Amplitude Only Direction of Arrival Estimation

(Invited Paper)

Gabriel G. Machado, Kd M. Raziul Islam
School of Engineering
Ulster University
Belfast, United Kingdom
Email: g.machado@ulster.ac.uk

Vincent Fusco, M. Ali Babar Abbasi
Centre for Wireless Innovation (CWI),
School of Electronics, Electrical
Engineering and Computer Science (EEECS),
Queen's University Belfast, United Kingdom
Email: m.abbasi@qub.ac.uk

***Abstract*—In this manuscript, we present a novel hardware concept for the estimation of the direction of arrival of electromagnetic signals. An arrangement of two patch antenna arrays, tilted with respect to each other, is used to create a monotonic relationship between the DoA and the received power difference between both arrays. The proof of concept is performed using numerical simulations, and we demonstrate that by maintaining the same boresight direction, but tilting the beam in relation to the propagation axis, DoA estimation through power difference can be achieved. The proposed technique aims to reduce the complexity of such estimation systems in the hardware, as well as in the digital signal processing domain, by removing the need for phase comparison.**

***Index Terms*—Direction of arrival, antennas, x-band, tilted beam**

I. Introduction

Direction of arrival (DoA) estimation techniques have been a topic of interest amongst the scientific community for its importance in several applications, such as radar, sonar, navigation, etc, [1] and, most recently, in current millimetre-wave (mmWave) mobile communication systems [2]. For the latter, beamforming networks require reliable target tracking data to provide the high gain antenna system accurate amplitude and phase to propagate the signal with maximum efficiency towards the end-user. Moreover, the correct DoA estimation is a key aspect in radar and satellite communication systems [3].

Several studies have reported different DoA estimation techniques using signal processing algorithms such as MUSIC (Multiple Signal Classification, high accuracy) [4] and ESPRIT (Estimation of Signal Parameters using Rotational Invariance Techniques) [5], with the common aspects amongst them being the use of a significantly large number of antennas and a computational method to estimate where the signal is coming from. In addition, each antenna is required to be connected directly to the signal processing unit via dedicated RF chains, enhancing its cost and complexity. Some recent efforts are being put into reducing the hardware complexity of DoA systems. For example, a physical frequency-diverse multimode lens-loaded cavity was proposed as a solution to reduce the hardware needed for an accurate DoA estimation, with [6], and without a diode detector [2], for mmWave for 5G and beyond applications. Additionally, in [7], the authors use a leaky wave antenna, reading the differential power output to create an analogue DoA estimation system. However, the antenna feeding network is rather complex with the need of a bias circuit and several varactors connected in series.

In this paper, we concentrate on a very simple structure that would be suitable for low-cost IoT applications where high accuracy is not of paramount importance, but where cost, size and mass is a premium [8]. Our design is frequency agnostic, and we demonstrate its operation in the X-Band. The objective of this design is to reduce the hardware needed to create a DoA estimation system based on the electromagnetic (EM) properties of antenna arrays, therefore reducing the complexity by creating a relationship between the received power and the direction of arrival, engineering a much simpler system when compared to the study performed in [7], and not requiring phase measurement as shown in [9]. The method proposed in this paper shows that just by purposely creating an unmatched polarisation alignment between a pair of microstrip patch antenna arrays with two elements and the signal source, we can obtain a monotonic curve for different angles of incidence in one plane. Our proposed arrangement results in a major reduction of hardware needed for DoA estimation for the antenna system whilst requiring trivial processing of the received signal yielding to a potential reduction of volume, weight and cost.

II. Antenna design

A pair of two elements microstrip patch antenna arrays working at $f_0 = 10$ GHz was designed on a 0.51 mm thick Rogers RO4003C substrate ($\epsilon_r = 3.55$, $\tan\delta = 0.0027$, 1 Oz Cu cladding), where both arrays are fed via a $50\ \Omega$ panel SMA connector. Fig. 1 depicts the antenna configuration where the a $\pm 30^\circ$ tilt is applied to the left and right arrays respectively.

