Angle of Arrival Estimation - Sionna Ray Tracing Versus Real-world Measurements

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***Abstract*—The properties of physical layer of the wireless communication link are more and more used to provide additional level of security. Besides the position-dependent wireless channel, one of such properties is the Angle of Arrival of the incoming signal. This paper presents the experiments with Angle of Arrival measurements with uniform antenna array software defined radio systems. Its main aim is to compare the angle of arrival estimation in practical scenario with the results from raytracing simulators, such as Nvidia Sionna.**

***Index Terms*—Angle of Arrival, Sionna, Raytracing, MUSIC, SDR.**

I. INTRODUCTION

Direction finding, also referred to as direction of arrival estimation, or Angle of Arrival (AoA) estimation, locates radio frequency signals in the environment [1]. The elevation and azimuth of the antenna pointing direction determines the angular location of the incoming signals. Besides its direct applications already investigated over several decades, AoA is also at the recent center of interest as one of the potential Physical Layer Authentication (PLA) mechanisms [2]. The importance of PLA is recently growing due to its potential lower complexity in contrast to classical cryptographic solutions. It can also help to fight various security threats, such as presence of non-legitimate devices, and can thus represent the alternative solution to other techniques, such as the cooperative principle based on Measurement reports [3].

The availability of low-cost coherent receivers, together with advances in machine learning, made the experiments with AoA much more accessible [4]. In some cases, the commonly used AoA techniques, such as MUltiple Signal Classification (MUSIC) suffer from poor performance, especially in multipath environment. The aim of this paper is thus to help to match the results of real-world AoA measurements with precise raytracing simulation to better understand the real performance of the used MUSIC method. The paper is structured as follows: In section II the principle of MUSIC AoA method is presented, together with a brief description of used receiver and ray-tracing framework. Section III describes the selected measurement scenario, section IV presents our first results and Section V concludes the paper.

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II. TECHNICAL BACKGROUND

A. AoA using MUSIC method

One of the most-used methods to estimate Angle of Arrival, MUSIC, belongs to the signal subspace methods. Based on the multiple signal observations at the uniform array elements at given consecutive times $t = 1 \ldots T$ collected into matrix $\mathbf{X} = [\mathbf{x}(1)\ \mathbf{x}(2)\ \ldots\ \mathbf{x}(T)]$, it first estimates the sample covariance matrix S_{xx}:

$$S_{xx} = \frac{1}{T}\mathbf{X}\mathbf{X}^H. \tag{1}$$

After the eigenvalue decomposition (EVD), a pseudospectrum is estimated (supposing here the dimension of the noise subspace is smaller than the dimension of the signal subspace) according to:

$$P_{MUSIC}(\theta) = \frac{1}{\sum_{k=p+1}^{N} \left|\mathbf{v}_k^H \mathbf{e}(f)\right|^2}, \tag{2}$$

where N is the dimension of signal subspace plus dimension of noise subspace p, $\mathbf{v}_k$ is the k-th eigenvector of the covariance matrix and $\mathbf{e}(f)$ is steering manifold vector containing complex exponentials.

A crucial part of the MUSIC algorithm is to estimate dimensionality of signal and noise subspace, i.e. to determine the number of incoming signals. Either sorting the eigenvalues according to their value with thresholding can be applied, or recently, the deep learning-assisted methods [5] have been proposed with a neural network serving for preprocessing, estimation of number of input signals and for pseudospectrum analysis.

B. Software radio for AoA measurements

Necessary device to implement AoA estimation method is a multichannel coherent receiver, sharing the same local oscillator for all input channels. The Software Defined Radio (SDR) technology allows replacing previously used high-quality instruments by the inexpensive devices. One of such example is a 5-channel receiver *Kraken RF* [6], that is the upgraded successor of a fourth-channel *Kerberos SDR* [7]. Both these devices are based on the RTL-SDR tuner, popular mainly among radio-amateurs.

The most important parameters of Kraken SDR are as follows: the radio tuner R820T2 (5x), the Analog to Digital Converters (ADC) RTL2832U (5x), ADC Bit Depth of 8-bits, frequency range of 24 MHz -1766 MHz, and maximum channel bandwidth 2.56 MHz The data are transferred to the control PC (e.g. to GNU Radio framework) via USB-C interface.

