Ph.D. in Information Technology
Thesis Defense

April 29th, 2025
At 1:30 p.m.
Sala Conferenze Emilio Gatti – Building 20

Davide ALBERTINI – XXXV Cycle

DISTRIBUTED NETWORKS OF ACOUSTIC SENSOR ARRAYS
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Abstract:

Wireless Acoustic Sensor Networks (WASNs) represent a significant advancement in acoustic signal processing. Rather than relying on a single, fixed microphone array, WASNs employ multiple spatially distributed acoustic sensor units, to collaboratively capture, process and interpret sound fields. Each unit is equipped with dedicated microphones, processing components, and communication modules.
Compared to traditional arrays, WASNs offer enhanced spatial diversity, greater scalability, and improved resilience to individual node failures. They also enable the integration of heterogeneous devices, from classical microphone arrays to smartphones, wearable devices, and IoT nodes. This allows WASNs to be used in a variety of applications such as teleconferencing, surveillance, environmental monitoring, industrial diagnostics and home automation.

Recent advancements in sensor miniaturization and low-power electronics have led to affordable WASNs comprising, battery-operated, low-cost acoustic sensor units. Deployed in large numbers, these units significantly increase spatial coverage and enable advanced acoustic processing in scenarios once considered infeasible. Although each low-cost node has limited sensing and computing capabilities, large-scale deployment and cooperative operation can match or even exceed the performance of smaller networks with high-end microphone arrays.
Despite these advantages, deploying numerous low-cost acoustic sensor units also presents challenges. Restricted on-board computing power mandates efficient algorithms, limited communication bandwidths necessitate compact data exchange, and variability in sensor quality or network topology can undermine reliability and accuracy. To fully realize the potential of these low-cost WASNs, robust, adaptable, and computationally efficient methods must be developed, ensuring scalability, resilience, and broad applicability.

This thesis addresses these challenges by introducing four novel acoustic signal processing methods tailored to resource-constrained WASNs, spanning both individual sensor unit and network-wide domains. At the sensor unit level, a computationally efficient approach for two-dimensional source localization is introduced, leveraging sound intensity (SI) measurements to derive robust direction of arrival (DoA) estimates. Moving to network-level processing, the thesis proposes a two-stage spatial filtering framework designed for clusters of acoustic sensor units. In this approach, each unit first applies local spatial filtering to its own signals before a centralized node fuses their outputs, further enhancing the target sound source while suppressing noise and interference. To enable more flexible sensor placements and broaden the range of applications, this framework is then extended to accommodate networks of spatially distributed acoustic sensor units. Finally, a fully distributed three-

dimensional localization approach is developed, eliminating the need for centralized fusion and leveraging cooperative strategies for acoustic parameter estimation. Although each of these four contributions focuses on distinct technical aspects, they collectively illustrate how local processing capabilities can be combined with coordinated, network-wide strategies to overcome the unique challenges of large-scale, cost-effective acoustic sensing.

The first contribution focuses on the estimation of the DoA, i.e., the angle from which a sound source reaches an acoustic array, as this is a fundamental building block in many audio processing tasks. Existing DoA methods often rely on computationally demanding searches or exhibit sensitivity to array geometry and reverberation. To address these drawbacks, we propose a technique grounded in SI measurements, which indicates the direction of acoustic energy flow. This approach yields robust, closed-form DoA estimates without iterative searches or dense angular grids and supports flexible centro-symmetric array (CSA) configurations that accommodate various form factors of acoustic units and allow any number of sensors to be added to improve robustness to noise.

The second contribution targets network-level spatial filtering (beamforming), a technique for enhancing a target signal while attenuating unwanted noise and interference. Here, a two-stage method is presented for networks of acoustic sensor units operating in the far-field of a sound source, where the distance to the source is significantly greater than the spacing between sensor units. In the first stage, each sensor unit applies a local spatial filter using its own acoustic measurements and local DoA estimates. In the second stage, a centralized fusion node integrates and refines these partially processed signals, further improving the desired signal while mitigating unwanted noise. This hierarchical approach not only leverages spatial diversity but also lowers communication overhead by transmitting filtered data instead of raw sensor outputs.

Building on the two-stage beamforming approach, the third contribution extends the framework to scenarios where acoustic sensor units are widely spaced in the environment, rather than confined to regions where far-field assumptions strictly apply. This adaptation enhances both local spatial filtering and second-stage filtering to accommodate the broader distribution of sensor units and account for differences in the perceived DoA at each unit. It thereby preserves the advantages of hierarchical beamforming, such as reduced communication load and parallelizable processing, while offering greater flexibility for large-scale or dispersed sensor deployments.

The last contribution transitions from centralized to fully distributed paradigms for three-dimensional sound source localization (SSL), eliminating the need for a dedicated fusion center. By framing 3D SSL as a distributed optimization problem, the networked sensing units collaborate via diffusion-based strategies. These strategies employ an iterative process where each node refines its estimates by integrating local sensor observations with partial information exchanged with neighboring nodes. The proposed method works directly with two-dimensional DoA measurements coming from local arrays, thus utilizing the previously developed efficient DoA estimation. Through adaptive learning strategies, the network identifies unreliable units that affect the localization accuracy and downweights them. The system naturally adapts to slow-moving sources and is robust to sensor variations and changing environmental conditions.

In summary, this thesis advances the state of the art in low-cost WASNs by introducing strategies that range from local parameter estimation to hierarchical beamforming and fully distributed source localization. By balancing computation, communication, and cooperation, these methods deliver scalable, high-performance solutions tailored to low-cost, low-power networks.
These contributions not only address the current challenges in the field, but also lay the groundwork for future research to ensure that WASNs evolves in increasingly complex and resource-constrained environments.

PhD Committee

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