http://www.mit.edu/~fadel/courses/MAS.s60/index.html

MAS.S60

How to Wirelessly Sense Almost Anything

Lecture 7:
Ocean IoT

Lecturers

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TA

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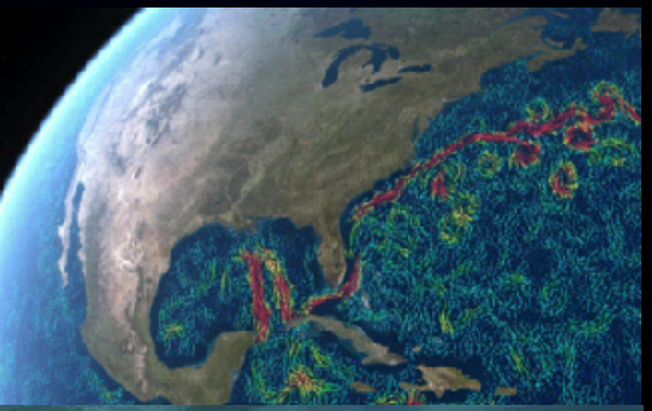
Announcement:
update proposal for grade



Let’s start with some trivia

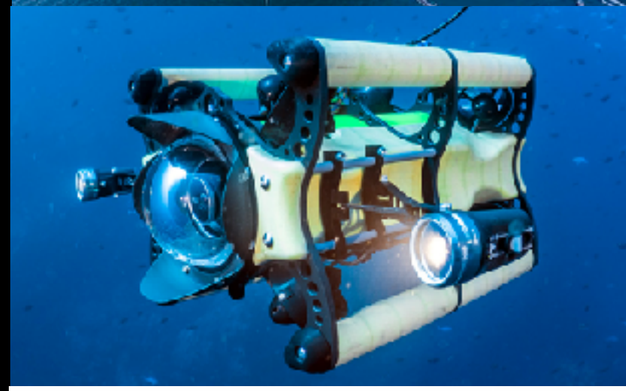
1. How percentage of the ocean floor has never been observed?

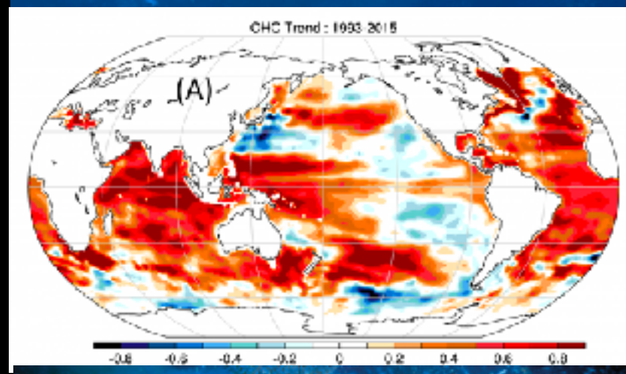
2. Out of every 10 marine organisms, how many have never been discovered?

3. What is the world’s fastest-growing food sector?

4. What has more heat content: the ocean or the atmosphere?

5. Which decade did the UN declare *“Decade of Ocean Science for Sustainable Development”*?





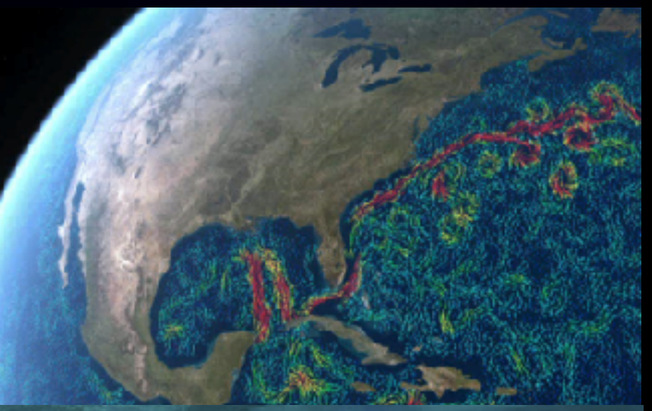
Taking the Internet of Things to the Ocean World

30 bn

IoT Devices

Less than 1 in a million of IoT is in the ocean, even it they covers >70% of the planet and has significant needs for food, climate, etc.

IoT Sensors → **Data** → **Decision Making & Prediction**



How Can IoT help?

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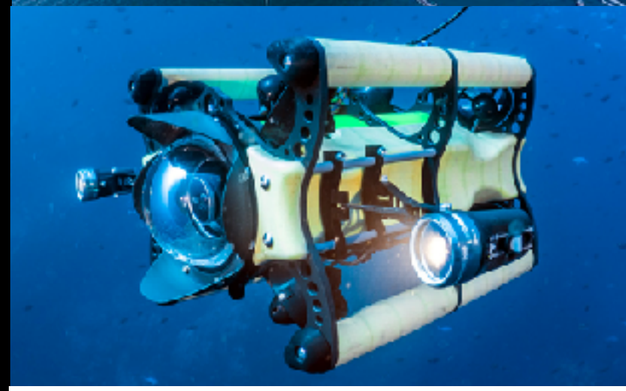
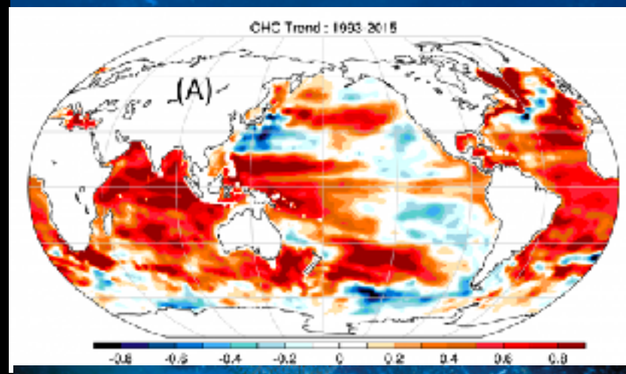




This Week in Wireless Sensing

The profound link between the climate crisis and the ocean – in pictures

Ahead of Cop27 as part of a drive to increase the diversity of imagery showing the impact of climate on marine environments, Climate Visuals has released a new collection of evidence-based images. Here is a selection

Seascape: the state of our oceans is supported by

the guardian .org

About this content

Fri 28 Oct 2022 02.15 EDT

https://www.theguardian.com/environment/gallery/2022/oct/28/the-profound-link-between-the-climate-crisis-and-the-ocean-in-pictures

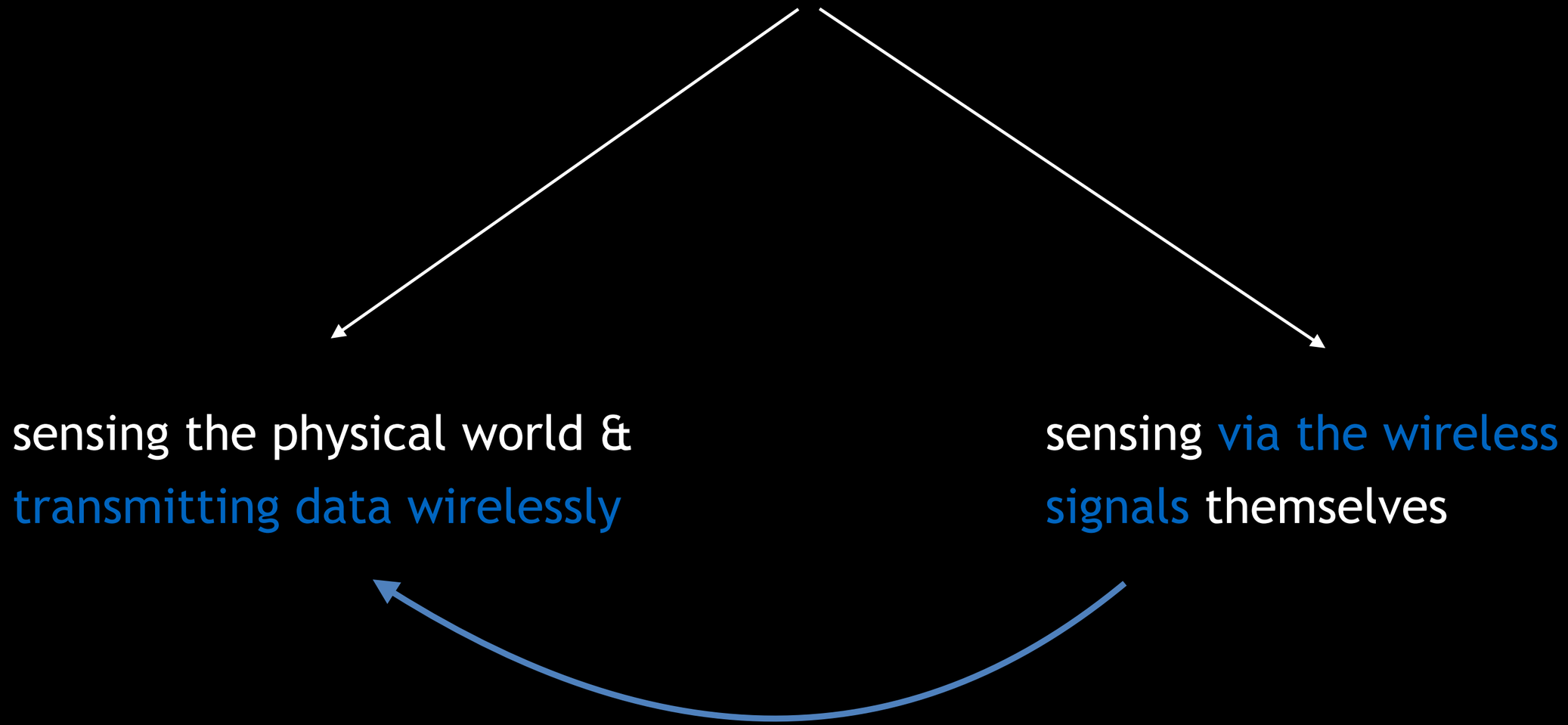
A wave breaks next to a house in Namkhana in India's West Bengal state, where sea levels have been rising at a faster rate than the global average

Photograph: Supratim Bhattacharjee/Climate Visuals

Women queue up to plant mangrove saplings along the banks of the Matla river in Sundarbans, India. Experts have suggested that planting mangroves, which are disappearing partly as a result of increased saline water due to sea-level rise, can help to reduce the impacts of flooding and cyclones in the area

Photograph: Avijit Ghosh/Climate Visuals

How to Wirelessly Sense Almost Anything



Objectives of Today's Lecture

Learn the **fundamentals, emerging technologies, and applications** of ocean IoT

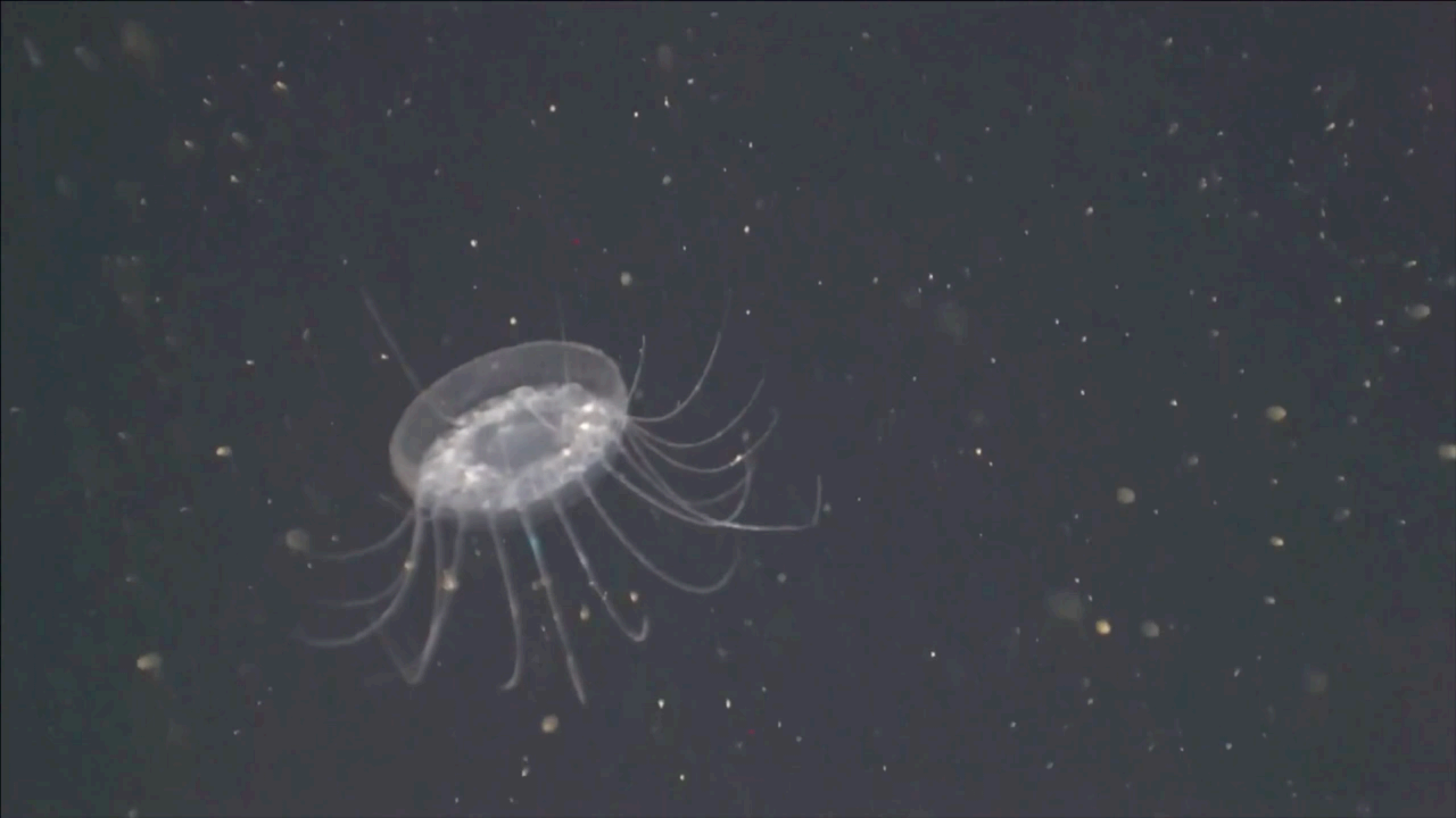
1. What makes underwater IoT different from in-air IoT?
2. What are the applications of underwater IoT?
3. What are the fundamental principles of underwater backscatter?
4. How do battery-free underwater localization and imaging work?

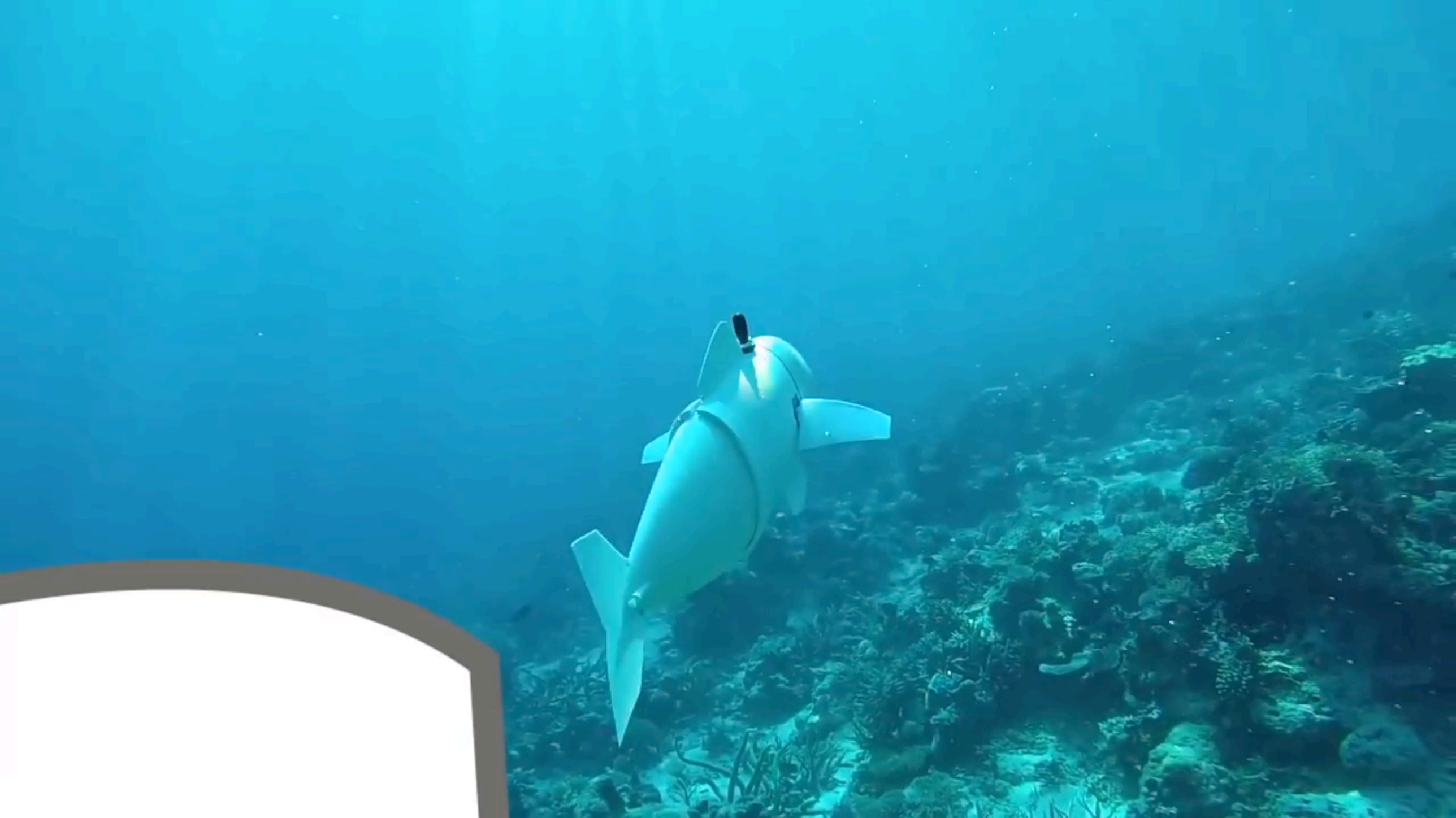
Why is bringing IoT to the ocean (esp. underwater) hard?

- **Communication:**
  - Can’t use radio (WiFi, bluetooth)
  - Direct underwater-to-air comms remains challenging
- **Power:**
  - No power outlet (access); hard to replace batteries
- **Sensing:**
  - Can’t use GPS (radio signals) for localization
  - Imaging is challenging (light interferes, refracts, etc.)

