Structure Assisted Spectrum Sensing for Low-power Acoustic Event Detection

Nakul Garg, Harshvardhan Takawale, Yang Bai, Irtaza Shahid, Nirupam Roy
{nakul22, htakawal, yangbai8, irtaza, niruroy}@umd.edu
University of Maryland College Park

ABSTRACT

Acoustic sensing has conventionally been dependent on high-frequency sampling of analog signals and frequency domain analysis in digital domain which is power-hungry. While these techniques work well for regular devices, low-power acoustic sensors demand for an alternative approach. In this work, we propose *Lyra*, a novel low-power acoustic sensing architecture that employs carefully designed passive structures to filter incoming sound waves and extract their frequency components. We eliminate power-hungry components such as ADC and digital FFT operations and instead propose to use low-power analog circuitry to process the signals. *Lyra* aims to provide a low-power platform for a range of maintenance-free acoustic event monitoring and ambient computing applications.

CCS CONCEPTS

• **Computer systems organization → Sensor networks**; *Embedded systems*; **Sensors and actuators**.

KEYWORDS

Low-power sensing; IoT; Ambient sensing; Ambient computing; Acoustic metamaterial; Spectral sensing; Structural filters; passive computing

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1 INTRODUCTION

Acoustic sensing has emerged as a key technology in ambient computing, enabling devices to understand and respond to their environment by detecting and analyzing events through sound. Furthermore, the ubiquitous nature of sound has made acoustic sensing and communication more accessible, with a majority of smart devices equipped with built-in microphones. Acoustic signals have demonstrated their utility in a diverse range of applications, including but not limited to gesture recognition and tracking [17, 30, 36, 48], early medical diagnosis [35], source localization [19, 43], acoustic imaging [3, 31], voice interfaces [5, 9, 41], drone defense and tracking [20, 32] and finer-grained activities such as eye blinks and heartbeats [29, 44].

The infrastructure for the future of ambient computing and maintenance-free sensing are in continuous pursuit of low-power sampling and processing methods. Like other modalities, acoustic sensing systems depend on sampling of analog signals and frequency domain analysis. These two operations are considered bottleneck in ultra-low-power sensing architecture. Fourier transforms are a crucial tool for spectral analysis and are extensively utilized in acoustic communication and sensing systems. Typically, acoustic systems first sample an incoming signal at Nyquist rate [26], a rate of at least twice the frequency of the signal, to acquire a digital copy of the signal, after which a Fast Fourier Transform (FFT) algorithm is employed to obtain the frequency domain representation of the signal. This high sampling rate and fourier transform operation consume a significant amount of

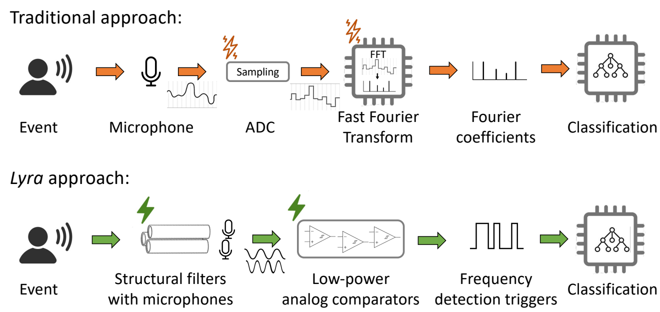

Figure 1: Traditional approach vs *Lyra* approach for spectral sensing. *Lyra* replaces ADC and FFT using structural filters and analog comparators.

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energy. The reliance on such high energy-consuming operations presents a significant challenge for low-power ambient acoustic sensors that must continuously listen for acoustic cues without depleting their battery life.

In this paper, we propose *Lyra*[1], a novel approach that utilizes passive structures for low-power acoustic frequency detection. As shown in Figure 1, *Lyra* gets rid of the power-hungry components of conventional systems, such as ADC and FFT, and replaces them with passive structures and low-power analog comparators. The passive structures are narrowband acoustic filters that are sensitive to a specific resonant frequency. Multiple of these structures are arranged in parallel to create a unique block that is highly sensitive to desired set of frequencies. These structures are incorporated with microphones that capture the resonating acoustic signal, and a low-power analog comparator is employed to detect if the energy is above a predefined threshold, indicating the presence of the resonant frequency. This approach significantly reduces the power consumption of the sensor and enables energy harvesting sensors which have limited energy budgets to sense acoustic signals and function continuously in remote areas for extended periods of time.