C. Sionna framework

NVIDIA Sionna [8] is an open-source library designed to facilitate the simulation of the physical layer in wireless communication systems. Built on TensorFlow, it allows for integration of machine learning techniques in communication research and development, specifically focused on 5G and 6G technologies. One of its standout features is its use of differentiable programming, which enables optimization tasks like end-to-end system modeling and deep learning. The ray tracing module within Sionna allows for signal propagation modeling. It includes a differentiable ray tracer, allowing for precise simulation of signal paths between transmitters and receivers in various environments. This is useful for generating accurate channel impulse responses (CIRs) or, in our case, obtaining accurate AoA of individual propagation paths. Sionna's ray tracer supports various propagation phenomena, including line-of-sight (LoS), reflection, scattering, and diffraction. Users can load complex 3D scenes, either built-in or custom-made using tools like OpenStreetMap and Blender, with the ability to configure shapes, dimensions, positions of objects, and also material properties necessary for signal propagation simulations.

III. Scenario description

The scenario used in this study was created using Blender and data from OpenStreetMap, imported using the Blosm plugin [9]. This tool facilitates the integration of OpenStreetMap data into Blender, allowing for the import of buildings, roads, sidewalks, terrain, vegetation, etc. The materials within the scenario were configured to Sionna's default material options provided in Table 1. Once the scenario was prepared, it was exported using the Mitsuba-Blender plugin [10], which generates files compatible with Sionna for ray tracing simulations. The specific location for the scenario is the Faculty of Electrical Engineering and Communication at Brno University of Technology, along with its surrounding areas where real-world measurements were conducted.

Our modelled scenario, shown in Fig. 1, includes terrain, buildings, roads and paths, and dry ground. Buildings

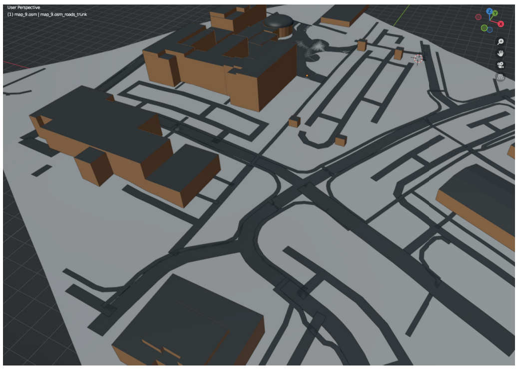

Fig. 1. Scenario model in Blender

are configured to use bricks for the walls and concrete on the top. Cars, trees, water objects and other similar entities are not modelled in our scenario for simplification purposes. Fig. 2 shows a map of TX and RX placements. Points 1-3 represent transmitter positions and point 4 represents receiver position, where an unilateral circular array (UCA) with 5 elements was placed to measure incoming signal and evaluate AoA. The UCA is shown in Fig. 3.

Material name	Relative permittivity	Conductivity [S/m]
Concrete	5.24	0.0462
Brick	3.91	0.0238
Very dry ground	3	0.00015

TABLE I. Material properties used in simulation

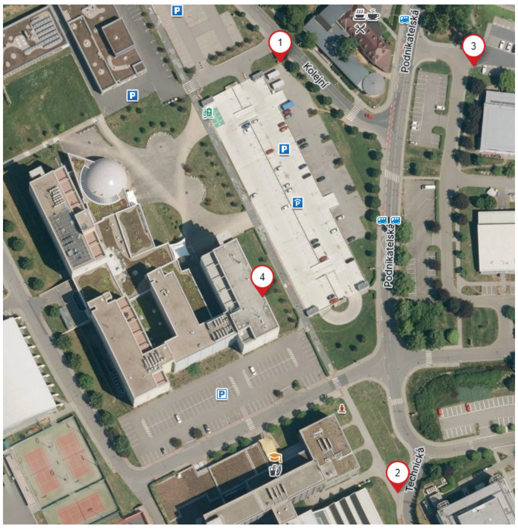

Fig. 2. Map of the TX and RX positions

The scenario was simulated using Sionna's ray tracing capability and measured in real world. TX and RX positions were configured in Sionna to match positions in real-world measurements. Kraken SDR system was used to estimate AoA using the MUSIC algorithm.

Measurements and simulations were conducted separately for each TX position, while maintaining the position of our UCA. Results of simulations were compared to results obtained from measurements. Measurements were

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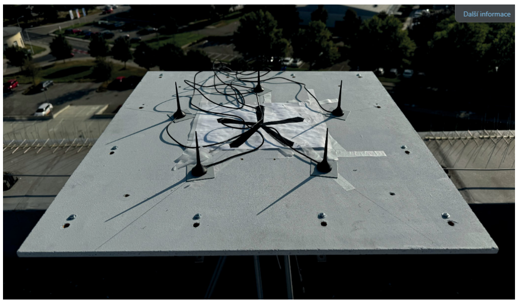

