DOA ESTIMATION OF MULTIPLE SPARSE SOURCES USING THREE WIDELY-SPACED SENSORS

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ABSTRACT

Traditionally, Direction Of Arrival (DOA) estimation methods require an inter-sensor spacing that does not exceed half the minimum wavelength of the impinging signal in order to avoid ambiguities. Placement of sensors at the minimum half wavelength is not physically realizable for some types of signals. Additionally, for some categories of signals, half wavelength spacing is not sufficient to achieve good DOA resolution. In this paper, our previously proposed delay disambiguation method is combined with a time-delay estimation method that exploits source sparsity in time-frequency domain to unambiguously estimate the DOAs of multiple sources impinging on three *widely-spaced* sensors. The approach is applied to DOA estimation of multiple ultrasonic Frequency Hopping Spread Spectrum (FHSS) sources in indoor environment. Experimental results emphasize the robustness of the approach even when the number of sources exceeds the number of sensors.

1. INTRODUCTION

Direction Of Arrival (DOA) estimation for multiple signals is a problem of great importance for many applications. Different methods have been proposed in the literature in the few last decades [12]. Normally, these methods require a number of sensors that exceeds the number of sources. Typically M sensors are required to resolve $M-1$ sources.

A simple way to estimate DOA of a signal is based on time-delay or Time Difference Of Arrival (TDOA), e.g., [11]. Despite the the fact that TDOA based DOA estimation is generally suitable for a single-source case, it has been shown that, it can be extended to the multi-source case by exploiting source sparsity [8, 9]. The extended methods have the advantage that multiple sources can be resolved using as few as two sensors [8].

A limitation that is inherent in most DOA estimation methods is that they impose some restrictions on the sensor configuration. Traditionally, the sensors must be placed *at most* $\lambda_{min}/2$ (minimum half wavelength) apart. Otherwise, a DOA ambiguity occurs due to spatial aliasing (or phase wrapping). For some categories of signals, including ultra-wideband radio [3] and ultrasonic [6], sensor placement at $\lambda_{min}/2$ is physically unrealizable due to the smallness of λ_{min} compared to the dimensions of the sensors. In this case, placing the sensors at distances that exceed $\lambda_{min}/2$ is inevitable. In many cases, increasing inter-sensor spacing is required for the purpose of increasing DOA estimation resolution [13]. In such systems, resolving ambiguities represents a significant problem.

In [6], a disambiguation method is proposed but is limited to a single and predefined frequency case, and is not suitable for multi-frequency signals. In [10], disambiguation is achieved by applying a phase unwrapping method. However, the approach assumes a single source scenario. Moreover, the existence of low frequency bands that contribute unambiguous estimates is essential for phase unwrapping to be performed. The presence of such estimates is not guaranteed in many cases of bandpass signals when inter-sensor spacing exceeds even the *maximum* half wavelength ($\lambda_{max}/2$). In [3], ambiguities in a subspace based method are resolved exploiting frequency diversity. The approach can be applied to multi-source cases. However, it relies on the assumption that the set of ambiguous estimates of DOA yielded by the subspace method includes the true DOA with sufficient density. This assumption is also hard to satisfy in many cases involving bandpass signals with maximum half wavelength below or comparable to the sensor spacing.

In [1], we proposed a solution for the phase-difference ambiguity problem applied to a single-frequency signal. In this paper, we show that exploiting source sparsity together with the method in [1], unambiguous DOA estimation of multiple sparse sources when the sensors are widely-spaced can be achieved. The approach does not depend on the presence of the true DOA estimates amongst the ambiguous set of estimates, and can hence be applied in the case of bandpass signals even when the sensor spacing exceeds the maximum half wavelength. The proposed method also has the ability of handling the case when the number of sources exceeds the number of sensors.

The proposed method is applied to DOA estimation of multiple ultrasonic Frequency Hopping Spread Spectrum (FHSS) signals in indoor environment in the context of indoor location and/or orientation estimation (see [4], [5]and [6]). The introduction of FHSS in such systems was motivated by the fact that FHSS was shown to improve performance against noise and reverberation compared to other techniques [7]. The frequency range of interest is (35-50 kHz). Sensor placement at $\lambda_{min}/2$ is unrealizable for this range [6].