The low-power design addresses the issue of high energy consumption by conventional systems and allows low-power devices to continuously monitor acoustic signals while minimizing energy consumption, which opens possibilities for new applications. *Lyra* can enable the deployment of energy harvesting sensors in remote areas such as forests, for wildlife monitoring and tracking, and as SOS devices, always listening for emergency signals played by lost individuals seeking help. The sensors would require no maintenance and offer a cost-effective and long-term solution for various applications, including environmental monitoring, disaster response, and other remote sensing applications.

Lyra's architecture is designed to extract a time-series representation of the frequencies present in incoming sound waves. Our passive structures are designed based on the principles of standing wave resonance [33] and Helmhotz resonance [46]. The placement of microphones inside the resonating structure is carefully determined to create a salient feature for resonance detection. We then use passive envelope detectors, low-power analog comparators and logic gates to classify the occurrence of resonance in the structure, thus indicating the presence of the resonating frequency.

Needless to say, this paper is only a first step toward this broader vision, and we aim to inquire about the opportunities it presents. We start by experimenting with the technique of acoustic event detection system that employs passive structures to identify frequencies present in an acoustic signal.

[1]Named after the Lyra constellation in the northern sky, representing a harp which is a musical instrument with strings that produce standing waves.

2 APPLICATION SCENARIOS

This paper focuses on exploring the technical cores that enable structure-assisted spectrum sensing. While the ideal applications and application-specific advantages and limitations are yet to be analyzed, we outline a few target application domains here.

Ultra-low-power wake-word detection: The core idea of *Lyra* can lead to applications that require frequency analysis. One specific example is wake word detection, which recognizes a specific word or phrase spoken by the user using frequency analysis of human speech. Some common examples of wake words include "Hey Siri" for Apple's virtual assistant, "OK Google" for Google Assistant, and "Alexa" for Amazon's voice assistant. We look forward to applying *Lyra* on more applications requiring ultra-low-power and maintenance-free acoustic signal processing.

Large scale ambient computing: The inexpensive design of *Lyra* can be seamlessly integrated into infrastructure and enable acoustic interfaces for device-free event detection and thereby enabling closer interaction between computing infrastructure and the living space, both indoor and outdoor. For example, smart city infrastructure can use *Lyra* to detect the number of cars passing through and adjust traffic signals to optimize traffic flow. Inaccessible locations can automate monitoring, such as an elevator shaft can monitor its long-term structural consistency using acoustic cues.

Maintenance-free SOS system: With the features of ultra-low-power and maintenance-free, this work can be a means for SOS system that can be widely deployed in a variety of situations, such as hiking, boating, or traveling in remote areas where access to emergency services is limited. It can be used by people who may require urgent assistance due to medical emergencies, accidents, or other unforeseen events.

Wildlife monitoring: It is natural to wonder if *Lyra* can be an interface for acoustic monitoring of wildlife – a scenario where scheduled maintenance is difficult and standard power supply is limited. Since the proposed acoustic interface needs limited power and maintenance, it can be a critical tool to better understand the ecology and behavior of wildlife populations and make informed decisions about how best to protect them.

3 THEORETICAL FOUNDATIONS

3.1 Passive filtering

An acoustic passive filter is a type of filter used in audio systems to eliminate or attenuate specific frequencies. Passive

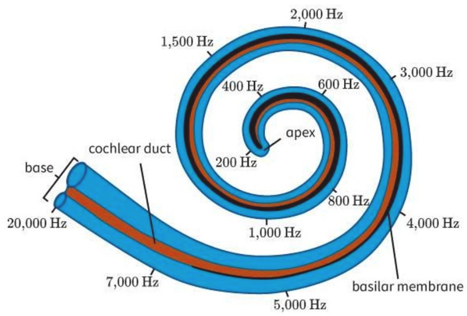

Figure 2: The cochlea located in the inner ear is a natural multiresonant structure that provides acoustic filtering.

