Enhanced Angle Estimation Accuracy of Ultra Compact Radars Inspired by a Biomimetic Approach

Patrik Grüner, Tobias Chaloun, and Christian Waldschmidt
Institute of Microwave Engineering, Ulm University, 89081 Ulm, Germany
Email: patrik.gruener@uni-ulm.de

***Abstract*—The theoretical and experimental evaluation of using biomimetic antenna arrays (BMAAs) in an angle sensing radar system is presented. This ultra compact antenna system can enhance the angle estimation accuracy for radar systems which allow only small antenna separations due to the limited available space. A quality criterion will be given to indicate which BMAA parameters are necessary to achieve precise angle estimation accuracy. Radar measurements show a reduction in the RMS angle estimation error by a factor of 2 compared to conventional antenna systems of the same size.**

***Index Terms*—Biomimetic Antenna Array, Direction of Arrival, Radar Systems.**

I. Introduction

In angle sensing radar systems the element spacing of the receiving antenna array is usually chosen to half a wavelength in free space ($\lambda/2$) to allow for a high phase progression as well as an unambiguous angle estimation. In some cases, e.g. in on-chip systems, due to external constraints or cost, there is only little space left for placing the antennas and therefore no precise angle estimation is possible.

The biomimetic antenna array (BMAA) as a principle to overcome this issue has been recently presented [1]. This antenna system mimics the auditory system of the parasitoid fly *Ormia ochracea* which achieves an angle estimation accuracy of about 2° with an acoustical aperture of length $\lambda/20$ only [2]. Some antenna designs were presented in the UHF-band [1], [3] where large wave lengths prevent the placement of antenna elements with a separation of $\lambda/2$. Recent work showed a planar design for the K-band around 20 GHz with an element separation of $\lambda/5$ [4]. An application of a BMAA in a direction finding system at 20 MHz is shown in [5] where some system considerations concerning the angle estimation accuracy are discussed.

In this paper, a first theoretical and experimental examination of the angle estimation capability of biomimetic antenna arrays in radar operation is given. A simple formula to quantify this increase for the system design of radars will be derived and verified by measurements.

II. Biomimetic Antenna Arrays

The basic principle of a two-element BMAA is shown in Fig. 1. When a wave is incident under the angle θ from the boresight direction, a phase progression of $\phi_{\text{in}} = kd\sin\theta$ can be measured at the antenna terminals. d hereby denotes the separation of the antenna elements and $k = 2\pi/\lambda$ is the wave number in free space. The BMAA then applies a special coupling which mimics the auditory system of *Ormia ochracea*. As a result, the phase progression ϕ_{out} after this biomimetic coupling is significantly increased [4]. The trade-off is a loss in Signal-to-Noise-Ratio (SNR).

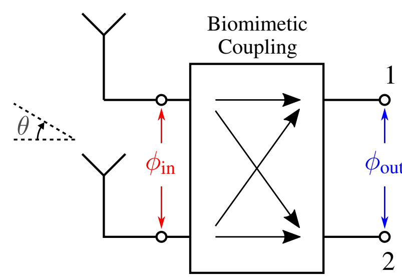


Fig. 1. Principle of the biomimetic antenna array (BMAA) [4].

From a system point of view, the BMAA can be described by the parameters phase gain η and normalized output power L_{out} [1], [4]. The phase gain is defined by the ratio of the slopes of the respective phase progression curves at the terminals of a BMAA (ϕ_{out}) and a regular antenna array (ϕ_{in}) in boresight direction:

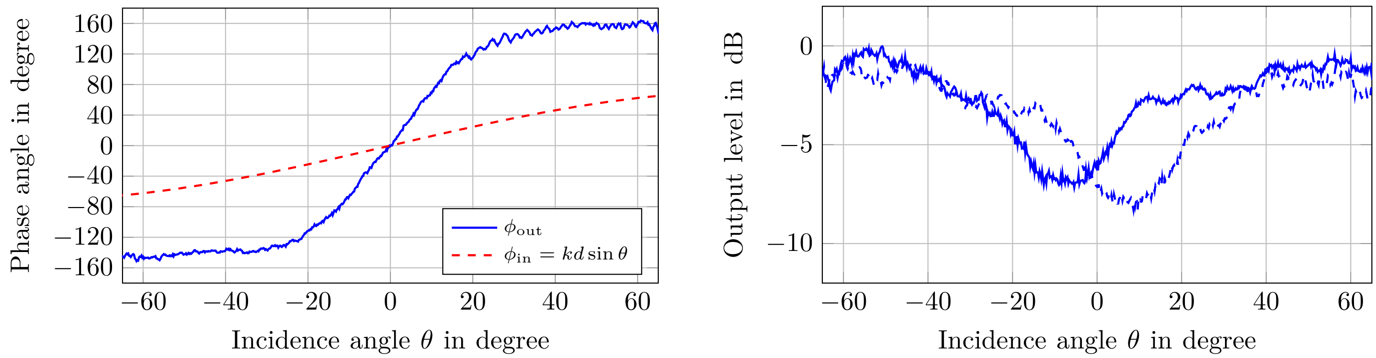
$$\eta = \frac{\left.\frac{\mathrm{d}\phi_{\text{out}}}{\mathrm{d}\theta}\right|_{\theta=0}}{\left.\frac{\mathrm{d}\phi_{\text{in}}}{\mathrm{d}\theta}\right|_{\theta=0}} \ . \tag{1}$$