Fig. 3. UCA placed at the roof with line-of-sight to TX positions

conducted using handheld radios as transmitters and the UCA as a stationary receiver. There were no other receivers present. Each antenna element was connected to Kraken SDR system as a separate input. During each transmission, Kraken SDR used the MUSIC algorithm to estimate AoA of an expected signal. Signal frequency (446 MHz) and number of transmitters (1) were configured in advance to optimize the algorithm. During each measurement, the IQ data from Kraken SDR were observed and recorded for further evaluation. Each transmission lasted approximately one minute to allow MUSIC algorithm to process enough samples for maximum AoA accuracy. Azimuth shown in Fig. 3 has been labeled as 0 degrees, other directions are then labeled counterclockwise. Signals coming from the left direction are further shown as azimuth 90 degrees, and signals coming from the right are shown as azimuth 270 degrees. MUSIC calculated a pseudospectrum with angle on the x-axis and amplitude on the y-axis. The higher the amplitude at a given angle, the higher the probability the signal is arriving from that direction.

IV. Results

Fig. 4 shows AoA estimation by Kraken SDR using the MUSIC algorithm for the first TX position. Ten separate measurements were selected to illustrate oscillations during measurement. The maximum amplitude in the pseudospectrum is at 80 degrees.

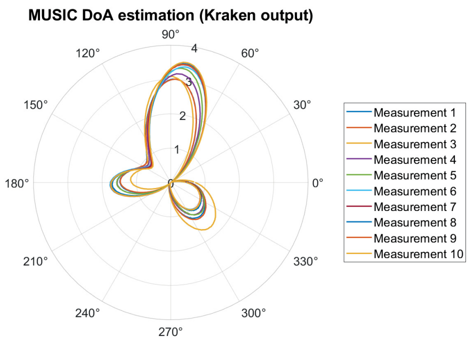

Fig. 4. MUSIC AoA estimation, TX position 1

AoA from simulation for first TX position are shown in Fig. 5. Each point in the polar graph shows a ray emitted from TX, which reaches RX at a given angle of arrival. The maximum amplitude shows the direct line-of-sight ray. Other points show rays that are reflected at least once. Fig. 5 shows, that true AoA is 55 degrees. The difference of 25 degrees indicates lower precision of MUSIC in this particular setup.

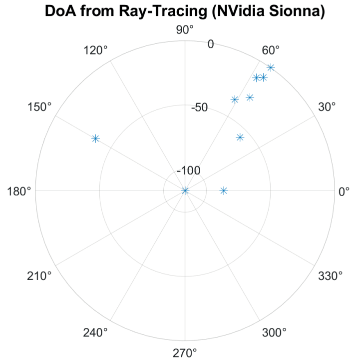

Fig. 5. AoA from ray tracing, TX position 1

Results from second TX position are slightly improved compared to the first TX position. MUSIC algorithm returns AoA value of 290 degrees, the pseudospectrum is shown in Fig. 6. The result obtained from ray tracing (Fig. 7) calculated the AoA as 278 degrees. The difference of 12 degrees represents an improvement compared to the 25 degree difference for TX position 1.

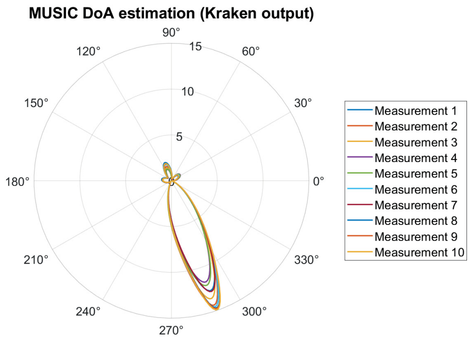

Fig. 6. MUSIC AoA estimation, TX position 2

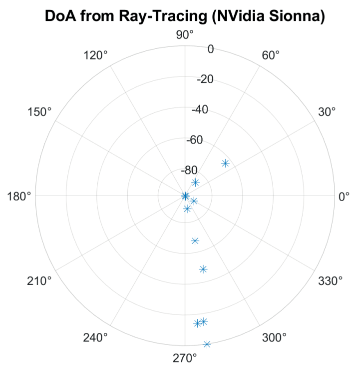

Fig. 7. AoA from ray tracing, TX position 2

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Results from third TX position show an even smaller difference between AoA obtained from MUSIC and AoA from the ray tracing simulation. AoA from MUSIC (fig. 8) was calculated as 27 degrees. AoA from ray tracing (fig. 9) shows a value of 23 degrees. The difference of only 4 degrees is smaller than with previous two TX positions.