filters are designed to work without an external power source and are made up of passive components. Interestingly, the use of passive acoustic filtering is pretty common in nature. For instance, the structure of the human ear plays a crucial role in shaping the frequency response of sounds that reach the eardrum. The shape and size of the external ear create a frequency-dependent filtering effect on incoming sounds. This filtering effect is due to the fact that different frequencies of sound waves interact differently with the shape and size of the external ear [42]. In particular, the ear acts as a frequency-dependent amplifier, boosting sounds in certain frequency ranges while attenuating others. This amplification effect is most pronounced in the range of frequencies that are important for speech perception. Moreover, cochlea in the inner ear also acts as a passive filter to help us hear and perceive different frequencies of sound [38], as shown in Figure 2. The cochlea is a spiral-shaped organ located in the inner ear that is responsible for converting sound waves into neural signals that are sent to the brain for processing. Unlike using frequency domain transforms (e.g., FFT) for analysis used in modern acoustic systems, cochlea senses frequencies through the vibration on different parts of it. Specifically, high-frequency sounds cause vibrations near the base of the cochlea, while low-frequency sounds cause vibrations near the apex.

3.2 Standing wave resonance

In the discussion of the impact of structure on sound waves, the understanding of standing waves is relevant. A standing wave is a type of wave pattern that occurs when two waves of the same frequency and amplitude travel in opposite directions and interfere with each other [33]. When the waves interact with each other, the resulting wave appears to "stand still" in place and does not move. As shown in Figure 3a, we can achieve this using a pipe with one closed end that can be utilized to generate a reflected signal and thus, create a standing wave. The shape and size of the medium or a tube defines the properties of a standing wave for a given frequency. The mathematical equation of a standing wave is

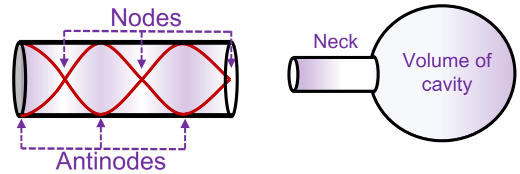

Figure 3: *Lyra*'s structural acoustic filters. (a) A longitudinal single-frequency resonant pipe (b) A spherical multi-frequency Helmholtz resonator.

given by

$$y(x,t) = sin(2\pi x/\lambda)cos(2\pi f t) \quad (1)$$

where x is the spatial distance, λ is the wavelength, and f is the frequency of the wave. The term $sin(2\pi x/\lambda)$ represents the sinusoidal shape in space, and the term $cos(2\pi f t)$ describes the up-down oscillatory motion in time domain. Standing waves also explain the production of sound by musical instruments. Instruments create standing waves on a string or in a tube or pipe and the perceived pitch of the sound is related to the frequency of the standing wave.

3.3 Helmholtz resonance

Helmholtz resonators amplify certain frequencies when oscillating air pressures meet cavities on their way [46]. As shown in Figure 3b, a Helmholtz resonator consists of a cavity of air connected to the outside world by a narrow neck or tube. When sound waves enter the container, they set up a standing wave pattern that resonates at a specific frequency determined by the volume of the container and the size of the opening [1]. The resonance frequency f is

$$f = \frac{c}{2\pi}\sqrt{\frac{S}{VL}} \quad (2)$$

where c is the speed of sound, S is the cross-sectional area of the tube, V is the volume of the cavity, and L is the length of the tube.

4 *LYRA* ARCHITECTURE

Our objective is to design an architecture using passive structures to extract a time-series representation of the frequencies present in an acoustic signal, similar to a spectrogram. To accomplish this, we designed a series of structural filters and a low-power analog logic to identify the presence of frequencies. A standing wave is an interference phenomenon of waves characterized by nodes and antinodes. As illustrated in Figure 3a, nodes are points on the standing wave that remain stationary with no pressure variations, while antinodes are points that undergo maximum pressure variations. We aim to detect these nodes and antinodes inside the structure, whose precise location is determined by the wavelength of the incoming acoustic wave.

