

Lamphone

Real-Time Passive Sound Recovery Using Light Emitted from a Hanging Bulb

Ben Nassi

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About Me

- Computer Scientist & Former **Google** Employee
- Ph.D. Student @ Ben-Gurion University of the Negev, Israel
- Researcher at CBG (Cyber @ BGU)
- Research Focus:
 - Privacy (side-channel attacks, covert channel attacks)
 - Security of IoT devices (drones, advanced driver-assistance systems, etc.)
- Read more about my research at www.nassiben.com



Researchers



Ben Nassi



Yaron Pirutin



Prof. Adi Shamir



Prof. Yuval Elovici



Dr. Boris Zadov



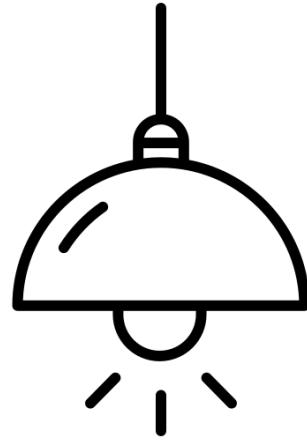
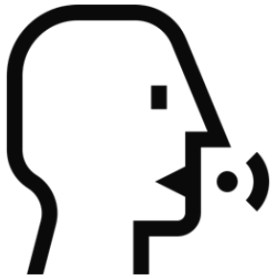
Agenda

- Research Question
- Background
 - What is sound?
 - What is eavesdropping?
 - Related sound recovery research
- Lamphone's Threat Model
- Bulbs as Microphones
- Evaluation
- Potential Improvements
- Takeaways
- Q&A



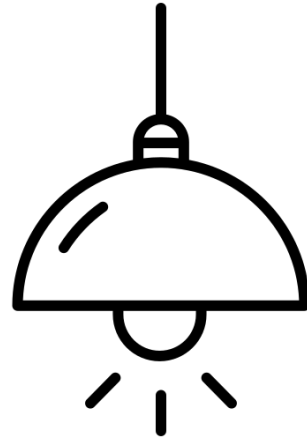
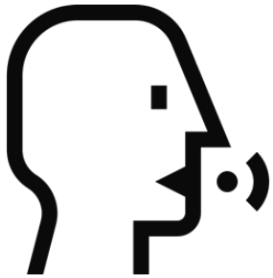


A Hanging Bulb as a Microphone?





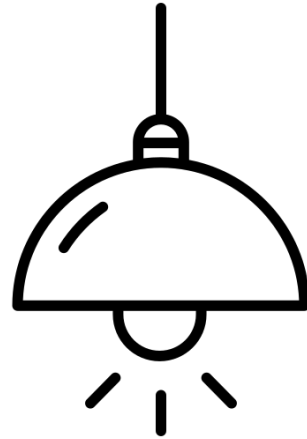
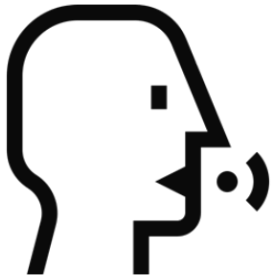
A Hanging Bulb as a Microphone?



➤ Question: Can a hanging bulb be used as a microphone?



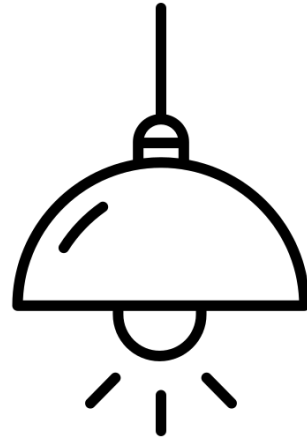
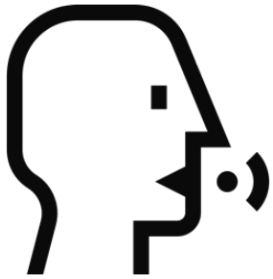
A Hanging Bulb as a Microphone?



- Question: Can a hanging bulb be used as a microphone?
- Answer: By using scientific tools to analyze the vibrations of a hanging bulb, attackers can recover high quality speech and non-speech audio.



A Hanging Bulb as a Microphone?

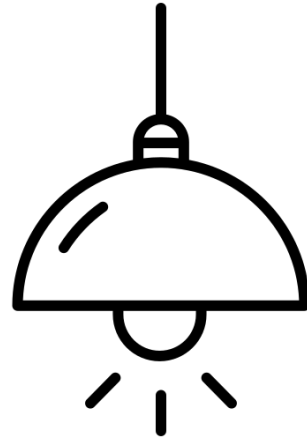
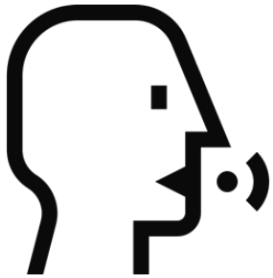


- Warning: Turning a hanging light bulb into a microphone is challenging.





A Hanging Bulb as a Microphone?



- Warning: Turning a hanging light bulb into a microphone is challenging.
- Primary reason: Light bulbs were not designed to be used as microphones.

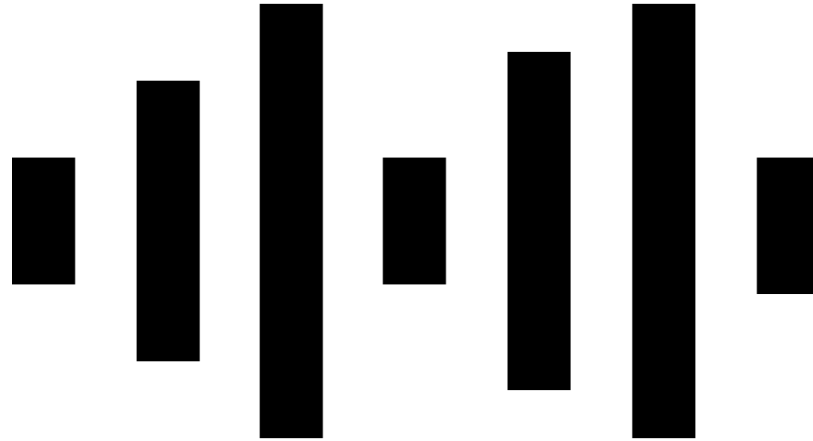




Background



Sound Wave



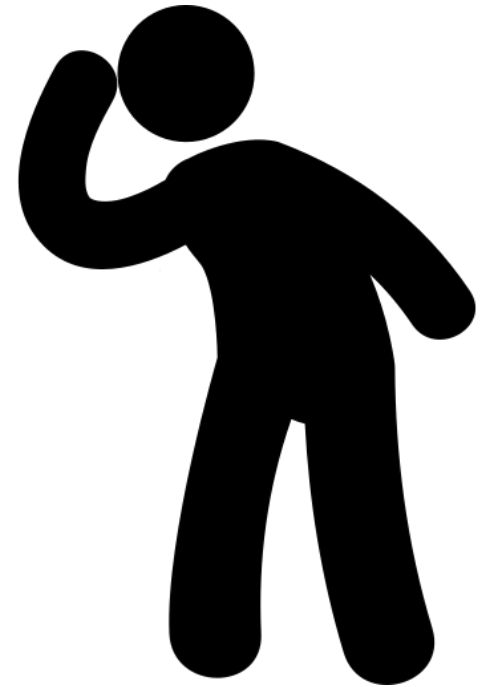
1. A sound wave is air traveling through space.
2. The source is some object that causes a vibration, for example, a person's vocal chords.
3. Acoustic waves that have frequencies from around 20 Hz to 20 kHz can be heard by humans.



Eavesdropping



The act of secretly recovering sound from a target/victim without his/her consent (Wikipedia).





Eavesdropping

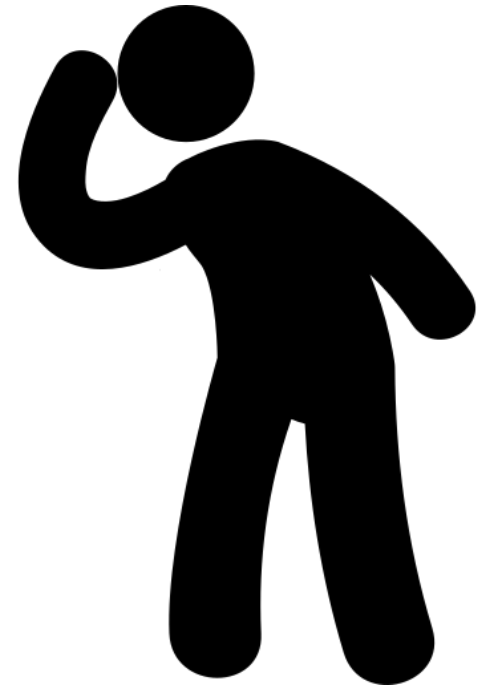


The act of secretly recovering sound from a target/victim without his/her consent (Wikipedia).

Eavesdropping can be performed digitally and physically.

Physical eavesdropping relies on objects that are located in physical proximity to the sound source:

1. When a sound wave hits the surface of an object, it causes the object to vibrate.
2. By analyzing the object's response to sound (the vibrations) with a proper device/sensor, sound can be recovered.





How do Microphones Work?



Microphones are used to convert sound waves to electrical signals using three primary components:





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1. Diaphragm: a diaphragm is a thin piece of material (e.g., plastic, aluminum) that vibrates when it is struck by sound waves.





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1. Diaphragm: a diaphragm is a thin piece of material (e.g., plastic, aluminum) that vibrates when it is struck by sound waves.
2. Transducer: the diaphragm's vibrations are converted to current.





How do Microphones Work?



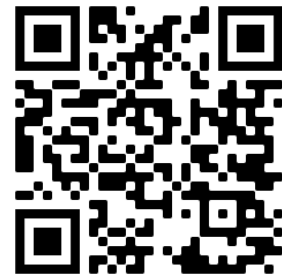
Microphones are used to convert sound waves to electrical signals using three primary components:

1. Diaphragm: a diaphragm is a thin piece of material (e.g., plastic, aluminum) that vibrates when it is struck by sound waves.
2. Transducer: the diaphragm's vibrations are converted to current.
3. ADC (analog-to-digital converter): the analog electric signal is sampled at standard audio sample rates (e.g., 44.1 kHz).





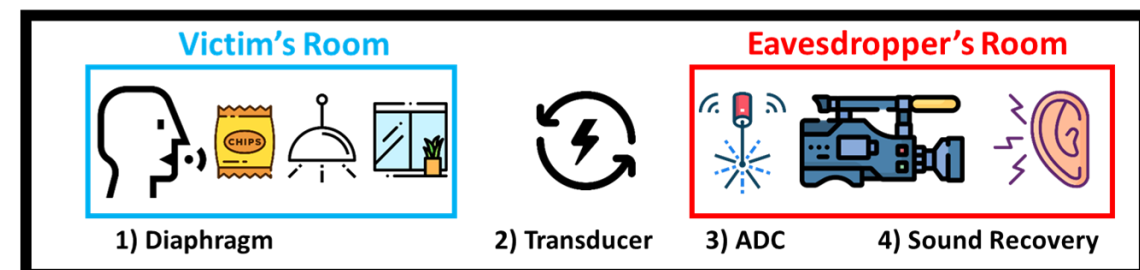
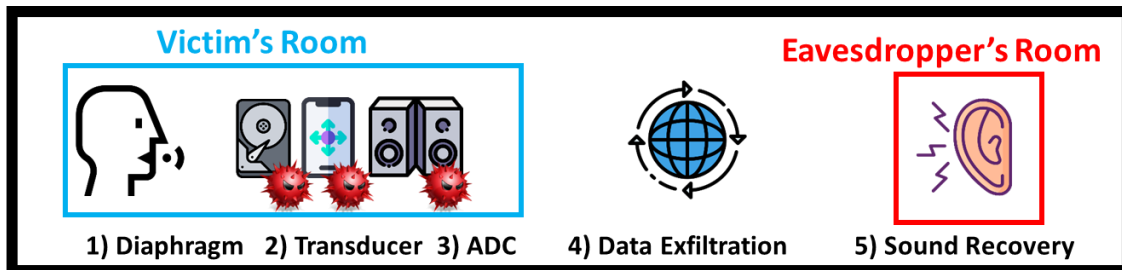
Eavesdropping Related Research



- In recent years, the scientific community has suggested various ways to recover sound.
- There are two categories of methods:

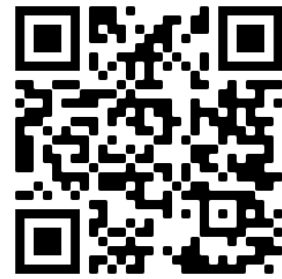
Internal Methods

External Methods

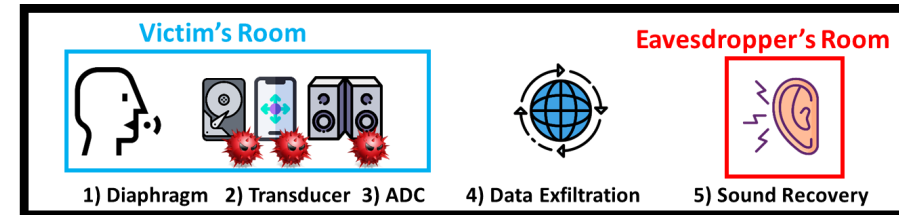


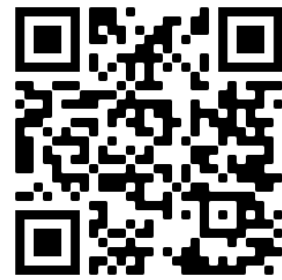


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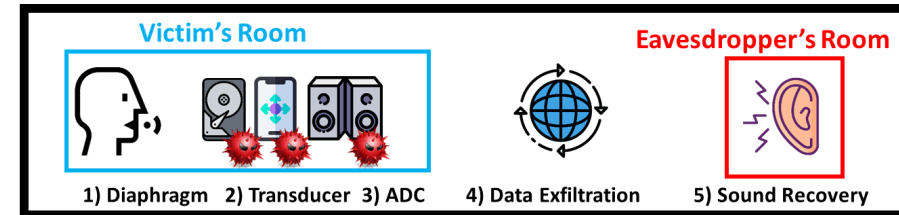
- Methods that rely on data obtained by a device located in proximity to a victim





Internal Methods

➤ Methods that rely on data obtained by a device located in proximity to a victim



Motion Sensors

Gyroscope [1]

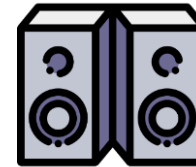
Accelerometer [2-4]



Output Devices

Speakers [5]

Vibration Motor [6]



Misc.