To quantify the reduction of the output power level, the dimensionless quantity L_{out} is defined as

$$L_{\text{out}} = \frac{P_{\text{out,BMAA}}}{P_{\text{out,reg. Array}}} \ . \tag{2}$$

This quantity indicates the power level at the output of the BMAA normalized to the power level of a regular antenna array using the same radiating elements with similar spacing but without biomimetic coupling. This value is always less than or equal to 1.

In Fig. 2 these parameters are shown for the BMAA used in this paper [4]. Figure 2a shows the measured output phase progression ϕ_{out} at the operating frequency (21.5 GHz) as well as the phase progression ϕ_{in} which is given only by the physical separation $d = \lambda/5$ of the antenna elements. Comparing the slopes of the two curves in Fig. 2 according to (1) gives a phase gain of $\eta = 5$. Measured output levels for both antenna ports at 21.5 GHz are depicted in Fig. 2b showing a reduction in the power level of 6.5 dB at boresight.



(a) Measured phase difference ϕ_{out} at the output of the biomimetic antenna array at 21.5 GHz. For comparison, the phase progression of a conventional antenna array (ϕ_{in}) is also given.

(b) Measured output power level L_{out} of the BMAA at 21.5 GHz for port 1 (solid) and port 2 (dashed).

Fig. 2. Measured output phase progression (a) and output power level L_{out} (b) of the BMAA at 21.5 GHz.

III. Angle Estimation Accuracy for BMAAs

The measurements given in Fig. 2 show the already mentioned fundamental trade-off of the biomimetic antenna system. Any increase in phase gain comes along with a decrease in SNR. In this section, this trade-off is theoretically examined and its impact on radar angle estimation performance is discussed.

Angle estimation with antenna arrays is usually done by measuring the phase progression between the antenna terminals. The angle of incidence θ is then determined from the measured phase progression ϕ by

$$\theta(\phi) = \arcsin\left(\frac{\phi}{kd}\right) \approx \frac{\phi}{kd} \; . \tag{3}$$

The approximation made in (3) is valid for small phase progressions ϕ in the vicinity of the boresight direction.

The phase of a signal can only be measured with limited accuracy. Consequently, the estimated angle of incidence θ will also be erroneous. This can be modeled by the propagation of uncertainty by the linear approximation

$$\theta(\phi + \Delta\phi) \approx \theta(\phi) + \underbrace{\frac{\mathrm{d}\theta}{\mathrm{d}\phi}\Delta\phi}_{\Delta\theta} \; , \tag{4}$$

where $\Delta\phi$ is the RMS error of the measured phase progression. The second term in (4) gives the RMS error $\Delta\theta$ of the estimated angle θ.

The error $\Delta\phi$ is proportional to the square root of the inverse Signal-to-Noise-Ratio (SNR) [6]:

$$\Delta\phi \propto \frac{1}{\sqrt{\text{SNR}}} \; . \tag{5}$$

Inserting (5) into (4) and calculating the derivative, the angle estimation error $\Delta\theta$ conducts to

$$\Delta\theta \propto \frac{1}{kd\sqrt{\text{SNR}}} \; . \tag{6}$$

This equation is generally valid for any antenna array. For BMAAs, some modifications can be made. Due to the increased phase progression in boresight direction, the antenna element separation appears to be scaled by the phase gain η. At the same time, the SNR is degraded by the factor L_{out}. This leads to

$$\Delta\theta_{\text{BMAA}} \propto \frac{1}{k\,\eta d\,\sqrt{\text{SNR}\,L_{\text{out}}}} = \frac{\Delta\theta}{\eta\,\sqrt{L_{\text{out}}}} \; . \tag{7}$$

From (7) it can be seen that the angle estimation error $\Delta\theta$ is scaled by the BMAA parameters η and L_{out}. By the proper choice of these parameters this error can be decreased. A radar using a BMAA therefore achieves superior angle estimation accuracy compared to a radar using a conventional antenna array with the same element spacing d, if the product of phase gain η and square root of power level L_{out} is greater than one:

$$\eta\,\sqrt{L_{\text{out}}} > 1 \; . \tag{8}$$

This enables very robust direction of arrival estimations even for radar systems occupying little space. Note that the reduced SNR at the input reduces the sensitivity and with this the maximum range of the radar system.

