Reducing Ground Reflection Multipath Errors for Bluetooth Angle-of-Arrival Estimation by Combining Independent Antenna Arrays

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***Abstract*—For outdoor navigation using Bluetooth direction finding, elevation angle estimate errors due to ground reflection multipath interference is a significant challenge at low elevation angles. One of the ways to reduce this issue is to increase the vertical dimension of the array. We consider the synchronization of measurements from two independent arrays stacked vertically to achieve the same effect without needing to construct a larger array, allowing hardware modularity using low-cost equipment. The measurement synchronization is itself affected by the multipath, and a method to handle this effect is proposed. Using measurements from a 15 cm x 15 cm array in field experiments, we demonstrate a reduction in elevation error of up to 10° at elevation angles in the 7° to 15° range, where the error was largest when using a single array.**

***Index Terms*—Bluetooth, direction finding, angle-of-arrival estimation, array processing, multipath**

I. INTRODUCTION

MULTIPATH interference from ground reflections is a known problem for elevation determination in radar tracking of aircraft at low elevation angles [1]–[3]. This problem "has no simple solution and is generally minimized by using narrow-beam antennas" [4, p. 9.38], i.e. antenna reflectors or antenna arrays with large apertures and/or operating at high frequencies, yielding high angular resolution. The multipath effect also occurs for other direction finding systems, such as Bluetooth angle-of-arrival (AoA) determination. For Bluetooth the problem can be significant due to the use of arrays that are much smaller than those typically used for aircraft tracking radar, resulting in low angular resolution. Both the direct signal and the ground reflection can then be within the array main lobe for elevation angles of tens of degrees. The elevation error can be significant up to an elevation angle approximately equal to the one-way beamwidth of the array [4, Fig. 9.28], which corresponds to the Rayleigh resolution limit [5] for angular separation. Direction estimation algorithms such as beamformers [5], [6], Multiple Signal Classification (MUSIC) [7], or Estimation of Signal Parameters via Rotational Invariance Technique (ESPIRIT) [8] are not able to separate the direct and reflected signals unless they have enough angular separation, especially for coherent signals.

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Modeling the reflection and taking it into account in the direction estimation is possible, but requires knowledge or assumptions on the reflection geometry, signal polarization and reflection coefficient. This was considered in [9], which assumed a flat surface and a known reflection coefficient using horizontal polarization. The approach to model the reflection is not ideal if the reflection coefficient is unknown, the ground surface cannot be assumed flat (such as being uneven or having an unknown slope), or the reflection polarization depends on the angle of incidence, such as for circular polarization [10]. This is especially the case for portable equipment, which can be moved between different locations and therefore be subject to different reflection conditions.

Instead of designing and producing a single large array, an alternative method is to synchronize measurements from multiple separate arrays, and process the measurements together. This way, low-cost equipment can be assembled in a modular fashion. A challenge of using multiple separate receivers is that they each use their own reference oscillator for IQ sampling. This means that measurements cannot directly be processed as if they are the output from a single receiver, as the oscillators can run at slightly different frequencies and can not at any specific time be expected to have the same phase angle. In [11], synchronization of multiple independent sub-arrays for the Internet-of-Things (IoT) DASH7 Alliance Protocol was demonstrated, increasing the accuracy of signal direction determination. Optimization was used for synchronization of signal frequency, timing and phase, with separate receiver channels used for each receiving antenna in the sub-arrays. Multipath interference was not considered, and experimental verification was performed only with a linear array for azimuth angle determination, thus not encountering the multipath elevation problem.

In the field experiments using Bluetooth AoA in [12], it was found that elevation estimation errors due to ground reflection multipath was the main error source at elevation angles below approximately $25°$, using a $15 \times 15\,\mathrm{cm}$ array. For an array placed high enough above the ground, multiple true elevation angles can map to the same elevation angle measurement. Due to this non-uniqueness of measurements, the effect is not easily removed by a calibration in all situations. Synchronizing smaller, low-cost arrays, combined in a modular setup using vertical separation can increase the angular resolution of the combined elevation estimate, and thereby reduce the multipath effect. This way the error can be reduced without modeling or requiring knowledge of the reflection conditions.

The main contribution of this paper is the proposition and testing of a method to use two independent arrays together for direction estimation, in the same way as a single larger array. We demonstrate that a simple synchronization procedure can significantly improve the elevation angle estimates, and verify this in field experiments using two Bluetooth antenna arrays.