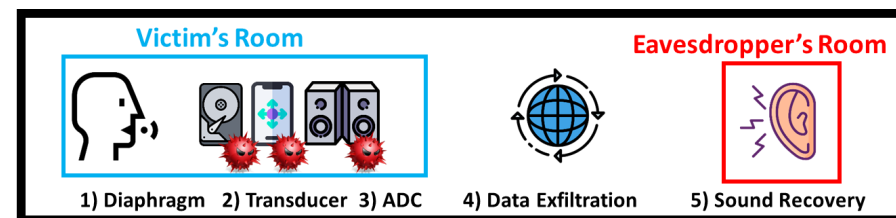
Hard Drive [7]





Internal Methods

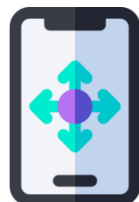
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Motion Sensors

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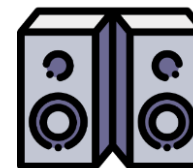
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From the eavesdropper's perspective, these methods

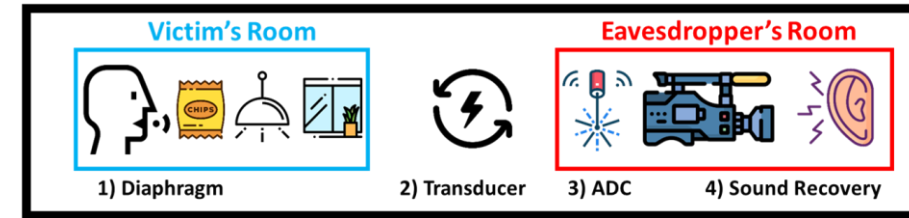
- Are **permission-less** - applications that implement these methods do not require any permissions to obtain data from the devices
- Require the attacker to **place a malware compromised device near a victim** in order to obtain and exfiltrate data



External Methods



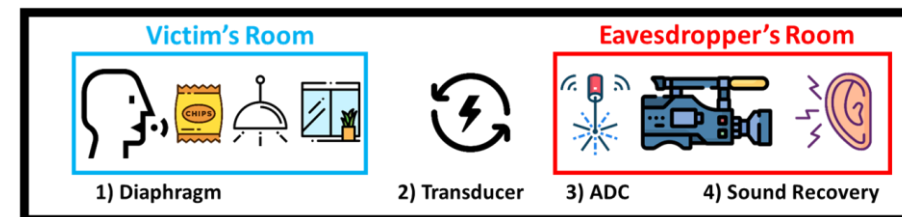
- Methods that rely on data obtained by a device that is not located near a victim





External Methods

➤ Methods that rely on data obtained by a device that is not located near a victim



Laser Microphone [8]

Uses a laser transceiver to recover sound by directing a laser beam at an object and analyzing the object's response to sound.



From the eavesdropper's perspective, this method

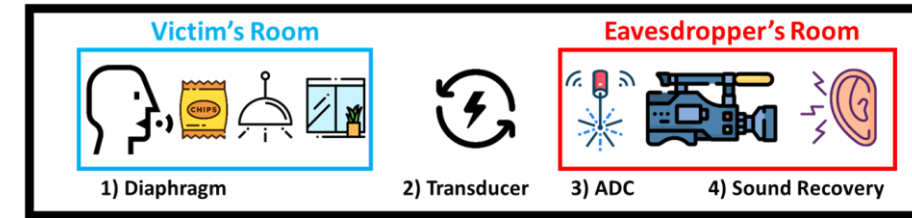
- Is **external** - does not require placing a malware compromised device near the victim
- Can be applied in **real time**
- Is **active** - the laser beam can be detected by victims/organizations by using an optical sensor



External Methods

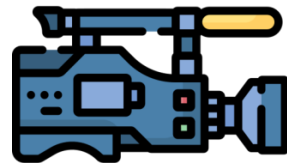


- Methods that rely on data obtained by a device that is not located near a victim



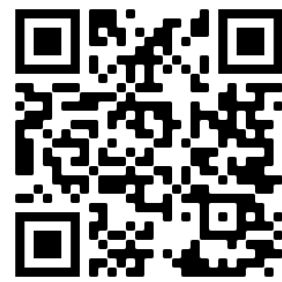
Visual Microphone [9]

Uses a high frequency video camera (~2000 FPS) to recover sound by analyzing the object's (e.g., a bag of chips) response to sound.



From the eavesdropper's perspective, this method

- Is **external** - does not require placing a malware compromised device near the victim
- Is **passive** - making its detection very difficult for victims/organizations
- Cannot be applied in **real time** - requires heavy computational resources (it takes a few hours to reconstruct a few seconds of sound)

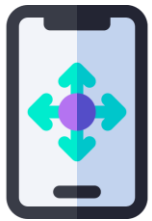


Summary of Related Work

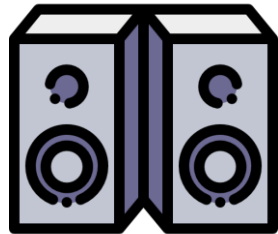
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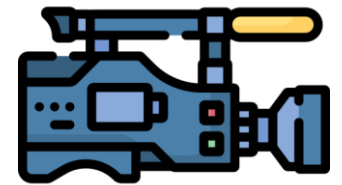
Misc.



Laser Microphone



Visual Microphone



From the eavesdropper's perspective, each method is limited by one of the following:

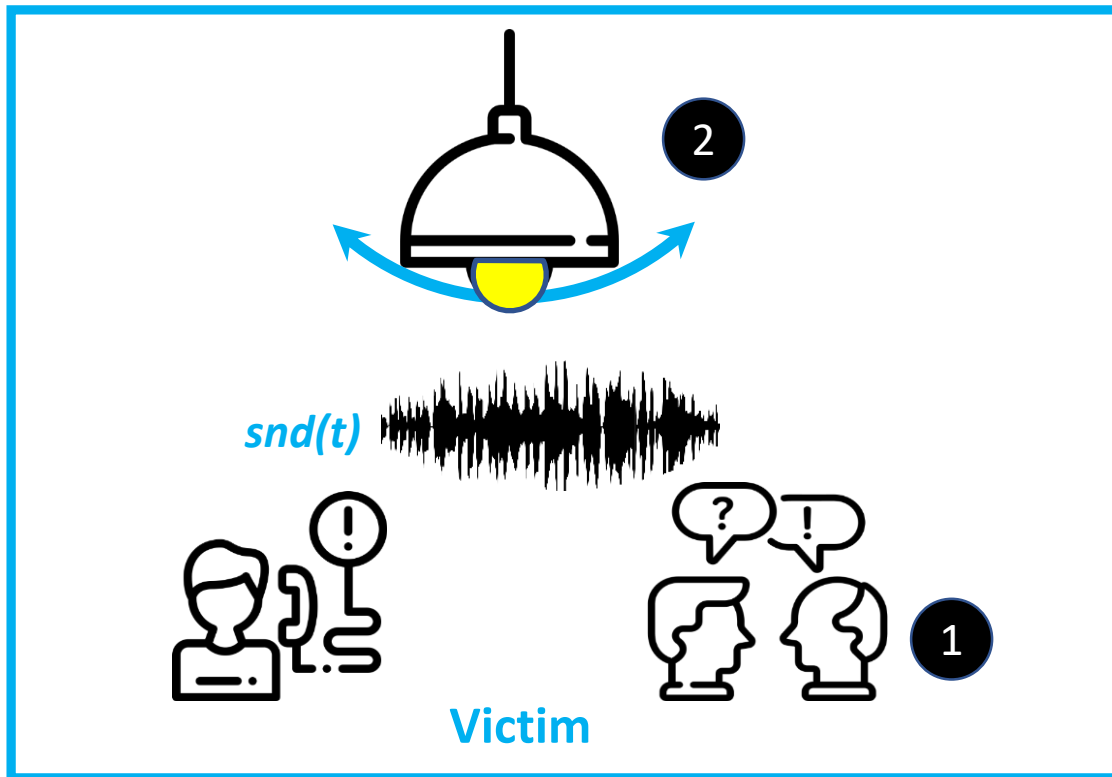
- **Relies on a remotely controlled device** - eavesdroppers must compromise a device with a malware
- **Active** - which makes it easier for the victim to detect the use of the method
- **Cannot be applied in real time** - because it requires heavy computational resources



Lamphone's Threat Model



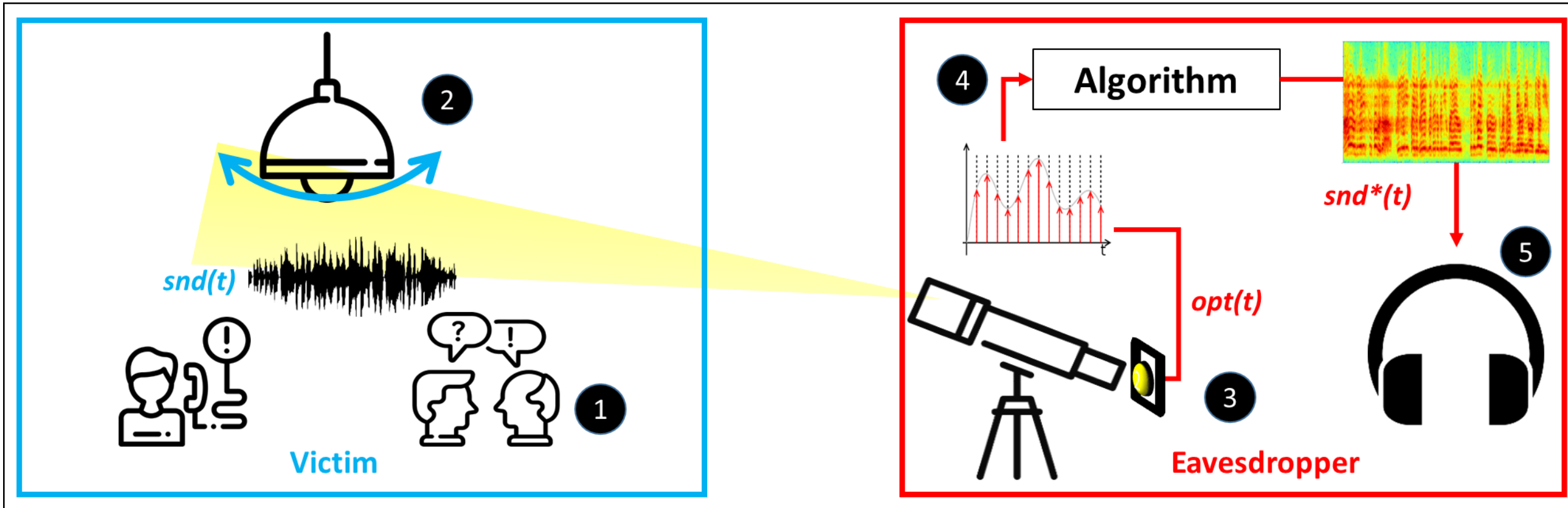
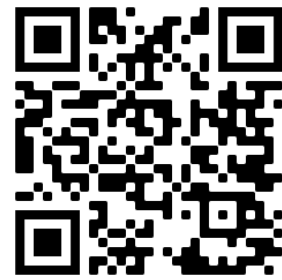
Lamphone's Threat Model



We assume that a hanging light bulb exists in a target room. A sound (1) $snd(t)$ in the room (which can be the result of a conversation) creates fluctuations on the surface of the hanging bulb (the diaphragm) (2).



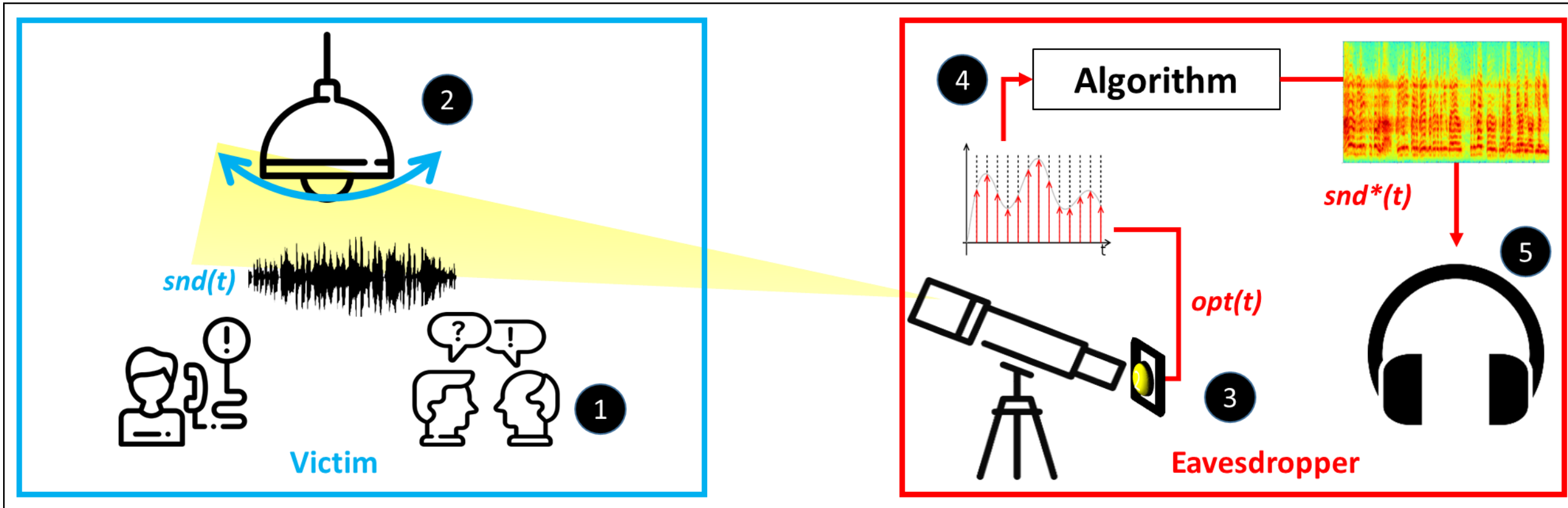
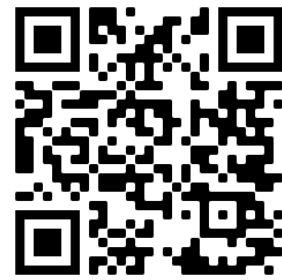
Lamphone's Threat Model



The eavesdropper directs an electro-optical sensor (the transducer) at the hanging bulb via a telescope (3). The optical signal $opt(t)$ is sampled from the electro-optical sensor via an ADC (4) and processed using a dedicated sound recovery algorithm into an acoustic signal $snd^*(t)$ (5).



Lamphone's Threat Model



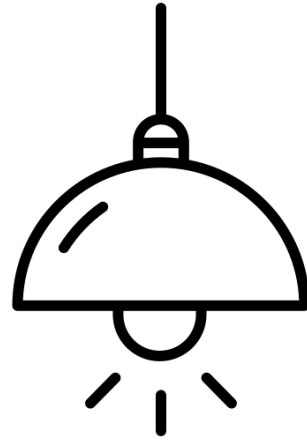
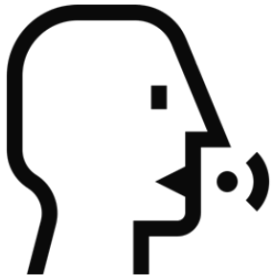
From an eavesdropper's perspective, Lamphone's threat model is **external**, **passive**, and can be applied in **real time**.



Light Bulbs as Microphones



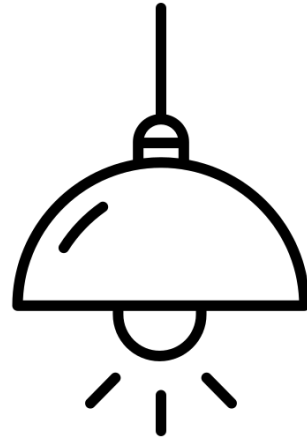
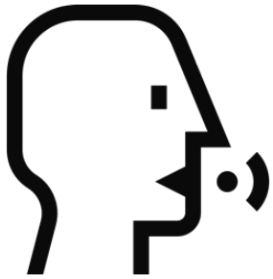
A Hanging Bulb as a Microphone



➤ A sound wave is air traveling through space.