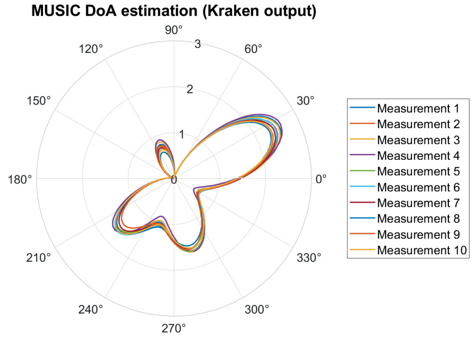

Fig. 8. MUSIC AoA estimation, TX position 3

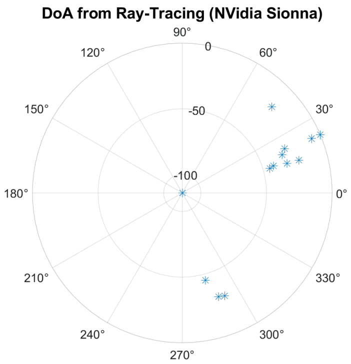

Fig. 9. AoA from ray tracing, TX position 3

The highest accuracy of MUSIC was obtained from measurement with TX at position 3. In this particular setup, the distance between TX and RX is larger than in the two previous cases. Because of the distance, in the real-world scenario there is a higher number of objects that were not present in the simulation model, and that can contribute to multi-path propagation. It might be expected, that measurement for TX position 3 will return the highest difference between AoA from MUSIC and AoA from ray tracing, but it is in fact the best result amongst the 3 TX positions. This may be due to the fact that the direction of TX position 3 was almost perpendicular to the edge of the building our UCA was placed on. Transmission from position 1 and 2 could have been slightly blocked by the building edge due to the angle of arrival, leading to lower precision of MUSIC. By looking at the graphs for each TX position, it can be observed that multi-path propagation plays a role in MUSIC precision. For TX position 2, line-of-sight signal and reflections are arriving mostly from one direction (fig. 7) and MUSIC pseudospectrum (fig. 6) has a lower beam width and minimal side lobes. In comparison, for TX position 3 there are multiple reflections arriving from a direction perpendicular to the real direction of TX, which could lead to the higher beam width and larger side lobes in MUSIC pseudospectrum. These effects shall be evaluated in further research.

V. Conclusions

The aim of the paper was to demonstrate the performance of selected angle of arrival detection method (MUSIC algorithm) in real environment of university campus and investigate how the results match with the results obtained from digital twin of the environment, obtained from widespread Sionna raytracing framework. The experiment has proven that both results match quite well, at least in the selected simple scenario of narrowband signals and only a single transmitter. The experiments with much higher number of transmitters were not done, due to relatively low number of receiving antennas of the used software defined radio. Similarly, it would be interesting to investigate how the results will be affected by pure NLOS conditions, but this is let for further investigations.

References

[1] *Direction Finding*. John Wiley Sons, Ltd, 2020, ch. 8, pp. 301–323. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119419204.ch8

[2] T. M. Pham, L. Senigagliesi, M. Baldi, G. P. Fettweis, and A. Chorti, "Machine learning-based robust physical layer authentication using angle of arrival estimation," in *GLOBECOM 2023 - 2023 IEEE Global Communications Conference*, 2023, pp. 13–18.

[3] L. Karaçay, Z. Bilgin, A. B. Gündüz, P. Çomak, E. Tomur, E. U. Soykan, U. Gülen, and F. Karakoç, "A network-based positioning method to locate false base stations," *IEEE Access*, vol. 9, pp. 111 368–111 382, 2021.

[4] Z. Dai, Y. He, V. Tran, N. Trigoni, and A. Markham, "Deepaoanet: Learning angle of arrival from software defined radios with deep neural networks," *IEEE Access*, vol. 10, pp. 3164–3176, 2022.

[5] J. P. Merkofer, G. Revach, N. Shlezinger, and R. J. G. van Sloun, "Deep augmented music algorithm for data-driven doa estimation," in *ICASSP 2022 - 2022 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 2022, pp. 3598–3602.

[6] "Home — KrakenRF — krakenrf.com," https://www.krakenrf.com/, [Accessed 15-10-2024].

[7] "KerberosSDR Quickstart Guide — rtl-sdr.com," https://www.rtl-sdr.com/ksdr/, [Accessed 15-10-2024].

[8] J. Hoydis, S. Cammerer, F. Ait Aoudia, A. Vem, N. Binder, G. Marcus, and A. Keller, "Sionna: An open-source library for next-generation physical layer research," *arXiv preprint*, Mar. 2022.

[9] Vvoovv, "Blosm - OpenStreetMap data for Blender," https://github.com/vvoovv/blosm, [Accessed 15-10-2024].

[10] Mitsuba-renderer, "Mitsuba Blender Add-on," https://github.com/mitsuba-renderer/mitsuba-blender, [Accessed 15-10-2024].