A. Working principle

The arrangement works using the principle of broadside antenna arrays, where the pattern is 'squeezed' at the plane perpendicular to the array elements. By tilting the antennas, the polarisation is purposely unmatched, and each array will receive a different power from an EM wave impinging from a given direction in the yz-plane, as shown in the computed

979-8-3503-2067-1/23/$31.00 ©2023 IEEE

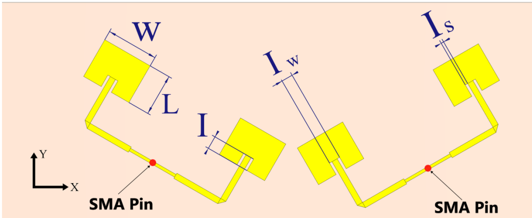


Fig. 1. Geometry of the designed dual microstrip patch array. $W = 9.5$ mm, $L = 7.7$ mm, $I = 2.4$ mm, $I_w = 2.1$ mm, $I_s = 0.4$ mm.

3D radiation patterns in Fig. 2(a) and (b). The S-Parameters are depicted in Fig. 2(c), though not shown, there is over 20 dB isolation between each array. Specifically, when scanned along the yz-plane, the radiation properties given by this arrangement can be used to identify the direction of incoming signals in that plane.

The antennas have been carefully optimised in CST Microwave Studio to perform in such a way that the radiation patterns on the yz-plane create a monotonic relationship between their received power difference and the DoA. Fig. 3 shows the yz-cut of both radiation patterns when the antennas are working in isolation. The gains cross each other approximately at boresight, where the received power difference is zero. Although tilted beam antennas have been reported in the literature for use in mmWave 5G communications [10], a few are dedicated for DoA estimation for 5G and beyond. For example, in [11], [12], the authors use tilted beams pointing in different directions and estimate the DoA based on power and phase. Our design differs from those in two key aspects. First, the beams are pointed towards the same direction, and therefore this approach requires two narrow beams of unmatched polarizations (not direction), and second, it the estimation the DoA based only on the difference between the received power by both antennas. The design eliminates the complexity of phase calculation, and relies on simple power level detection for both received signals.

III. Numerical results

In the numerical model, a simulation was performed by illuminating the arrangement with a plane wave ($|E| = 1$ V/m) from $-80°$ to $80°$ and the received power, in dBm, from each antenna is recorded. The simulation results for a plane wave scanning along the yz-plane are depicted in Fig. 4. We notice that when illuminated by a plane wave, the antennas present the power difference ΔP_r, $P_{\text{dBm},1} - P_{\text{dBm},2}$, as given in Fig. 4b. From this, we obtain a monotonic curve that directly corresponds the DoA to the power difference between port 1 (left array) and port 2 (right array). When compared to the work presented in [7], [11], [12], the arrangement proposed in this paper is significantly simpler to realise as there is no need for a complex feed and bias network.

From this result, the relationship between the power difference and the estimated angle of arrival of the signal is clear, where one can estimate an unambiguous DoA by simple calculation of ΔP_r. Further studies are required to better understand the accuracy of this method at different signal-to-noise-ratio (SNR) conditions, and environmental effects. This feasibility study focuses on the proof of concept of tilted antenna patterns for DoA estimation.