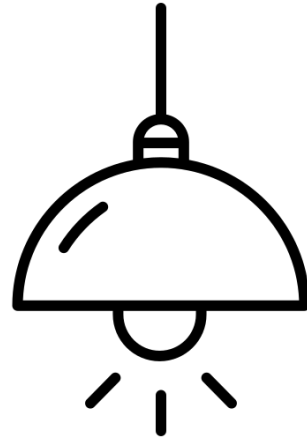
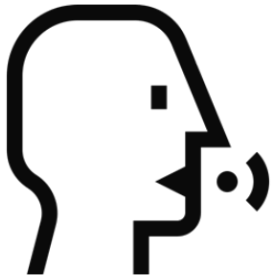
A Hanging Bulb as a Microphone



- A sound wave is air traveling through space.
- The air causes a hanging light bulb to vibrate.



A Hanging Bulb as a Microphone



- A sound wave is air traveling through space
- The air causes a hanging light bulb to vibrate.
- However, a bulb's vibrations are so small that they are invisible to the human eye.



A Hanging Bulb as a Microphone



How small are these vibrations?

... are so small that they are invisible to

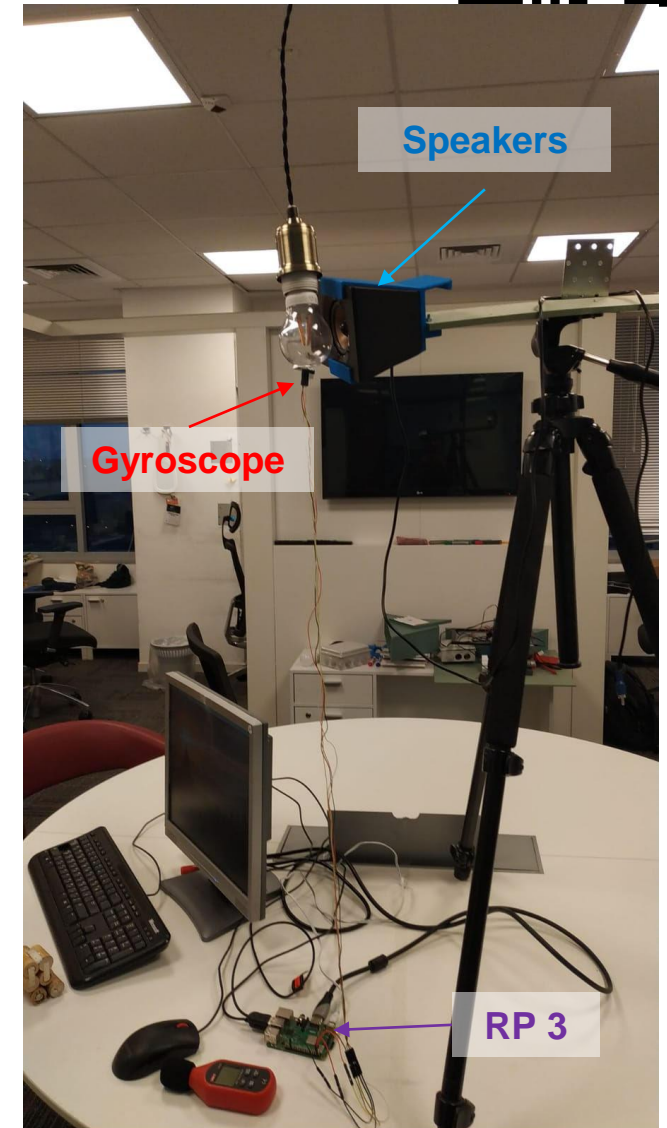


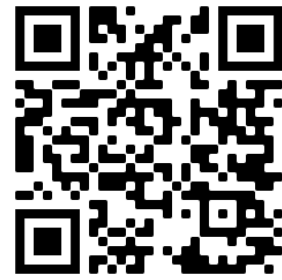
Measuring a Bulb's Vibrations



Experiment

- We attached a **gyroscope** to the bottom of hanging bulb (E27, 12 watts).
- We produced various sound waves (100-400 Hz) at different volumes (70, 95, 115) from **speakers**.
- We sampled the gyroscope at 800 Hz (using **RP 3**).

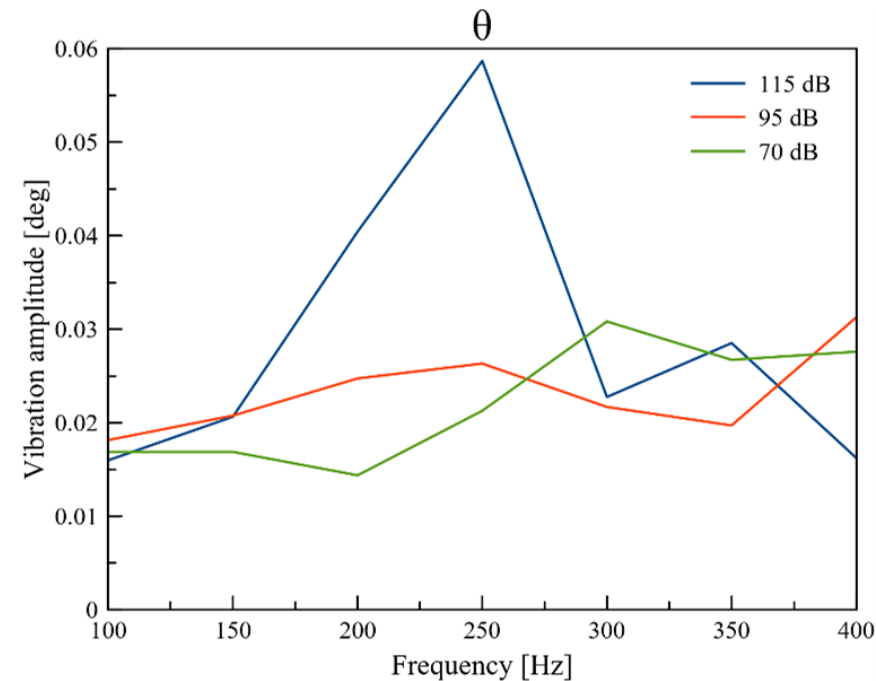
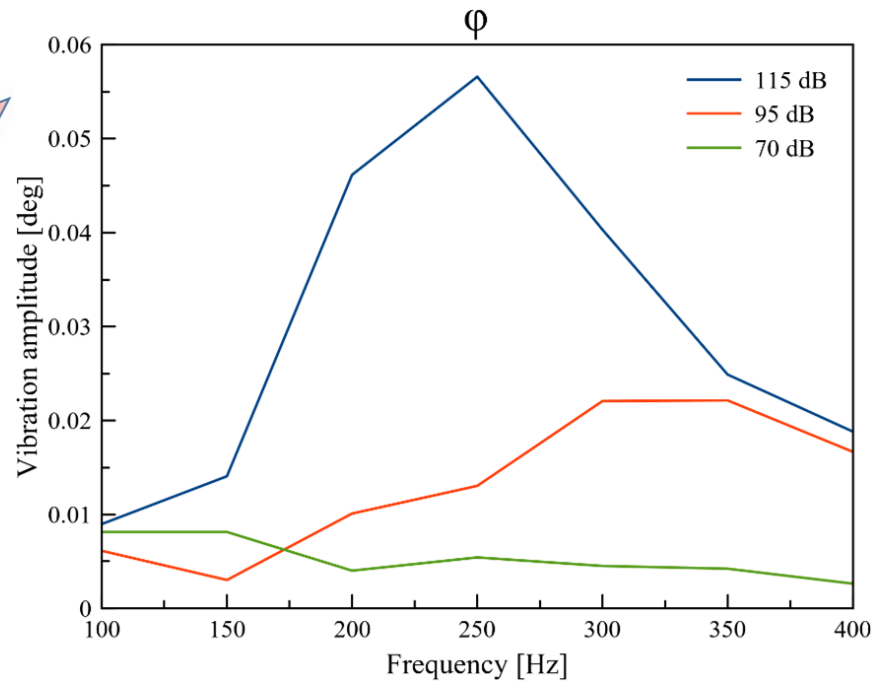
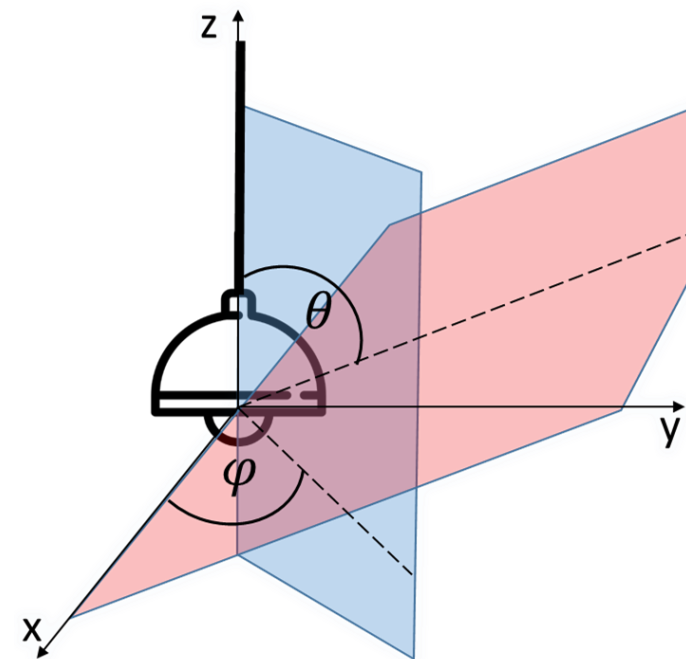


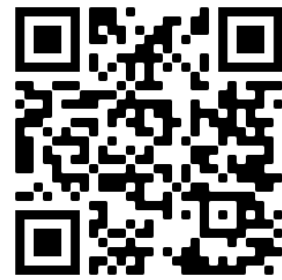


Measuring a Bulb's Vibrations

Results

We computed the angle as the function of the frequency (the sine wave that was played) for Phi and Theta.

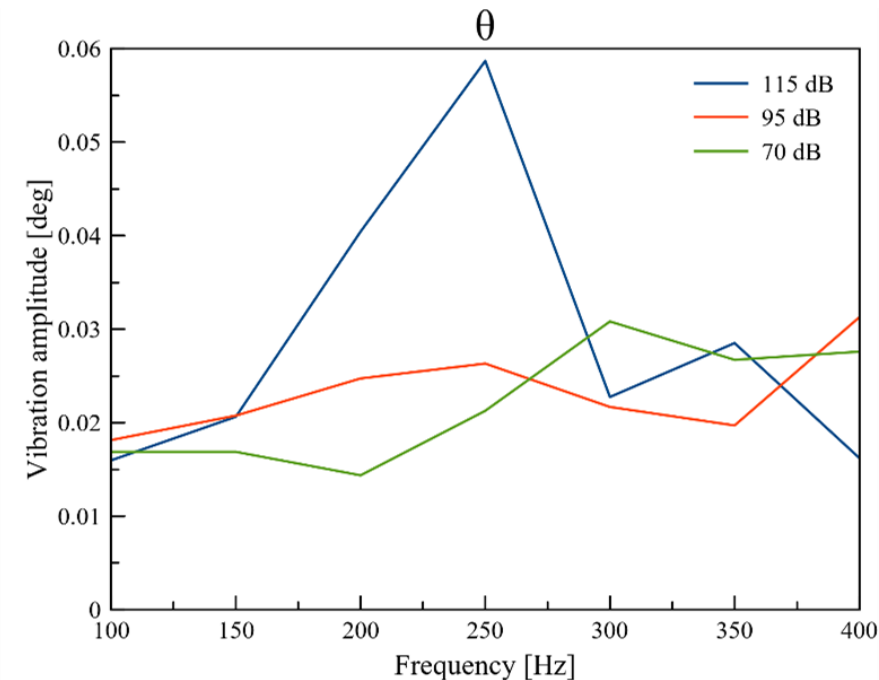
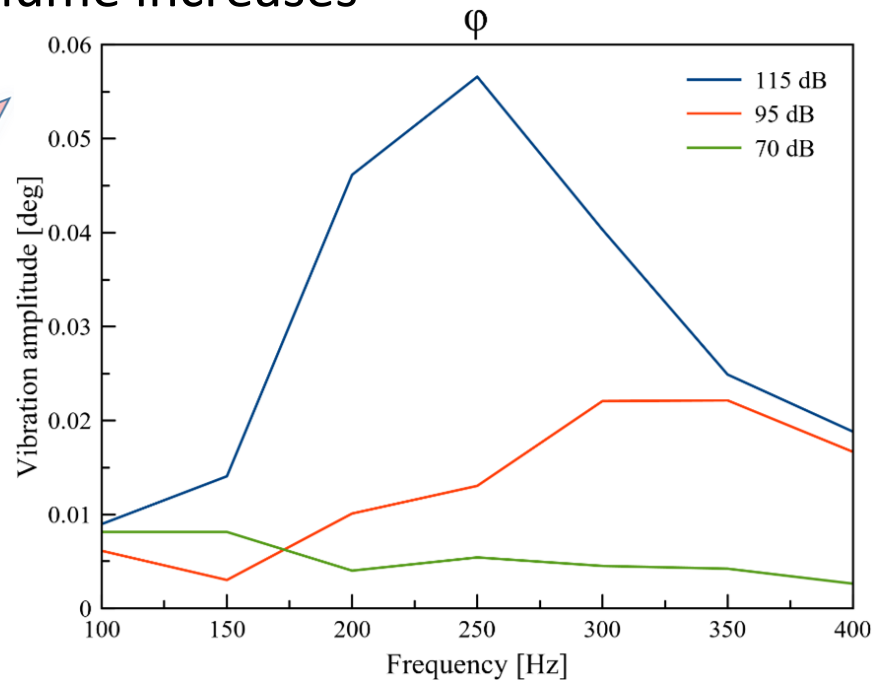
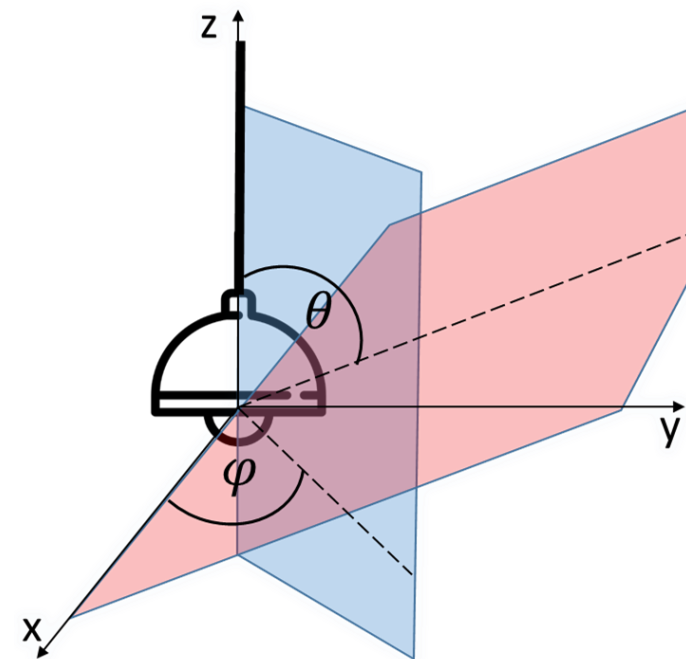




Measuring a Bulb's Vibrations

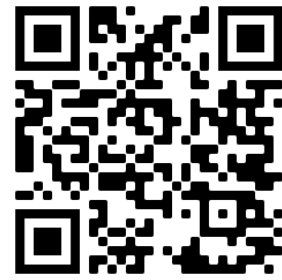
By analyzing the results, we conclude that the angle of vibrations:

- is in millidegrees (0.005-0.06 degrees)
- is not equal - changes as a function of the frequency
- increases as the volume increases

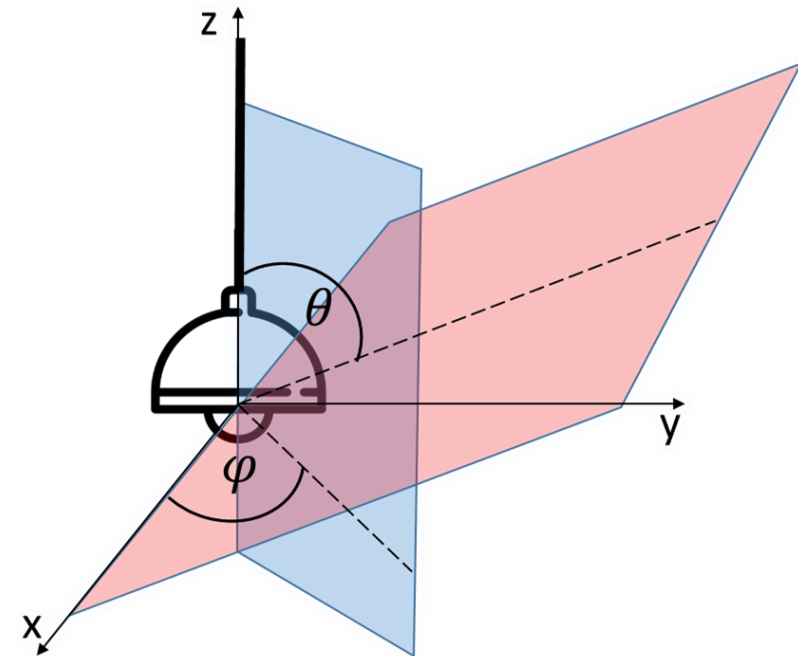




Measuring a Bulb's Vibrations



Based on the known formula of the [spherical coordinate](#) system, we computed the **total movement**, taking into account: Phi, Theta, and distance between the ceiling and the bottom of the hanging bulb.