IV. Measurement Setup

To verify the enhanced angle estimation performance of the BMAA, measurements were taken in an anechoic chamber. In order to setup a bistatic radar system, a K-band horn antenna and the BMAA were placed on a turntable. Their vertical separation was 15 cm to reduce leakage. A 4-port vector network analyzer (VNA) was connected to the horn antenna and both terminals of the BMAA. A corner reflector (RCS = 2.7 dBsm) was placed at a distance of 1.8 m in front of the turntable. The transmit power of the VNA was set to 0 dBm. Fig. 3 shows a photograph of the measurement setup.

In a first step, a calibration dataset for later maximum-likelihood angle estimation was recorded from 18 GHz to 22 GHz for incidence angles θ between $-35°$ and $35°$. This was done using the corner reflector placed in the anechoic chamber at $\theta = 0°$ while the radar itself was rotated from $-35°$ to $35°$ using the turntable.

In a second step, the radar was fixed pointing towards $\theta = 0°$. The corner reflector was placed at different

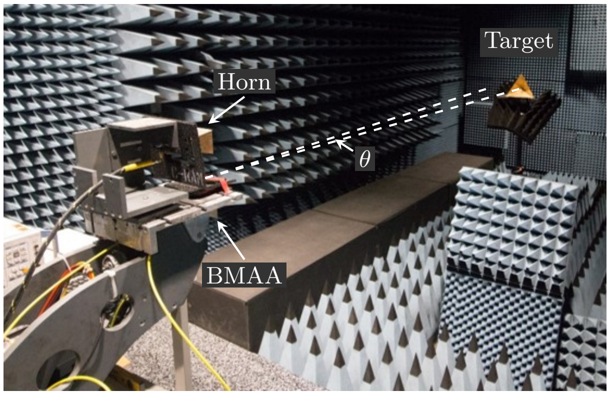


Fig. 3. Photograph of the measurement setup in an anechoic chamber.

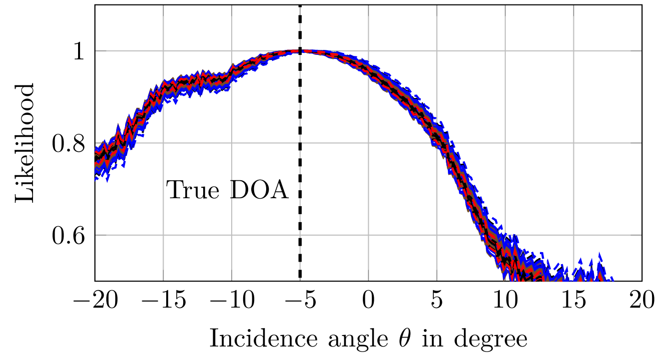
angles ($\pm 15°$, $\pm 10°$, $\pm 5°$, $0°$) relative to the radar boresight axis and the transmission coefficients from the horn antenna to either port of the BMAA were determined. For every target position, 100 measurements were performed to evaluate the variance of the angle estimation.

V. Measurement Results

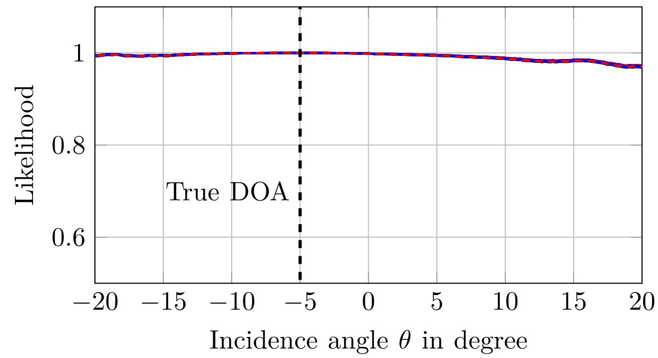
Using the measurement setup described in Section IV, two antenna configurations for the radar were compared. At first, the BMAA presented in Section II was used. With a phase gain of $\eta = 5$ and a power level of $L_{\text{out}} = -6.5\,\text{dB}$ the quality criterion of this antenna system according to (8) calculates to 2.4. This antenna system was compared to a conventional two-element antenna array configuration using the same radiating elements and equal spacing d but without biomimetic coupling. By definition, this antenna has a phase gain of 1 and a power level of $0\,\text{dB}$. According to the quality criterion, the first configuration should therefore show an angle estimation error in the range of factor 2.4 smaller compared to the second one.