Example Ocean Connectivity, Sensing, & Power Technologies


ARGO
PROGRAM
BUREAU OF METEOROLOGY





Problem: Battery life of underwater sensors is extremely limited

Low-power underwater transmitters consume 100s of Watts

(e.g., WHOI low-power micro-modem 2019)

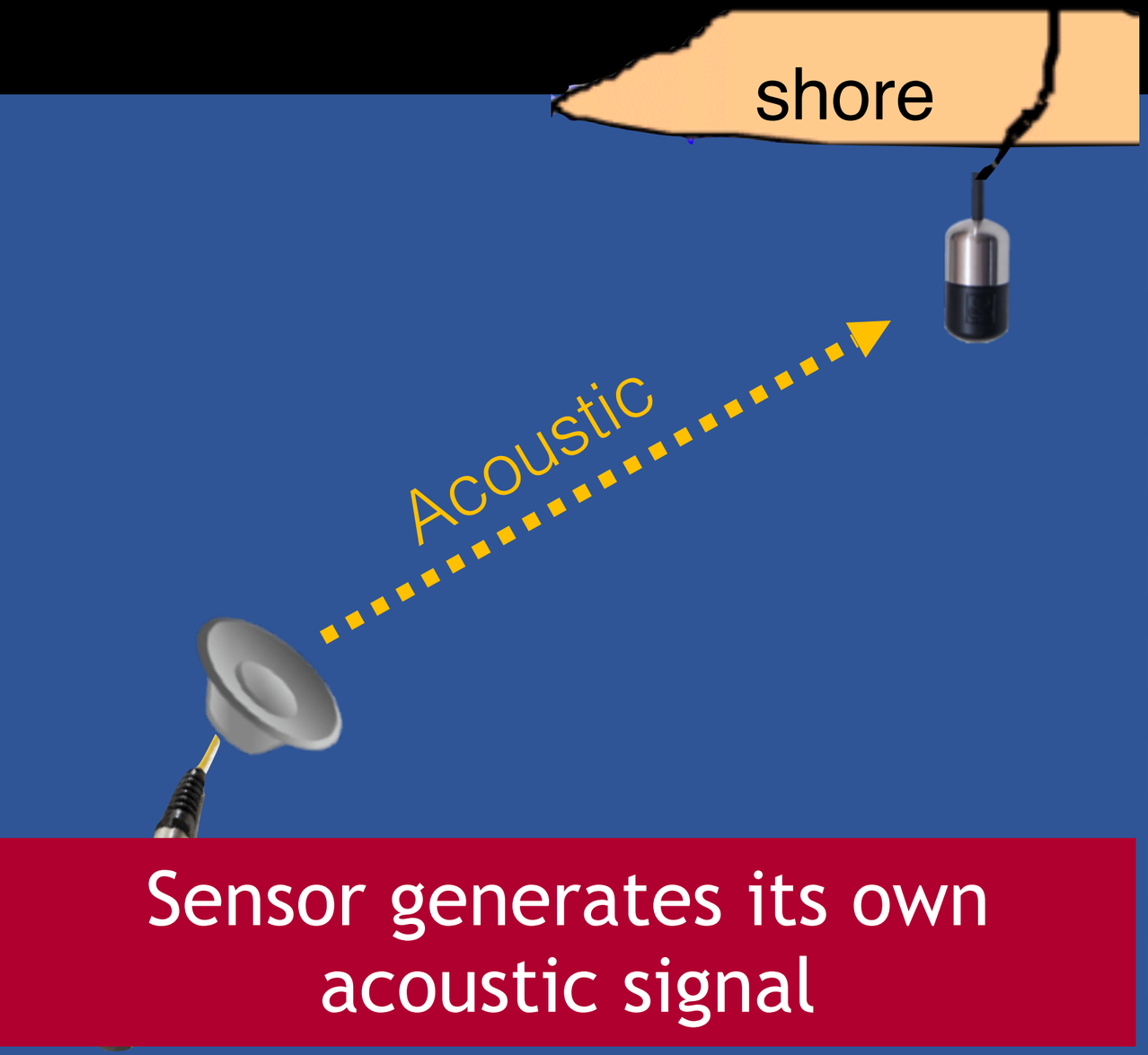
State-of-the-art sensors for tracking marine animals only last for few hours or days

[Animal Biotelemetry'15, Scientific Reports'17]

Technology that Enables Underwater Backscatter (Batteryless) Networking

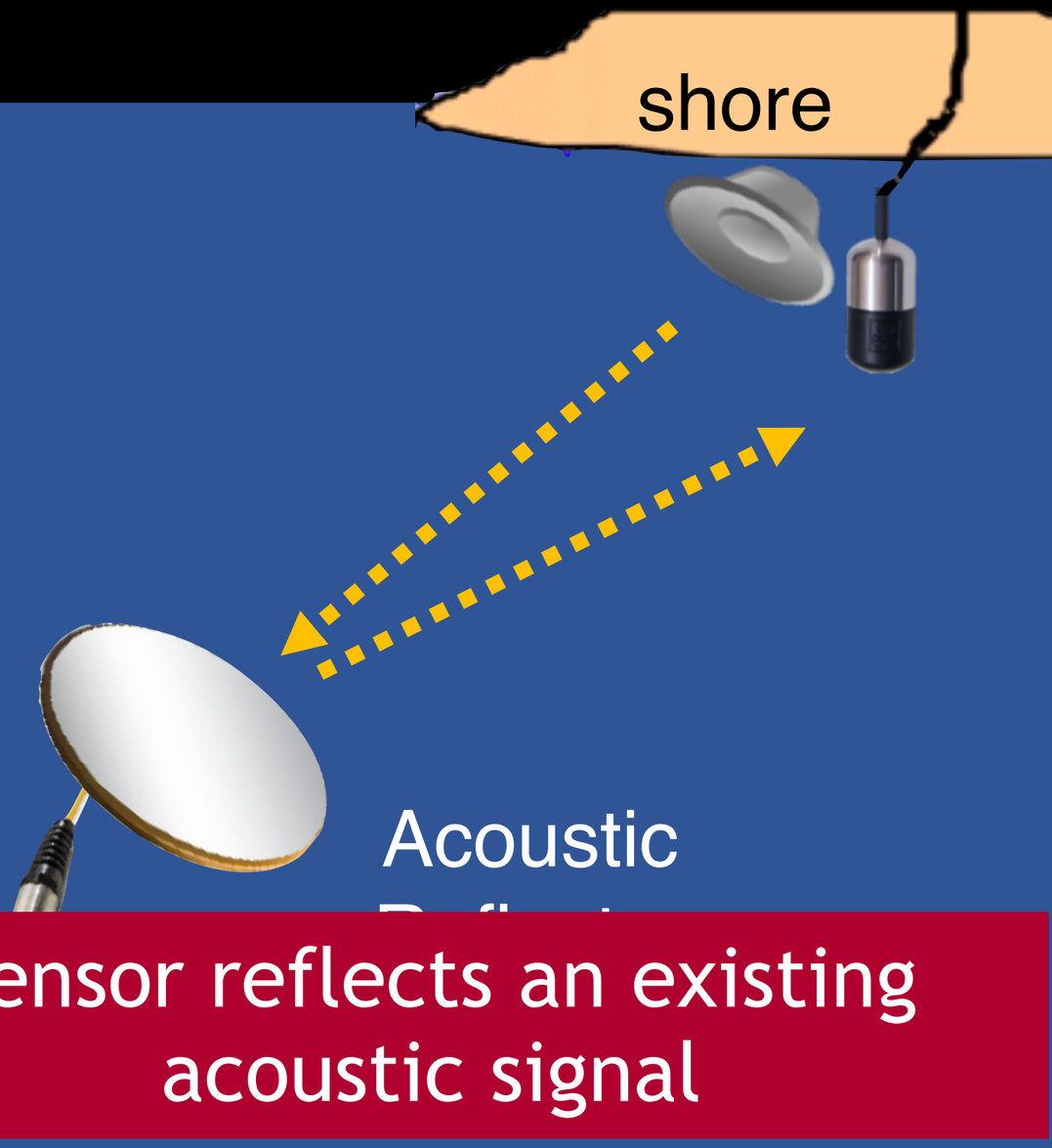
PAB (ACM SIGCOMM'19)

Traditional Approach



Sensor generates its own acoustic signal

Underwater Backscatter

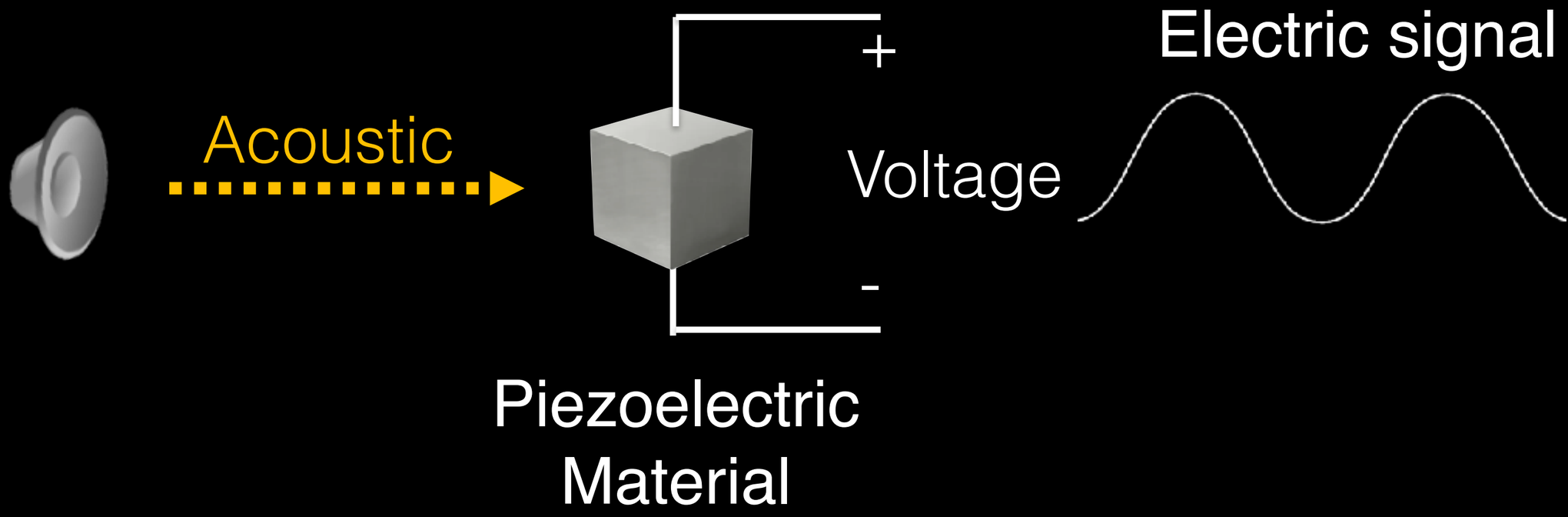


Sensor reflects an existing acoustic signal

How can we control the reflections of acoustic signals?

Key Idea: Use piezoelectricity to design programmable acoustic reflectors

Piezoelectric materials transform mechanical to electrical energy



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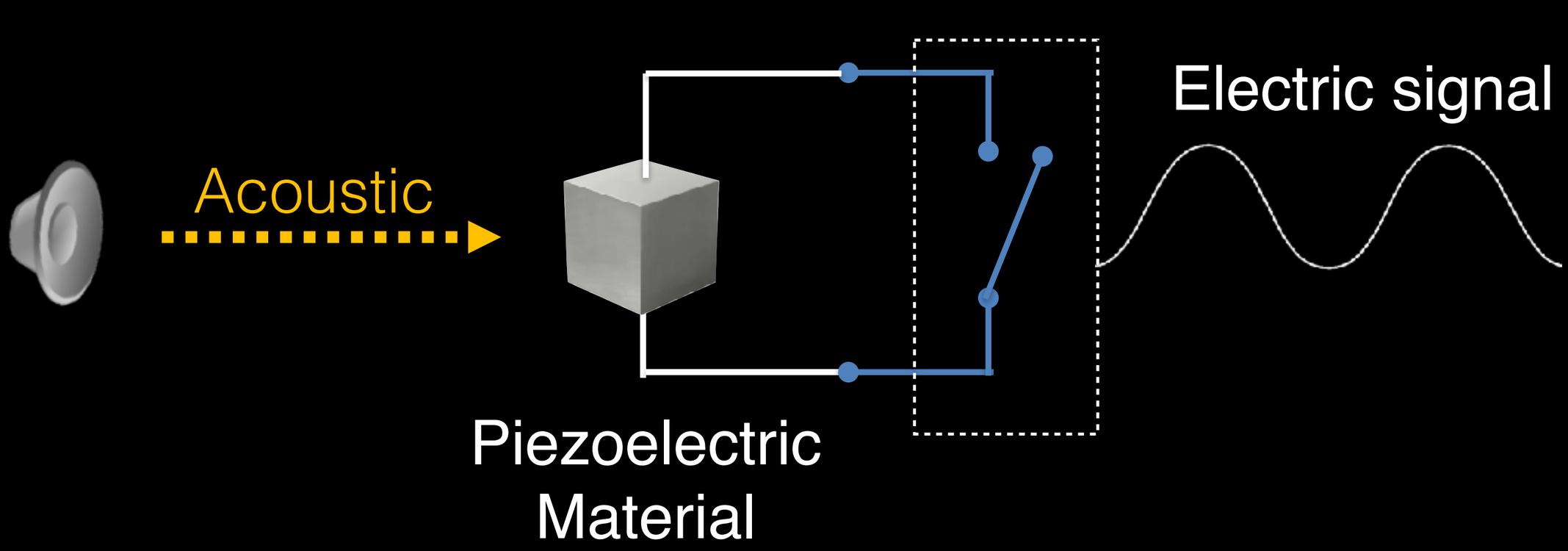

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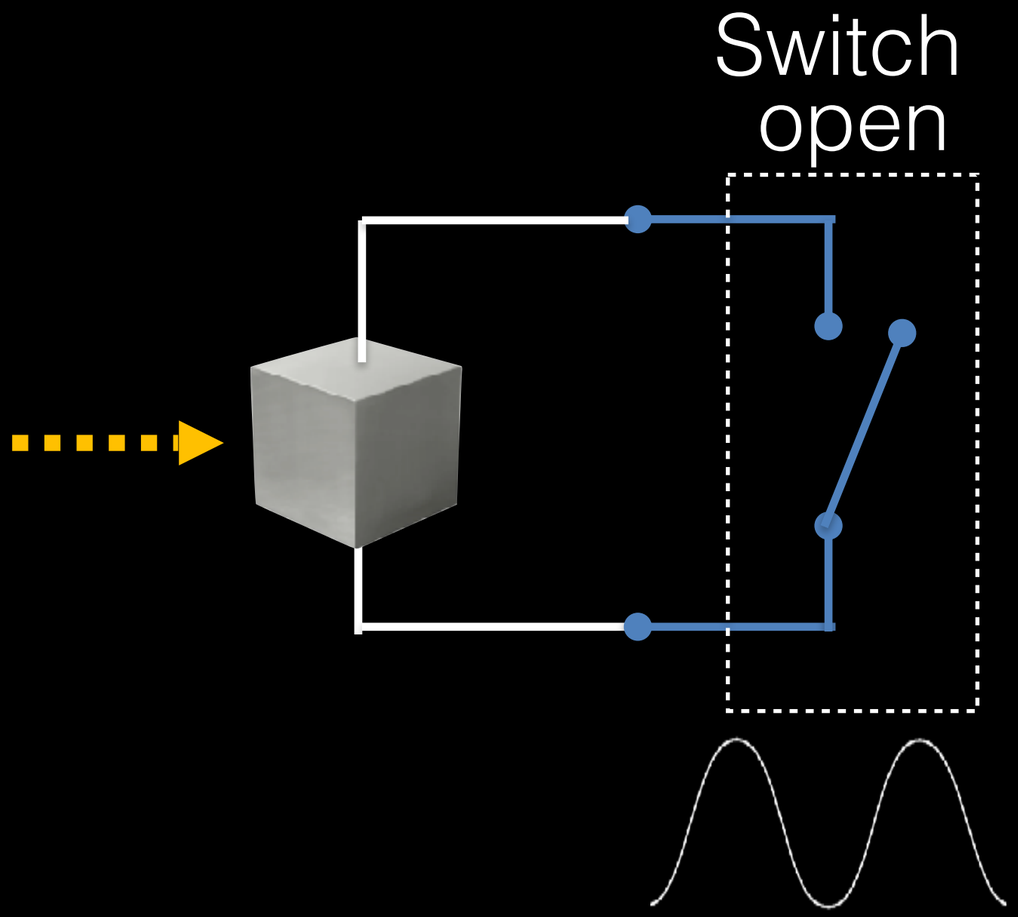
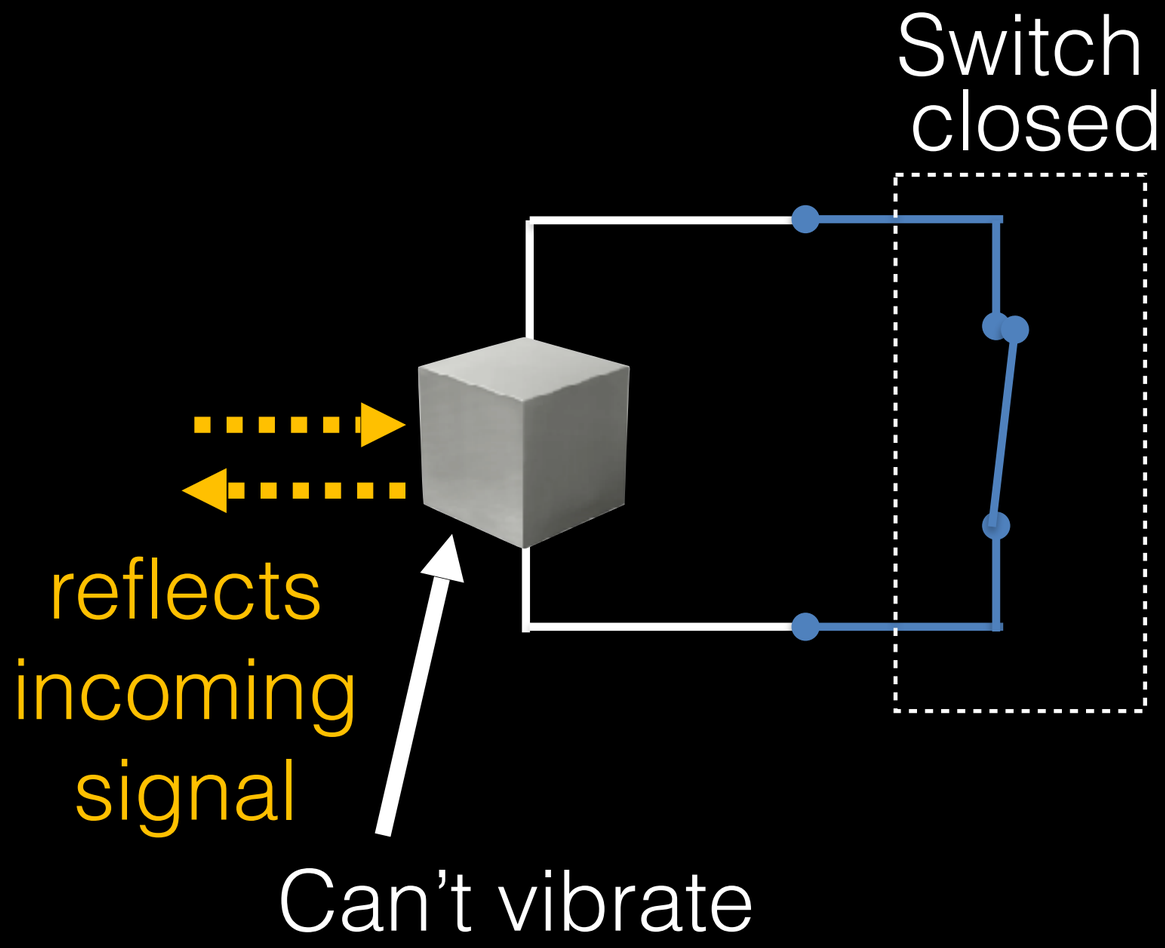
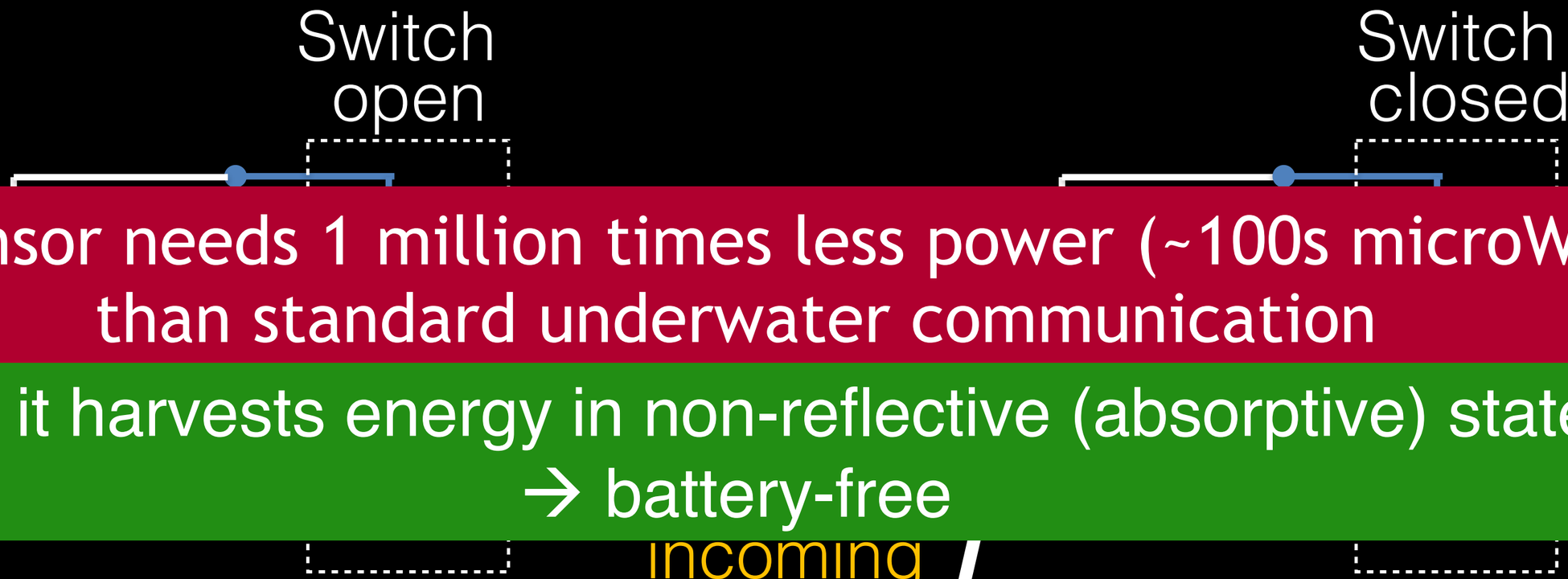