The remainder of this paper is organized as follows. Section 3 summarizes the delay disambiguation method we proposed in [1]. Section 3 summarizes the basic DOA estimation approach based on source sparsity. Section 4, extends the approach in Section 3 to the widely-spaced sensors case. Section 5 and 6 presents experimental and simulation results respectively. Finally, Section 7 gives the conclusion of the paper.

2. DELAY DISAMBIGUATION SUMMARY

The disambiguation method proposed in [1] exploits the spatial diversity provided by a third collinear sensor. Assuming the sensor configuration in Fig. 1, the method can be summarized as follows. For a frequency component f in a noise-free situation, the condition for *almost sure* identifiability of the delay between sensor 1 and sensor 2 can be stated as

$$\Delta < \frac{\lambda}{2} \tag{1}$$

where $\Delta = d_{23} - d_{12}$ as in Fig. 1, and λ is the wavelength corresponding to f. The relation between the true and the ambiguous delays is stated as

$$\delta_{12} = \delta_{12}^{a} + \frac{n_{12}}{f} \tag{2}$$

$$\delta_{23} = \delta_{23}^{a} + \frac{n_{23}}{f} \tag{3}$$

where $\left[\delta_{12}^{a}, \delta_{23}^{a}\right] \subset [-1/2f, 1/2f]$ are the ambiguous delays, and $[n_{12}, n_{23}] \subset \mathbb{Z}$ are the effects of phase wrapping. Exploiting the condition in (1), the set of candidate estimates for the true delay is

$$\delta_{12}^{(n)} = \frac{d_{12}}{\Delta}\left(\delta_{23}^{a} - \delta_{12}^{a} + \frac{n}{f}\right), \ \forall n \in \{-1,0,1\} \quad (4)$$

and the true delay is estimated as

$$\hat{\delta}_{12}^{t}, = \ \delta_{12}^{(l)}, \ l \in \{-1,0,1\}, \text{ where } \exists_{=1}\delta_{12}^{(l)} \in \left[\frac{-d_{12}}{c}, \ \frac{d_{12}}{c}\right] \quad (5)$$

and $\exists_{=1}$ reads "there is exactly one", and c is the speed of propagation of the signal.

Since $\exists_{=1}\delta_{12}^{(l)} \in [-d_{12}/c, \ d_{12}/c]$ also indicates that $\delta_{12}^{(l)}$ is the estimate with the minimum absolute value, (5) can be rewritten as

$$\hat{\delta}_{12}^{t} = \ \delta_{12}^{(l)}, \text{ where } |\delta_{12}^{(l)}| = \min\left(|\delta_{12}^{(n)}|\right), \ \{n,l\} \in \{-1,0,1\} \quad (6)$$

and min(.) denotes the minimum value.

Eq. (6) can perfectly restore the true delay in a noise-free situation. In a more realistic situation, $\hat{\delta}_{12}^{t}$ from (6) can be inserted into (2) to obtain an estimate for n_{12}. The estimate for n_{12} can then be rounded to the nearest integer to compensate for error due to noise and inserted back in (2) to obtain the final estimate of the true delay. The whole algorithm can be summarized as

$$\hat{\delta}_{12} = \quad \delta_{12}^{a} \quad + \frac{\Psi\left(\left(\hat{\delta}_{12}^{t} - \delta_{12}^{a}\right) \times f\right)}{f} \quad (7)$$

where $\Psi(.)$ is a rounding function, and $\hat{\delta}_{12}^{t}$ is given by (6).

3. SUMMARY OF DOA ESTIMATION BASED ON SOURCE SPARSITY

The basic approach for DOA estimation of multiple sources exploiting source sparsity in time-frequency domain is described in this section. The signal model can be summarized as [9]

$$X_m(f,\tau) \approx \sum_{i=1}^{I} H_{im}(f)\, S_i(f,\tau), \ \forall m \in \{1,...,M\} \quad (8)$$

where X_m are the Short-Time Fourier Transforms (STFTs) of the observations at each sensor; S_i are the STFTs of the source signals; H_{im} is the frequency response of the system between source i and sensor m; I and M are respectively the number of sources and the number of sensors; and f and τ are frequency and time respectively.