To resonate at a specific frequency, we adjust the shape and size of the structure and place two microphones at a node and antinode, respectively. Unlike traditional methods that require sampling of the signals, we aim to employ a passive envelope detector followed by analog comparators to identify the energy threshold and categorize a node and antinode. A logical AND gate can classify the presence of both node and antinode, which indicates the detection of the frequency as a binary signal output, where 1 represents the frequency's presence and 0 indicates its absence.

Our approach of using passive structure and analog components effectively eliminates the need for energy-intensive ADC and FFT operations. Conventional ADCs and digital computations require a significant amount of power and can consume milli-watts of power [19, 45] whereas high impedance analog comparators [2] consume micro-watts of power ($power \propto voltage^2/impedance$) and envelope detectors operate on passive electric components, resulting in zero additional energy consumption.

5 FEASIBILITY STUDY

For initial testing, we conduct a simulation study using passive structures utilizing both helmholtz and standing wave resonance. Figure 4 shows the spectral response of three helmholtz filters used in this simulation, where the filters are hollow cavities with resonant frequencies 800, 900, and 1300Hz. The standing wave structure is tuned to resonate at 2300Hz and Figure 5 shows the spectral responses of the sensors placed inside the structure. We record the signal using virtual sensors placed at the antinode and node locations of the standing wave. The shaded region shows the resonant frequency where the antinode sensor receives an amplified signal whereas the node sensor receives negligible power of signal, thus indicating a salient feature for resonance detection.

We conduct our simulation using Matlab and the k-wave acoustic toolbox, which is an acoustic wave propagation model that accounts for reflections, diffraction, nonlinearities and power law absorption for time domain analysis. We perform a 2D simulation with an arbitrary signal containing multiple frequencies and record the response from virtual sensors. We then emulate the operation of a passive envelope detector by applying a squaring operation and a low-pass filter. Finally, we use a threshold-based detection to classify if a frequency is present or not. Figure 6 shows the output of the combined acoustic filters when the corresponding signal is transmitted. We observe that the series of helmholtz filters act like traditional frequency bin detectors and give a similar-looking spectrogram without actually sampling the signal or performing FFT.

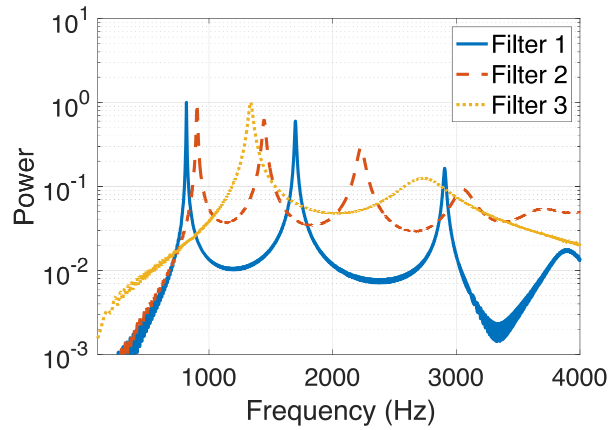

Figure 4: Spectral response of three different helmholtz resonators with different harmonic frequencies. These filters are used as passive filters to detect presence of frequencies in an acoustic signal.

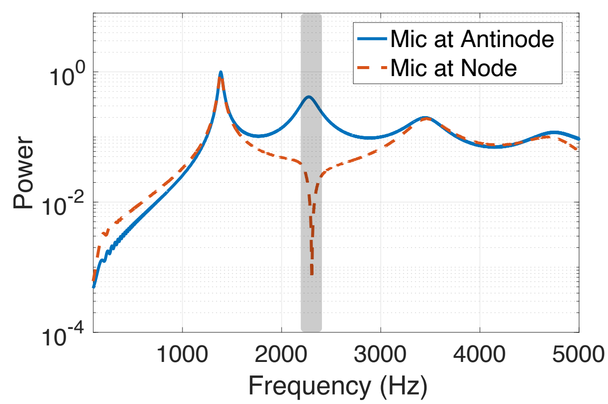

Figure 5: Spectral response of the standing wave structure for two different microphones placed in the structure. One microphone is located at a node and another is located at an antinode of the standing wave. This creates a salient feature for the passive structure to detect a resonating frequency.

