Poster: Distributed Voronoi-based Acoustic Source Localization with Wireless Sensor Networks

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ABSTRACT

This paper presents DiVA, a new acoustic source localization scheme that uses an ad-hoc network of microphone sensor nodes to produce an accurate estimate of the source's location. DiVA uses pairwise comparisons of sound detection timestamps between local Voronoi neighbors to identify the node closest to the acoustic source and then estimates the source's location. The scheme improves on the state of the art by effectively dealing with anchor nodes' position error, time stamp measurement error and time synchronization error in real world conditions. Through simulation and experimental evaluations, DiVA is shown to be more robust than existing solutions under different error conditions.

Categories and Subject Descriptors

J.0 [**Computer Applications**]: General

Keywords

Acoustic Source; Localization; Voronoi; Sensor Network

1. INTRODUCTION

The loss of flight MH370 in early 2014, and the failure to date to locate its wreckage, have shown the need for better methods of locating acoustic sources within a large area. An ad-hoc wireless sensor network deployed in the search area could use onboard microphones and a robust localization method to perform this task. A similar network could also be used for applications such as shooter localization [1], if deployed in advance.

This paper presents DiVA, a distributed Voronoi-based [2] acoustic source localization scheme. DiVA is based on the observation that an acoustic source may be roughly localized using only pairwise comparisons of sound detection timestamps of neighboring nodes, and that such comparisons are tolerant to reasonable amounts of error from either node.

DiVA is a unique hybrid solution, which first (1) uses a distributed Voronoi-based range-free method to identify a (small) final region where the source may reside, and then (2) uses a time difference of arrival based (TDOA-based) method to output a precise estimate of the source location by solving a constrained (on the identified final region) optimization formulation. DiVA is completely distributed, quick to converge, and robust to real-world conditions such as node failure, microphone position errors, sound time of arrival (TOA) measurement errors, and clock synchronization errors.

2. BASELINE APPROACH

DiVA's overall approach is to divide the area covered by the microphone nodes into local Voronoi cells and use pairwise comparisons between neighbors to traverse the diagram to the acoustic source. This is accomplished in four phases. In the initialization phase, nodes determine their local Voronoi neighbors (LVNs), a subset of their neighbors. Then, when a sound is heard, nodes collaborate with their LVNs to identify the node closest to the source of the sound. This node then uses information from its LVNs to narrow down the location to a target subregion. Finally, TDOA estimates are used to produce a final location estimate within the target subregion.

2.1 Phase I - Initialization

To participate in localization, a node must first determine its *Local Voronoi Neighbors* (LVNs) using its local neighbor information and a Voronoi diagram. Specifically, if V_A is the set of A's Voronoi Neighbors (VNs), C_A is the set of A's Communication Neighbor (CNs), and Φ_A is the set of A's LVNs, then $\Phi_A = V_A \cap C_A$.

When a node enters Phase I, it broadcasts a request to discover its CNs and their positions. With this information, the node can determine its set of LVNs by computing its local Voronoi diagram. This set is maintained over time as sensors join and leave. Since nodes in DiVA only track the information of their neighbors, DiVA is highly scalable.

2.2 Phase II - Target Cell Identification

In Phase II, each node that hears a sound matching the target acoustic signature, called a *beep*, designates itself the *leader*, shown in Figure 1(a), of its own *localization instance*, a unique execution of DiVA's localization process. This

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leader then probes its LVNs in a circular pattern, looking for an LVN closer to ▲, determined by comparing timestamps for the beep. These timestamps are corrected for clock offset between the nodes using a well-known one-hop local time synchronization method [3]. If the leader finds an LVN that is closer to ▲, it resigns leadership and promotes the closer LVN to leader, shown in Figures 1(a) - 1(c). In this way, leadership is passed among the nodes until the node closest to ▲ becomes the leader. This node probes all of its LVNs and finds none closer to ▲, and this node's cell is thus identified as the target cell, as shown in Figure 1(d).

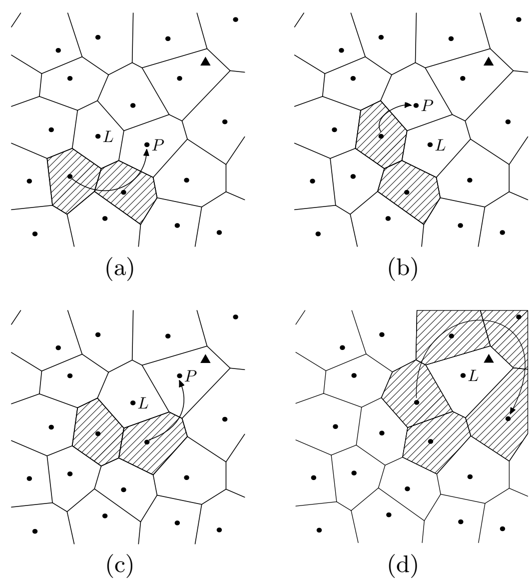


Figure 1: Example of Target Cell Identification.