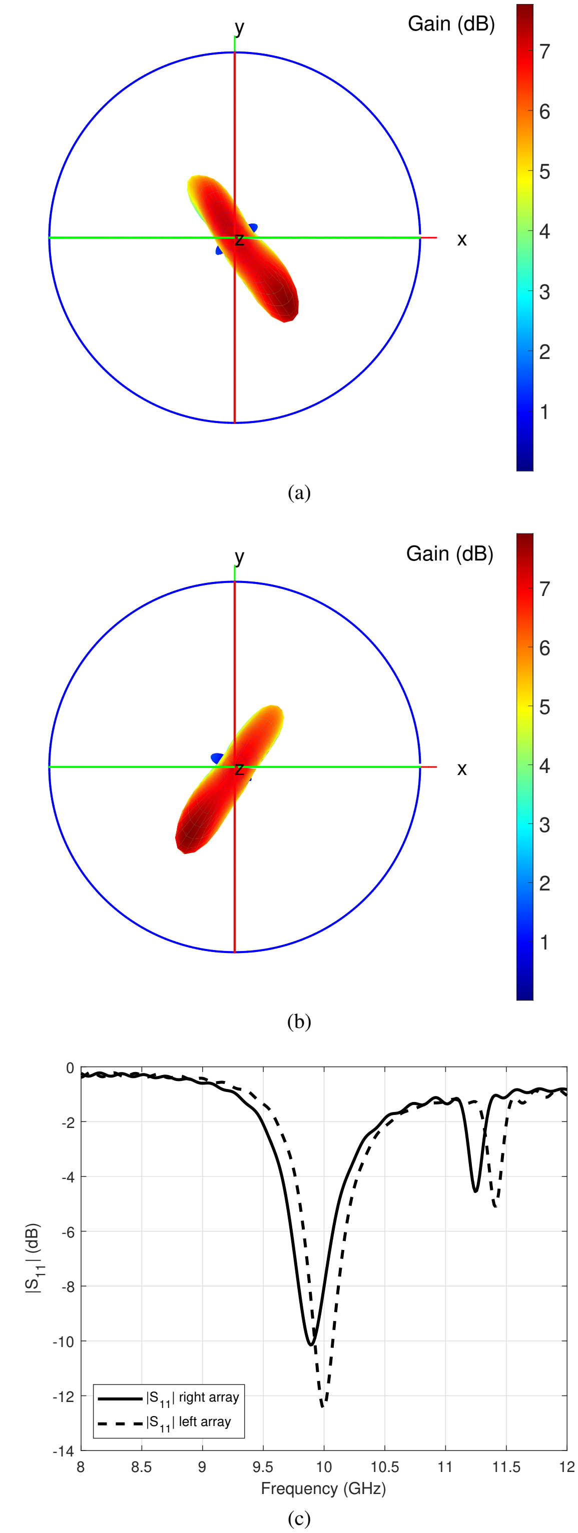


Fig. 2. 3D radiation pattern from each patch array working in isolation. (a) right patch array; (b) left patch array; (c) S-Parameter of each patch array.

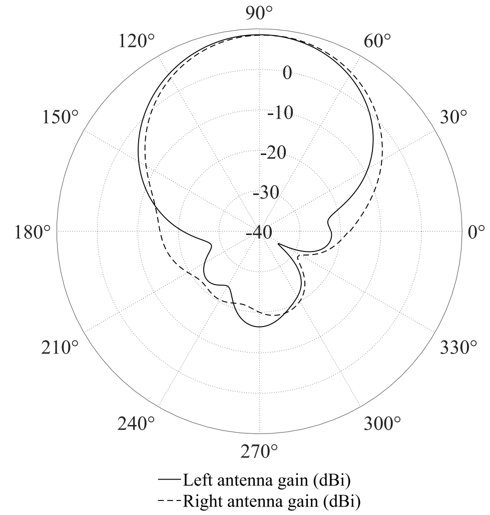
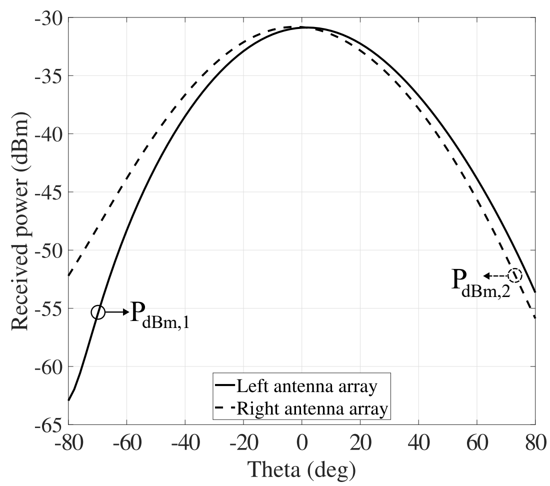
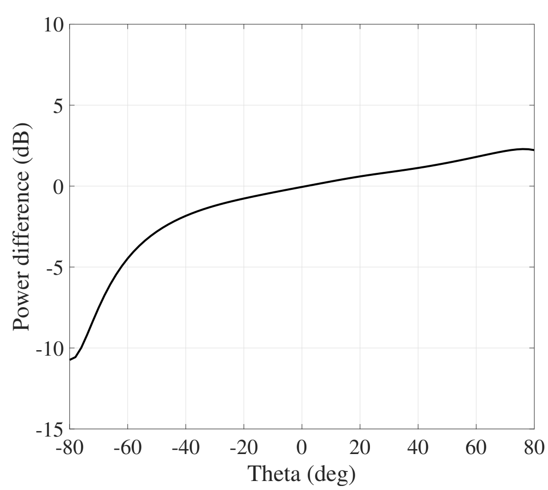


Fig. 3. Farfield gain patterns for both antenna arrays on the YZ plane.



(a)



(b)

Fig. 4. (a) Numerical results for the received power of each antenna array. (b) Calculated power difference (ΔP_r) between ports 1 and 2.