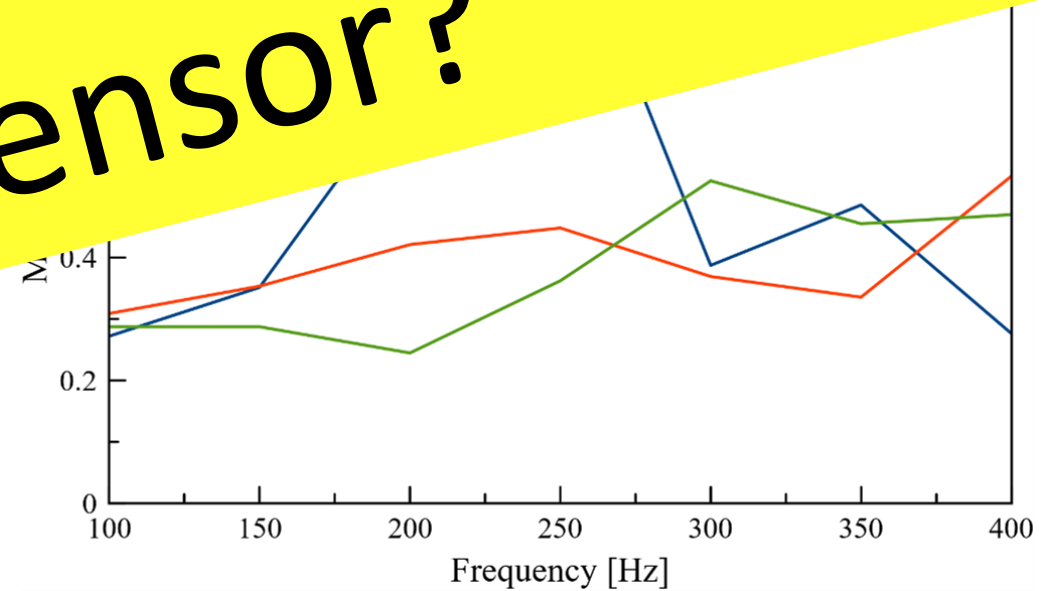


Measuring a Bulb's Vibrations

Results

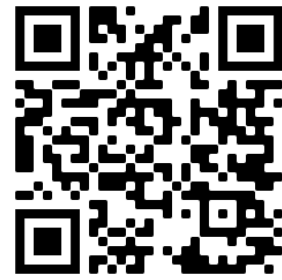
Sound affected the bulb
between

Can we detect a movement of
microns by using an electro-
optical sensor?





Intensity of Light vs. the Bulb's Angle



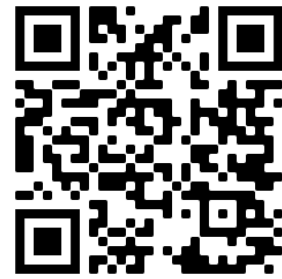
Experiment

- We directed an electro-optical sensor toward a hanging light bulb (when illuminated).
- We measured the voltage that was produced by the electro-optical sensor from various distances (100-950 cm).



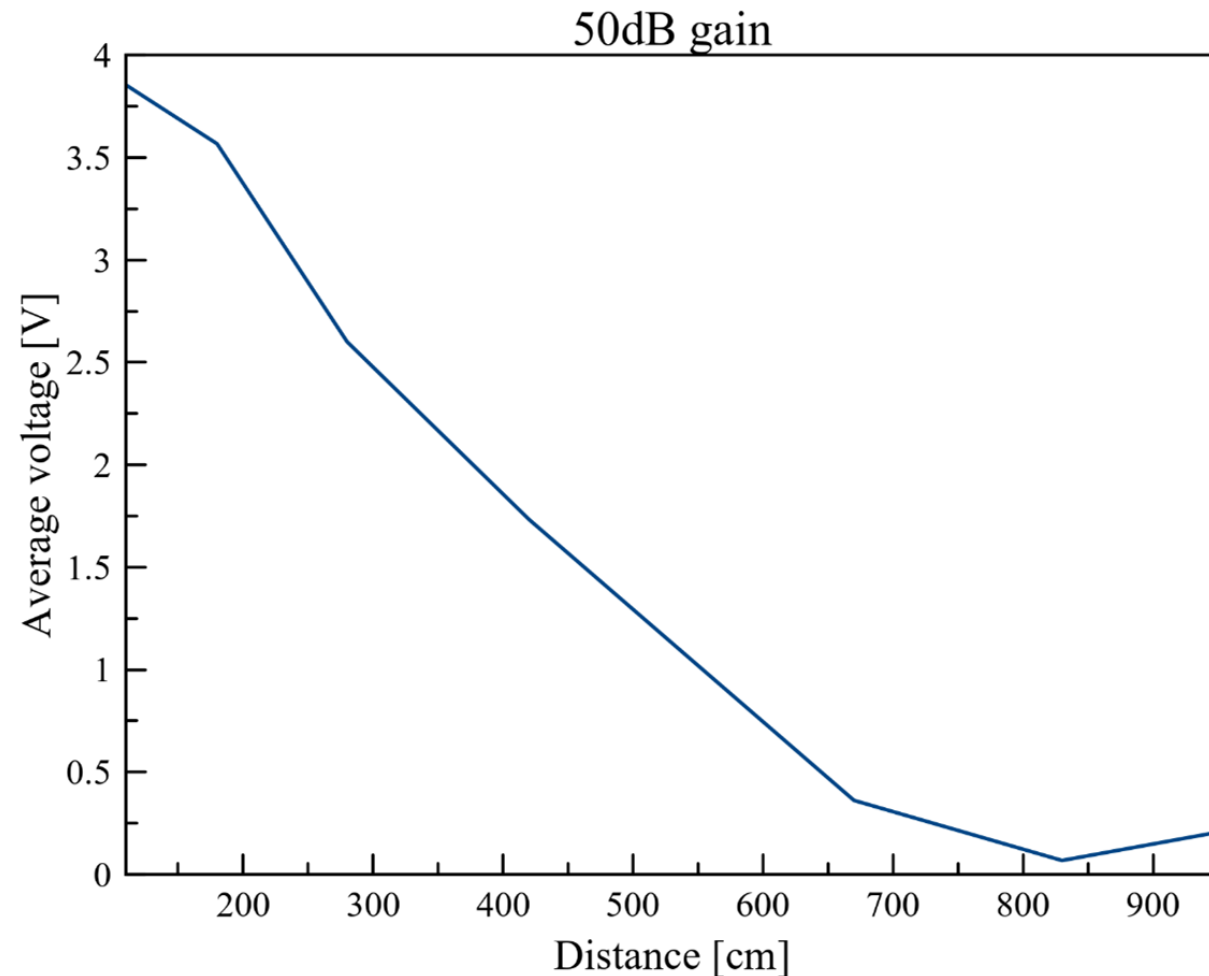


Intensity of Light vs. the Bulb's Angle



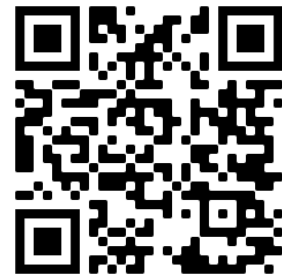
Results

A different amount of voltage is produced by the electro-optical sensor when the sensor is placed 200 cm (3.5 V) than is produced when the sensor is 600 cm (0.5 V) from the bulb.





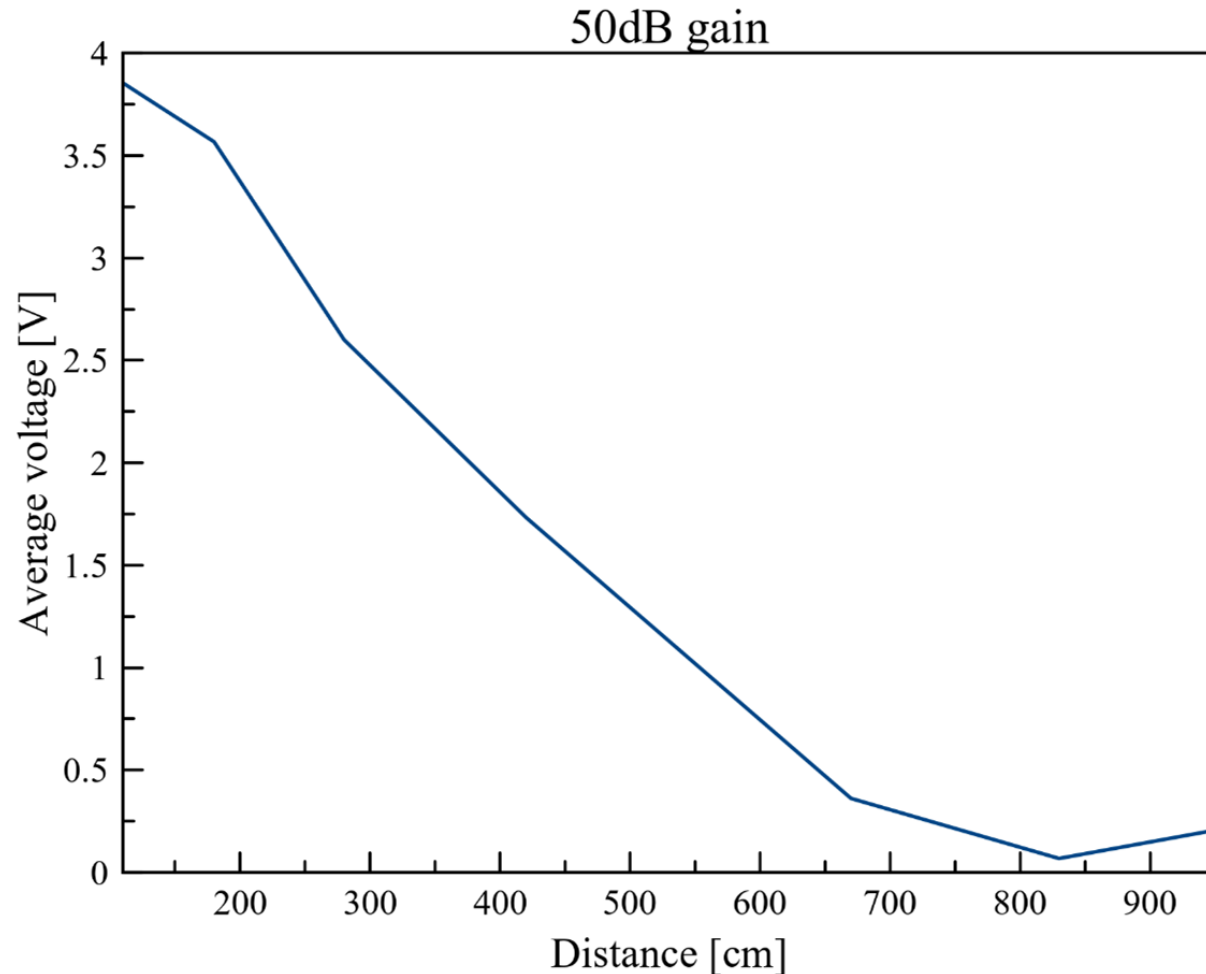
Intensity of Light vs. the Bulb's Angle



Results

A different amount of voltage is produced by the electro-optical sensor when the sensor is placed 200 cm (3.5 V) than is produced when the sensor is 600 cm (0.5 V) from the bulb.

However, we are interested in measuring small movements of the bulb rather than large movements of the sensor.