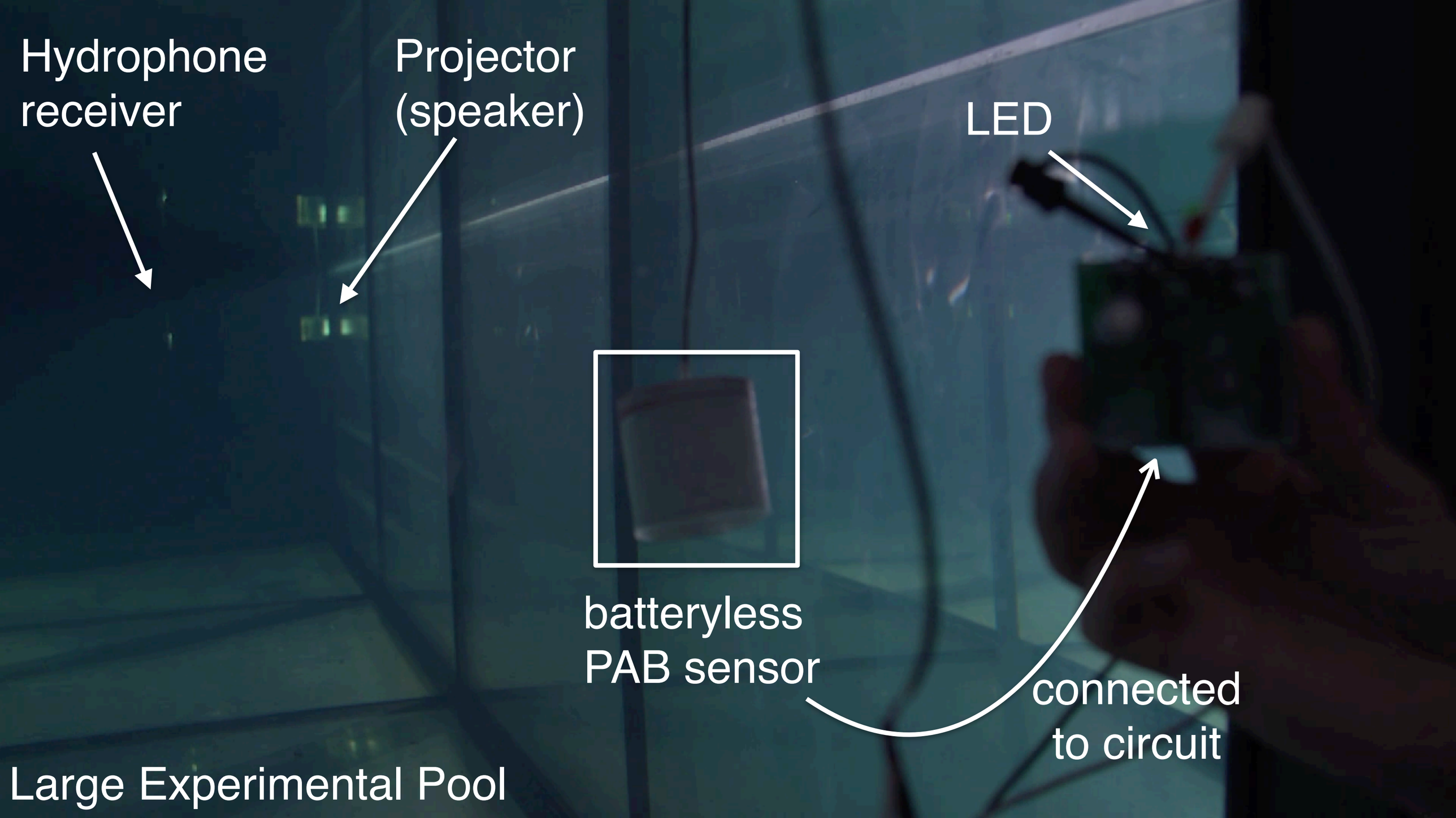


Piezo-Acoustic Backscatter

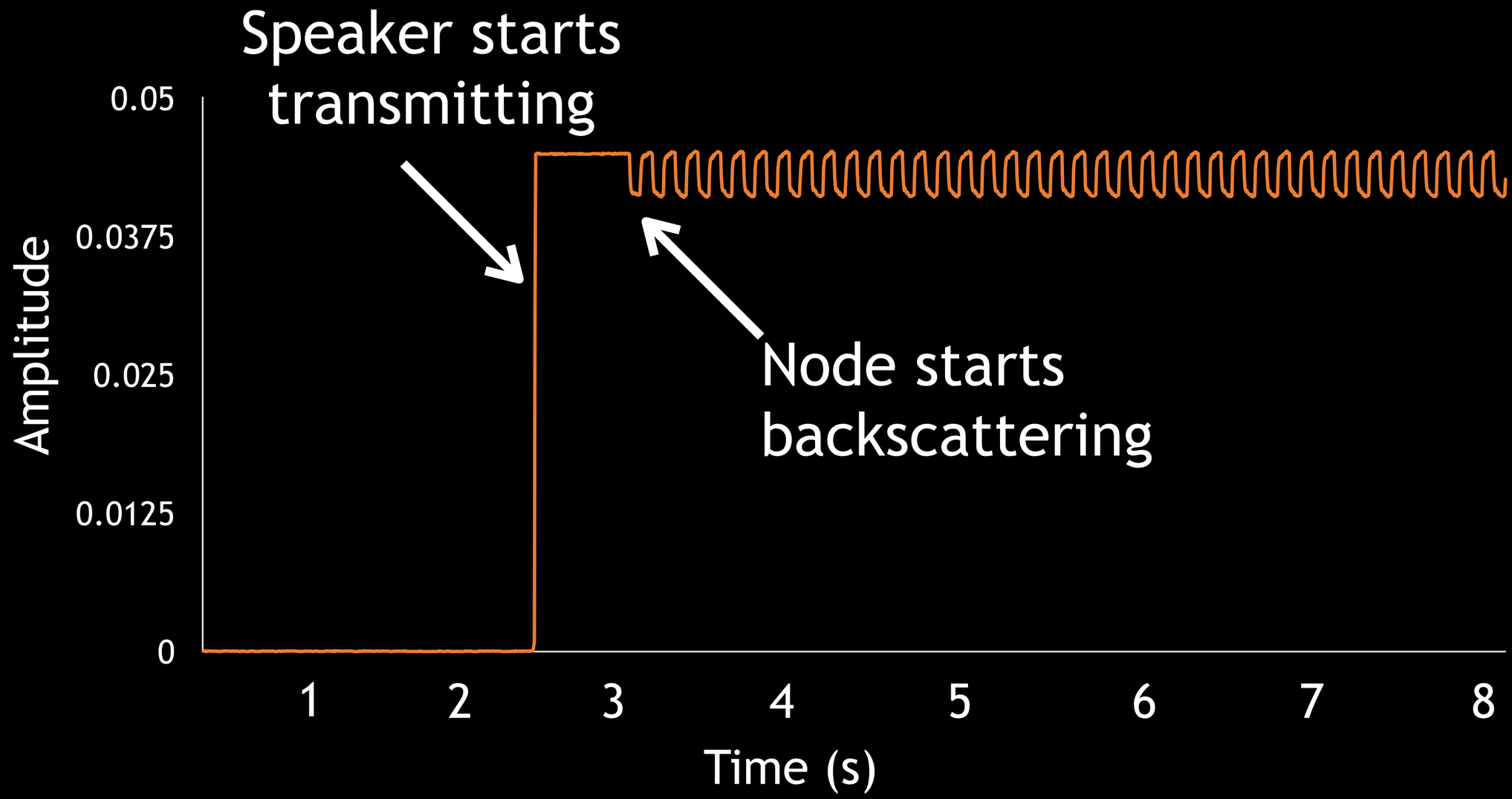


PAB sensor needs 1 million times less power (~100s microWatt) than standard underwater communication

And it harvests energy in non-reflective (absorptive) state → battery-free


Hydrophone
receiver
Projector
(speaker)
LED
batteryless
PAB sensor
connected
to circuit
Large Experimental Pool

Measuring the Backscatter Signal (by Hydrophone)

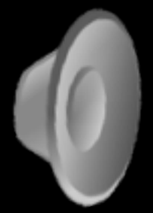


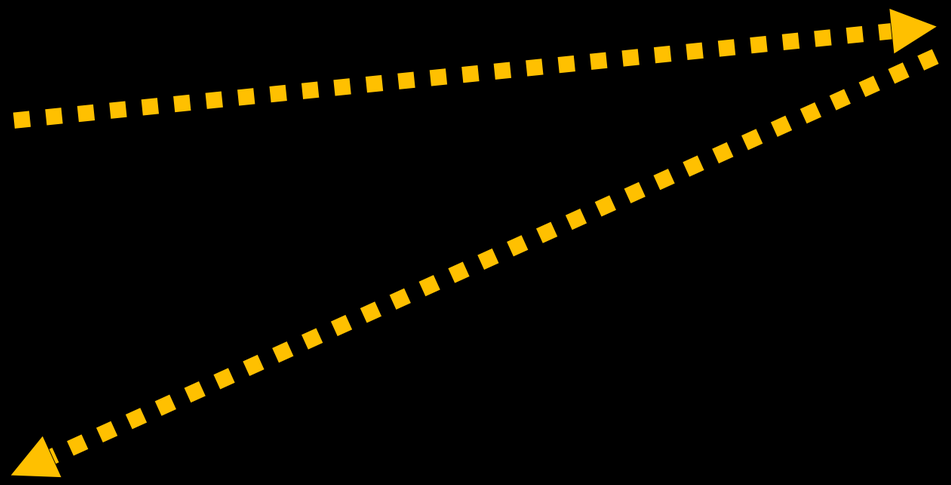
How can we extend underwater backscatter to multiple nodes?

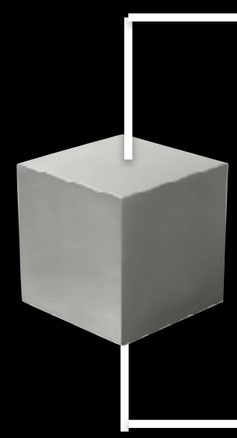
Extending to Multiple Nodes

Option 1: Time Division Multiplexing

Projector

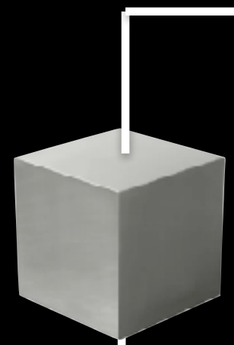






Batteryless hardware

Hydrophone



Batteryless hardware

Extending to Multiple Nodes

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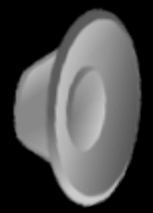
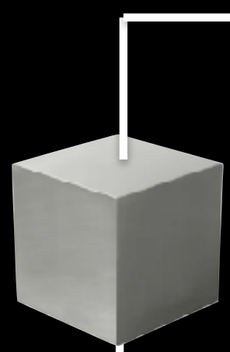