To assess the feasibility of our proposed approach in the real-world, we fabricate the standing wave structure using 3D printing and conduct experiments to detect the resonating frequency. Figure 7 shows our experimental setup, where an acoustic signal is transmitted using a speaker towards the structure, which is designed to resonate at the fifth harmonic with frequency $f = 4200Hz$ and wavelength $\lambda = 8.16cm$. We place two microphones in the structure at the antinode and node locations of standing wave to extract the features for the standing wave.

Figure 8 shows the time domain response of the two microphones, for input frequencies ranging from $200Hz$ to $6200Hz$. The figure shows that only at the resonance frequency the

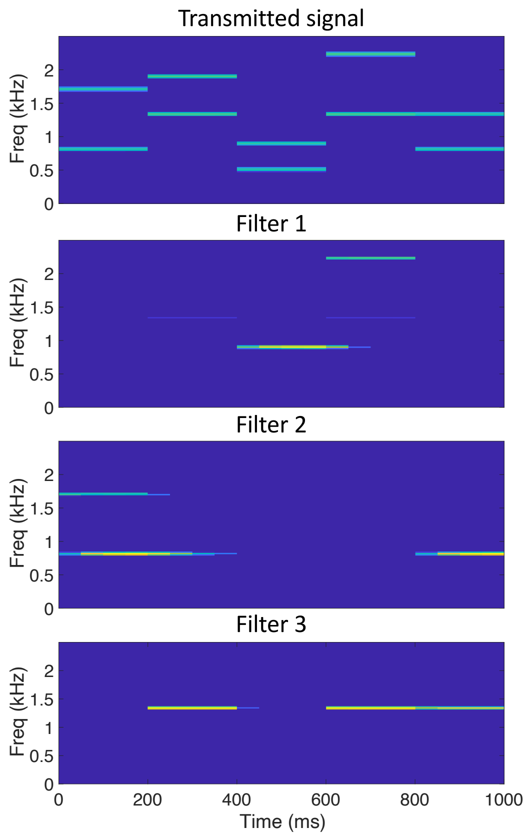

Figure 6: Spectrogram of filtered responses from each of the helmholtz filters for a wide-band transmit signal.

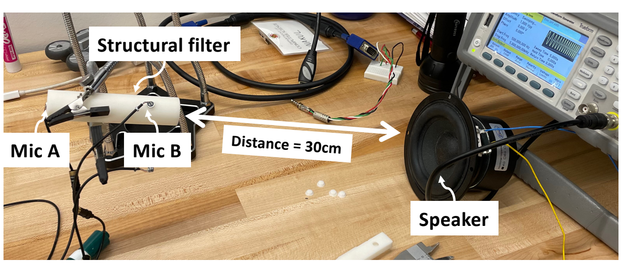

Figure 7: One of the setups for the feasibility experiments.

two microphones exhibit a high-energy contrast, high amplitude for the microphone positioned at the antinode, while zero amplitude for the one at node, indicating successful detection.

6 LIMITATION AND FUTURE WORK

Lyra is an initial exploration of utilizing passive structures for acoustic event detection and that there is room for further improvements and future work.

Temperature variations: The speed of sound is affected by temperature variations in the medium, which in turn, affects the wavelength of the acoustic signal. Since the passive

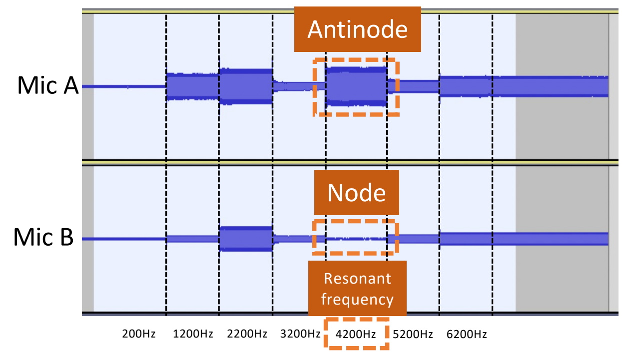

Figure 8: The structure resonates to create a standing wave at 4200Hz (the 5^{th} harmonic. Plot shows the time domain amplitudes at two locations.

structures are designed to detect wavelengths rather than frequencies from the principles of resonance, the system may fail to detect a frequency if temperature changes. To accommodate temperature-induced changes, one could employ reconfigurable structures. Such structures would enable a one-time actuation/reconfiguration to adapt to temperature variations by changing shape or size of the structure.