Figure 4 shows the likelihood functions (normalized to 1) of 100 measurements for the radar using the BMAA (a) and the conventional antenna array (b) with a target placed at $\theta = -5°$. Each antenna was used in its operating frequency band, i.e. the conventional antenna at 20 GHz and the BMAA at 21.5 GHz. It can be noted that the lobe of the likelihood function for the BMAA configuration is much smaller than the lobe of the configuration using the conventional antenna. This is due to the increased phase progression which results in a virtually larger aperture and therefore smaller lobe. The likelihood curve of the BMAA configuration is apparently more sensitive to noise due to the lower SNR at the output, but the smaller main lobe overcompensates this shortcoming.

For every single measurement a maximum-likelihood estimation has been performed. The distributions of the estimation error $\Delta\theta$ for both configurations are shown in Fig. 5. The variance of the estimation error is significantly lower when using the BMAA compared to the conventional antenna with the same element spacing. Additionally, the root mean square

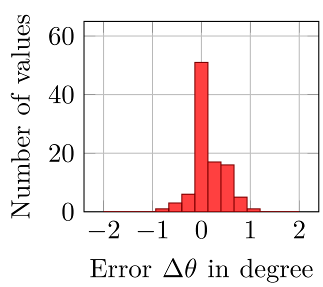


(a) BMAA at 21.5 GHz

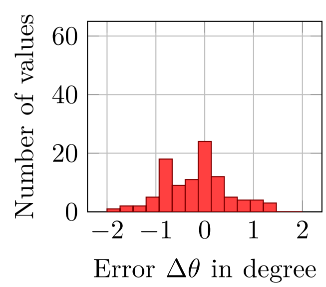


(b) Conventional two-element antenna array at 20 GHz

Fig. 4. Normalized likelihood functions of 100 measurements for a radar using the BMAA (a) and the conventional antenna (b) with a target placed at $\theta = -5°$.



(a) BMAA at 21.5 GHz



(b) Conventional antenna at 20 GHz

Fig. 5. Distribution of angle estimation errors out of 100 measurements for a target placed at $-5°$.

error (RMSE) of the estimation was calculated for both radar configurations according to

$$\text{RMSE} = \sqrt{\frac{1}{M}\sum_{m=1}^{M}\left(\theta_m - \theta_{\text{ref}}\right)^2}\,, \tag{9}$$

where $M = 100$ is the number of measurements, θ_m is the estimated angle in the m-th measurement, and $\theta_{\text{ref}} = -5°$ is the true incidence angle. The RMS error for the angle estimation using the conventional antenna calculates to $0.69°$, with the BMAA the error reduces to $0.36°$. Thus, the RMS angle estimation error is reduced by a factor of about 1.9.

VI. CONCLUSION

A first investigation on using biomimetic antenna arrays in a bistatic radar configuration was shown. A quality criterion was derived showing how the parameters of a BMAA should be chosen for high angle estimation accuracy. Radar measurements for a target at -5° showed that the BMAA achieves an RMS error in angle estimation which is lower by a factor of about 2 compared to a conventional antenna array with the same dimensions.

ACKNOWLEDGMENT

This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – WA 3506/6-1.

REFERENCES

[1] A. Masoumi and N. Behdad, "An Improved Architecture for Two-Element Biomimetic Antenna Arrays," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 12, pp. 6224–6228, Dec. 2013.

[2] R. N. Miles, D. Robert, and R. R. Hoy, "Mechanically coupled ears for directional hearing in the parasitoid fly Ormia ochracea," *The Journal of the Acoustical Society of America*, vol. 98, no. 6, pp. 3059–3070, Dec. 1995.

[3] J. Zhong, A. Kiourti, and J. Volakis, "Reducing and Controlling the Beamwidth of Electrically Small Antenna Arrays," in *9th European Conference on Antennas and Propagation (EuCAP)*, Apr. 2015, pp. 1–2.

[4] P. Grüner, T. Chaloun, and C. Waldschmidt, "Towards a mm-Wave Planar Biomimetic Antenna Array with Enhanced Phase Sensitivity," in *10th European Conference on Antennas and Propagation (EuCAP)*, Apr. 2016, pp. 1–5.

[5] F. Dagefu, J. Oh, and K. Sarabandi, "A Sub-Wavelength RF Source Tracking System for GPS-Denied Environments," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 4, pp. 2252–2262, Apr. 2013.

[6] M. I. Skolnik, *Introduction to radar systems*, 3rd ed., ser. McGraw-Hill electrical engineering series. Boston, Mass.: McGraw Hill, 2001.