Hydrophone

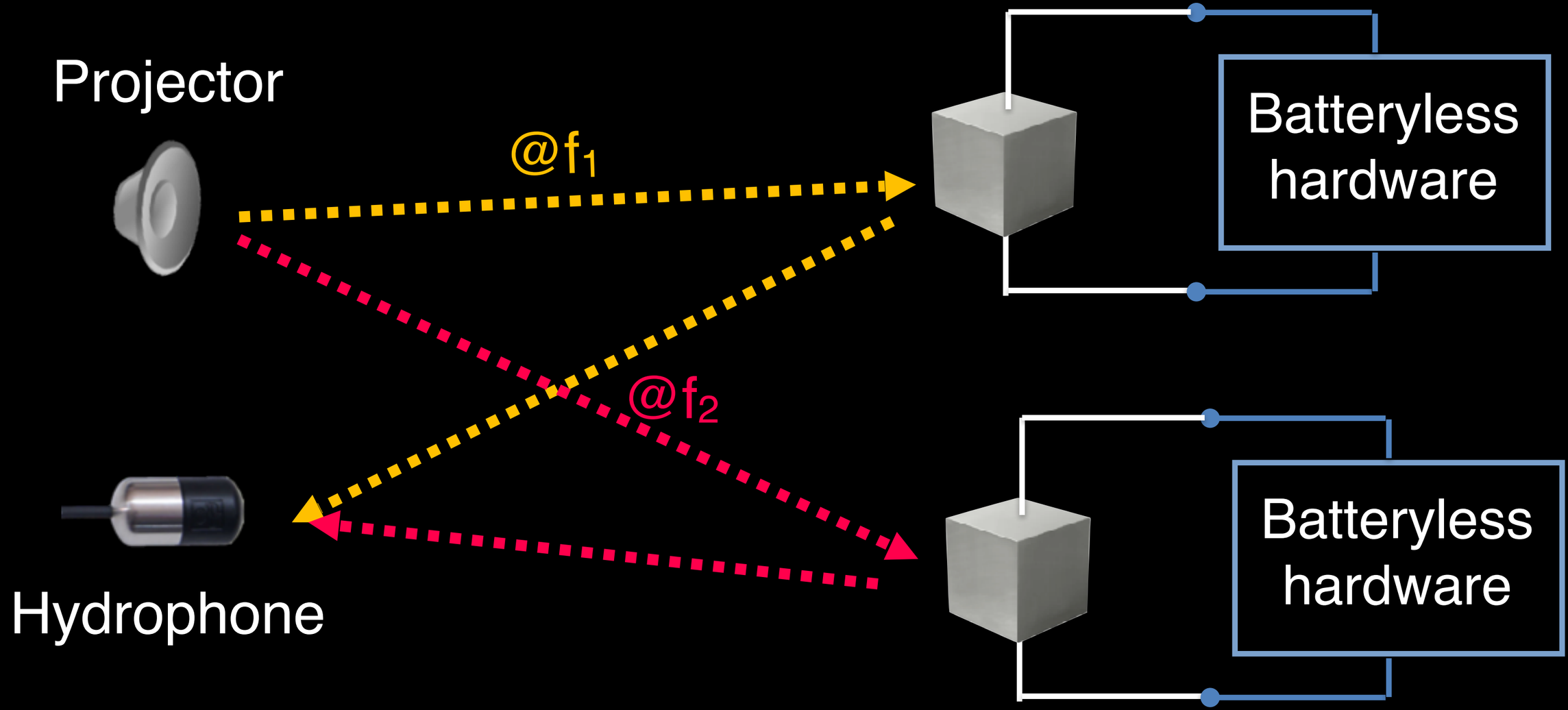
Batteryless hardware



Batteryless hardware

Extending to Multiple Nodes

Option 2: Frequency Division Multiplexing



Extending to Multiple Nodes

Problem: Resonance of piezoelectrics limits their bandwidth

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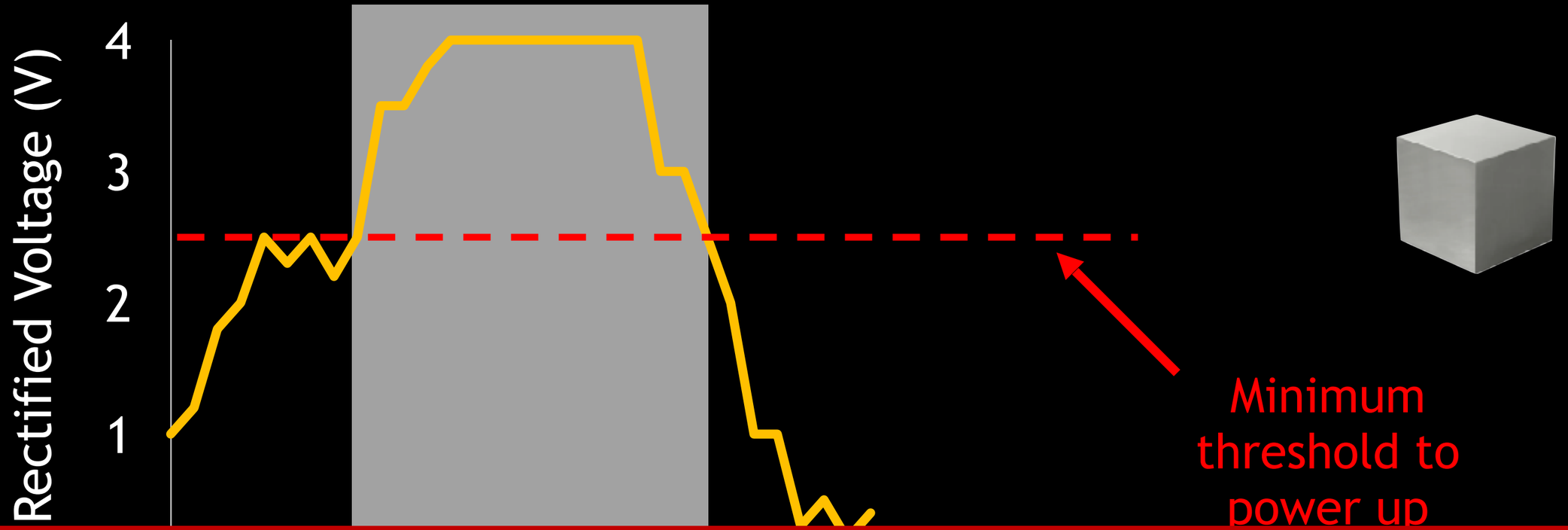
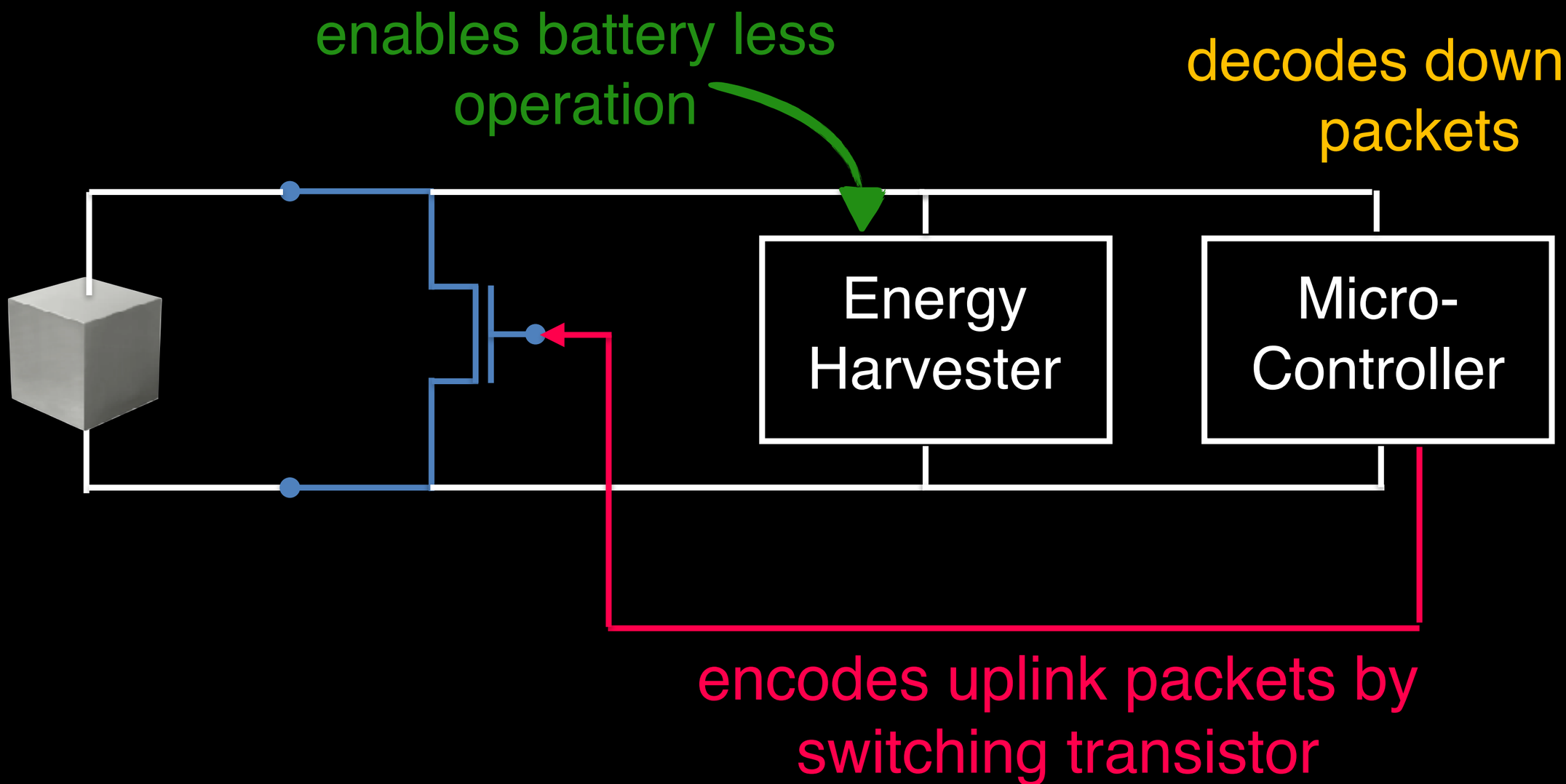


Operating at resonance maximizes energy harvesting but limits concurrent transmissions (and FDMA)

Solution Idea: Shift the resonance frequency *itself* to a different channel

Solution Idea: Shift the resonance frequency itself to a different channel



Solution Idea: Shift the resonance frequency *itself* to a different channel

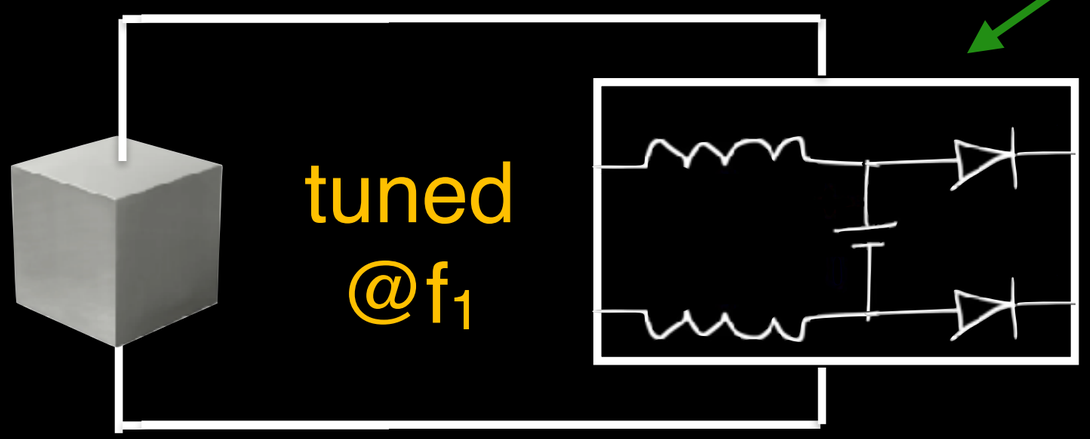
resonance frequency determined by interaction between piezo & the batteryless circuit

$$Z_{circuit}(f) = Z^*_{piezo}(f)$$

frequency dependent

→Tune the circuit to a different frequency

Solution Idea: Shift the resonance frequency *itself* to a different channel



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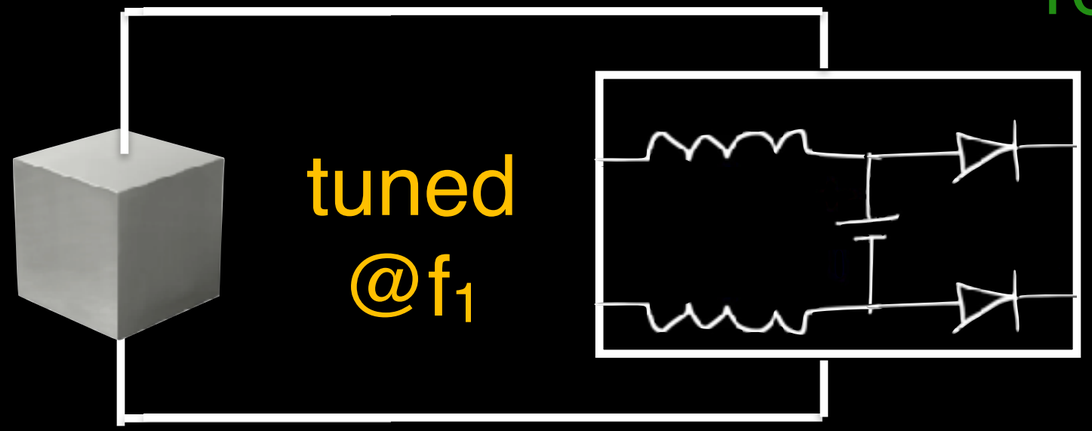

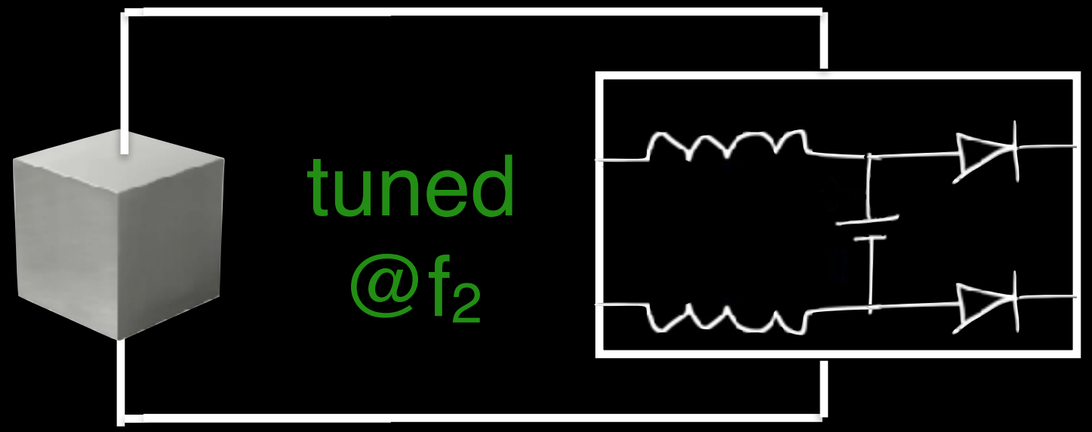

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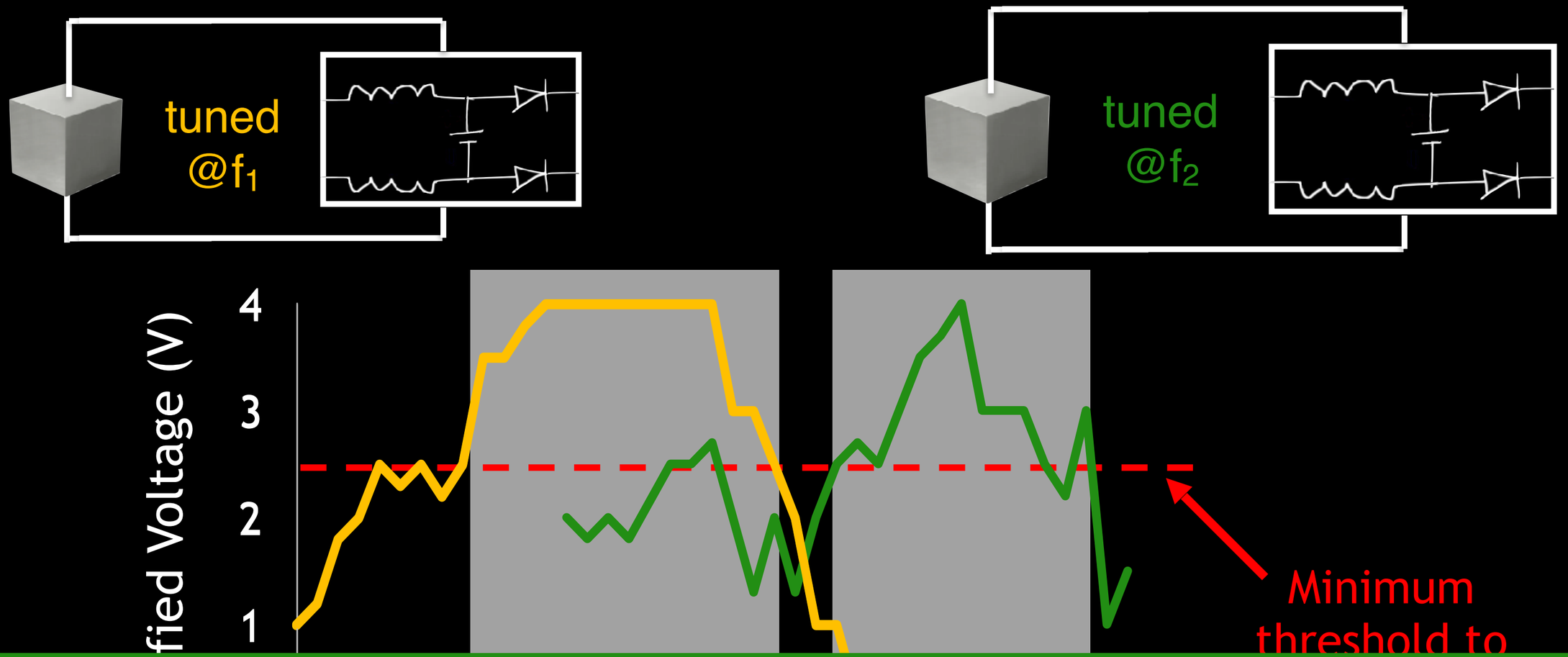
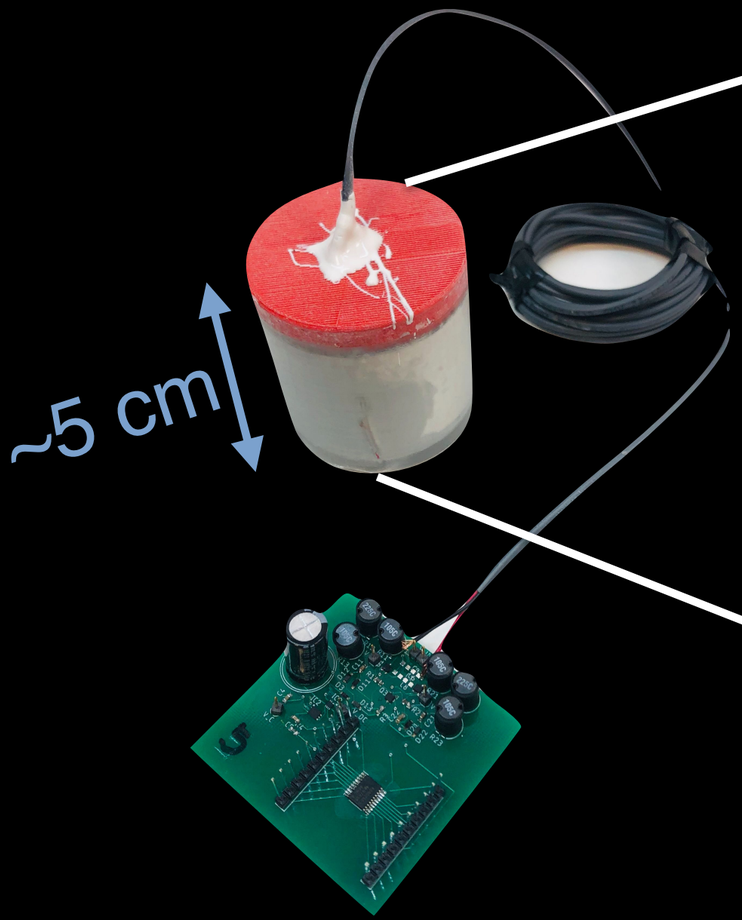


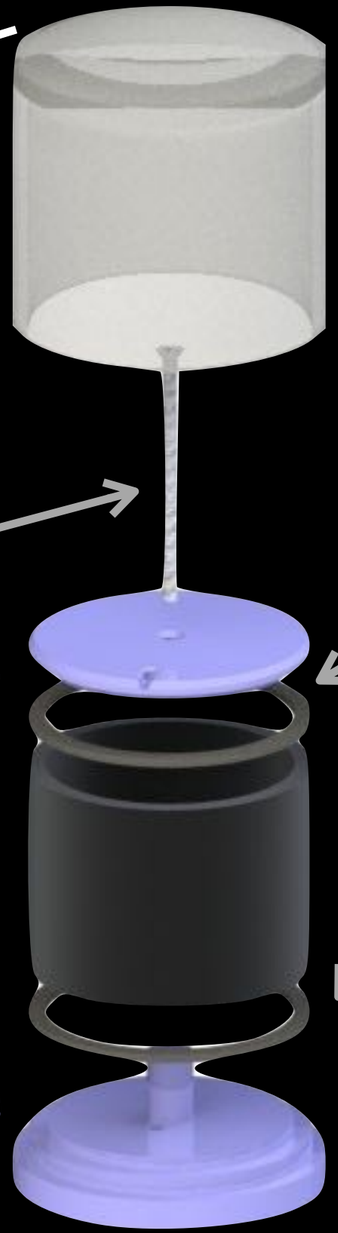
Extend the idea to uplink communication using a MIMO-style decoder adapted to backscatter resonance modes

Implementation

Batteryless PAB sensor

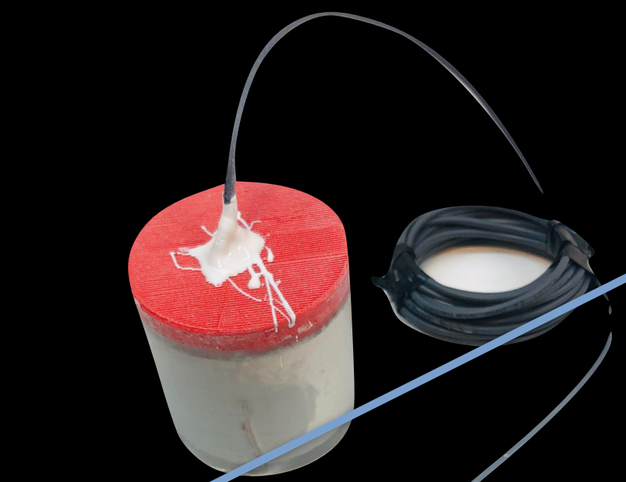


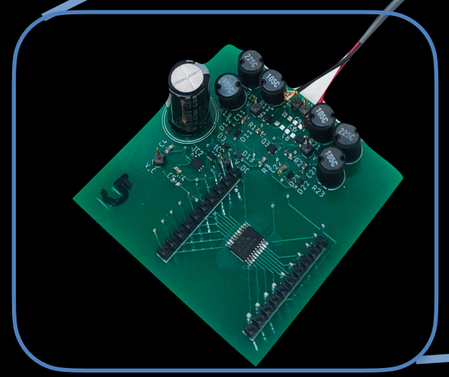
Exploded transducer view

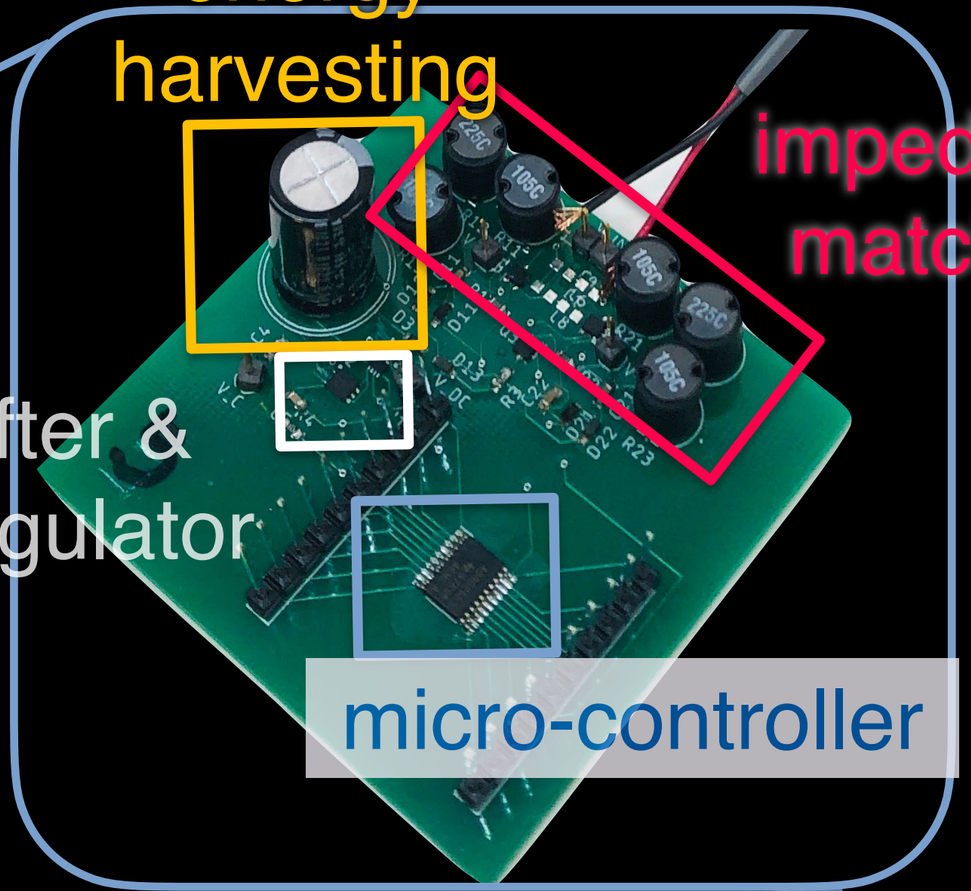


Implementation

Batteryless PAB sensor







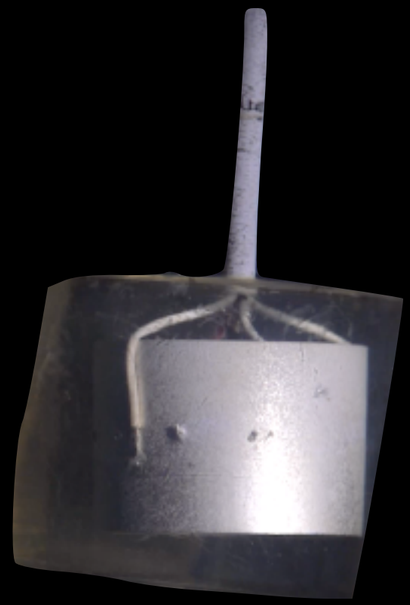
Open Source Code+Schematics:

https://github.com/saadafzal24/Underwater-Backscatter

Implementation

Batteryless PAB sensor

Projector

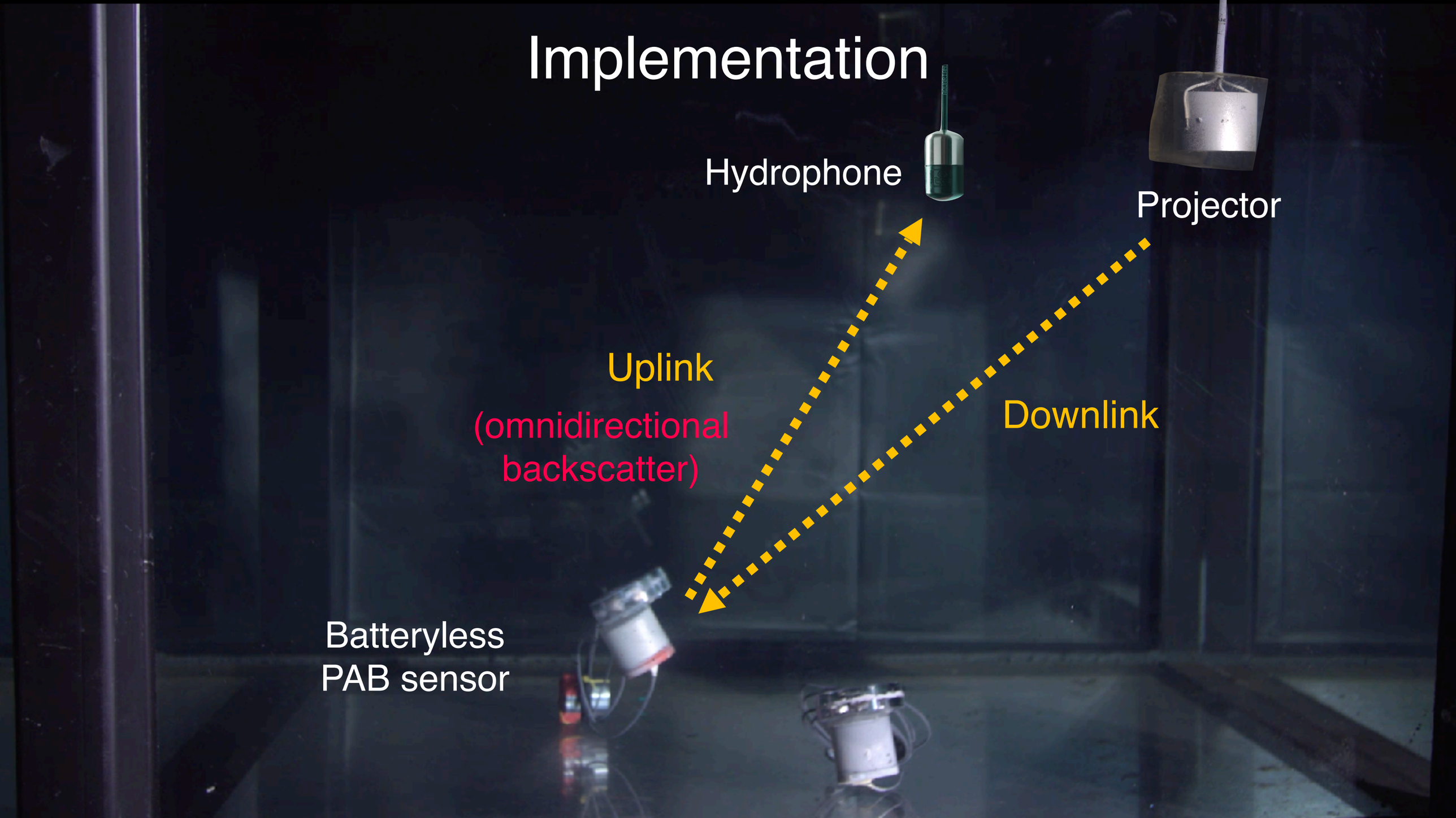


fabricated in-house

Hydrophone

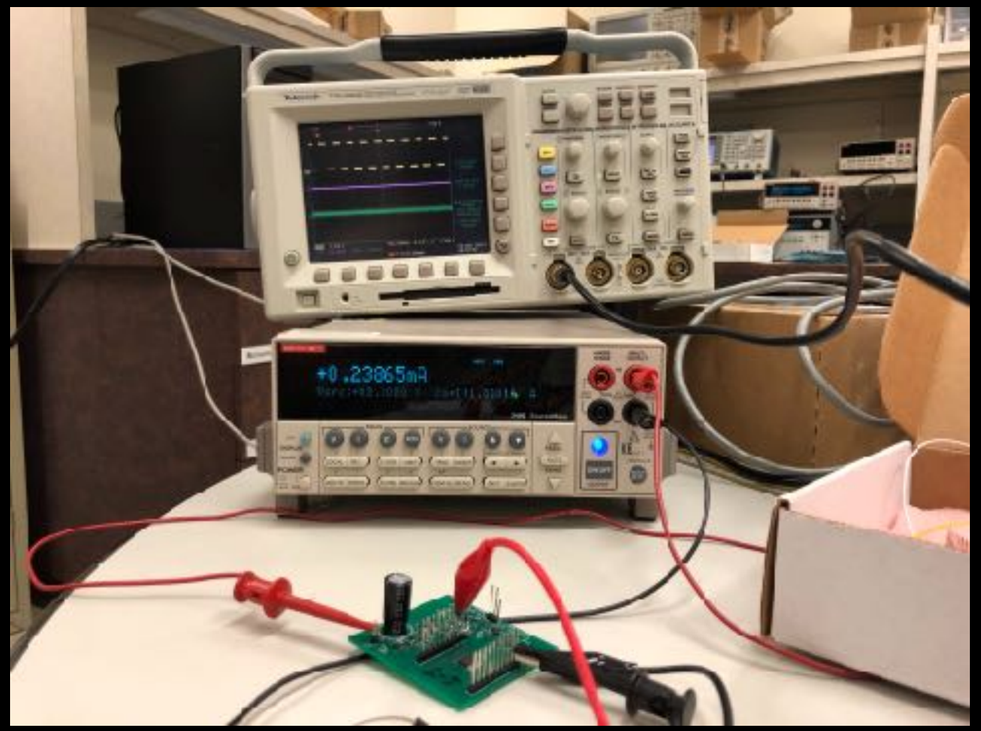
Aquarian H2A

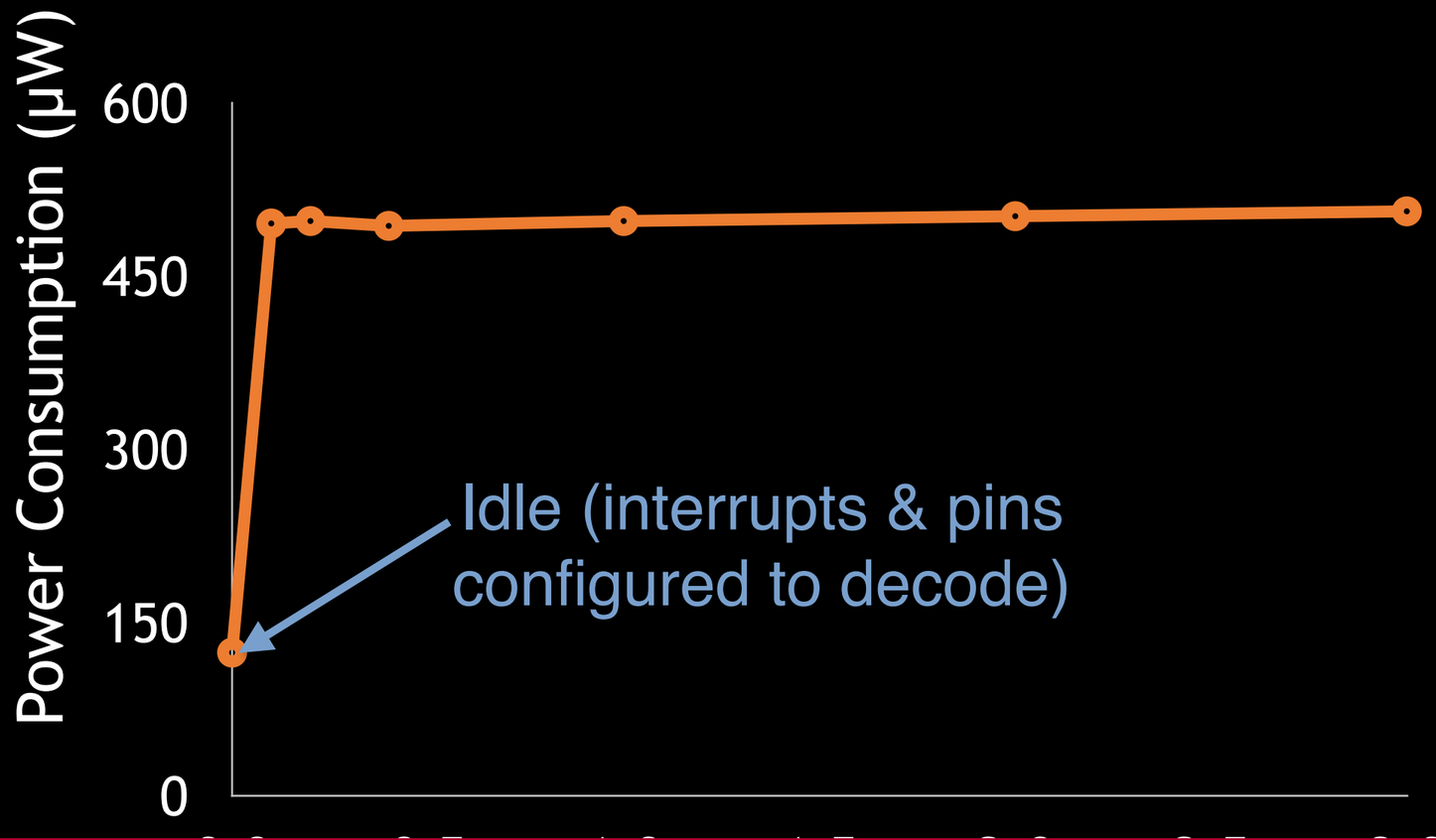
Implementation



Power Consumption

Empirically measured using Keithley 2400 source meter

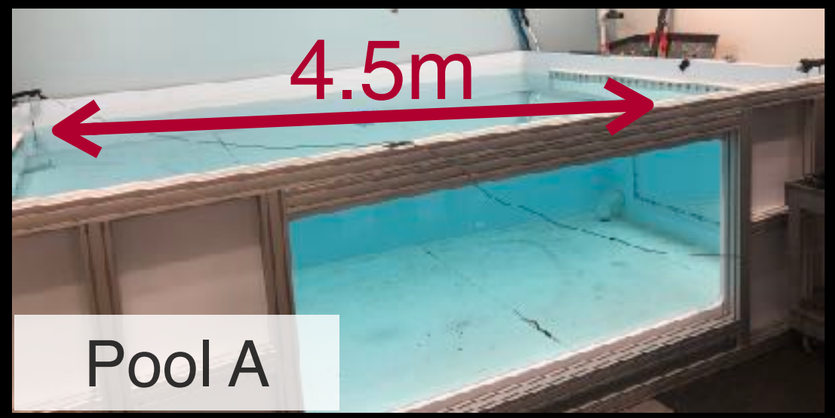


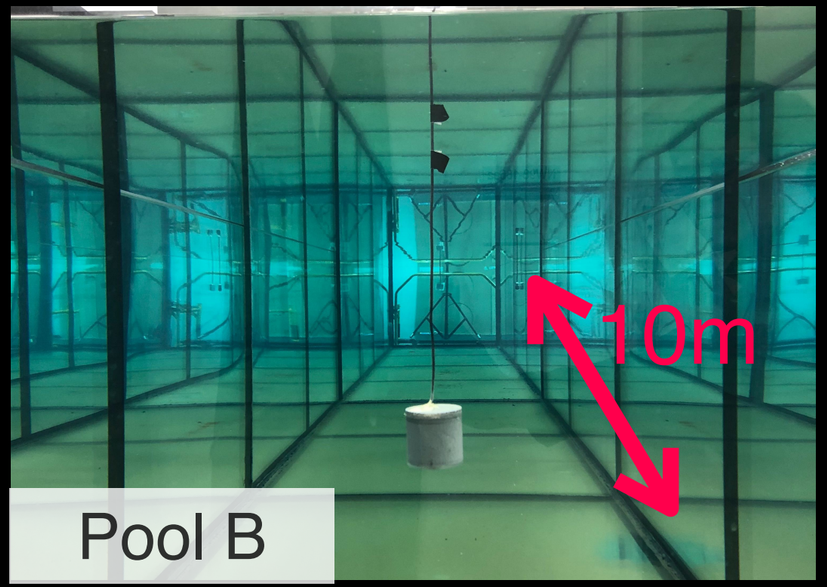


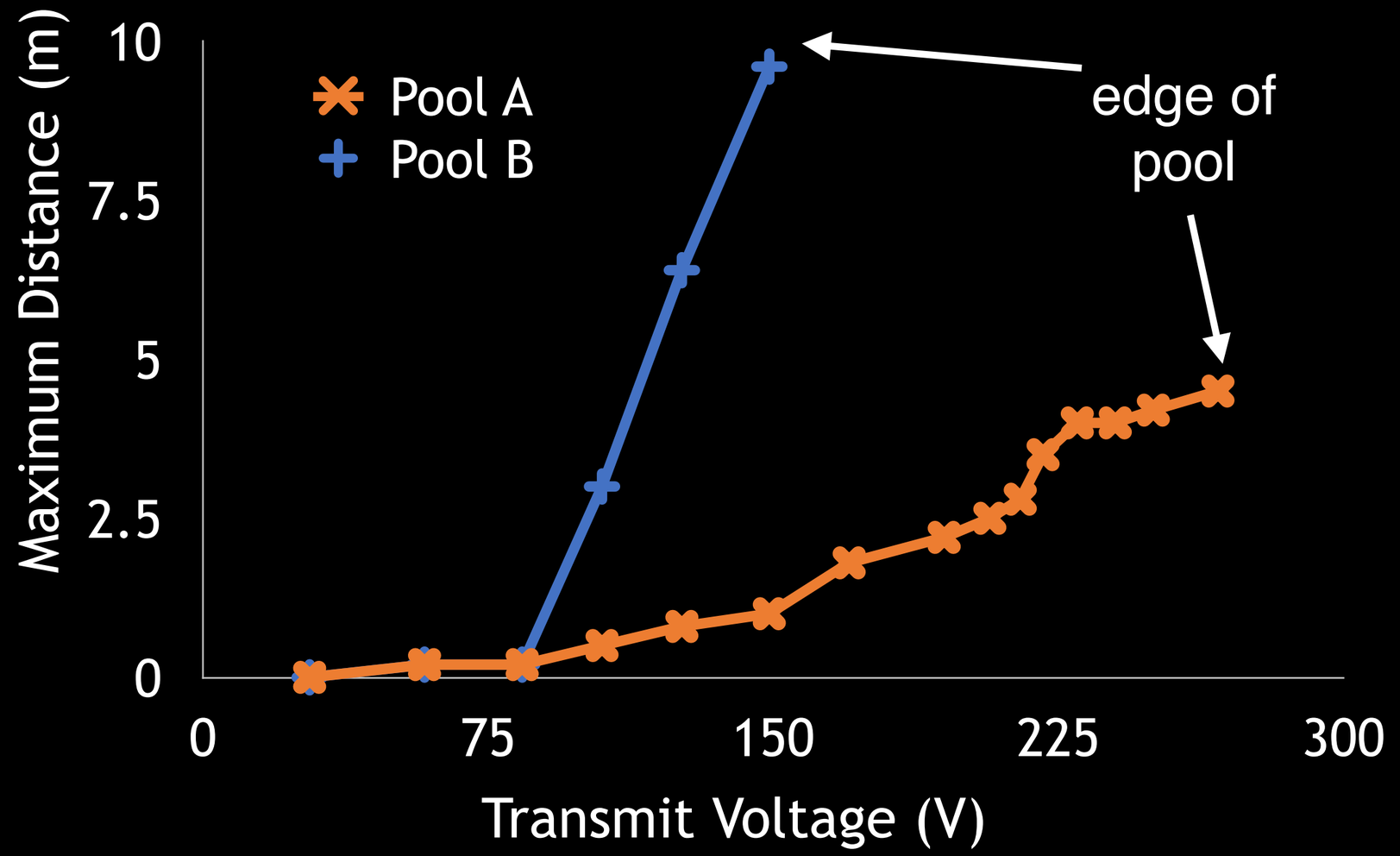
1 million times less power than state-of-the-art low-power underwater sensors [WHOI micro-modem 2019]