If the sources are sufficiently sparse, (8) can be reduced to

$$X_m(f,\tau)_i \approx H_{im}(f)\, S_i(f,\tau)_i, \ \forall i, \forall m \quad (9)$$

where $(f,\tau)_i$ are the time-frequency points for which source i is *dominant*.

Further, ignoring reverberation, (9) can be further approximated as:

$$X_m(f,\tau)_i \approx \exp(-j2\pi f T_{im})\, S_i(f,\tau)_i, \ \forall i, \forall m \quad (10)$$

where T_{im} is the time delay between source i and sensor m locations.

Given only two observations X_1 and X_2, the delay of source i between sensor 1 and sensor 2 can be estimated as [8]

$$\delta_{12,i}(f,\tau)_i = \frac{1}{2\pi f} \arg(X_1(f,\tau)_i \ X_2^*(f,\tau)_i), \ \forall i \quad (11)$$

where "*" denotes the complex conjugate. Eq. (11) results in a set of estimates that correspond to the delays of all sources that are present. These estimates can be clustered [8, 9] and the center of the clusters can be taken as the final delay estimates of the sources ($\hat{\delta}_{12,i}$). DOAs can then be estimated as:

$$\hat{\theta}_i = \arcsin\left(\frac{c\,\hat{\delta}_{12,i}}{d_{12}}\right), \ \forall i \quad (12)$$

where c is the speed of propagation, and d_{12} is the distance between sensor 1 and sensor 2.

4. PROPOSED METHOD FOR DOA ESTIMATION USING WIDELY-SPACED SENSORS

The proposed DOA method exploits the sensor configuration in Fig. 1. For the widely-spaced sensors case, d_{12} *at least* exceeds $\lambda_{min}/2$. The proposed method requires that the distance Δ satisfies (1) for $\lambda = \lambda_{min}$. For this configuration, the ambiguous delays can be estimated as

$$\hat{\delta}_{12}^{a}(f,\tau) = \frac{1}{2\pi f} \arg(X_1(f,\tau)\ X_2^*(f,\tau)), \ \forall (f,\tau) \quad (13)$$

and

$$\hat{\delta}_{23}^{a}(f,\tau) = \frac{1}{2\pi f} \arg(X_2(f,\tau)\ X_3^*(f,\tau)), \ \forall (f,\tau) \quad (14)$$

To obtain the estimates of the true delays $\hat{\delta}_{12}(f,\tau)$, (7) is applied on the ambiguous estimates in (13) and (14). Consequently, we obtain

$$\hat{\delta}_{12}(f,\tau) = \delta_{12}^{a}(f,\tau) \quad + \frac{\Psi(\ (\hat{\delta}_{12}^{t}(f,\tau) - \delta_{12}^{a}(f,\tau)) \times f\ )}{f}, \quad \forall (f,\tau) \quad (15)$$

where $\Psi(.)$ is a rounding function, and $\hat{\delta}_{12}^{t}(f,\tau)$ are estimated based on (6).

In other words, (7) is independently applied to each pair of ambiguous estimates from a time-frequency point (f,τ). This independence in the disambiguation process among all (f,τ) means that, finding the unambiguous DOA does not depend on the existence of (f,τ) points that yield unambiguous estimates. Based on that, the approach can be applied even in the case when the $\lambda_{max}/2$ limit is exceeded.

Finally, the delay estimates in (15) can be converted to DOA estimates using

$$\hat{\theta}(f,\tau) = \arcsin\left(\frac{c\,\hat{\delta}_{12}(f,\tau)}{d_{12}}\right), \ \forall (f,\tau) \quad (16)$$

The estimates in (16) represent estimates of the DOAs of all the sources present. In real situations, the estimates are contaminated with noise. The effect of noise causes deflections in the values of these estimates such that the estimates fluctuate around the true values of the DOAs. Extraction of DOA information for different sources from the estimates generated by (16) requires classification of these estimates. Typically, clustering algorithms are used to achieve this classification (e.g., [8] and [9]). A clustering algorithm classifies the DOA estimates into clusters, the centroids of which can be taken the final DOA estimates.