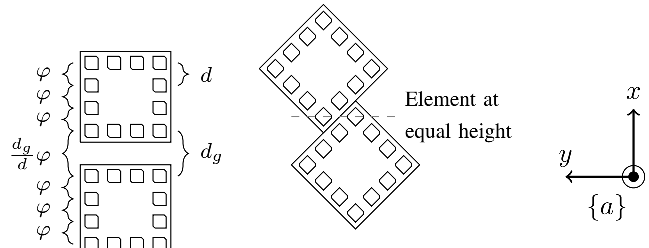
The paper proceeds as follows: In Section II we discuss the positioning of two arrays to enable phase synchronization in the presence of ground reflection multipath. Section III presents the measurement processing and direction estimation method, and presents simulation results for predicted results. Results from a field experiment are presented in Section IV, and finally, conclusions are drawn in Section V.

II. Array positioning for synchronization in the presence of multipath

Large spacing between arrays would be beneficial for multipath error reduction. In the absence of multipath, receiving only a signal directly propagating from the transmitter to all array elements, finding the phase bias between the arrays would be straightforward, allowing easy synchronization. Consider for example the two vertically spaced arrays in Fig. 1a. The phase angle difference between antennas placed along a straight line would differ only due to differences in the distance along the line. Therefore, for arrays with element spacing d and vertical phase differences φ, the deviation between the phase difference measured across the gap d_g between arrays and the expected phase difference $\frac{d_g}{d}\varphi$ for the element gap would be the bias in the phase between arrays.

In the presence of multipath, the measured phase difference between vertically uniformly spaced antennas is not equal but depends on the distance from the reflection surface, which in the following is assumed to be the ground. This effect can, in theory, be modeled, but in practice, the ground surface is often uneven, not perfectly level, and the height over the surface may not be exactly known. Determining the phase bias is therefore no longer trivial with a gap between the arrays. With a high number of antenna elements with a small spacing, the phase difference between pairs along the vertical would be smoothly varying, and it could be possible to predict the phase difference across the array gap by using curve fitting. The accuracy of this would be reduced as the gap between arrays increases.

By eliminating the gap between arrays, with both arrays having at least one element each at the same height, multipath should no longer be an issue in determining the phase bias. Fig. 1b illustrates an example of such setup.



(a) With gap (b) With one element at equal height (c) Frame definition

Fig. 1: Two different configurations of vertically stacked arrays, and the array frame definition used in Section III.

The elements at the same height for both arrays can be expected to be affected equally by ground reflection multipath interference. The difference in phase measurement between these after azimuth angle correction can therefore provide information about the reference phase difference between the arrays, without needing to model the interference with the reflected signal.

III. Measurement processing and direction estimation

The method considered for AoA estimation for an in-phase and quadrature (IQ) complex measurement vector $\boldsymbol{x}$ from a single array, is to find the direction parameters Ψ, α maximizing the conventional beamformer [5], [6] spatial pseudo-spectrum

$$P(\Psi, \alpha) = |\boldsymbol{a}(\Psi, \alpha)^H \boldsymbol{x}|^2, \tag{1}$$

with the steering vector

$$\boldsymbol{a}(\Psi, \alpha) = e^{\frac{2\pi j}{\lambda} \boldsymbol{P}^{a\top} \boldsymbol{l}^a(\Psi, \alpha)}. \tag{2}$$

λ is the signal wavelength, $\boldsymbol{P}^a$ is the matrix of array element positions in the array frame $\{a\}$, and $\boldsymbol{l}^a(\Psi, \alpha)$ is the line-of-sight vector corresponding to the direction parameters Ψ, α. See Fig. 1c for definition of $\{a\}$. For two arrays it is assumed that both sample the Constant Tone Extension (CTE) of the same Bluetooth packets, meaning that they sample at nearly identical times and using the same frequency channel. It is important to distinguish between only combining the signal power from both arrays, and combining the measurements as if we have a single large array with increased size. The former can be done by simply averaging the direction result from each array, or by combining the spectrum from each array,

$$P(\Psi, \alpha) = |\boldsymbol{a}_1(\Psi, \alpha)^H \boldsymbol{x}_1|^2 + |\boldsymbol{a}_2(\Psi, \alpha)^H \boldsymbol{x}_2|^2, \tag{3}$$

and finding the new combined peak. Since the phase angle of $\boldsymbol{a}_1(\Psi, \alpha)^H \boldsymbol{x}_1$ and $\boldsymbol{a}_2(\Psi, \alpha)^H \boldsymbol{x}_2$ do not influence the spectrum values in (3), the relative positions of the arrays make no difference in the processing, and the element positions in each steering vector are independent and do not have to use the same origin for this method. This essentially results in a weighted average of the two independent estimates, by combining the spectra of each, and does not result in increased angular resolution in any direction, as would be the case for an array of increased size. The multipath error is not reduced in the way processing the measurements as one large array would. The goal of processing the measurements together is to produce a better estimate than what can be obtained by combining the direction estimates from each array.