Power-up Range

Experiment: Vary power and distance to sensor



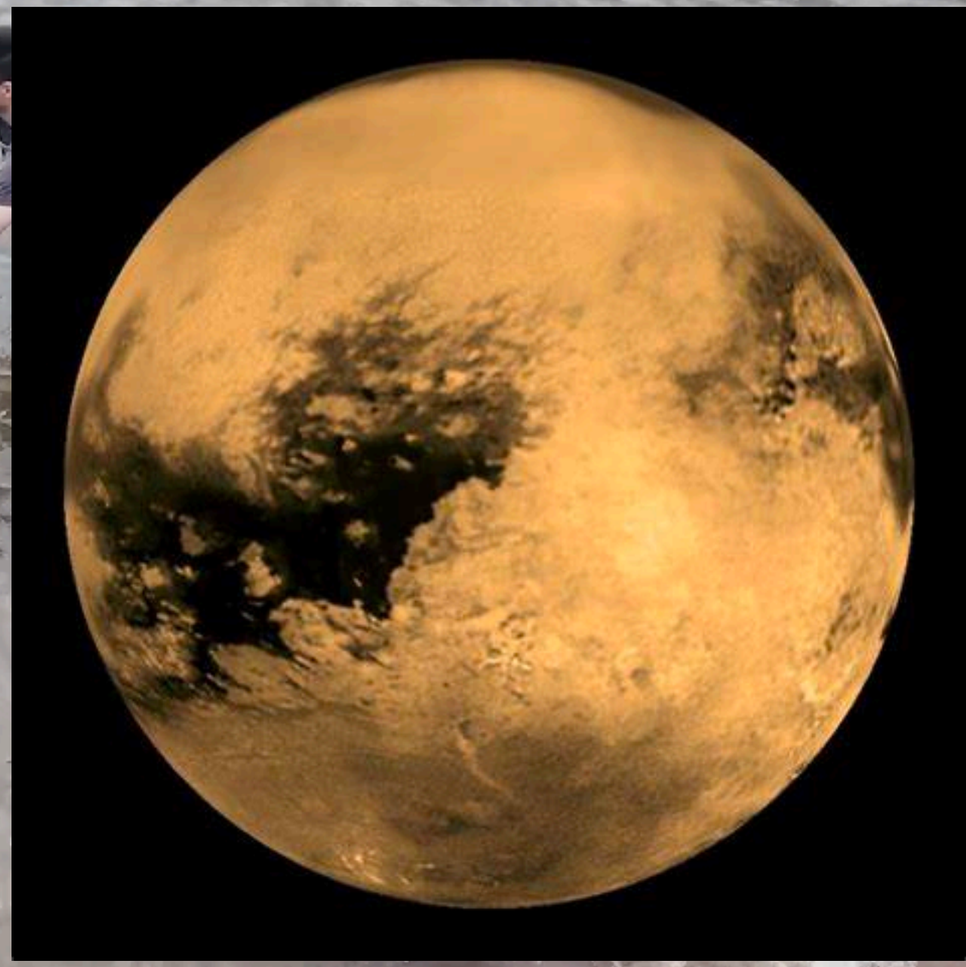




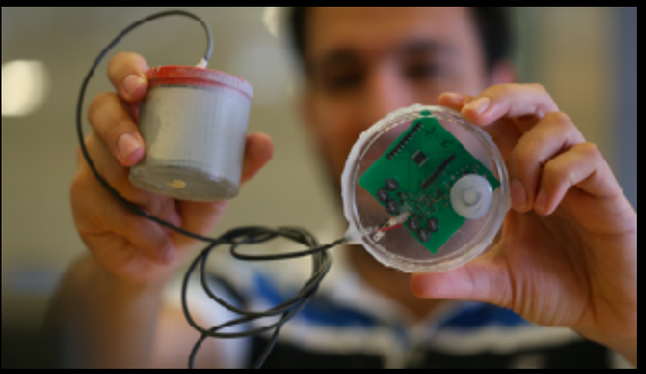
1,000s of experimental trials

battery-free node with
temp & pressure sensor

Extraterrestrial
oceans (e.g., Titan)



Batteryless Ocean Sensing
[ACM SIGCOMM'19]



Fabrication
[ACM SIGCOMM'20]

Metamaterials for UWB (40 kHz)

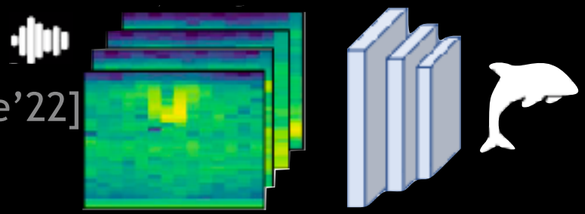
Communication
[MITS/IEEE OCEANS'20]

MIMO, Full-duplex, FDMA (20kbps, 60+m)

Localization
[ACM HotNets'20]

Battery-free GPS (~10cm)

AI
[ACM HotMobile'22]



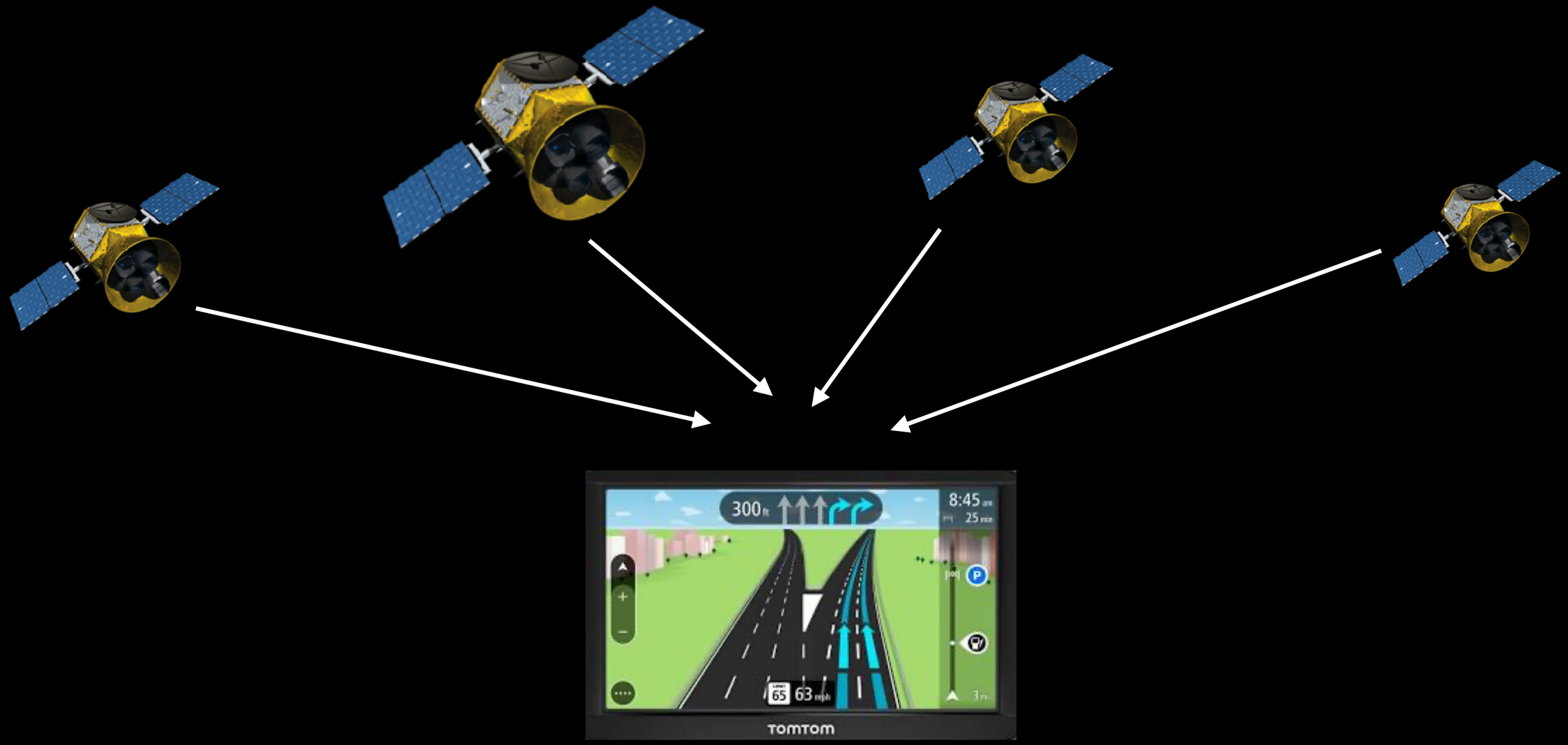
Bioacoustics (animal/climate sensing)

Imaging

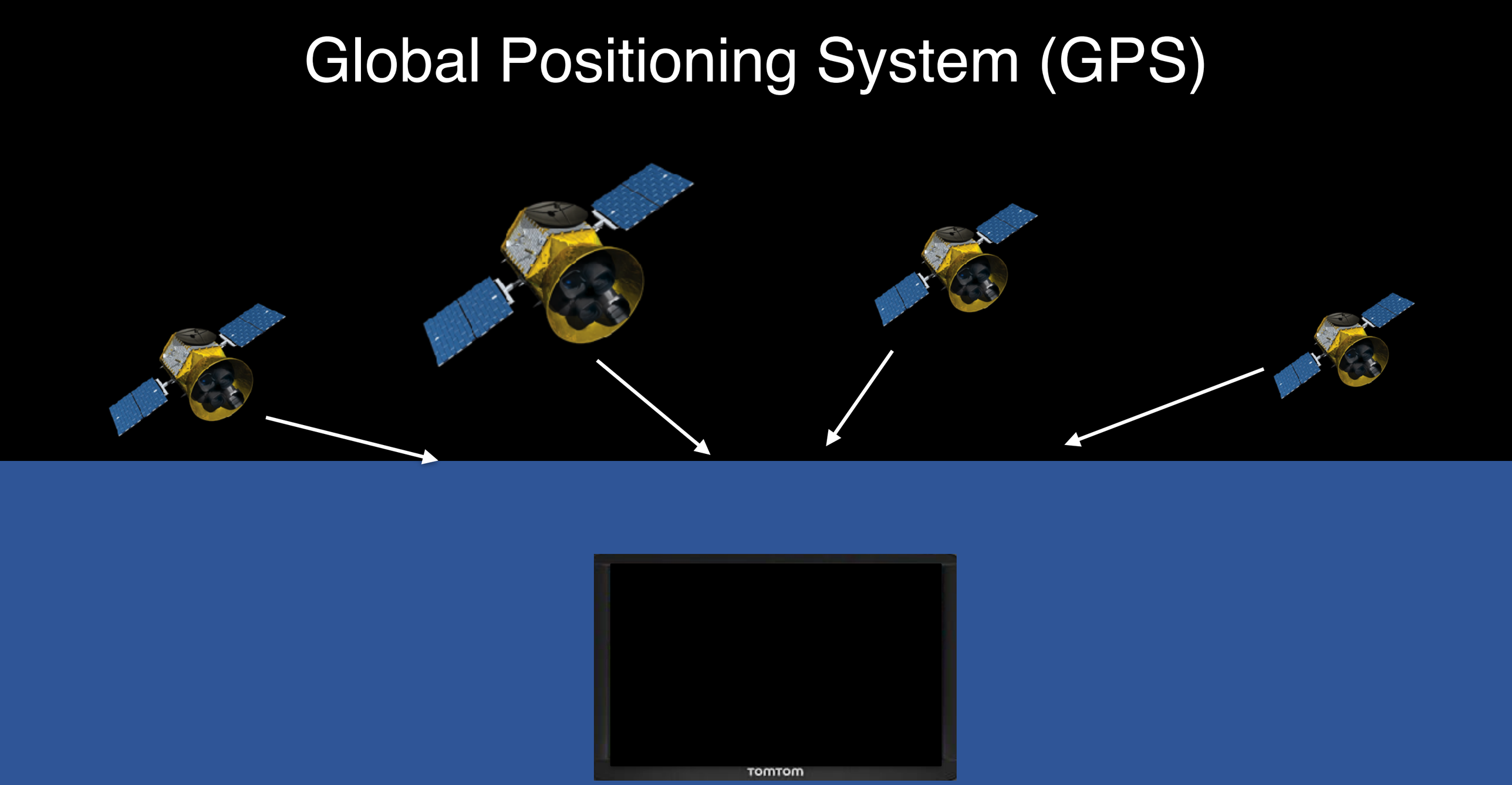
Monitoring for climate, ecology, defense

Can we enable battery-free underwater localization?

Global Positioning System (GPS)

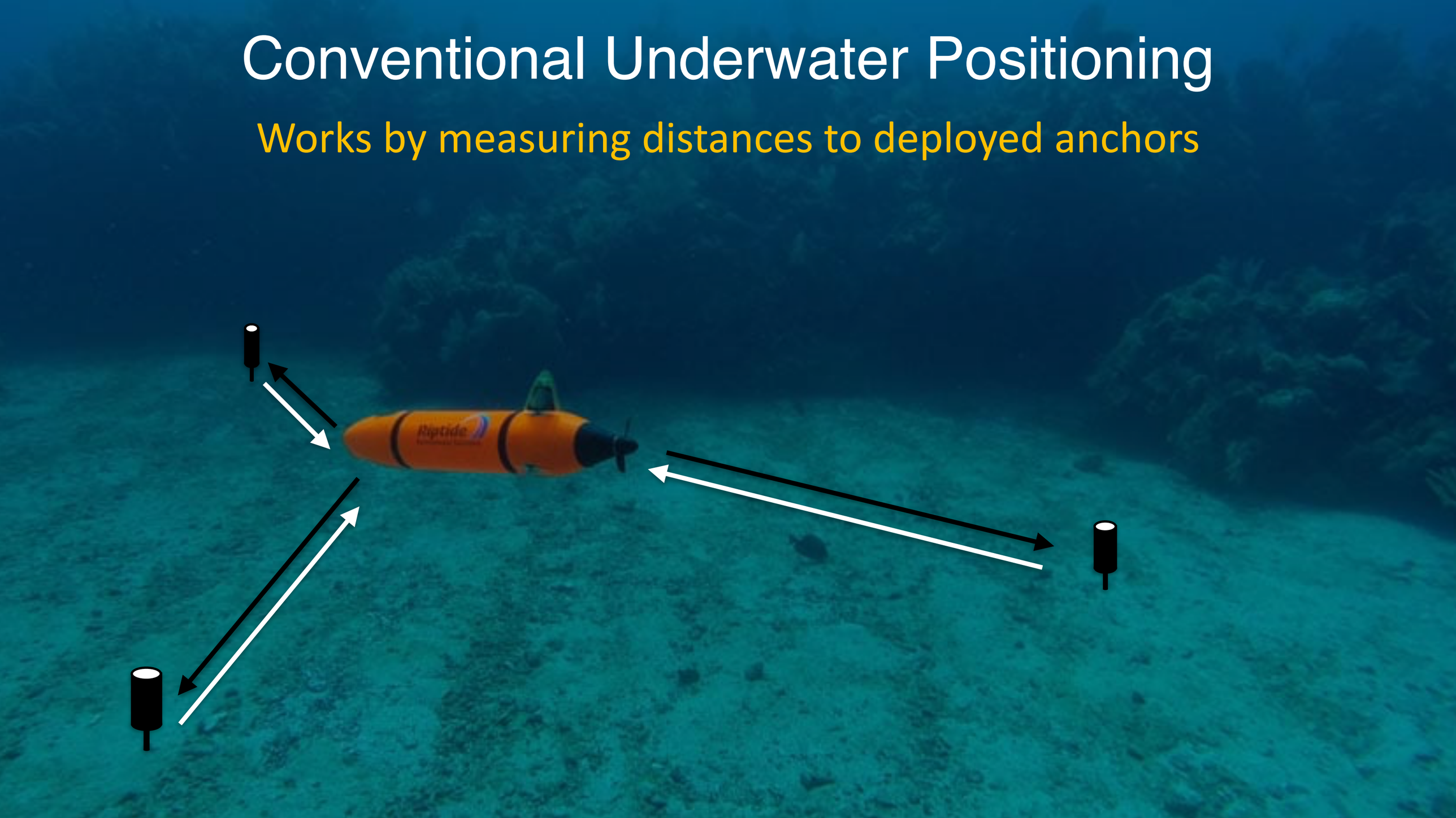


Global Positioning System (GPS)



Conventional Underwater Positioning

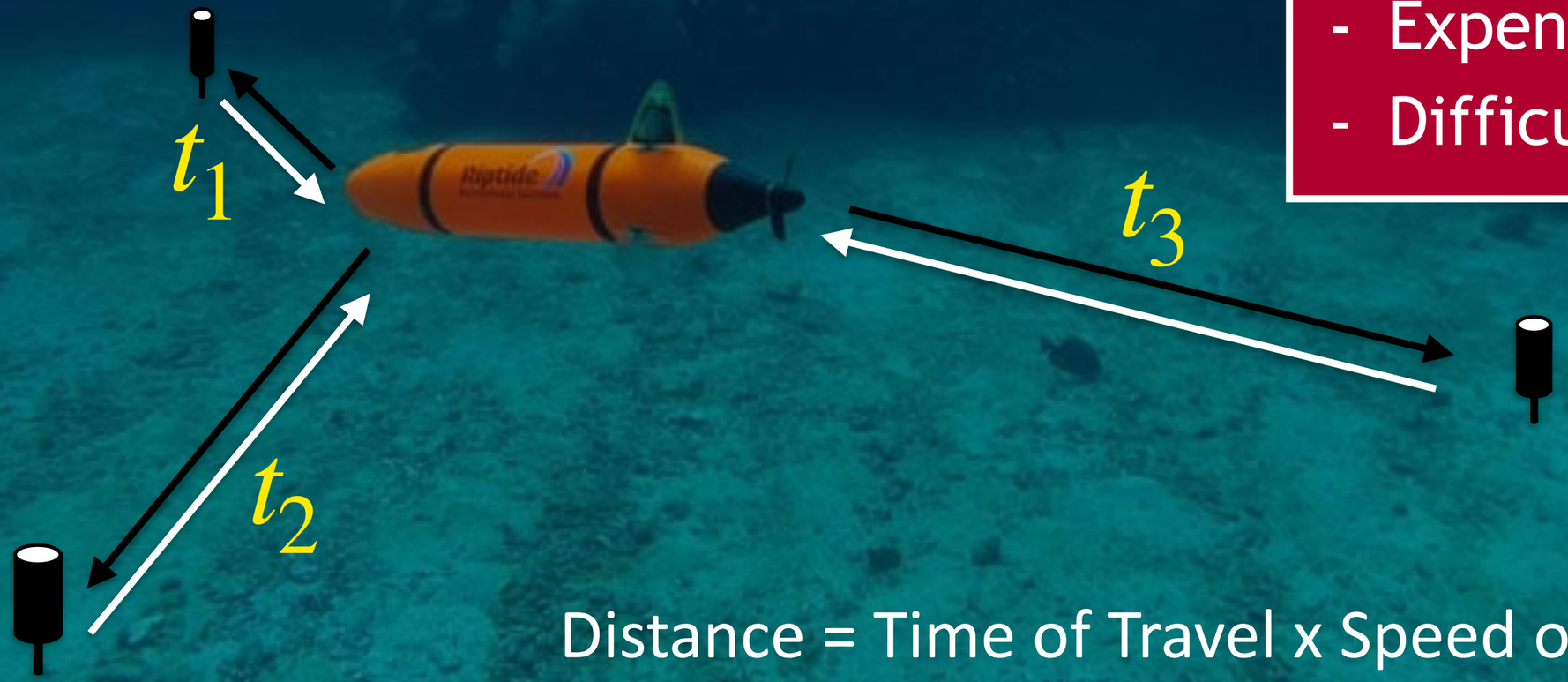
Works by measuring distances to deployed anchors