In order for the clustering to be carried out, first, the number of sources has to be estimated. The number of sources can be estimated as the number of peaks of the histogram of the delay estimates [8, 9]. This approach for estimating the number of sources suggests the histogram as an alternative method for carrying out the estimates classification, and taking the locations of the histogram peaks directly as the final DOA estimates. Herein, the latter Histogram Peaks (HP) approach is compared with the former clustering of estimates approach. The standard k-means algorithm [14] was used to achieve the clustering.

The complete method for DOA estimation using three widely-spaced sensors is summarized as:

1) Estimate the ambiguous delays using Eq. (13) and (14).
2) Disambiguate the delays using Eq. (15).
3) Convert the delays to DOAs using Eq. (16).
4) Construct the Histogram of all the DOA estimates.
5) Number of sources = number histogram peaks = I.
6) Clustering: DOAs = centroids of the clusters, *or*
DOAs = location of histogram peaks.

5. EXPERIMENTAL TESTS

The proposed method as described in Section 4 was experimentally tested in a real office (see Fig. 2) that contained normal office equipment. Ultrasonic FHSS signals were used in the tests. An SMT361A DSP board [15], E-152/40 wideband ultrasonic transducers [16] and SPM0204UD5 ultrasonic sensors [17] were used in the implementation. The FHSS used 20 equally-spaced frequencies in the range (35 - 49.5) kHz with a hop duration of 3.2 ms. The modulation scheme was Binary Frequency-Shift Keying (BFSK) applied using randomly generated bits. The signals were sampled at approximately 168 kHz. The STFT used a Blackman window of length 512 and 384 overlap between successive windows together with a Fourier Transform size of 1024. Fig. 2 shows the locations of the transmitters and the receiver for all the tests with the heights given in the table attached with the figure. The transmitters and the receivers were situated on tripods that enabled control of height and angle. The receiver was composed of three ultrasonic sensors configured according to Fig. 1, with d_{12} = 10mm and Δ = 3mm (compare to $\lambda_{min}/2 = 3.6$mm and $\lambda_{max}/2 = 4.9$mm for $c = 343$ m/s!). This means that *all* the delay estimates for *all* the frequency components in the frequency range of interest were subject to the ambiguity problem.

5.1 Single-source Tests

As a proof of concept, a single-source scenario was considered. The transmitter was located at location T0 and the receiver at location R1, as indicted in Fig. 2. Different DOAs were tested by rotating the panel containing the sensors around the tripod axis. Fig. 3 demonstrates how the delay disambiguation method is employed to unambiguously estimate the DOA of a signal. The true DOA was measured as -47.7^o. Fig. 3 (a) and (b) depict histograms of DOA estimated from the ambiguous delay estimates $\hat{\delta}^a_{12}(f,\tau)$ and $\hat{\delta}^a_{23}(f,\tau)$ respectively. The number of signal snapshots used was 1500. Due to the phase wrapping phenomenon that varies among the frequencies, several spurious peaks appear in Fig. 3(a) and (b). On the other hand, Fig. 3 (c) shows the result of disambiguation which combines the apparently random estimates in Fig. 3 (a) and (b) to produce a clear peak at approximately -45.0^o.

The proposed method was exhaustively tested and was seen to yield consistent DOA estimates without noticeable failure. Table 1 summarizes the results for the single-source tests. Results for four different DOAs are presented. For each DOA, the mean, bias (estimated as the deviation of the mean from the ground truth) and RMSE (Root Mean Square Error) were estimated from 10 different tests, each used 1500 snapshots.

5.2 Multi-source Tests

Two sets of tests were conducted for the multi-source case. The first involved 3 sources and the second involved 4 sources using only 3 sensors in both cases. The results were calculated from 35 tests for the same setting. Each test used 3000 snapshots.