To use the measurements together for estimation with improved resolution, the relative position of the arrays should be known with high accuracy and precision. The steering vector for each array, including phase offsets φ_1 and φ_2, can be formulated as

$$\boldsymbol{a}_1(\Psi, \alpha, \varphi_1) = e^{\frac{2\pi j}{\lambda} \boldsymbol{P}_1^{a\top} \boldsymbol{l}^a(\Psi, \alpha) + \varphi_1 j}, \tag{4}$$

$$\boldsymbol{a}_2(\Psi, \alpha, \varphi_2) = e^{\frac{2\pi j}{\lambda} \boldsymbol{P}_2^{a\top} \boldsymbol{l}^a(\Psi, \alpha) + \varphi_2 j}, \tag{5}$$

where $\boldsymbol{P}_1^a$ and $\boldsymbol{P}_2^a$ should have the same origin. Considering only the phase bias of one array relative to the other, the steering vectors can instead be formulated as

$$\boldsymbol{a}_1(\Psi,\alpha) = \boldsymbol{a}_1(\Psi,\alpha,0) = e^{\frac{2\pi j}{\lambda}\boldsymbol{P}_1^{a\top}\boldsymbol{l}^a(\Psi,\alpha)}, \quad (6)$$

$$\boldsymbol{a}_2(\Psi,\alpha,\Delta\varphi) = e^{\frac{2\pi j}{\lambda}\boldsymbol{P}_2^{a\top}\boldsymbol{l}^a(\Psi,\alpha)+\Delta\varphi j}, \quad (7)$$

with the combined steering vector for all measurements being

$$\boldsymbol{a}(\Psi,\alpha,\Delta\varphi) = \begin{bmatrix}\boldsymbol{a}_1(\Psi,\alpha)\\ \boldsymbol{a}_2(\Psi,\alpha,\Delta\varphi)\end{bmatrix}. \quad (8)$$

If $\Delta\varphi$ is known, and the measurements from each array have been compensated for carrier frequency offset (CFO) to transform all measurements to baseband, the same method can be used for direction estimation for the combined array as for each array individually. By creating simulated measurements using a spherical-wave model and multipath as in [12] with the array configuration in Fig. 1b with element spacing $d = 5\text{cm}$, the lowermost element $10\,\text{cm}$ over the flat reflecting surface, and the combined array's boresight direction pointing horizontally, Fig. 2 shows the estimated elevation angle for different methods. The estimate error from the lowermost array has a lower spatial frequency than the top array, with both having significant deviation in the $5°$ to $15°$ range. Averaging the independent estimates does not yield the same result as using (3), although they behave similarly. For elevation angles where both independent estimates are above or below the true value, both of these methods also result in an estimate above or below the true value, respectively. This is in contrast to the result from treating the array combination as a single array using perfectly synchronized measurements. An interesting observation is that even if the $\Delta\varphi$ assumed in processing is inaccurate, the elevation angle estimate may still be improved. A $15°$ offset in the phase bias results in approximately $1°$ offset in the elevation angle estimate for the array positioning used. Estimation error noise for $\Delta\varphi$ can therefore be expected to reduce the systematic elevation error at the expense of increased elevation noise. Since multipath error is primarily height-dependent, we can calculate an estimate of the phase bias between arrays by assuming that the difference in phase measurement between elements at the same height in each array, after compensation for azimuth angle error estimated using only a single array, must be caused by the phase offset between the arrays. The following method is proposed:

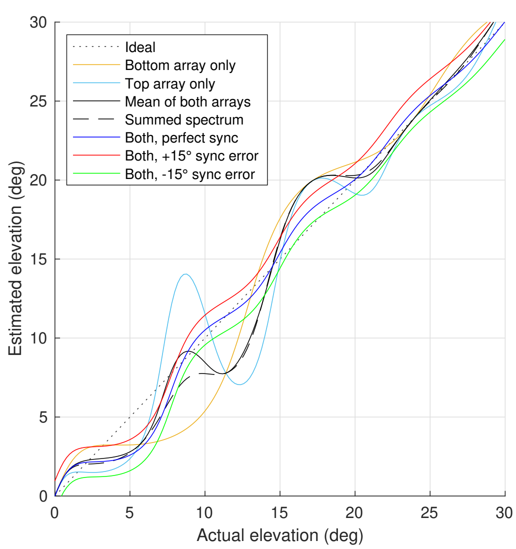


Fig. 2: Comparison of processing methods for simulated measurements.