Conventional Underwater Positioning

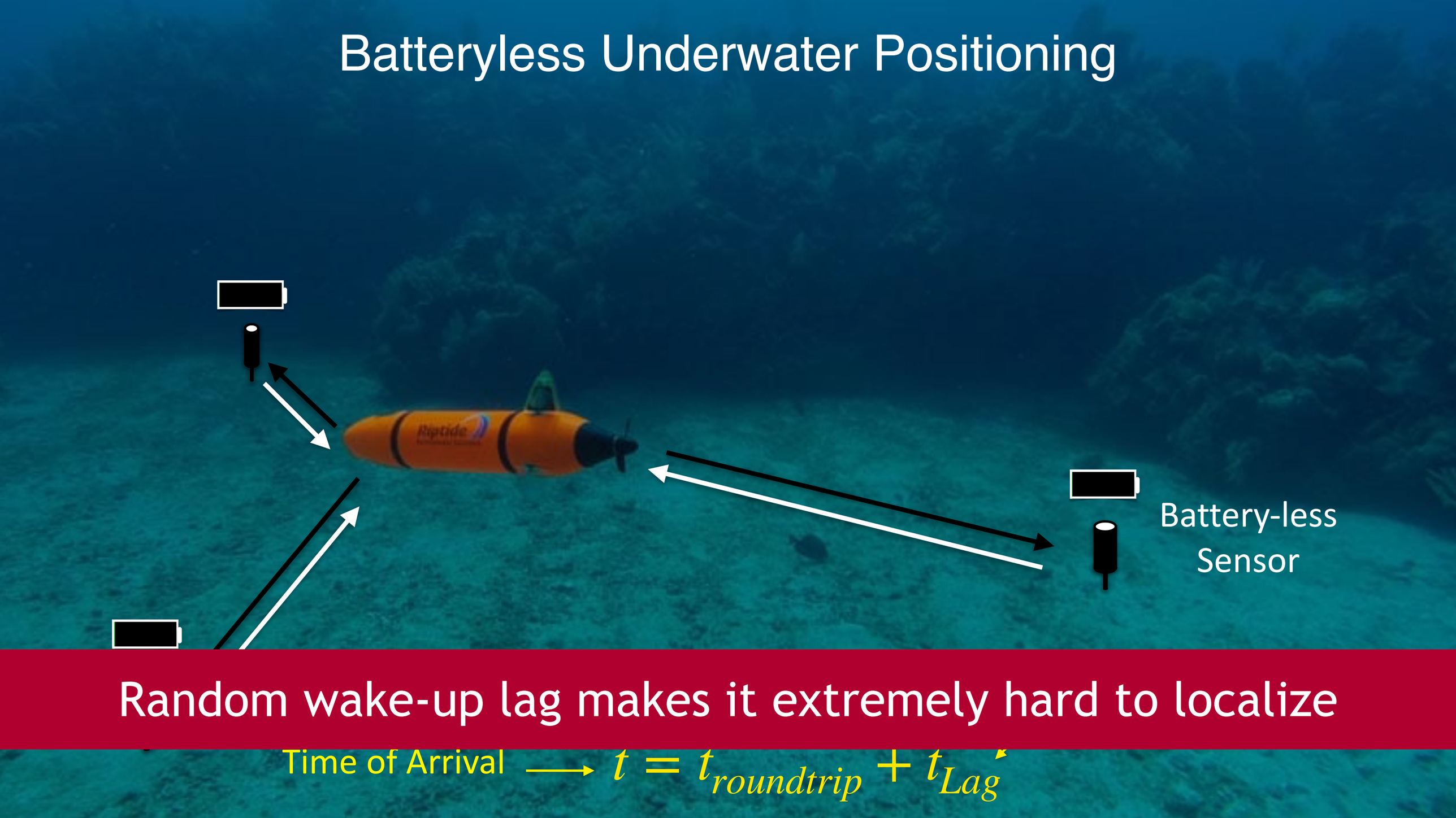
Works by measuring distances to deployed anchors

- Batteries run out of energy
- Expensive packaging
- Difficult to scale



Distance = Time of Travel x Speed of Sound

Batteryless Underwater Positioning



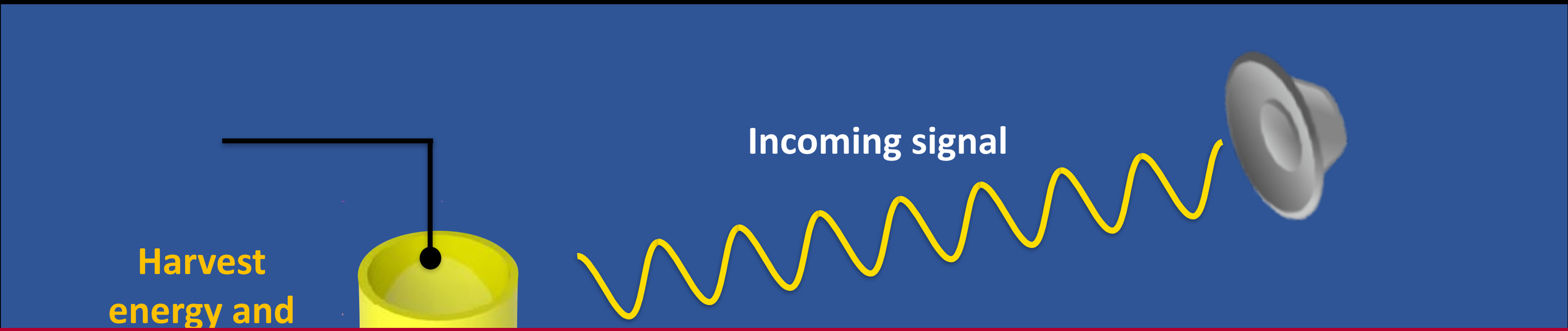
Random wake-up lag makes it extremely hard to localize

Time of Arrival $\longrightarrow t = t_{roundtrip} + t_{Lag}$

Key Idea: Underwater positioning using backscatter sensor

Key Idea: Underwater positioning using backscatter sensor

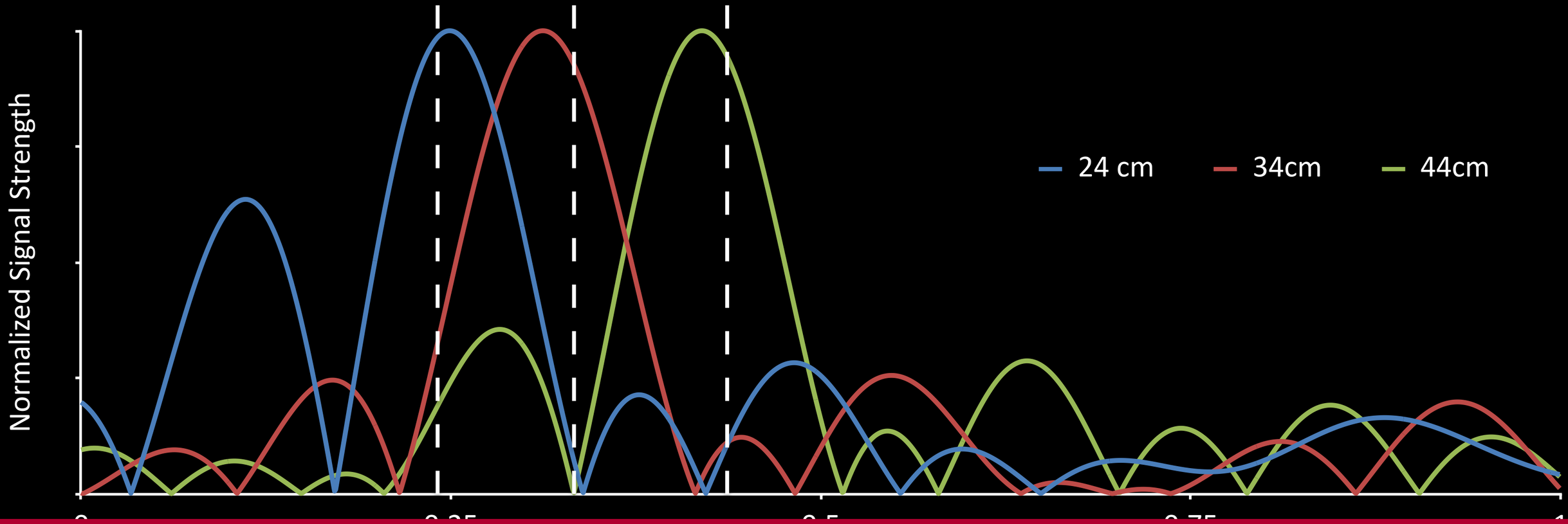
Measure “phase” instead of measuring time



Backscatter acts as a code and the phase of the continuous signal is not impacted by the wake-up lag

Use multi-frequency estimation to compute the time-of-flight from backscatter reflections [ACM HotNets’20]

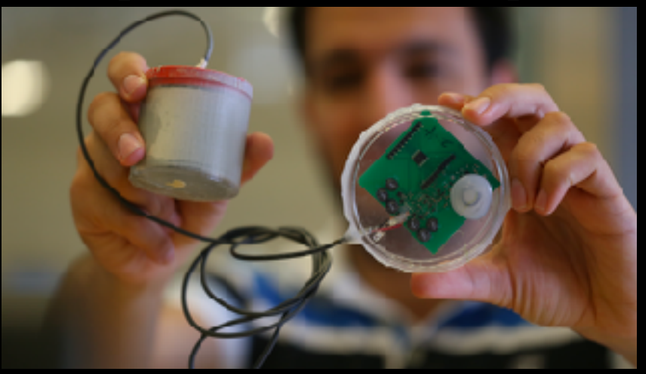
Experimental Evaluation in the River



Early results show localization accuracy of ~10 cm

Can we enable battery-free underwater localization?

Batteryless Ocean Sensing
[ACM SIGCOMM'19]



Fabrication
[ACM SIGCOMM'20]

Metamaterials for UWB (40 kHz)

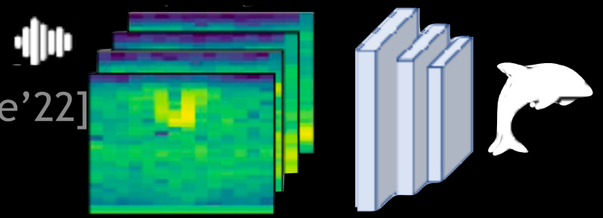
Communication
[MITS/IEEE OCEANS'20]

MIMO, Full-duplex, FDMA (20kbps, 60+m)

Localization
[ACM HotNets'20]

Battery-free GPS (~10cm)

AI
[ACM HotMobile'22]



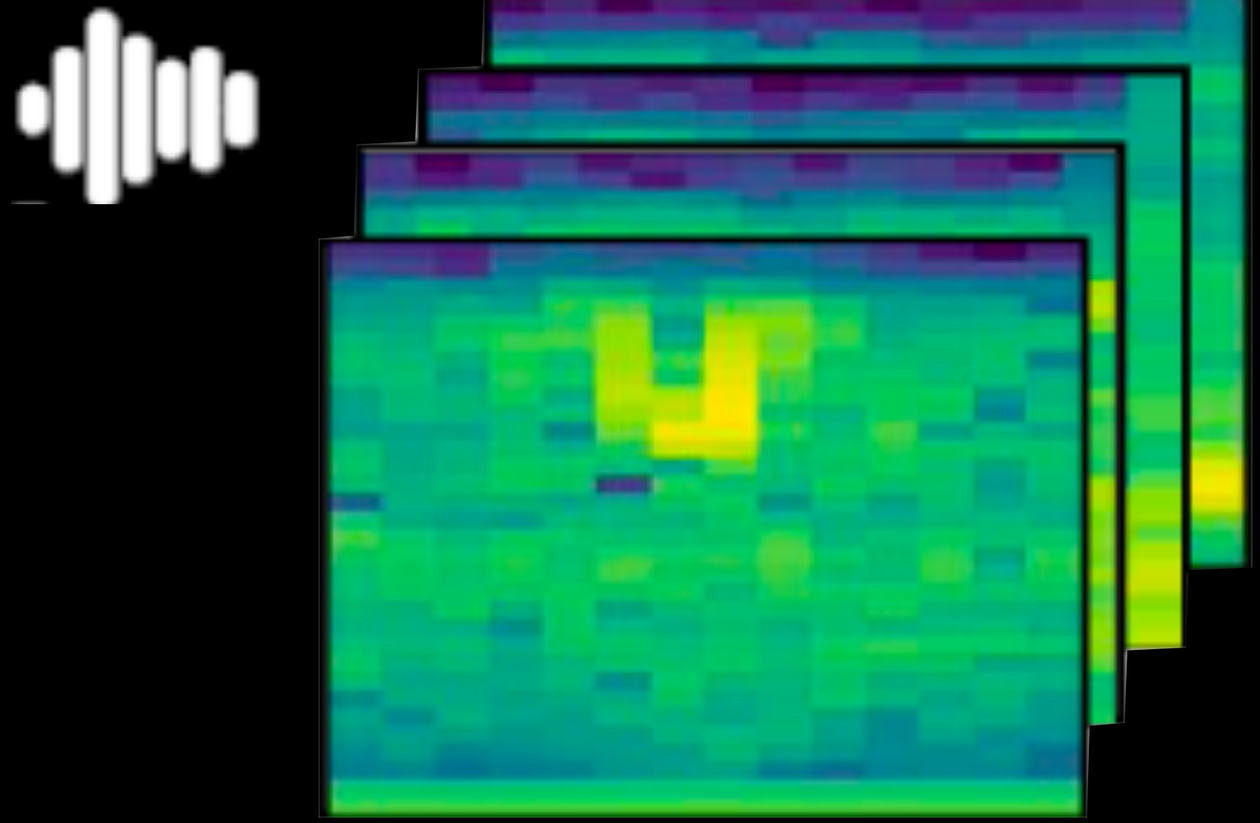
Bioacoustics (animal/climate sensing)

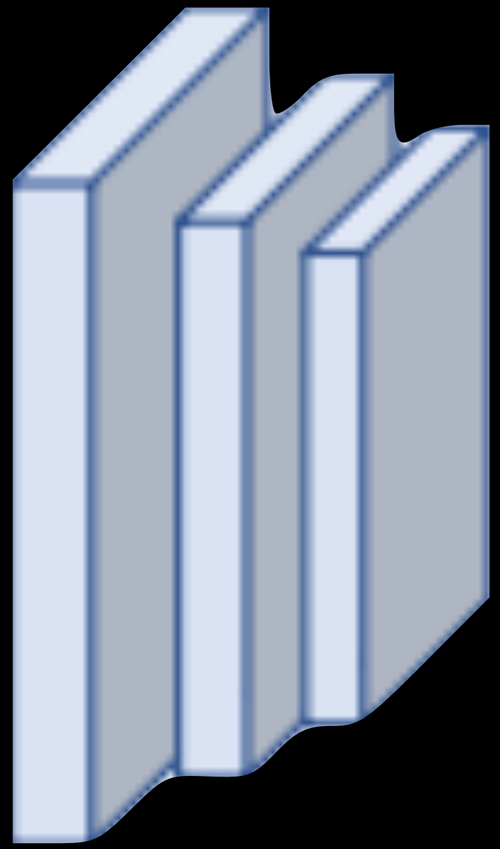
Imaging

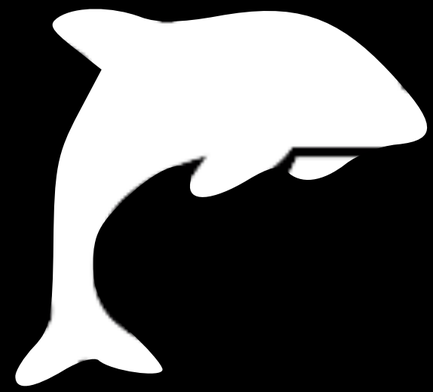
Monitoring for climate, ecology, defense

Can we enable battery-free underwater AI?

Early results demonstrate 85%+ accuracy in identifying marine species (without any batteries)



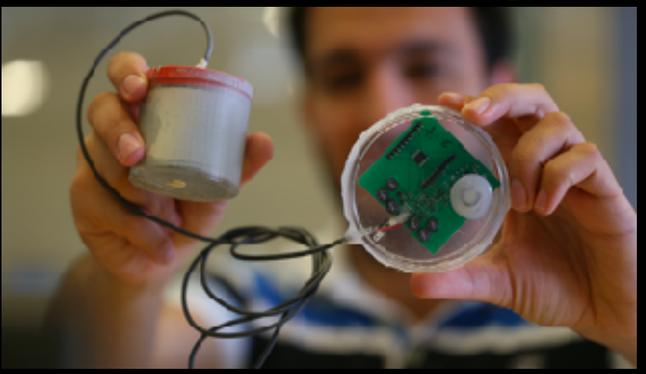




[ACM HotMobile'22]

Imperial College London

Batteryless Ocean Sensing
[ACM SIGCOMM'19]



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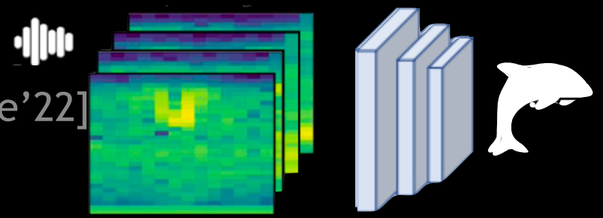

Bioacoustics (animal/climate sensing)