5.2.1 Three Sources

Three transmitters were located at T1, T2 and T3.1 while the receiver was placed at R2. The setting corresponds to DOAs of 48.8^o, -15.4^o and -58.2^o. The results are summarized in Table 2. Table 2 compares the HP approach with k-means clustering based on the mean, bias and the RMSE (Root Mean quare Error). It is noticeable from the table that the HP approach significantly outperforms k-means clustering. This result may be specific to the type of signals used in the tests, since clustering was effectively used for DOA estimation of speech signals (e.g., [9] and [10]).

5.2.2 Four Sources

The transmitters locations were at T1, T2, T3.2 and T4. The receiver was at R2. The setting corresponds to DOAs of 48.8^o, 11.3^o, -15.4^o and -52.3^o. Fig. 4 shows an example histogram of the DOA estimates with four clear peaks at 49.8^o, 12.8^o, -15.5^o and -52.4^o. Table 3 summarizes the results for this setting, and again the superiority of the HP approach for the ultrasonic FHSS case is observable.

5.2.3 Calibration Error Effect

For the same four-source scenario, the a test was performed to study the effect of calibration on the performance of the proposed method. The purpose was to see how robust the proposed method to calibration errors (see Eq. (15)). Random noise was added to the measurements of d_{12} and Δ giving noisy measurements $d_{12}+\varepsilon_d$ and $\Delta+\varepsilon_\Delta$. The noise values ($\varepsilon_d$ and ε_Δ) were uniformly distributed in the interval $[-\beta,\beta]$. The value of β was varied and for each value of β, the proposed method was applied to 3000 signal snapshots. The process was repeated 100 times for each β allowing new random values of ε_d and ε_Δ to be tested. The RMSE corresponding to each β was estimated based on the 100 DOA estimates. Fig. 5 shows the variation of the RMSE in degree with β. It can be seen that the RMSE increases as β increases. However, the RMSE remains reasonably small for moderate values of β (e.g., $\beta <$ 1mm). Fig. 5 also reveals that the RMSE increases as we approach the end-fire of the array (source 1 and source 4). In general, Fig. 5 emphasizes the fact that the proposed method does not suffer from disambiguation failures due to calibrations errors, as severe failures are expected to cause *jumps* in the RMSE. The RMSE is seen to consistently increase as the calibration error increases.

6. IMPROVING DOA RESOLUTION

In this section, we show how the proposed method can be used to improve DOA resolution even when the sensor placement at $\lambda_{min}/2$ is possible. This implies that the method can be used with other categories of sparse signals, e.g., speech to improve DOA resolution. Here, we define resolution as the ability to resolve closely-spaced sources [12]. The signals used were same as those in Section 5. Due to the difficulty of placing ultrasonic sensors at distances as small as $\lambda_{min}/2$, the tests that demonstrate the benefit of the proposed method in improving DOA resolution were carried out in simulation. Sensors were modeled as points, and small inter-sensor spacing were hence implementable.

To carry out the task, a scenario was defined such that three sources are located at approximately 1.5m, 1.4, and 1.5m from the sensor triplet. The DOAs were -19.5^o, 0^o and 19.5^o respectively. SNR was 3dB and was defined as a mixture power to noise power. Fig. 6 compares the histograms of the DOA estimates from unambiguous delays for different inter-sensor spacings. In Fig. 6 (a), sensor 1 and sensor 2 were placed 3mm (compare to $\lambda_{min} \approx 3.5$mm). This represents an unambiguous case, however, the histogram does not show any noticeable peaks near the true DOAs. Note that only two sensors are sufficient to unambiguously estimate the delays between sensor 1 and sensor 2. In Fig. 6 (b), d_{12} was increased to 4mm and a third sensor was added for disambiguation. The sources are still unobservable. Fig. 6 (c) shows an improvement in resolution for d_{12}=6mm. The resolution was further improved in Fig. 6 (d) for d_{12}=10mm, which represents the best case. Increasing d_{12} further, resulted in a slight deterioration in resolution as in Fig. 6 (e) (d_{12}=20mm), and a significant deterioration in Fig. 6 (f) (d_{12}=40mm). The conclusion of this section is that the proposed method can be applied to improve the DOA resolution by allowing large inter-sensor spacing. However, increasing the spacing does not persistently increase resolution. The factors that impose this limitation will be addressed by our future research.