Phase II is the key to guarantee DiVA's high robustness. In Phase II, DiVA is capable of detouring around nodes that have failed or are reporting excessively high microphone position error or beep measurement error. In these cases, a leader L may not promote P to leader, even though P may be closer to ▲ than L. However, if a second route exists, the leadership will be transferred around P and eventually to the node closest to ▲.

2.3 Phase III - Target Subregion Identification

Let L be the node whose local Voronoi cell was determined to contain ▲ in Phase II. In Phase III, L uses pairwise timestamp comparisons to narrow down the location of ▲ to a *target subregion* of its local Voronoi cell. First, L cuts its cell into subregions by drawing a perpendicular bisector between each pair of its LVNs. Then, for each cut, L determines which side of the cut contains ▲ by comparing the time stamp for the corresponding LVNs. L discards all subregions on the side of the cut without ▲. After slicing and discarding for each pair of LVNs, only the subregion containing ▲ remains.

2.4 Phase IV - Constrained Target Location Estimation

In Phase IV, L produces a final estimate of the target's location. The target subregion R identified in Phase III is trusted to contain ▲, so R is used as a constraint to aid in estimation.

First, L calculates TDOA estimates of the location of ▲ using all combinations of three nodes in $L \cup \Phi_L$, where Φ_L is the set of L's LVNs. The set of TDOA location estimates is denoted as T. L then performs a simple Grubbs' test [4] on these estimates to remove the outliers from T. Let T' denote the set of TDOA estimates remaining after the Grubbs' test. Then the final location estimate $\hat{t}$ is the point in R that minimizes the mean squared error (MSE) for $t_i = (x_i, y_i) \in T'$, as follows:

$$\hat{t} = (x^*, y^*) = \underset{(\hat{x},\hat{y})\in R}{\operatorname{argmin}} \frac{1}{|T'|} \sum_{t_i \in T'} \left[(x_i - \hat{x})^2 + (y_i - \hat{y})^2 \right]. \tag{1}$$

Finally, L reports $\hat{t}$ and its MSE to the user. If multiple estimates are reported for a single beep, the user selects the $\hat{t}$ with the lowest MSE as the most likely location of ▲. This ability to filter out false readings is another aspect of DiVA's robustness.

3. PRELIMINARY RESULTS

3.1 Simulation Study

A MATLAB simulation was used to evaluate DiVA in comparison to TOA and TDOA, as well as to gauge the effect of microphone position and beep measurement error on DiVA. The average distance from a node to its nearest neighbor, R, was used to normalize the results. Using a well-known formula, R was calculated for the 2D case as $R \approx 1.58$ m. The speed of sound, v_s, was taken to be 340 m/s. The clock synchronization error for DiVA was assumed to be 44 μs [3].

TOA and TDOA can use any group of three microphones to produce a location estimate. In the simulation, the estimates of all possible groups were calculated and sorted in ascending order by output error. The 40th percentile (denoted as $K = 0.4$) and 80th percentile ($K = 0.8$) measurements were then used in the comparisons with DiVA's average, shown in Figure 2. Figure 2 also shows a reduced version of DiVA that does not include Phase IV. This reduced version of DiVA uses the center of gravity of the target subregion found in Phase III as the location estimate.

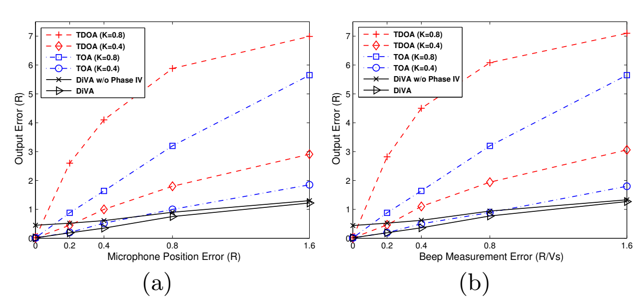
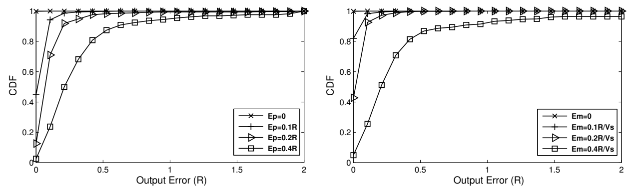


Figure 2: DiVA's output error versus (a) microphone position error and (b) beep measurement error, compared to TOA and TDOA.