Structure size: At lower frequencies, the physical size of structures can become considerably large. This is due to the slower speed of sound, which results in longer wavelengths. For example, an acoustic signal of 100 Hz has a wavelength of 3.43 meters in air. We aim to investigate novel miniaturized designs that leverage interferometry and metamaterials to enable the detection of longer wavelengths.

7 RELATED WORK

The core intuition of *Lyra* builds on the foundational works in physics and computational acoustics, while presenting a new sensing architecture with a unique goal to achieve ultra-low-power acoustic perception. We sample from relevant works in these fields.

Structural acoustics: As sound waves pass through a cavity, they can be influenced by the structure of the cavity, causing certain frequencies to be amplified or suppressed. The art of using structure to manipulate sound waves is known for a very long time and its application is seen in many ancient architectures [50]. Previous works [12, 23, 40] have established theories for noise reduction using carefully designed acoustic structures, which have been improved upon by incorporating sub-chamber structures [40], varying inlet and outlet sizes [12], or perforated liners [10]. Researchers have also investigated the use of acoustic metamaterials to design structural materials that provide frequency-selective characteristics [52]. Xie et al [49] demonstrate that carefully designed acoustic structures can be used for selective listening to solve cocktail party problems. Acoustic Voxels [28], proposed a method that assembles pre-designed structures into a complex geometry to achieve the desired acoustic filtering. Owlet [18, 19], showed the potential of using acoustic microstructure to embed directional clues to the signal recorded by a microphone, enabling direction of arrival estimation without using large microphone arrays. One of our past works, SPiDR [3, 4], proposed an acoustic microstructure to produce a cross-sectional map of the field of view for ultra-low-power spatial sensing. In this paper, we are building on previous research and investigating the possibility of using acoustic structures for low-power spectrum sensing.

Metamaterial resonators: Helmholtz resonators have been studied extensively in the field of acoustics and have been used in various applications, including noise reduction, sound absorption, and musical instruments [14]. The seminal work on Helmholtz resonators dates back to 19^{th} century by German physicist Hermann von Helmholtz [47]. Studies have explored the use of Helmholtz resonators in automotive exhaust systems to reduce engine noise [34], as well as in industry for damping heavy machinery noise [6, 51]. Helmholtz resonators have also been used in architectural acoustics to control sound reflections in large rooms and concert halls [24, 25]. Recent research has focused on the use of Helmholtz resonators in acoustic metamaterial for a perfect absorption of sound wave [39]. In summary, the study of Helmholtz resonators is an active area of research in acoustics for the past few decades. In this paper, we are exploring the concepts of Helmholtz resonators in designing passive sensors for acoustic spectrum sensing.

Coded sensing in other modalities: Coded sensing is a technique used for data acquisition that involves taking measurements of a signal through a linear combination of a random or structured pattern. It has gained significant attention in the field of computer vision [11]. Previous work has explored the use of coded phase plates to capture high-resolution depth information [13], and all-focus images [8]. Levin et al [27] inserted a patterned occluder within the aperture of the camera lens, which enabled simultaneous recovery of both high-resolution depth and all-focus images. Additionally, coded exposure in the temporal domain has been used for motion deblurring [37]. Coded aperture imaging methods have also been employed in astronomy and medical imaging to capture the high-quality images [7, 16]. Similarly, the projection of structured light has been explored for 3D surface imaging [21]. In addition, the use of light masking patterns has been proposed [15] and leveraged [22] for single-pixel imaging. In this paper, we investigate the potential of using coded structures to develop low-power spectrum sensing techniques in the acoustic domain.

8 CONCLUSION

This paper presents the feasibility experiments and early results of a new low-power acoustic sensing architecture. It shows the possibility of using carefully designed passive shapes for filtering incoming sound waves to reveal its frequency components. It then proposes a low-power sensing circuitry to use this filtered signal as a spectral feature vector for further processing. This sensing model aims to provide a low-power platform for a range of maintenance-free acoustic event monitoring and ambient computing applications.

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