna is linearly translated during the measurements, picking up signals with different phases at different positions. In contrast to expensive and complex multi-channel antenna arrays, this synthetic linear antenna array only requires a single receiver channel. The movement of the antenna is controlled and synchronized with network analyzer measurements by a PC. While the resulting setup is not suitable for communication testing, it can be used for localization and indoor propagation measurements, as long as the environment and transmitter position do not change. A similar principle was presented in [8], describing a circular synthetic array for GNSS purposes. This paper presents various design challenges and results that can be obtained with the proposed measurement setup. Section II provides a theoretical summary of AoA estimation. Section III presents the proposed system and its characteristics. In section IV, system performance is evaluated for different antenna configurations. The conclusions and future work can be found in section V.

II. ANGLE OF ARRIVAL ESTIMATION

Indoor RF localization with AoA estimation relies on antenna arrays. The antennas in such a conformation receive the
same signals with phase shifts, depending on the direction of arrival [3]. Several methods exist to determine the direction of impinging signals, but the most straightforward consists of scanning all angles by electronically steering the beam of the array. This is achieved by linearly combining all antenna signals with complex weight vectors [9]. These vectors can be chosen for power maximization in the looking direction (Beamscan algorithm), or for unity gain in this direction while minimizing power in all other directions (Multiple Variance Distortionless Response (MVDR) algorithm) [2]. In comparison to other AoA algorithms, MVDR has been proven to perform well, therefore it is applied in this research. The comparison to other AoA algorithms, MVDR has been proven to perform well, therefore it is applied in this research. The result of this algorithm is a spatial spectrum $P_{MVDR}(\theta)$, which expresses the received power as a function of the beam direction $\theta (-90^\circ .. 90^\circ)$. The peaks in this curve indicate the estimated AoA, as demonstrated in Fig. 2. The maximum number of AoA values that can be estimated, is always one less than the number of antennas in the array. In Uniform Linear Arrays (ULA), spacing between the elements is usually half a wavelength ($\lambda/2$). A larger inter-element distance increases the resolution, but also reduces the field of view due to grating lobes. A smaller antenna spacing increases susceptibility to fading and coupling between antennas [10].

### III. System setup

In standard antenna arrays for receive beamforming, the signals of multiple antennas are sampled simultaneously. These phase shifted signals are used as an input for AoA algorithms, as discussed in section II. However, multiple synchronized receiver channels are required in such a setup, increasing the cost and complexity of hardware, which possibly also affects the accuracy of the system. Another disadvantage exists in mutual coupling between the antennas in the array, reducing system performance. For indoor localization and indoor propagation research purposes, a more accurate, flexible and less complex setup might be desirable. Therefore, a synthetic linear antenna array is proposed, as depicted in Fig. 1. Instead of performing synchronous readings of multiple receiver channels, only a single channel is sampled for multiple positions of the receiver antenna. Since the transmitter and receiver antenna are both connected to a network analyzer (R&S® ZVH-8), no further steps are required for synchronization. The signals are measured by reading S21 parameters at 2.45 GHz with zero span at each position. Both the network analyzer and antenna motion controller are controlled by a PC. The motion controller consists of an ethernet-connected microcontroller, driving a stepper motor that transfers its rotation into a linear motion with the help of a timing belt. The antenna positions can be set with a 169 μm accuracy, representing 0.50° phase accuracy at 2.45 GHz. The total width of the array is 450 mm, which is wide enough for 8 antenna measurements with a half-wavelength spacing at 2.45 GHz. The mechanical setup consists of plastic and wooden parts, minimizing its impact on signal propagation and antenna characteristics. Another important aspect of the system consists of RF cabling, indicated as cable $a$ and $b$ in Fig. 1. In contrast to traditional AoA systems, the receiving antenna and the mobile transmitter are both wired to a network analyzer, requiring long cables. Furthermore, cable $b$ is flexed during measurements, possibly changing cable characteristics. Bending the cable alters its cylindrical shape and consequently also the electrical length, producing phase instability [11], [12]. Therefore, cable $b$ was selected to be flexible, while limiting bending variations during antenna movements. The phase change of this cable in the setup was evaluated for a complete sweep of all antenna positions, resulting in a maximum deviation of 0.24°, as depicted in Fig. 3. Given this minimal phase change, one can conclude that antenna movements have no significant influence on cable phase stability in the evaluated setup. Since cable $b$ is thin and flexible, it will generally show a higher attenuation per unit of length compared to more sturdy alternatives. Therefore, its length was limited to just 0.8 m, keeping the network analyzer close to the antenna array and requiring a long cable $a$ (several meters). In order to obtain accurate measurement results, this cable should show a low attenuation and high shielding effectiveness at the used frequency, allowing a precise measurement of antenna signals without the cables themselves operating as antennas. In this setup, a 10 m RG-213 coax was used, with 3.5 dB attenuation at 2.45 GHz. Alternatives might be advisable for other frequency ranges (e.g., LMR-400® , Ecoflex® 10 Plus,...).

The resulting setup is less complex and more flexible than common antenna arrays, while the adverse effects of antenna
coupling are prevented. Instead of choosing commercial hardware, a highly accurate vector network analyzer is used. However, one should remark that this setup is designed for indoor AoA research purposes only. It is not aimed at communication testing and the mobile transmitter is not wireless.