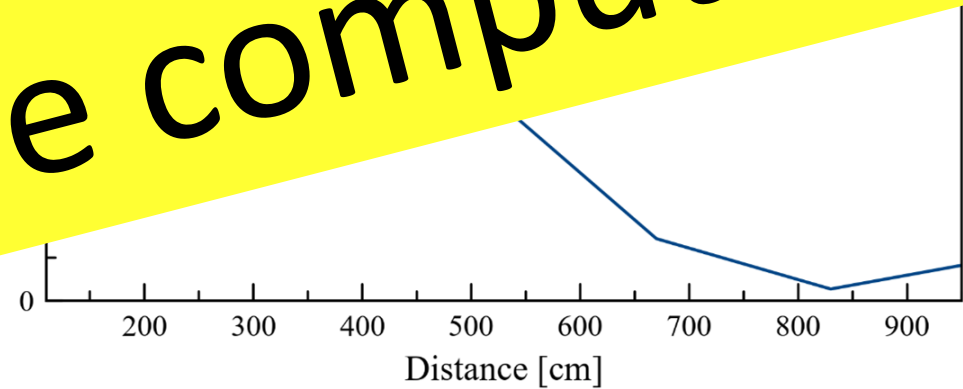


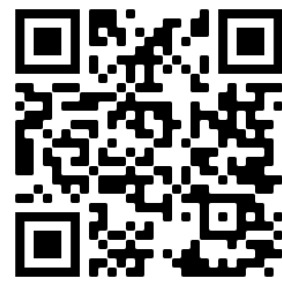
Intensity of Light vs. the Bulb's Angle

Experiment

We directed an el
sen

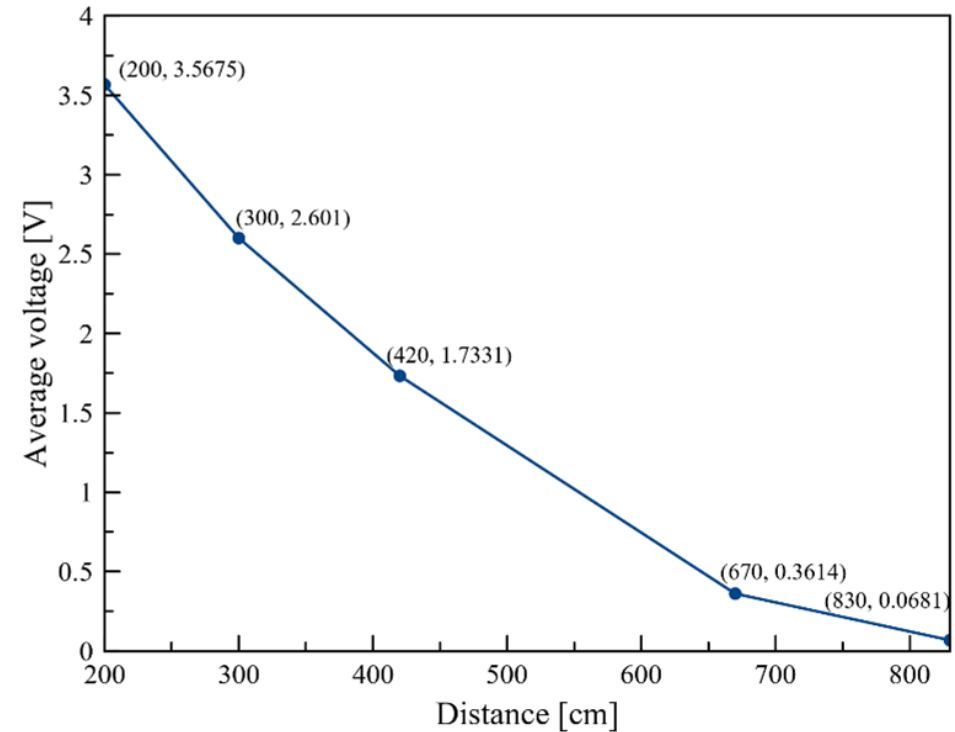
How can the amount of light expected for displacements of 300-950 microns be computed?



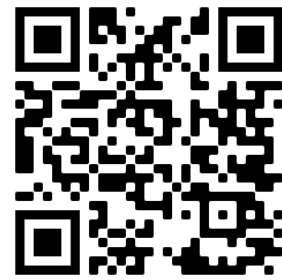


Setting the Criteria

- We computed linear equations between two consecutive points on the graph.

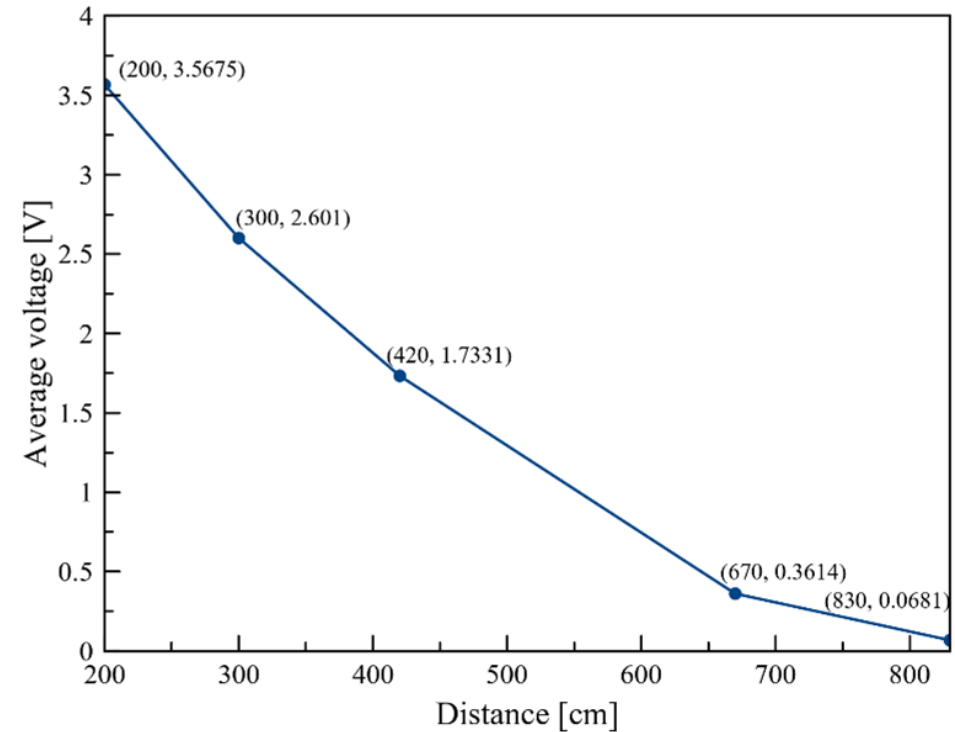


Distance	Linear Equation
200-300	$y = -0.01x + 5.367$
300-420	$y = -0.0062x + 4.3371$
420-670	$y = -0.0055x + 4.037$
670-830	$y = -0.0018x + 1.59$



Setting the Criteria

- We computed linear equations between two consecutive points on the graph.
- Based on the linear equations, we computed the expected voltage resulting from displacements of 300 microns (0.3 mm) and 1000 microns (1 mm).



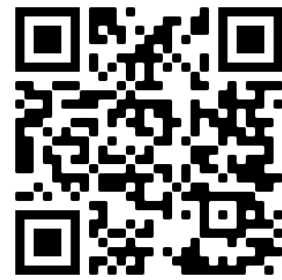
Distance	Linear Equation	Expected Voltage Difference	
		at 0.3 mm	at 1 mm
200-300	$y = -0.01x + 5.367$	0.0003	0.001
300-420	$y = -0.0062x + 4.3371$	0.000186	0.00062
420-670	$y = -0.0055x + 4.037$	0.000165	0.00055
670-830	$y = -0.0018x + 1.59$	0.000054	0.00018



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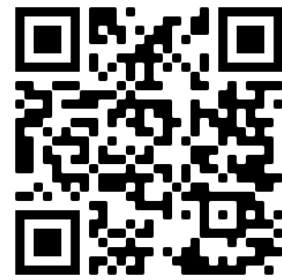
- A 16-bit ADC provides a sensitivity of 300 microvolts: $\frac{20}{2^{16} - 1} \approx 300$ microvolts



Setting the Criteria

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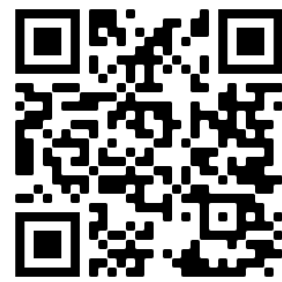
- A 16-bit ADC provides a sensitivity of 300 microvolts.
- Conclusion 1: A sensitivity of 300 microvolts is sufficient to recover the entire spectrum (100-400 Hz) from a distance of 200-300 cm, because the smallest vibration of 0.3 mm produces a difference of 300 microvolts.



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- A 16-bit ADC provides a sensitivity of 300 microvolts.
- Conclusion 1: A sensitivity of 300 microvolts is sufficient to recover the entire spectrum (100-400 Hz) from a distance of 200-300 cm, because the smallest vibration of 0.3 mm produces a difference of 300 microvolts.
- Conclusion 2: In order to detect a bulb's vibration from 300 cm away: 1) the sensitivity of the system needs to be increased, or 2) the signal obtained needs to be amplified.



What Exactly is Vibrating?

Experiment

We obtained optical measurements via the electro-optical sensor when playing sine waves from speakers in these two scenarios:

With a defuser covering the LED bulb

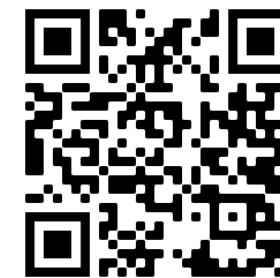


Without a defuser covering the bulb





What Exactly is Vibrating?

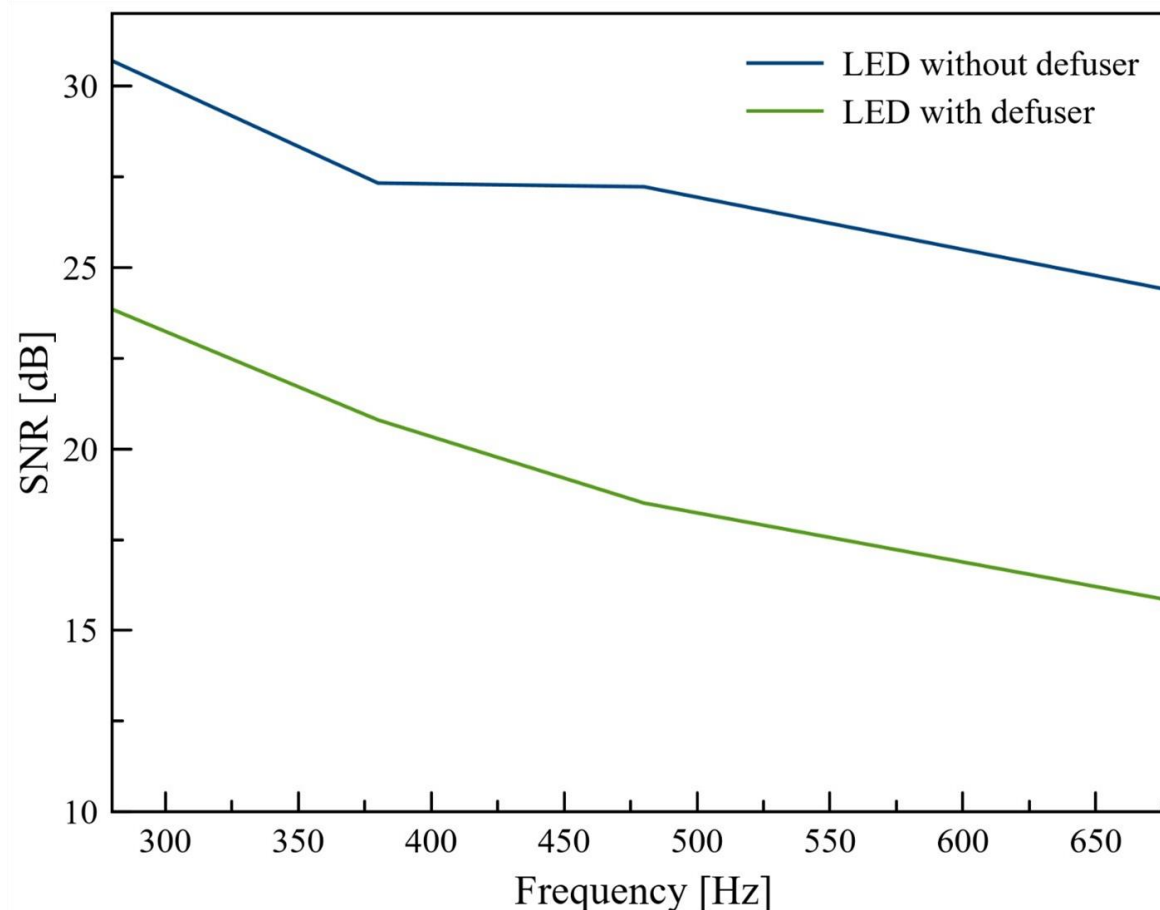


Results

The SNR decreases when a defuser covers the light bulb.

Conclusion 1: The diaphragm is the light bulb and not the defuser.

Conclusion 2: The defuser decreases the SNR due to the fact it is aimed at distributing the light uniformly.



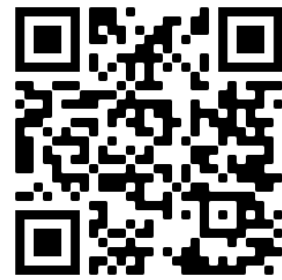


Light Intensity vs. Angle



Experiment

Obtaining optical measurements via the electro-optical sensor when no sound is played near the light bulb.



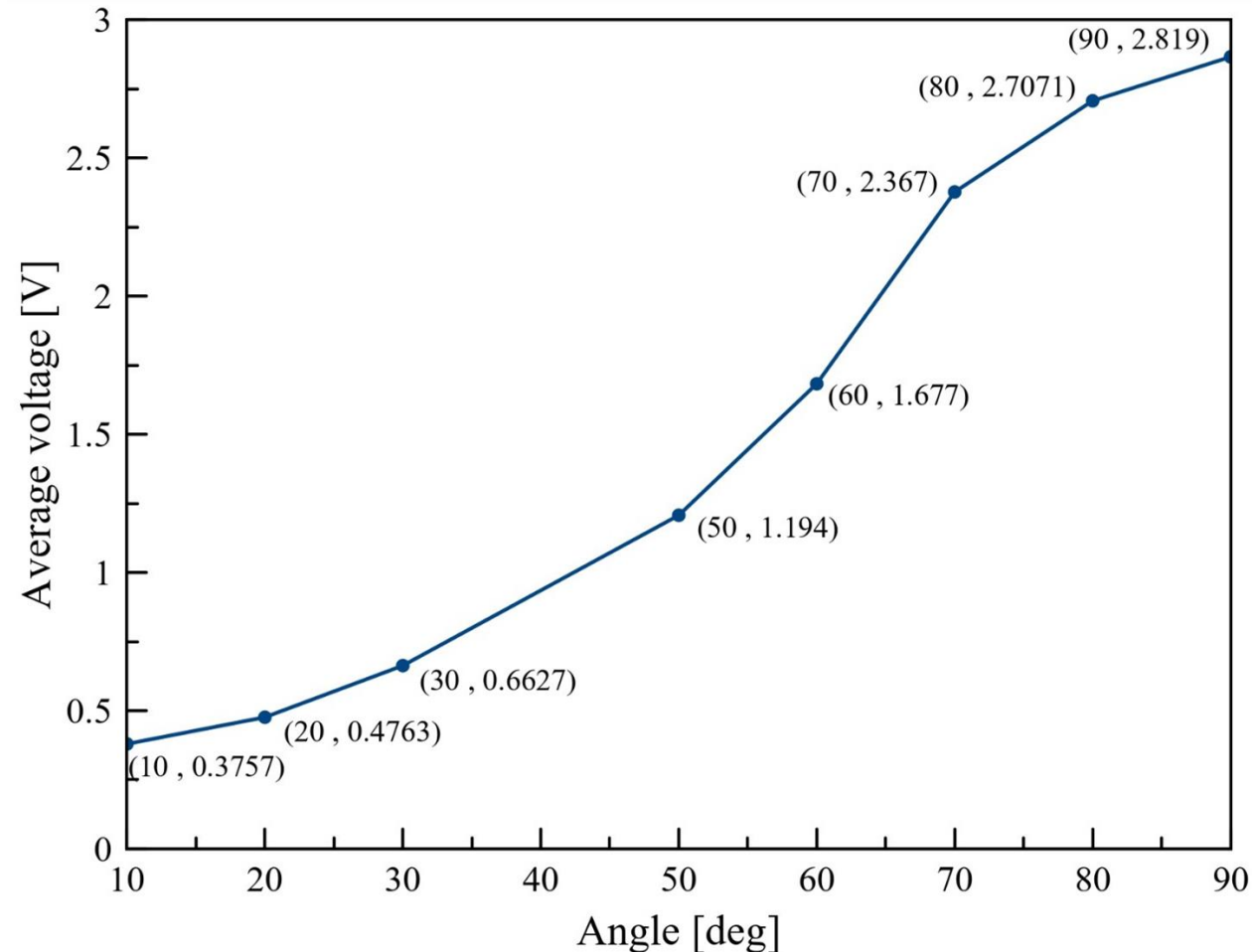
Light Intensity vs. Angle

Results

The defuser does not distribute the light uniformly.