7. CONCLUSION

In this paper, a DOA estimation method for multiple signals received by three widely-spaced sensors is presented. The method exploits both the sparsity of the sources and a specific sensor configuration to achieve an ambiguity-free DOA estimation. The performance of the method was experimentally studied and evaluated

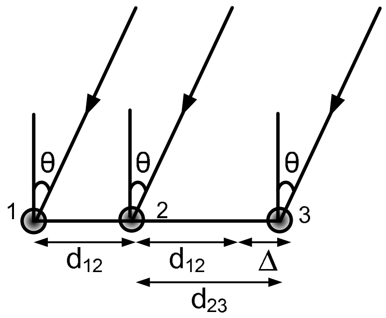
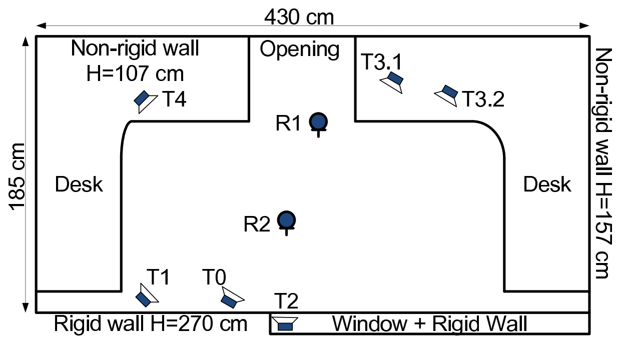


Figure 1: Sensor configuration.



Location	T0	T1	T2	T3.1	T3.2	T4	R1	R2
Height (cm)	150	150	150	150	175	175	62	62

Figure 2: Test room with the locations of the transmitters (T) and the receiver (R) for different tests marked. Heights are given in the attached table.

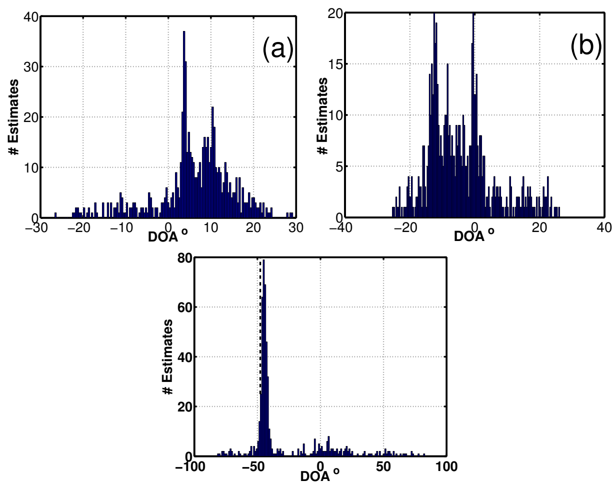


Figure 3: DOA histograms for a single source case: a) DOA based on ambiguous delays between sensor 1 and sensor 2; b) DOA based on ambiguous delays between sensor 2 and sensor 3; c) DOA based on disambiguated delays.

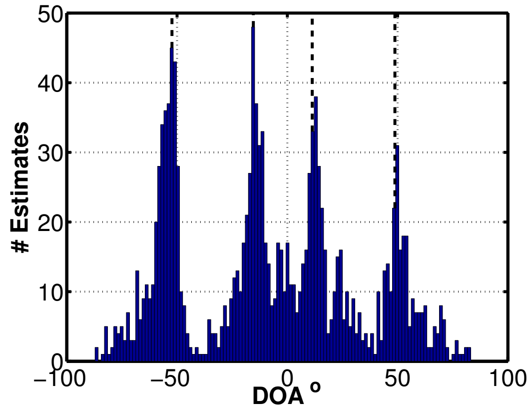


Figure 4: Histogram from experimental data. Four sources present.