IV. Conclusion

This work presented a novel antenna hardware architecture for DoA estimation. By purposely misaligning the polarisation of two pairs of microstrip patch antenna arrays, we create a radiation pattern which provides the necessary directivity in order to obtain a different power reading from both antenna arrays. When scanned along the $yz-$plane, this power difference reveals a monotonic behaviour which directly corresponds to a specific DoA of the impinged EM wave. When compared to the relevant work in the literature, our proposed architecture is shown to reduce the hardware and computational complexity needed for DoA estimation by eliminating the need for phase measurement. Finally, by computing the output power difference between the two ports of the antenna arrangement, we can remove the ambiguity of the power level of the incoming signals from the same direction, whilst only using two antenna arrays.

References

[1] Z. Yang, J. Li, P. Stoica, and L. Xie, "Chapter 11 - Sparse methods for direction-of-arrival estimation," in *Academic Press Library in Signal Processing, Volume 7*, R. Chellappa and S. Theodoridis, Eds. Academic Press, Jan. 2018, pp. 509–581. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128118870000110

[2] M. a. B. Abbasi, V. F. Fusco, O. Yurduseven, and T. Fromenteze, "Frequency-diverse multimode millimetre-wave constant- ϵ_r lens-loaded cavity," *Scientific Reports*, vol. 10, no. 1, p. 22145, Dec. 2020. [Online]. Available: https://www.nature.com/articles/s41598-020-78964-1

[3] M. Hasib, S. Kandeepan, W. S. T. Rowe, and A. Al-Hourani, "Direction-of-arrival (doa) estimation performance for satellite applications in a multipath environment with rician fading and spatial correlation," *Sensors*, vol. 23, no. 12, 2023. [Online]. Available: https://www.mdpi.com/1424-8220/23/12/5458

[4] P. Gupta and S. Kar, "MUSIC and improved MUSIC algorithm to estimate direction of arrival," in *2015 International Conference on Communications and Signal Processing (ICCSP)*, Apr. 2015, pp. 0757–0761.

[5] S. Li, Y. Zhang, and R. Edwards, "Two Dimension DOA ESPRIT Algorithm Based on Parallel Coprime Arrays and Complementary Sequence in MIMO Communication System," in *2019 IEEE International Conference on Signal, Information and Data Processing (ICSIDP)*, Dec. 2019, pp. 1–4.

[6] M. A. B. Abbasi, V. Fusco, O. Yurduseven, R. I. Ansari, and S. L. Cotton, "Lens-loaded cavity antenna with detector diode as a direction-of-arrival estimator," *IEEE Antennas and Wireless Propagation Letters*, vol. 20, no. 11, pp. 2176–2180, 2021.

[7] S. Abielmona, H. V. Nguyen, and C. Caloz, "Analog Direction of Arrival Estimation Using an Electronically-Scanned CRLH Leaky-Wave Antenna," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 4, pp. 1408–1412, Apr. 2011.

[8] N. BniLam, D. Joosens, J. Steckel, and M. Weyn, "Low Cost AoA Unit for IoT Applications," in *2019 13th European Conference on Antennas and Propagation (EuCAP)*, Mar. 2019, pp. 1–5.

[9] H. Xin and J. Ding, "An improved two-antenna direction of arrival (DOA) technique inspired by human ears," in *2008 IEEE Antennas and Propagation Society International Symposium*, Jul. 2008, pp. 1–4.

[10] J.-S. Park, J.-B. Ko, H.-K. Kwon, B.-S. Kang, B. Park, and D. Kim, "A tilted combined beam antenna for 5g communications using a 28-ghz band," *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 1685–1688, 2016.

[11] S. Maddio, A. Cidronali, M. Passafiume, G. Collodi, and S. Maurri, "Fine-grained azimuthal direction of arrival estimation using received signal strengths," *Electronics Letters*, vol. 53, no. 10, pp. 687–689, 2017. [Online]. Available: https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/el.2017.0456

[12] J. L. Gómez-Tornero, D. Cañete-Rebenaque, J. A. López-Pastor, and A. S. Martínez-Sala, "Hybrid analog-digital processing system for amplitude-monopulse rssi-based mimo wifi direction-of-arrival estimation," *IEEE Journal of Selected Topics in Signal Processing*, vol. 12, no. 3, pp. 529–540, 2018.