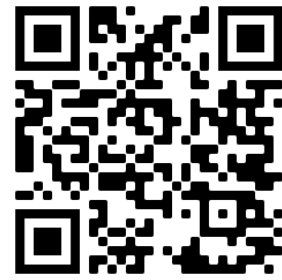
Side note:

If the defuser was able to perfectly distribute the light uniformly, then we were unable to detect the small light changes that are the result of displacements of microns.





Comparison of Various Types of Bulbs



Experiment

We compared the SNR that was obtained from three types of E27 light bulbs:

Incandescent



LED



Fluorescent



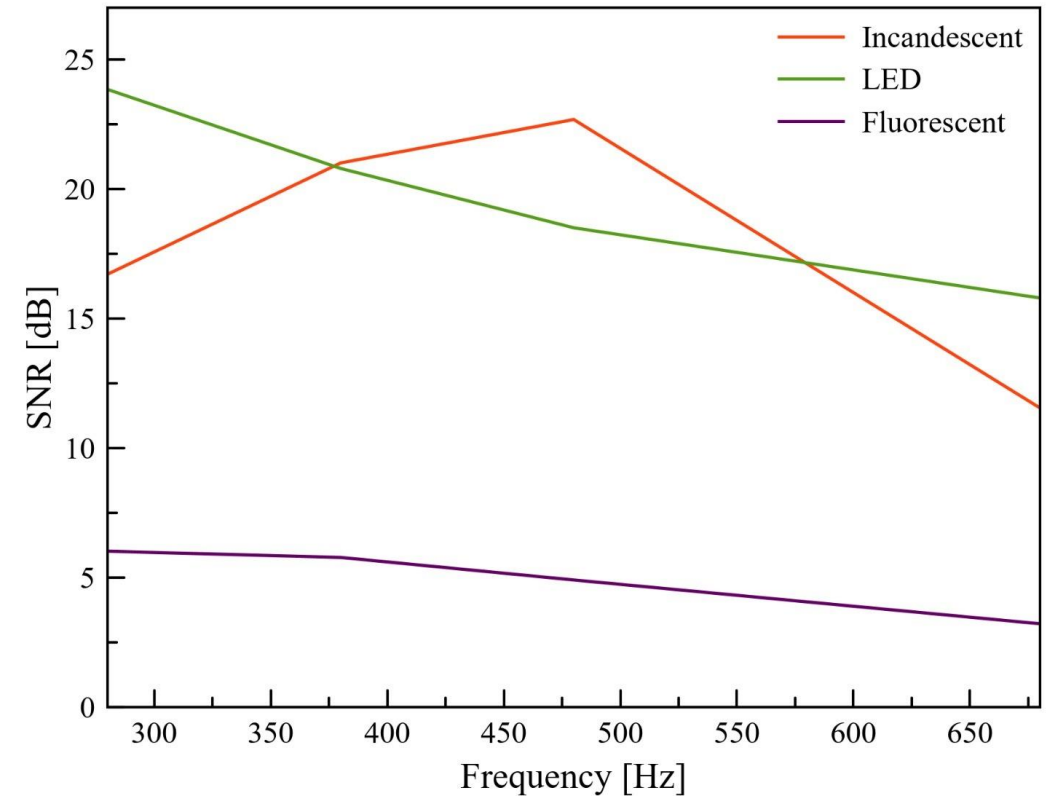


Comparison of Various Types of Bulbs



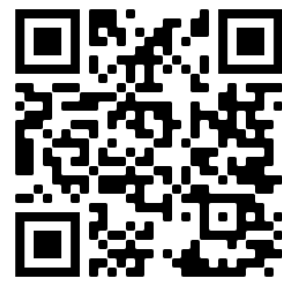
Results

- 1) Sound could be reconstructed from every type of hanging light bulb that was examined.
- 2) The SNR of incandescent and LED light bulbs is higher than the SNR of fluorescent bulbs.



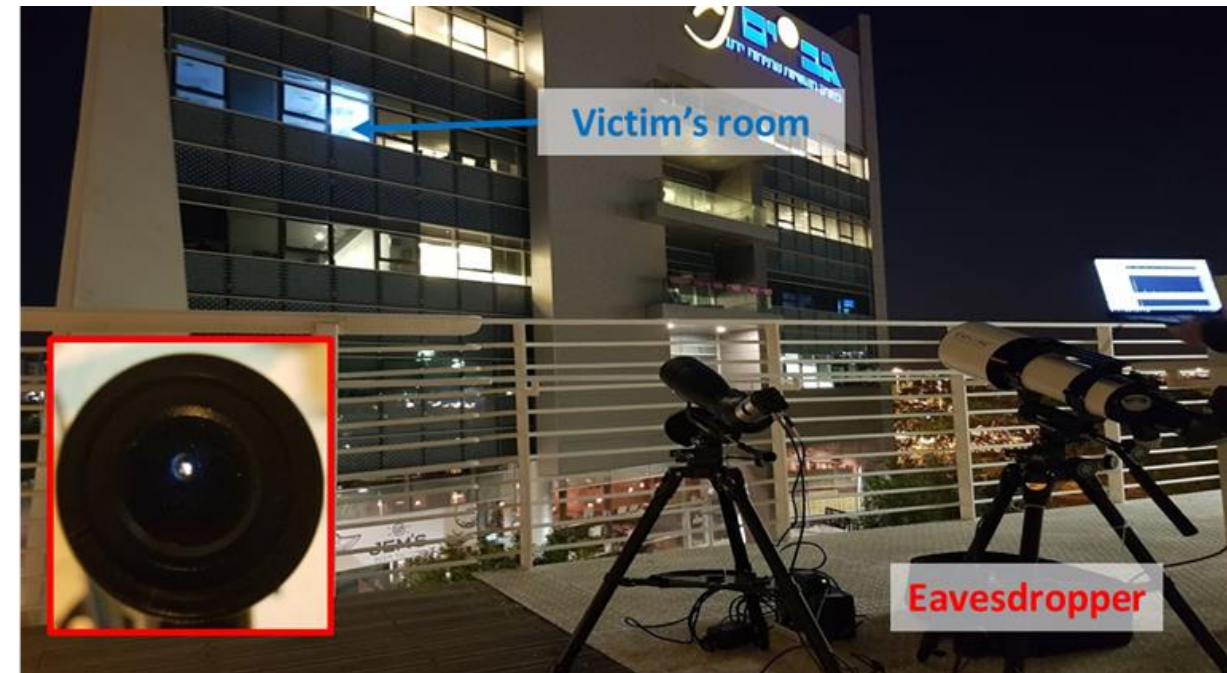


Evaluation in a Real Setup



Experimental Setup

- We evaluated Lamphone's performance for recovering sound from a bridge located 25 meters from an office.
- The office contains a 12 watt E27 hanging light bulb.





Experimental Setup



The sound that was played inside the office cannot be heard from the bridge.

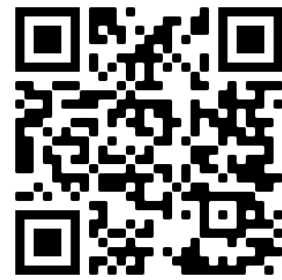


Characterizing the Baseline



Experiment

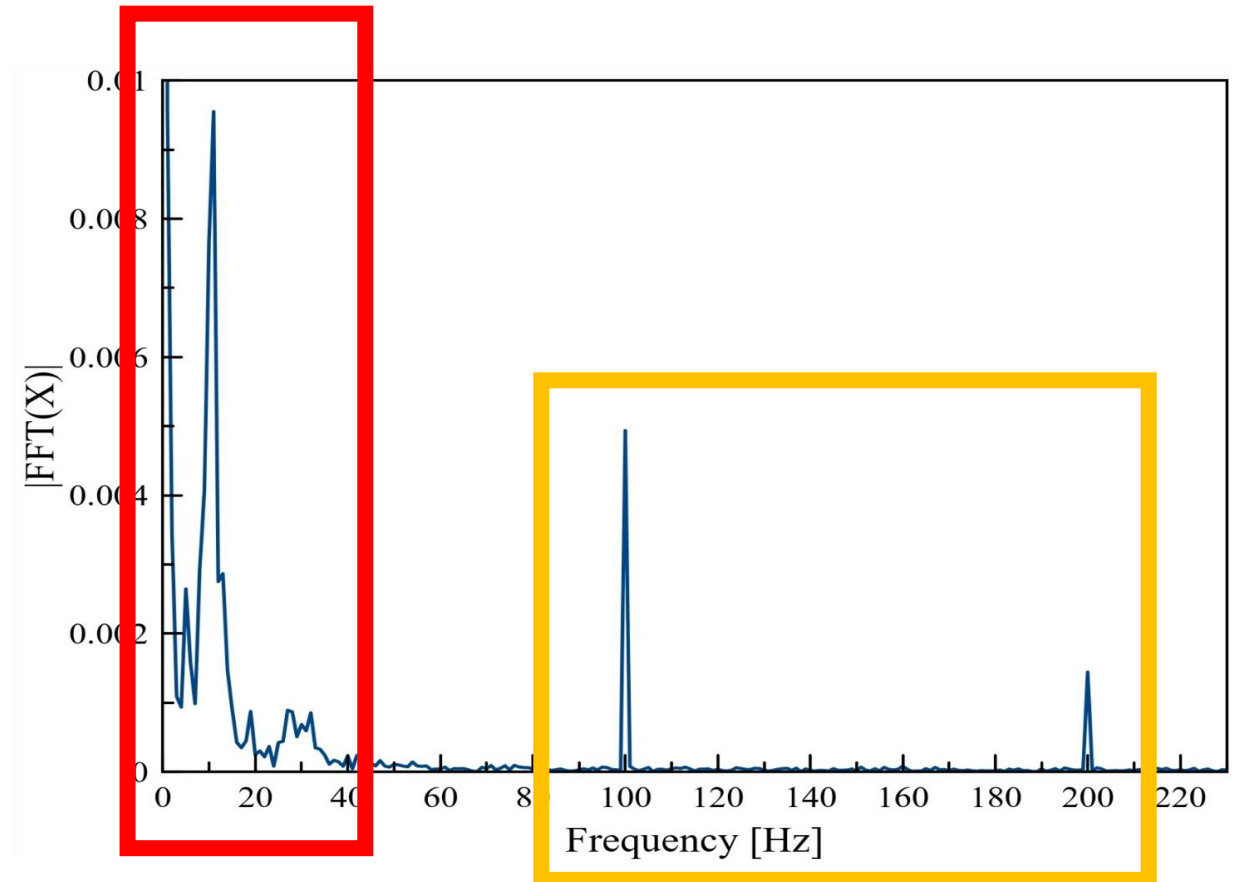
Obtaining optical measurements via the electro-optical sensor when no sound is played in the office.



Results

Results

- The LED bulb works at 100 Hz.
There are Peaks on the FFT graph at each of the harmonics (200 Hz, 300 Hz, etc.).
 - We need to filter this noise with bandstop filters.
- There is noise at low frequencies (below 50 Hz).
 - We need to filter this noise with a highpass filter.





Analyzing the Frequency Response

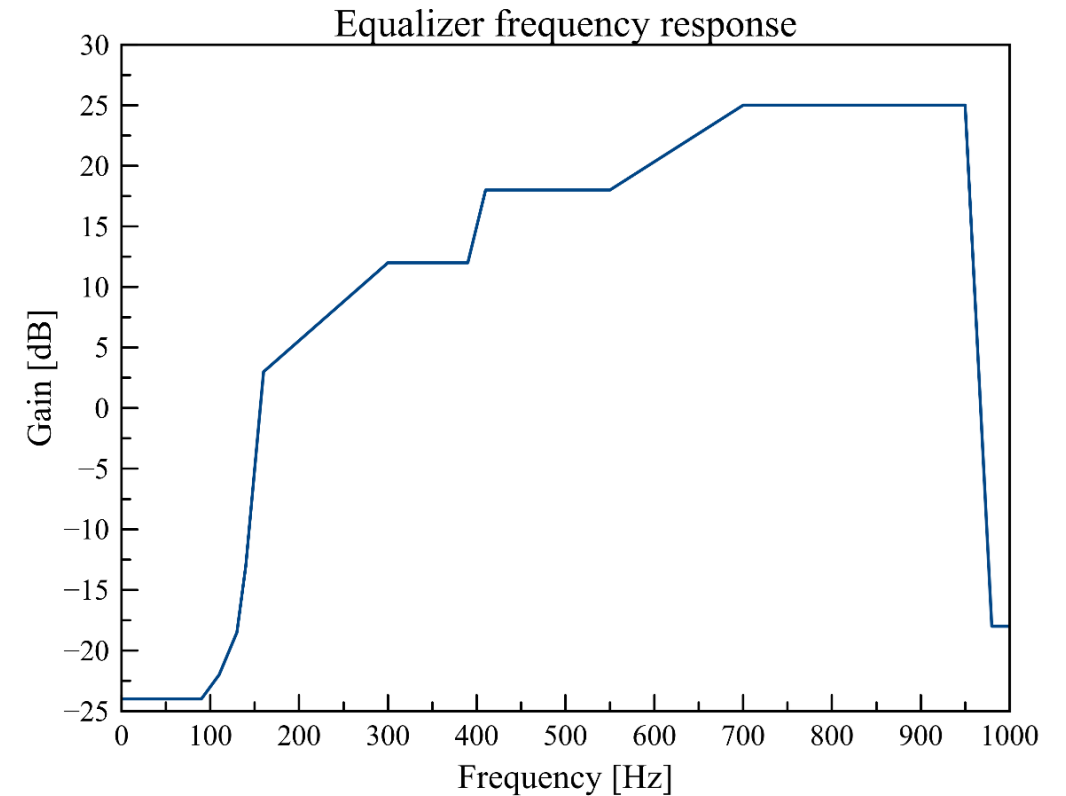
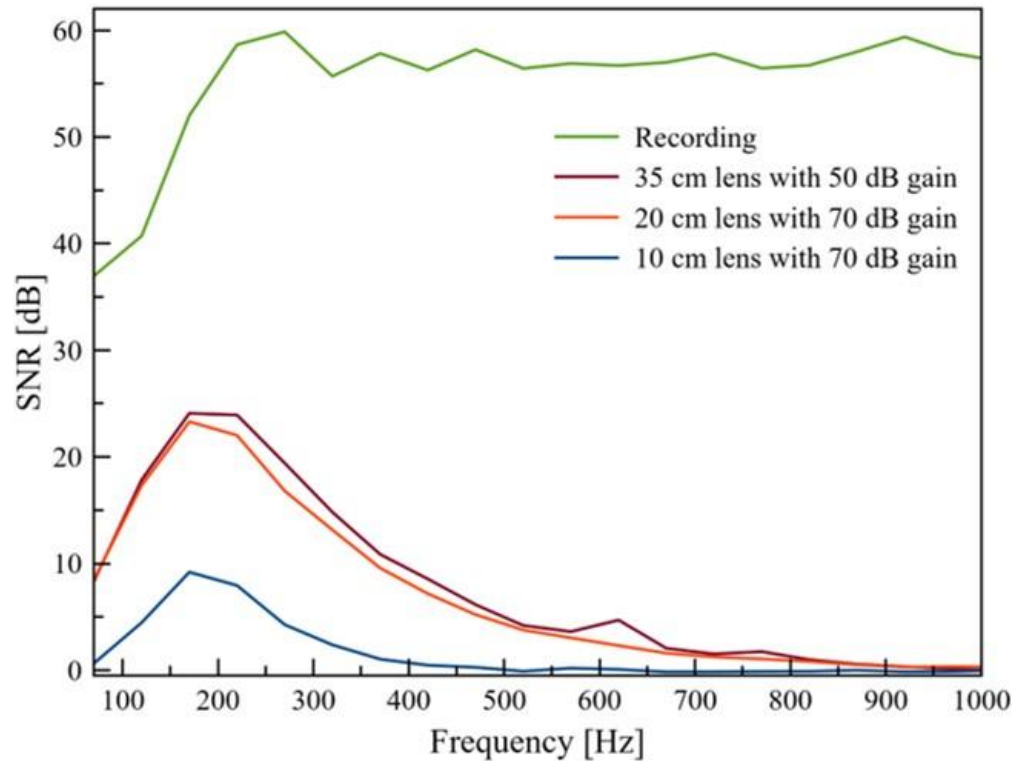
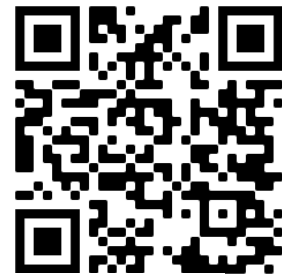


Experiment

Obtaining optical measurements via the electro-optical sensor when a frequency scan is played via speakers in proximity to a hanging bulb.