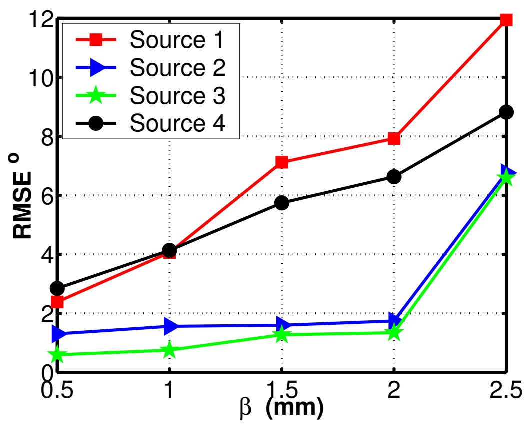


Figure 5: Calibration Error Effect.

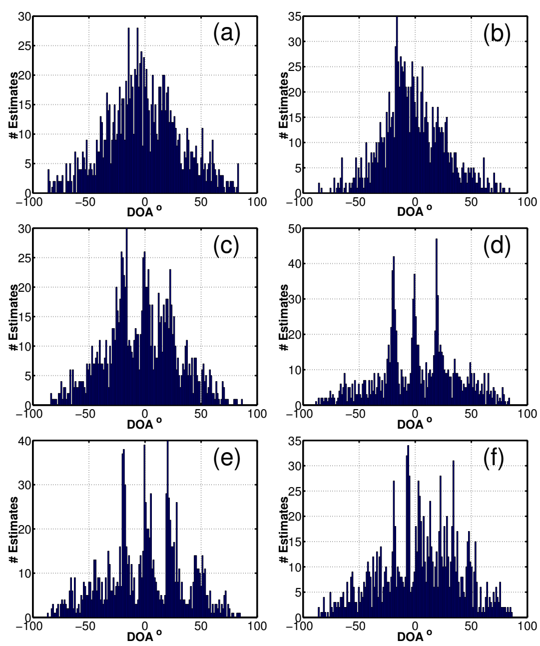


Figure 6: Improving DOA resolution using the proposed method.

Table 1: Experimental Results: DOA of a single source using 3 widely-spaced sensors.

DOA	*mean*	*Bias*	*RMSE*
0.9^o	0.7^o	-0.2^o	0.4^o
-24.7^o	-25.8^o	-1.1^o	1.1^o
-47.7^o	-45.0^o	2.7^o	2.8^o
-60.1^o	-57.9^o	2.2^o	2.2^o

Table 2: Experimental Results: DOA of 3 sources using 3 widely-spaced sensors.

	HP			K-means		
DOA	*mean*	*Bias*	*RMSE*	*mean*	*Bias*	*RMSE*
-58.2^o	-56.8^o	1.4^o	2.1^o	-59.7^o	-1.5^o	2.1^o
-15.4^o	-14.9^o	0.5^o	1.4^o	-11.8^o	3.6^o	8.2^o
48.8^o	46.9^o	-1.9^o	2.1^o	42.1^o	-6.7^o	8.6^o

based on the mean, bias and RMSE of the DOA estimates. The effect of calibration errors was also considered. The method was applied to ultrasonic FHSS signals in indoor environment, however, the general formulation of the method renders it applicable to other types of sparse signals in different environments.

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Table 3: Experimental Results: DOA of 4 sources using 3 widely-spaced sensors.

	HP			K-means		
DOA	*mean*	*Bias*	*RMSE*	*mean*	*Bias*	*RMSE*
-52.3^o	-52.3^o	0.0^o	0.8^o	-60.2^o	-7.9^o	9.9^o
-15.4^o	-15.0^o	0.4^o	1.3^o	-25.4^o	-10.0^o	20.0^o
11.3^o	11.7^o	0.4^o	0.9^o	9.6^o	-1.7^o	8.6^o
48.8^o	47.5^o	-1.3^o	1.9^o	52.4^o	3.6^o	4.6^o

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