1) For each array individually, estimate the CFO and correct the measurements to baseband, see [12].
2) Estimate the signal line-of-sight vector $\hat{\boldsymbol{l}}^a$ using only the lowest array, with a coarse search and an NLP solver, [12]. This will provide the steering vector to compensate for the difference between the phase of the elements at equal heights due to the azimuth angle to the transmitter.
3) Calculate the estimated phase offset

$$\widehat{\Delta\varphi} = \text{Arg}\left(\boldsymbol{a}_{\text{azimuth}}(\Psi,\alpha)^H \sum_{i=1}^{n_1}\boldsymbol{x}_{1,i}\right) - \text{Arg}\left(\sum_{i=1}^{n_2}\boldsymbol{x}_{2,i}\right) \quad (9)$$

where

$$\boldsymbol{a}_{\text{azimuth}}(\Psi,\alpha) = e^{\frac{2\pi j}{\lambda}\begin{bmatrix}0 & d & 0\end{bmatrix}\hat{\boldsymbol{l}}^a}$$

is the compensation for azimuth angle for two elements at the same height, spread by the distance d. $\text{Arg}(\cdot)$ is the complex argument. A weakness of this simple approach is that azimuth estimation error will influence the elevation angle estimate.
4) Using coarse search and optimization, find Ψ,α by maximizing

$$P(\Psi,\alpha,\widehat{\Delta\varphi}) = \left|\begin{bmatrix}\boldsymbol{a}_1(\Psi,\alpha)\\ \boldsymbol{a}_2(\Psi,\alpha,\widehat{\Delta\varphi})\end{bmatrix}^H \begin{bmatrix}\boldsymbol{x}_1\\ \boldsymbol{x}_2\end{bmatrix}\right|^2. \quad (10)$$

IV. Field Experiments

Two experimental reference design antenna arrays from Nordic Semiconductor were assembled as in Fig. 1b. This was done by mounting the arrays on a thick and completely flat plate, resulting in minimal deviation in the mounting planes of the arrays. The assembly is shown in Fig. 3, set up on a grass runway. A small two-dimensional bubble level mounted on the assembly was used for visual leveling.

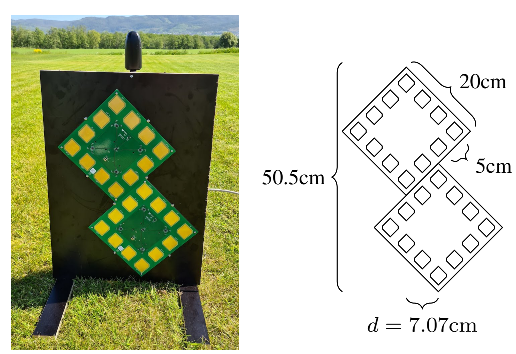


Fig. 3: Setup of array assembly for experiments.

A multirotor UAV with the same Bluetooth transmitter payload and GNSS receiver as in [12] was used, with a GNSS receiver working as a real-time kinematic (RTK) base mounted on the top of the array mounting plate. The UAV performed a flight using waypoints along approximately a constant azimuth angle in front of the arrays, varying the distance and height. A plot of the UAV position is shown in Fig. 4. IQ measurements from both arrays were logged for offline estimation. Only the 2402 MHz advertising channel was used.

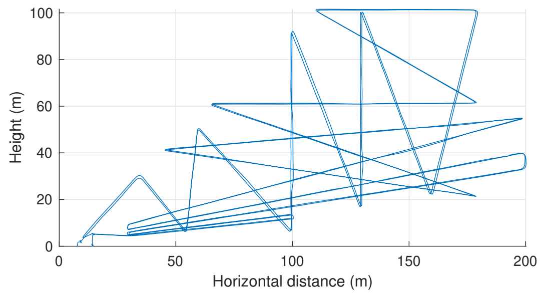


Fig. 4: Side view of the UAV flight path. The array is located at the origin, with the horizontal axis indicating the distance from the array.

The elevation angles were estimated both individually for each array, and as one array by synchronizing the measurements. Fig. 5 shows the CFO estimates for each array used to convert the measurements to baseband.