Results



Conclusion 1: The SNR improves when a telescope with a bigger lens is used.

Conclusion 2: The SNR is not equal across the spectrum so an equalizer needs to be applied in order to balance the frequency response of the recovered signal.



Recovering Non-Speech Audio



Experiment

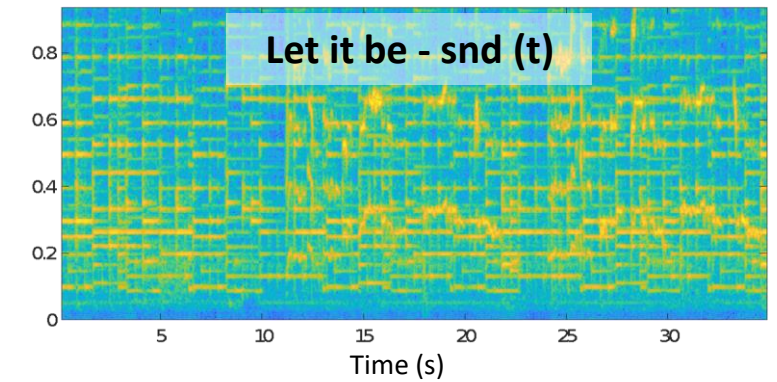
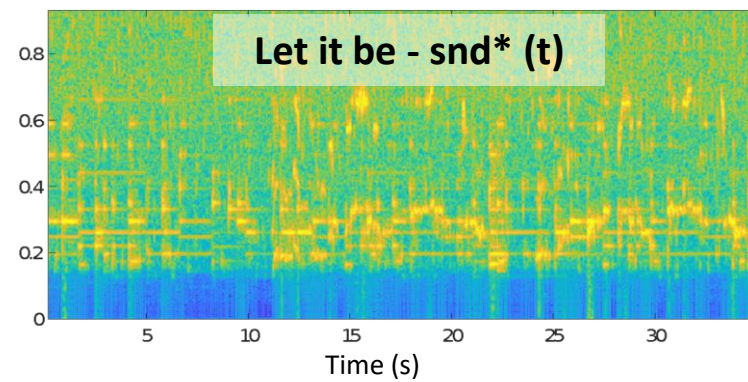
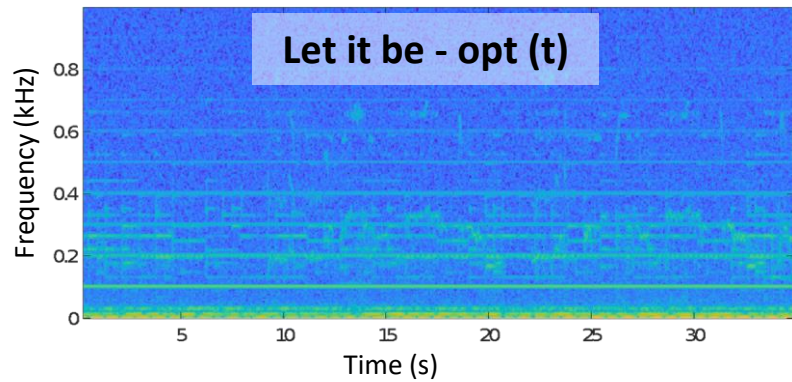
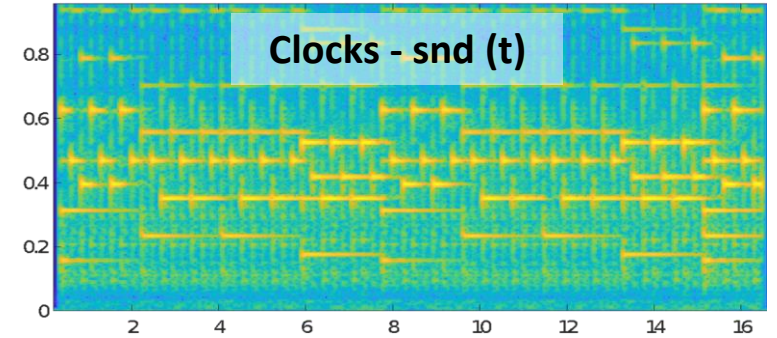
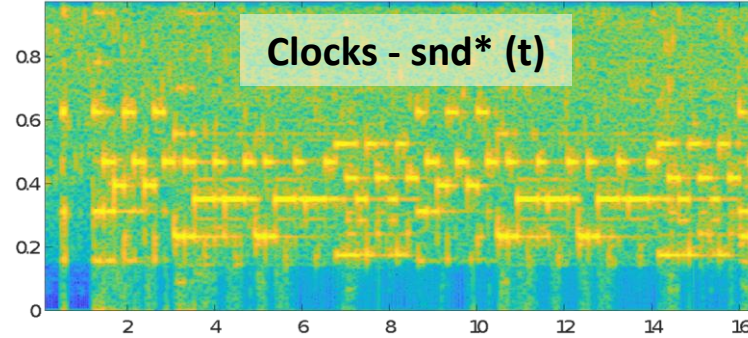
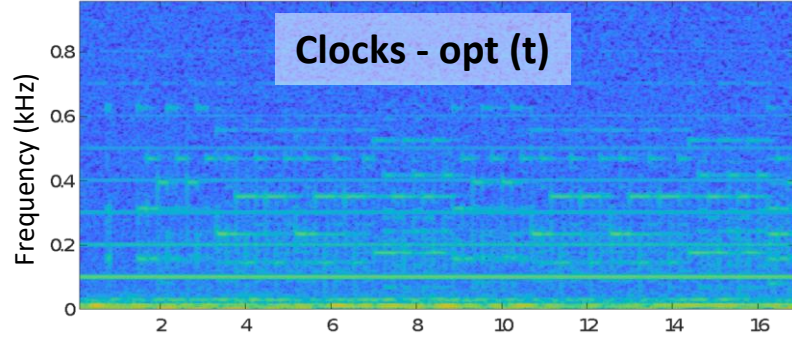
- We played two famous songs inside the office:
 - "Let it Be" (The Beatles)
 - "Clocks" (Coldplay)
- We obtained the optical measurements.
- We recovered the signals.



Recovering Non-Speech Audio



Results



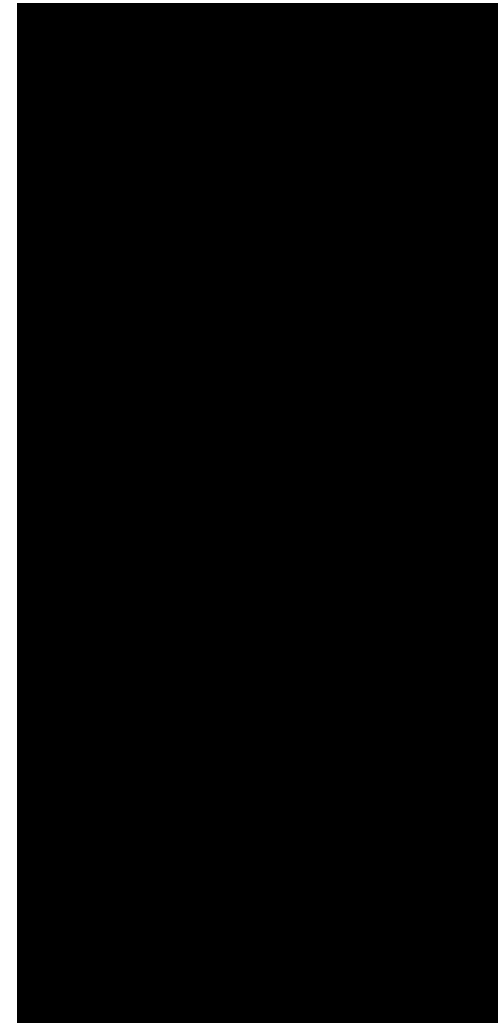
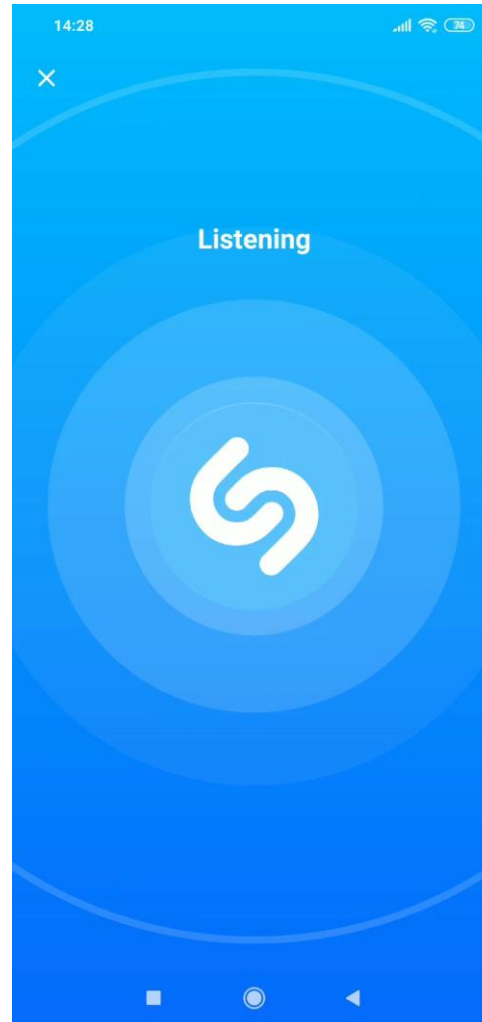


Recovering Non-Speech Audio



Results

We Shazamed the recovered signals.





Recovering Speech Audio



Experiment

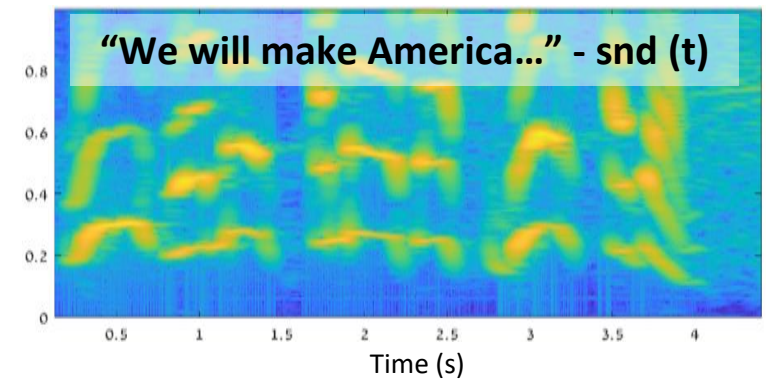
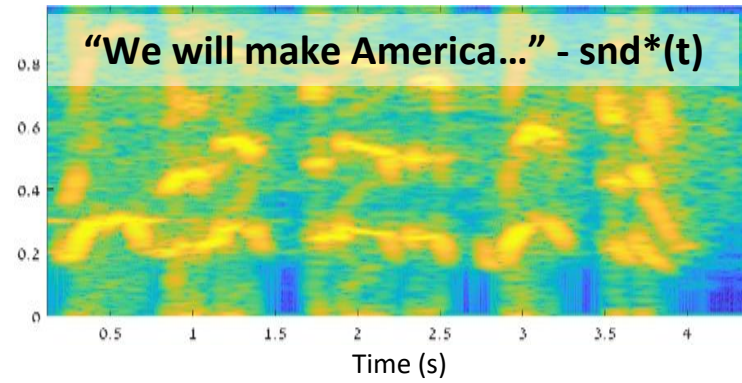
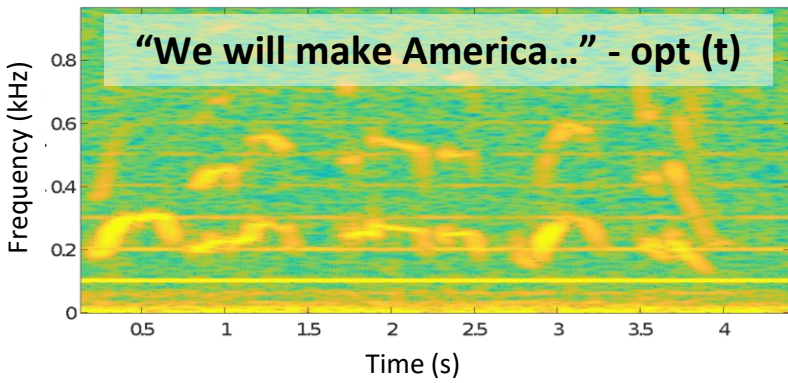
- We played a famous statement made by Donald Trump:
 - “We will make America great again!”
- We obtained the optical measurements.
- We recovered the signals.



Evaluation

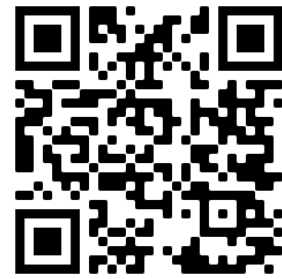


Results





Evaluation



Results

We investigated whether the recovered signal could be transcribed by Google's Speech-to-Text engine.