The detailed effects of microphone position and beep measurement on DiVA are shown in Figure 3, which shows the cumulative distribution functions (CDFs) for output error at four different levels of microphone position or beep measurement error. Clock synchronization error is held constant at 44 μs. DiVA performs well, almost always producing an output error less than R for position error up to $0.4R$ or measurement error up to $0.4R/v_s$. This means that ▲ is unlikely to be farther from the estimated location than any given node is from its "known" position.



(a) (b)

Figure 3: CDFs of DiVA's output error for various amounts of (a) microphone position error and (b) measurement error.

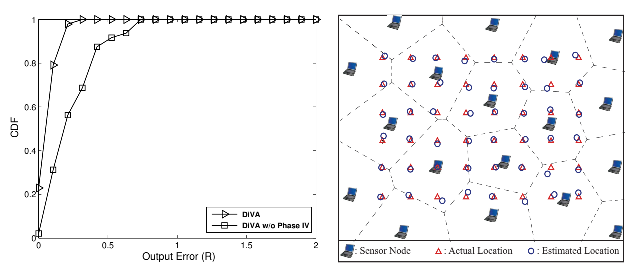
3.2 Experimental Evaluation

DiVA was implemented using Lenovo T400 laptops as sensor nodes. The audio capturer sampled at 8 KHz, and the audio analyzer used a speech analysis algorithm to verify a beep's signature and timestamp the beep. Both a regular and an irregular deployment of microphone nodes were tested.

3.2.1 Regular Deployment

In the regular deployment, 18 microphone nodes were arranged with $R \approx 1.58$ m, the same R as the simulation environment. Results were obtained for 48 acoustic sources arranged in a grid pattern, with all sources located in the interior of the network to avoid edge effects.

Figure 4(a) shows two CDFs of DiVA's output error for these sources. One CDF is for output error when the full DiVA scheme is used, and the second is for DiVA without Phase IV, in order to highlight the importance of Phase IV in refining the final estimate. The individual tests are shown in Figure 4(b).



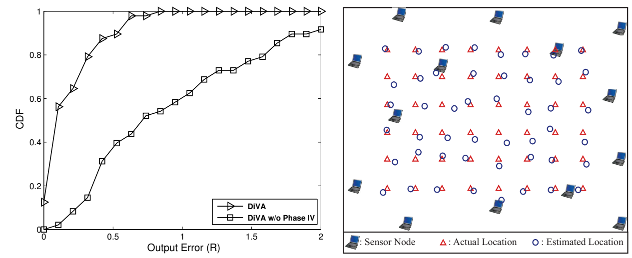
(a) CDF of output error for 48 tests. (b) Actual (△) and estimated (○) locations.

Figure 4: Experimental results for the regular deployment.

3.2.2 Irregular Deployment

The irregular deployment has a large void in the center, as shown in 5(b). Since some nodes lack LVNs on the side of the void, their local Voronoi cells extend into the void and overlap with each other. DiVA produces multiple location estimates for targets inside the overlapping region; in this case, all the nodes at the edge may produce an estimate. In the experiment, the estimate with the lowest associated MSE in Phase IV was used in the results.

The CDFs for the irregular deployment are shown in Figure 5(a), and the actual and estimated locations are shown in Figure 5(b). The output error is higher in general than the regular deployment case. The full DiVA scheme maintains good performance. Without Phase IV, the error is much higher. Therefore, Phase IV is especially critical for the irregular deployment case.



(a) CDF of output error for 48 tests. (b) Actual (△) and estimated (○) acoustic source locations.

Figure 5: Experimental results for the irregular deployment.

4. FUTURE WORK

This paper presents DiVA, a new acoustic source localization algorithm for wireless sensor networks that uses pairwise comparisons of the sound detection timestamps of neighboring microphone nodes to traverse the Voronoi diagram and find the node closest to the acoustic source, then estimates the source's location using a TDOA-based method. Simulation and experimental results show the ability of DiVA to localize a single beep and demonstrate the robustness of DiVA under real-world challenges such as measurement and position error. We are currently preparing for large-scale experiments and extending DiVA to localize beeps from multiple sources or multiple beeps from one source. Future work includes extending DiVA to 3D space and adapting DiVA to underwater environments.

5. REFERENCES

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