**IV. Evaluation**

Since the designed synthetic antenna array is aimed at indoor positioning, it will not operate in open field conditions. Instead, it will be placed indoors against a wall that possibly contains metal structures, influencing antenna characteristics. This boundary condition is considered in the evaluation of the array and the selection of antenna elements. Therefore, a worst-case scenario was considered, with the antenna array placed against a metal fence, while testing AoA accuracy of a line-of-sight signal. In a first test, the array is equipped with a standard omnidirectional 2.4 GHz band dipole antenna. In order to observe the influence of the fence, a second evaluation was performed with pyramidal RF absorbers (Eccosorb® VHP-8) placed between the array and the fence, cancelling out reflections. This setup is more preferable from a technical point of view, however given the price and dimensions of pyramidal RF absorbers, a more cost efficient and compact alternative was proposed and tested. This third configuration uses a directional patch antenna (Taoglas® WDP.2458.25.4.B.02) on a 100 x 100 mm² groundplane, instead of a dipole. The measured front-to-back ratio of this antenna was 9 dB at 2.45 GHz, providing a substantial attenuation of signals that impinge on the backside of the array.

In order to evaluate the performance of the three configurations, a test setup was built as depicted in Fig. 4. The omnidirectional transmitter is placed 4 m away from the array on 37 positions with 5° spacing, covering the −90° to 90° field of view. For these tests, an inter-element spacing of 61.2 mm was applied (half a wavelength at 2.45 GHz), resulting in an 8-element synthetic array. For the evaluation and comparison of the results, two criteria were studied. The first benchmark consists of the error of the estimated AoA (Δ(AoA)). This can simply be defined as the difference between the AoA of the impinging signal, and the estimated AoA (i.e. the peak in the spatial spectrum), as expressed in equation (1). The second criterion studies the shape of the spatial spectrum. Since only one signal impinges on the array, there should be a single sharp peak in the spatial spectrum. However, the structure of the array and the metallic fence might degrade performance, introducing wider and even extra peaks in the spatial spectrum, as presented in Fig. 2. In order to evaluate this phenomenon, all spatial spectra are first normalized to values between 0 and 1 before being integrated, resulting in a single value Σ_P(AoA) for each AoA, as expressed in equation (2). Normalization is performed by shifting the spectrum with its minimum to zero and consequently rescaling its maximum to one. The resulting value of Σ_P(AoA) represents the surface beneath the normalized curve and should be as low as possible, indicating sharp peaks.

\[
\Delta(AoA) = | peak(P_{MVDR}(\theta)) - AoA | \quad (1)
\]

\[
\Sigma_P(AoA) = \int_{-90^\circ}^{90^\circ} \frac{P_{MVDR}(\theta) - min(P_{MVDR}(\theta))}{max(P_{MVDR}(\theta) - min(P_{MVDR}(\theta)))} d\theta \quad (2)
\]

For the first criterion, Fig. 5 is investigated, depicting Δ(AoA) for the AoA ranging from −90° to 90°, for all three configurations (dipole antenna, dipole with absorbers and directional patch antenna). When a bare dipole antenna is used, significant AoA estimation errors can be detected over the complete field of view, resulting in highly inaccurate AoA estimation. These errors can be prevented by adding absorbers. However, this may introduce estimation errors close to 180° at the side of the field of view, which means that no distinction can be made between left and right when signals arrive almost in parallel to the array. When using a directional patch antenna,
similar results are obtained, but anomalies are detected in the
$-90^\circ \ldots -65^\circ$ field, resulting in accurate AoA estimation in
the $-60^\circ \ldots 75^\circ$ domain. The average AoA error in this field
is $28.2^\circ$ for a bare dipole, $1.6^\circ$ for a dipole with absorbers
and $1.8^\circ$ for the directive patch antenna.

The second benchmark can be studied with Fig. 6, which
clearly shows that a setup with a bare dipole causes large
values of $\Sigma_P(AoA)$, indicating many (wide) peaks in the
spatial spectrum. In more harsh environments, this might result
in poor estimation of LOS and indirect signal directions.
Adding absorbers behind the array significantly improves
results, especially in the center of the field of view. These
results are also reflected in the example of Fig. 2. Using the
directional patch antenna generally provides the best results
over the $-60^\circ \ldots 85^\circ$ field of view. Outside this area the results
for the patch antenna deteriorate, again indicating slightly
lower AoA estimation performance at the sides of the field
of view.

V. CONCLUSIONS AND FUTURE WORK

A 2.45 GHz synthetic linear antenna array for indoor AoA
localization research purposes was presented, discussed and
tested. The system consists of a vector network analyzer and
a single receiver antenna that moves across multiple positions.
The result is an uncomplicated setup that provides highly
accurate and flexible measurements of indoor propagation
characteristics. Specific design parameters were studied and
highlighted, indicating that the phase instability of flexed
coax cables should not necessarily compromise system perform-
ance. For longer cables in the setup, cable attenuation should
be considered. The total setup was tested against a metallic
fence, showing underperformance when a dipole antenna was
used. The negative effects of the fence were eliminated by
placing RF absorbers behind the antenna. A similar effect was
obtained for a cheaper and more compact solution, containing
a directional patch antenna. Future work involves the study
of indoor AoA localization with the proposed measurement
setup in multiple environments. These measurements will not
only be performed at 2.45 GHz with a half-wavelength inter-
antenna spacing, but also at other frequencies with variable
inter-antenna spacings.

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Fig. 6. $\Sigma_P(AoA)$ values for three antenna configurations