Convert your speech to text right now

Language
English (United States)

Speaker diarization BETA
Off

Speakers
1 speaker

Punctuation

Show JSON ▼

Models: Default Command / Search Phone call Video

" We will make America great again. "



Potential Improvements



Potential Improvements

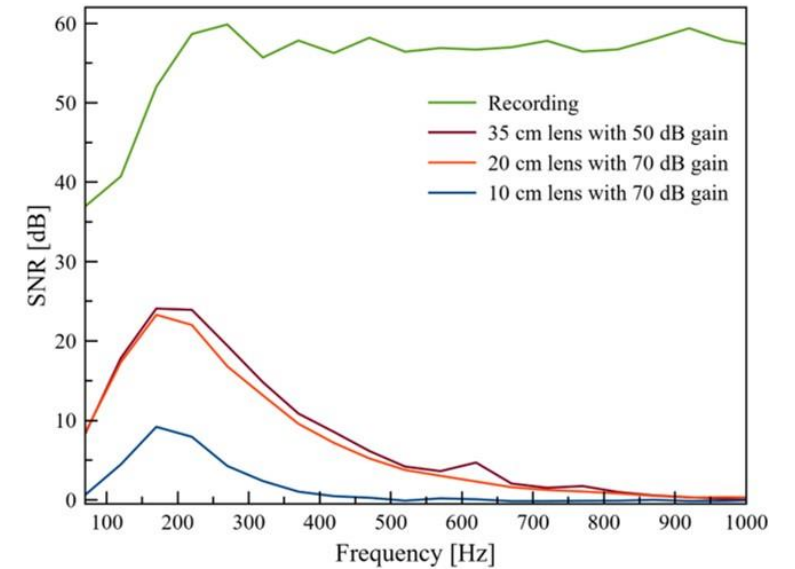


1. Telescope

- Using a telescope with a larger lens diameter (r).

Why?

The amount of light that is captured by the telescope is a function of its lens area (πr^2)





Potential Improvements

1. Telescope
 - Using a telescope with a larger lens diameter (r).
2. Electro-Optical Sensor
 - Using a better (more sensitive) electro-optical sensor than the one we used (PDA100A2).
 - Using multiple electro-optical sensors for multi-channel audio recovery.



Potential Improvements

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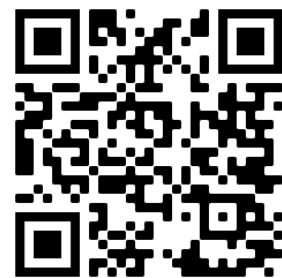
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3. ADC

- Using an ADC with a lower noise level.
- Using a 24/32-bit ADC instead of a 16-bit ADC.



Potential Improvements

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 - Using a telescope with a larger lens diameter (r).
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 - Using a better (more sensitive) electro-optical sensor than the one we used (PDA100A2).
 - Using multiple electro-optical sensors for multi-channel audio recovery.
3. ADC
 - Using an ADC with a lower noise level.
 - Using a 24/32-bit ADC instead of a 16-bit ADC.
4. Recovery Algorithm
 - Using advanced filtering techniques to filter noise (e.g., deep learning).



Takeaways



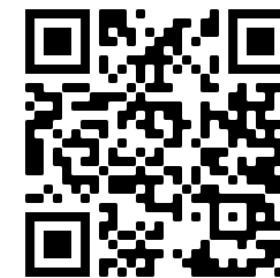
Primary Takeaway



Although it is now August 2020, please mark August 2026 on your calendars.

Why?

Let's examine Gyrophone's [1] scientific progress.



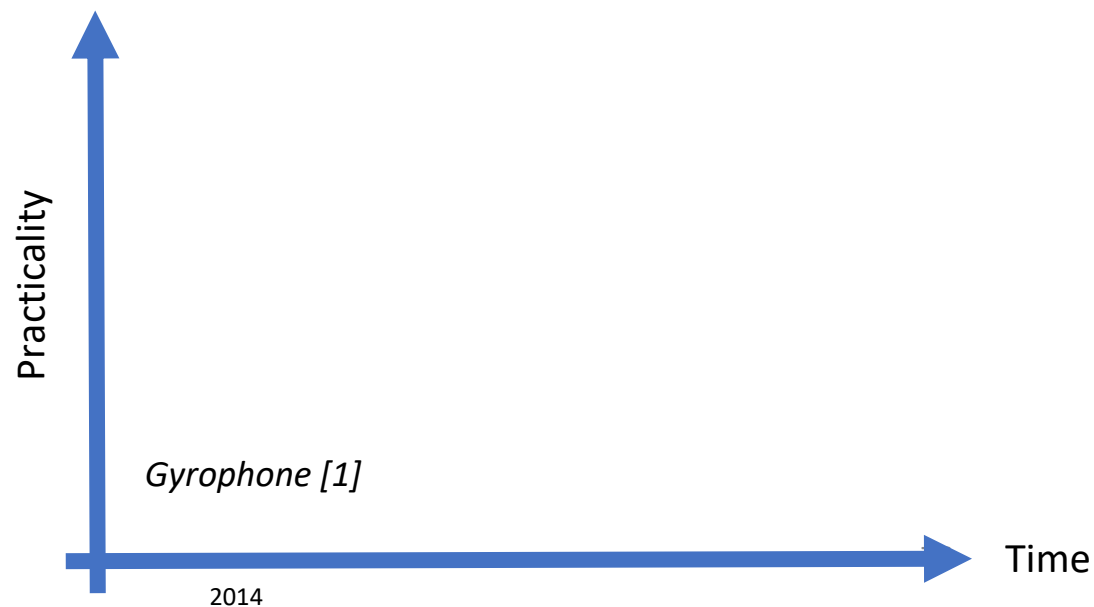
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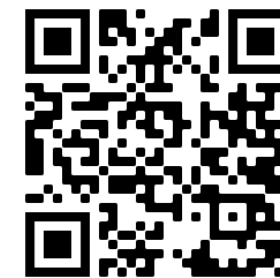
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Why?

Let's examine Gyrophone's [1] scientific progress.

- 2014 – The attack vector of eavesdropping via motion sensors is revealed.
 - ❑ A classification model to classify isolated words that yields results which are only slight better than a random guess
 - ❑ The attack vector relied on speech at high volume.





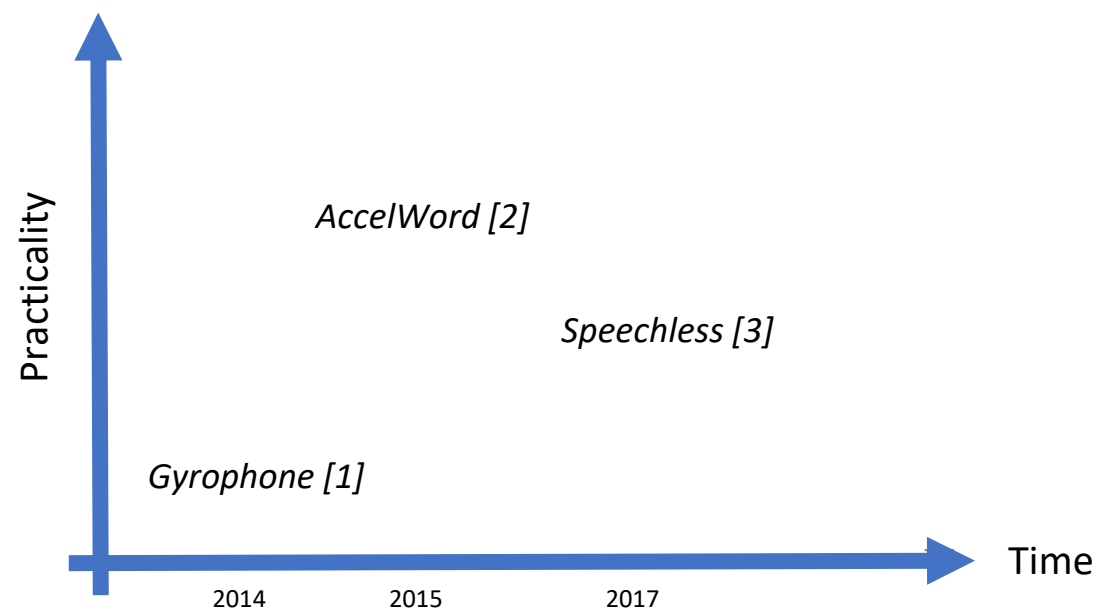
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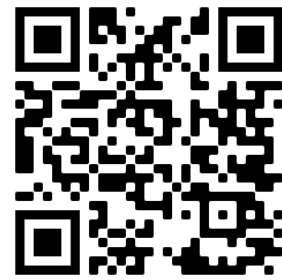
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Let's examine Gyrophone's [1] scientific progress.

- 2014 – The attack vector of eavesdropping via motion sensors is revealed.
- 2015 to 2018 – Increased understanding regarding this attack vector is gained.
 - ❑ The accuracy of the classification model improves.
 - ❑ Better understanding regarding the experimental setup is gained.





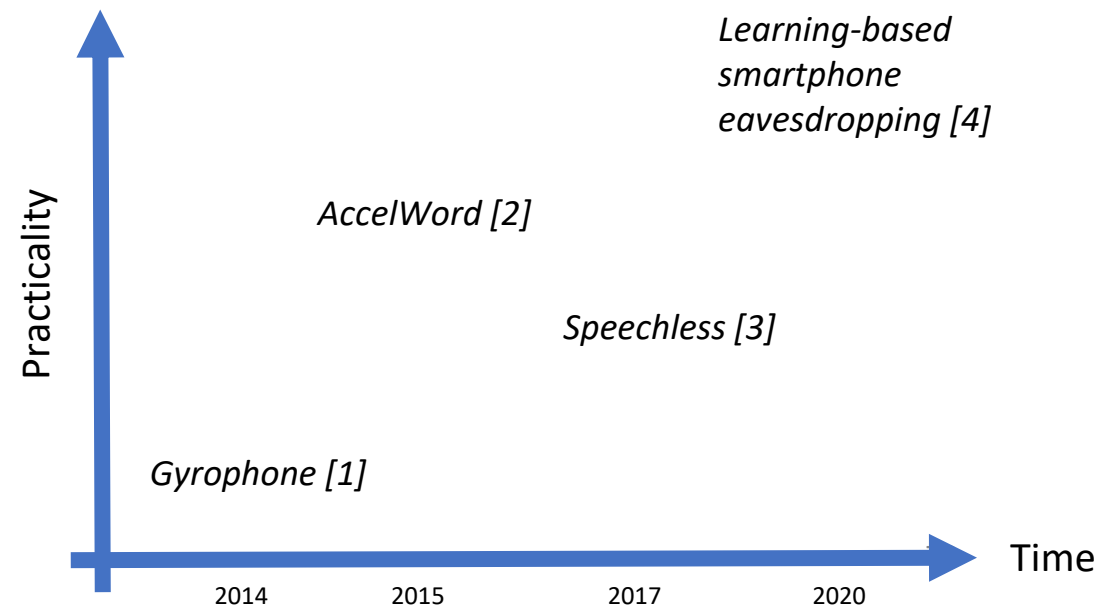
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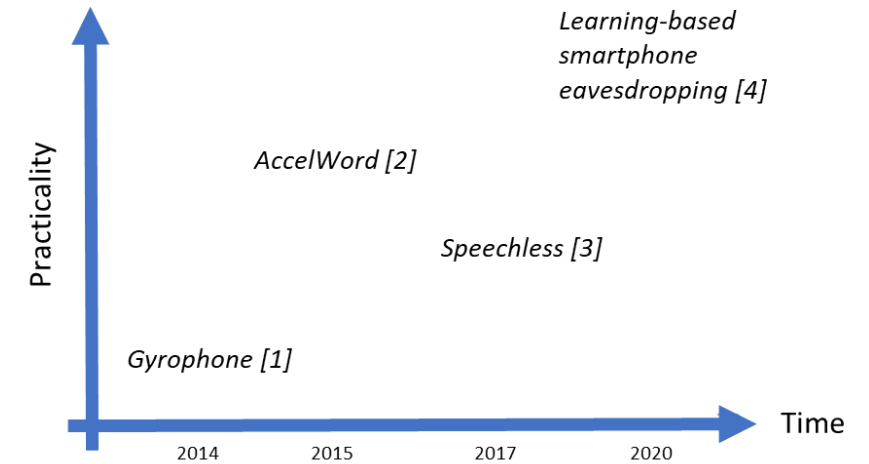
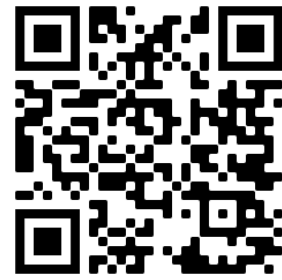
- 2014 – The attack vector of eavesdropping via motion sensors is revealed.
- 2015 to 2018 – Increased understanding regarding this attack vector is gained.
- 2020 – The attack vector is improved to make it a real and practical threat to privacy.
 - ❑ A classification model with excellent accuracy.
 - ❑ The attack vector relies on speech at normal volume.





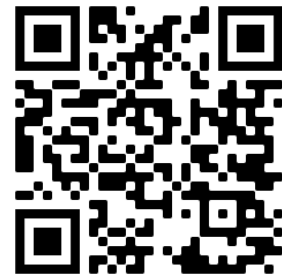
Primary Takeaway

Conclusion: It took scientists six years to improve Gyrophone, to the point that it now poses a real threat to privacy.



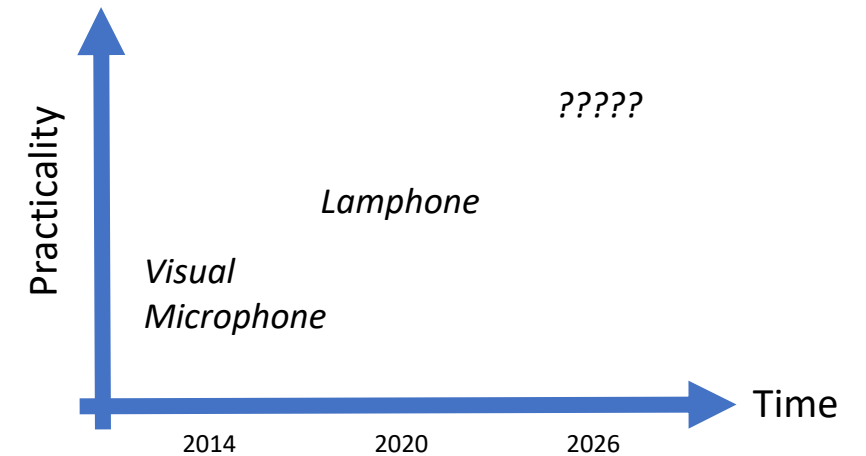
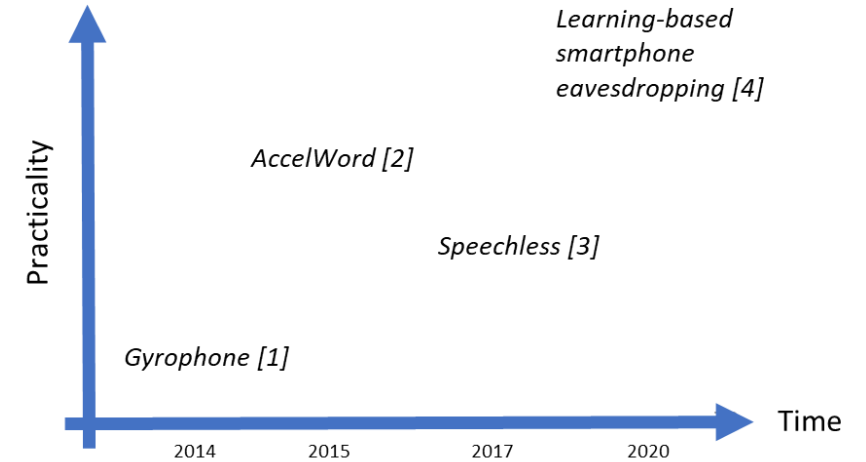


Primary Takeaway



Conclusion: It took scientists six years to improve Gyrophone, to the point that it now poses a real threat to privacy.

My Forecast: I expect that by 2026, scientists will have improved Lamphone so that it too poses a real threat to privacy.





Thank You!

Questions?



Bibliography

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