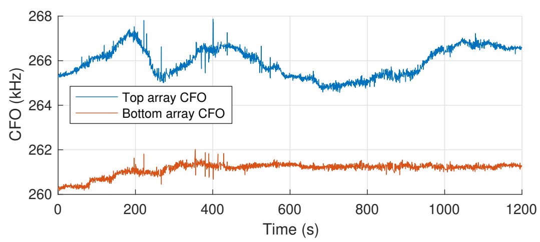


Fig. 5: CFO estimates for the two arrays

The elevation and azimuth angle estimates are plotted in Fig. 6. The path in Fig. 4 was flown twice, causing the repeated elevation pattern. Height offsets for RTK GNSS antennas were corrected when calculating the GNSS elevation angle. The variation in azimuth angle is likely the result of roll angle array leveling errors. The elevation angles are also plotted as a function of the GNSS elevation estimate in Fig. 7, showing

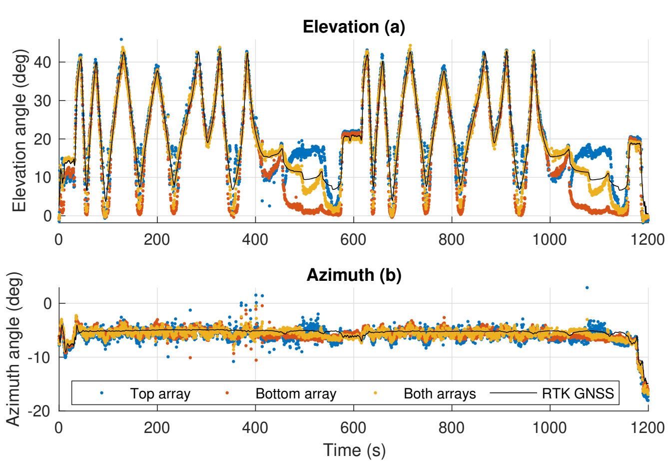


Fig. 6: Elevation (a) and azimuth (b) plots. The GNSS values cannot be used to assess accuracy for azimuth in this case, as the heading of the array boresight has been found by comparing the GNSS and Bluetooth estimates.

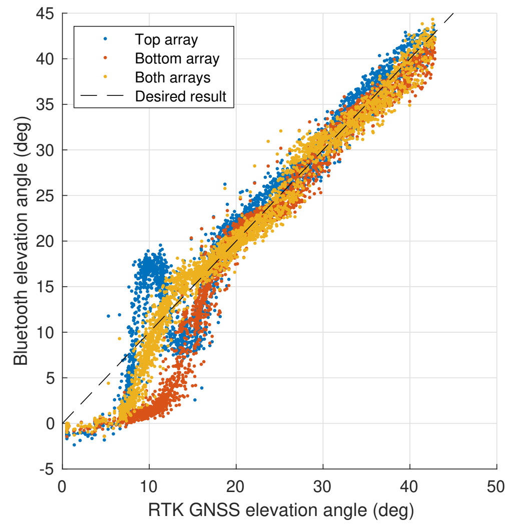
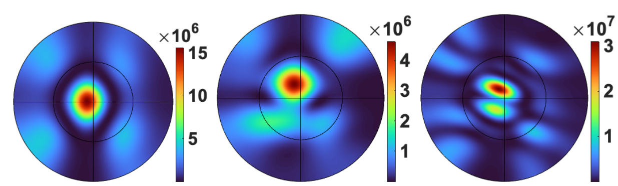


Fig. 7: Bluetooth elevation angle estimates plotted as a function of the RTK GNSS elevation angle.

the systematic error behavior. It is clear that the combined processing significantly reduces the error in the elevation angle range 7° to 15°. For the lowest angles, below approximately 7°, the results are similar, with negative elevation angle estimates. Above 20 degrees elevation the results are also similar. The error pattern for each array resembles the one predicted from simulation in Fig. 2. Examples of calculated spatial spectra for a common time are shown in Fig. 8, where it is clear that the combined processing increases the angular resolution in the vertical direction, allowing separation of the direct and reflected signals as individual peaks. Since the top array is offset to the side compared to the lower array, the direction of maximum resolution in the combined spectrum is not exactly in the vertical direction, but at an angle.



(a) Bottom array (b) Top array (c) Combined

Fig. 8: Example spatial pseudo-spectra, when the RTK GNSS elevation angle is 11.4°. The edges of the spectra are at 90° from the array boresight, with the top of each spectrum pointing towards the zenith, and the center pointing horizontally.

V. Conclusion

This paper has considered the combined use of two independent arrays and proposed a measurement synchronization procedure to allow the measurements from both arrays to be used together for direction estimation as for a single larger array. The results from a field experiment show that the proposed method yields a significant reduction of elevation error due to multipath in the 7° to 15° range, while maintaining similar azimuth estimation performance.

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