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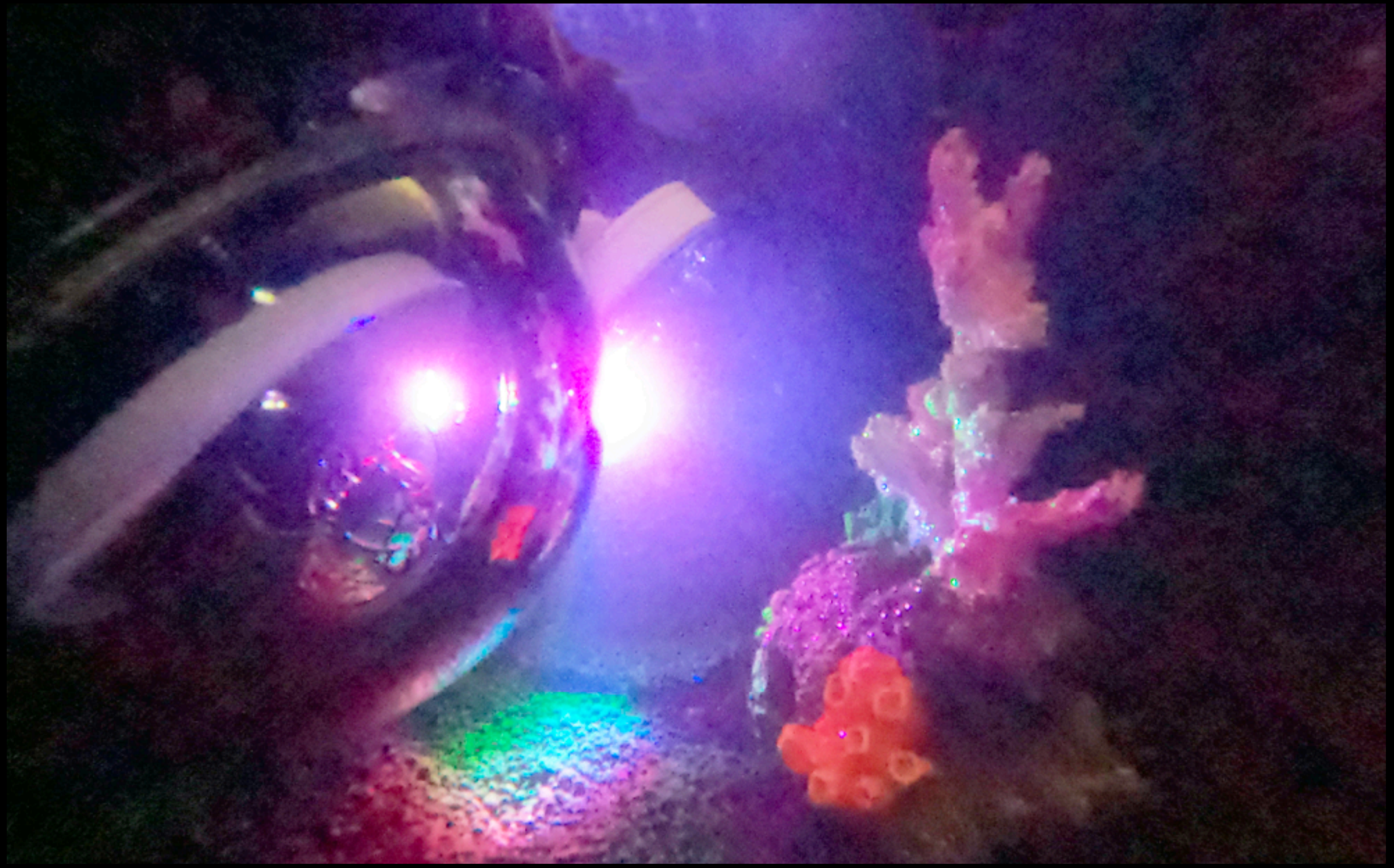
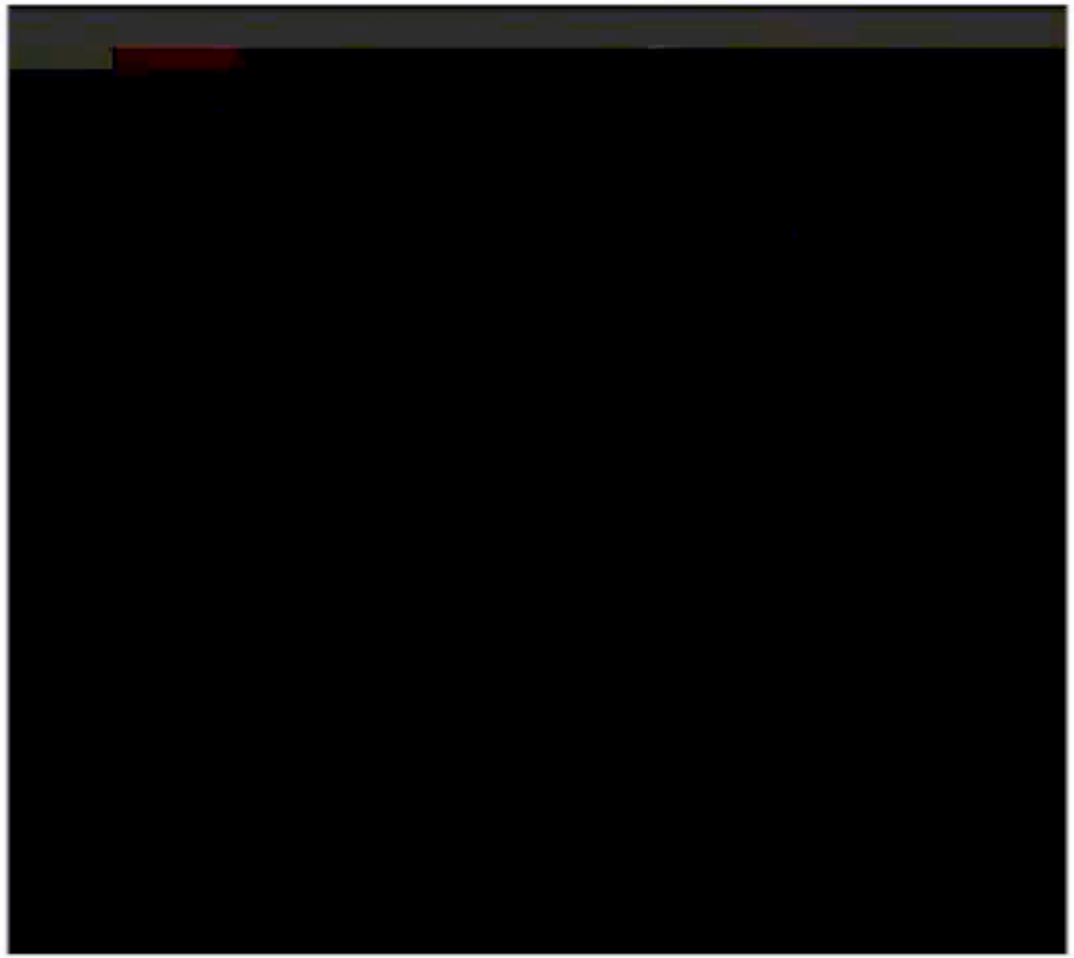
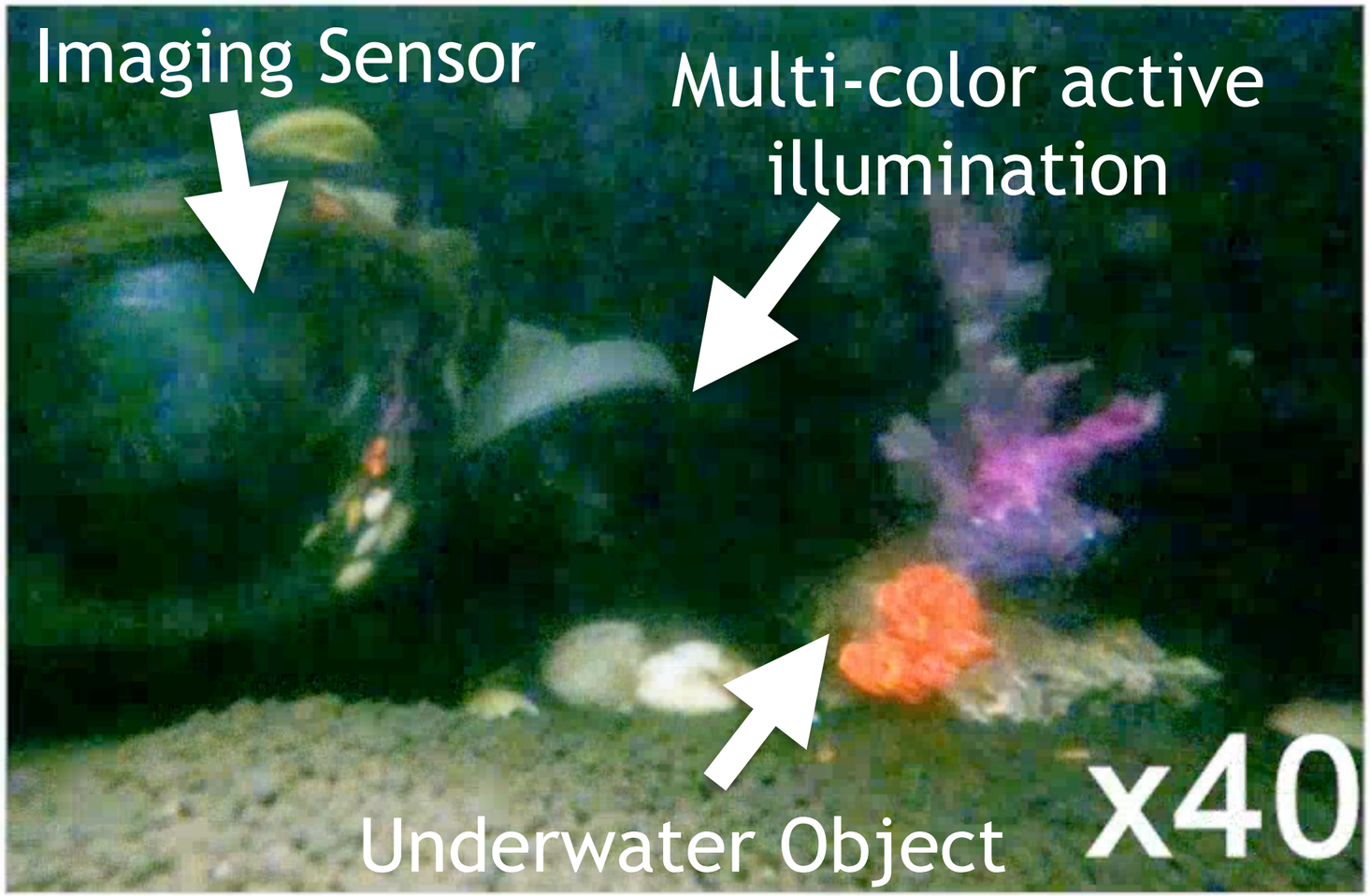
Can we enable battery-free underwater imaging?



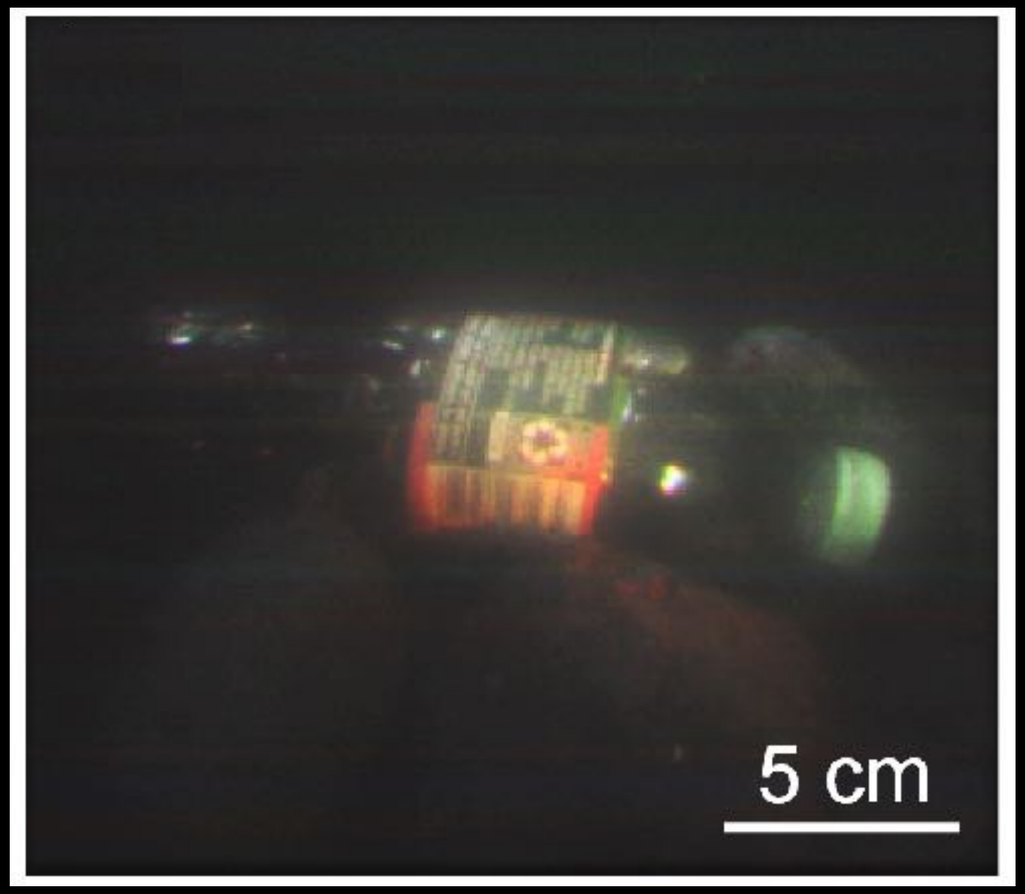
Received and Reconstructed Image

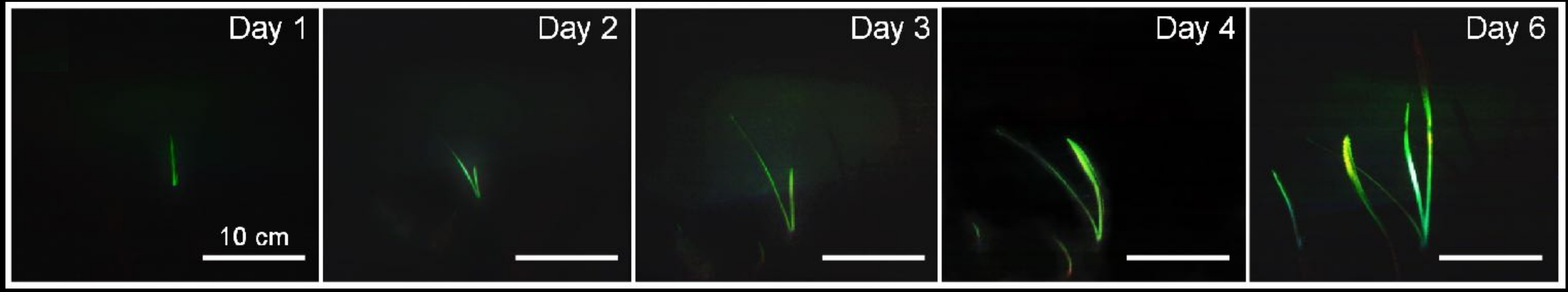
Underwater Measurement Setup
(batteryless including illumination)



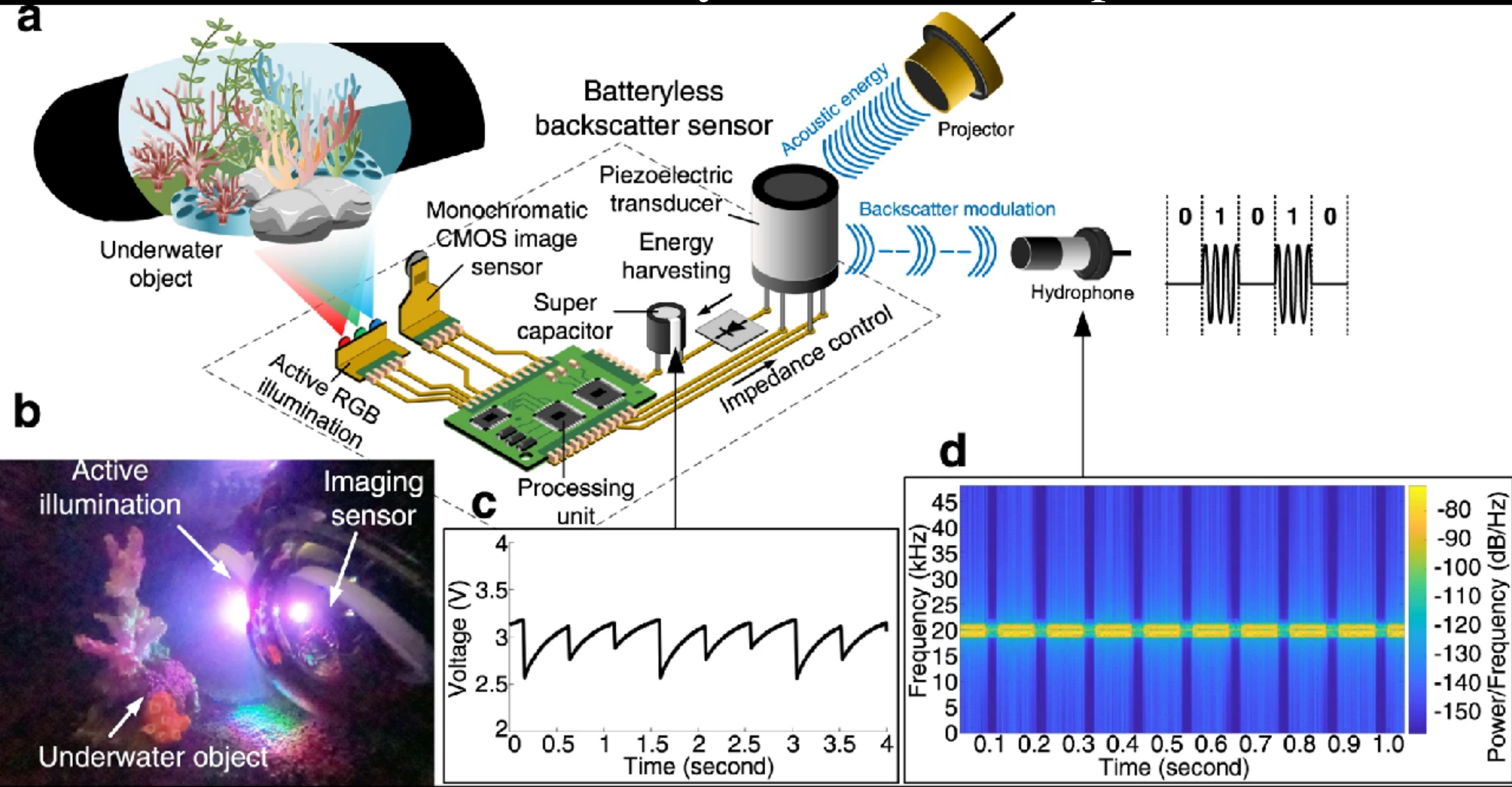



10 cm

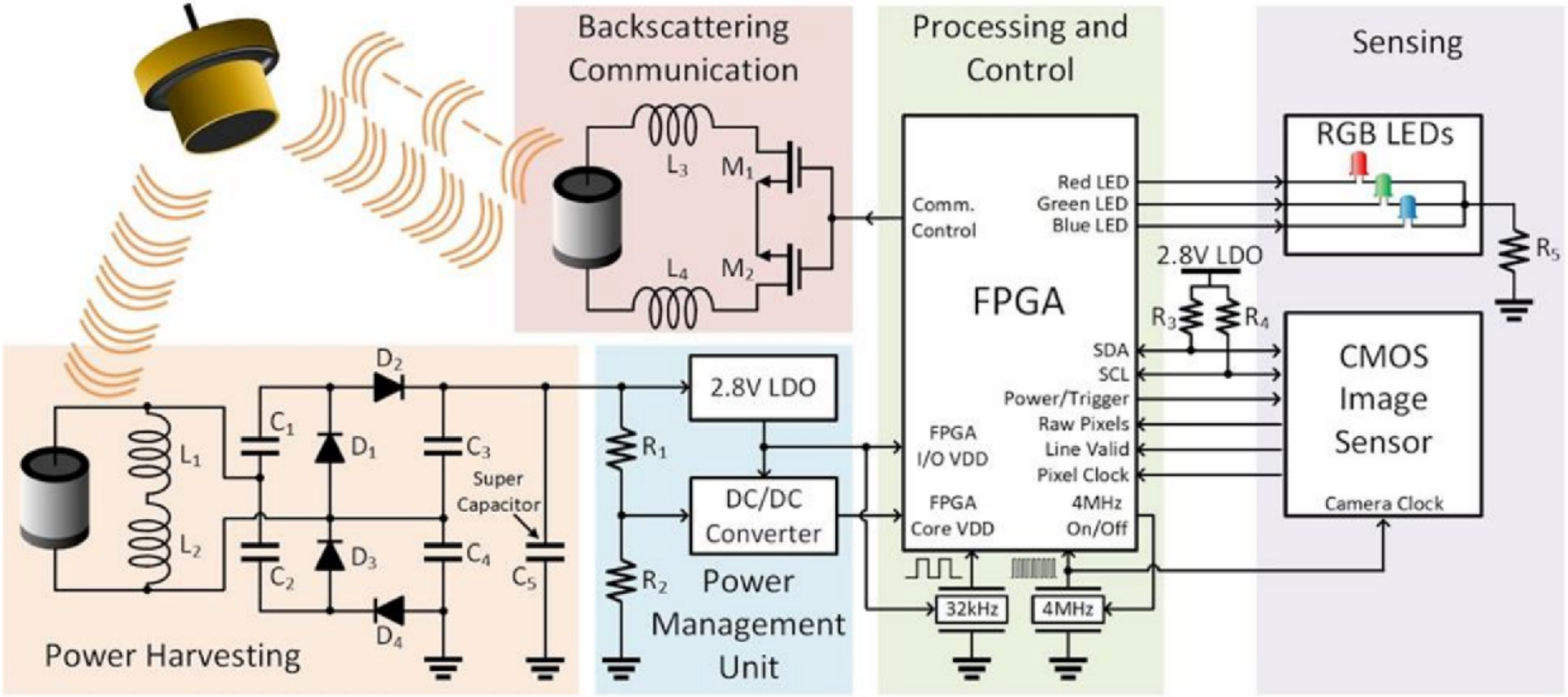

5 cm


Day 1
10 cm
Day 2
Day 3
Day 4
Day 6

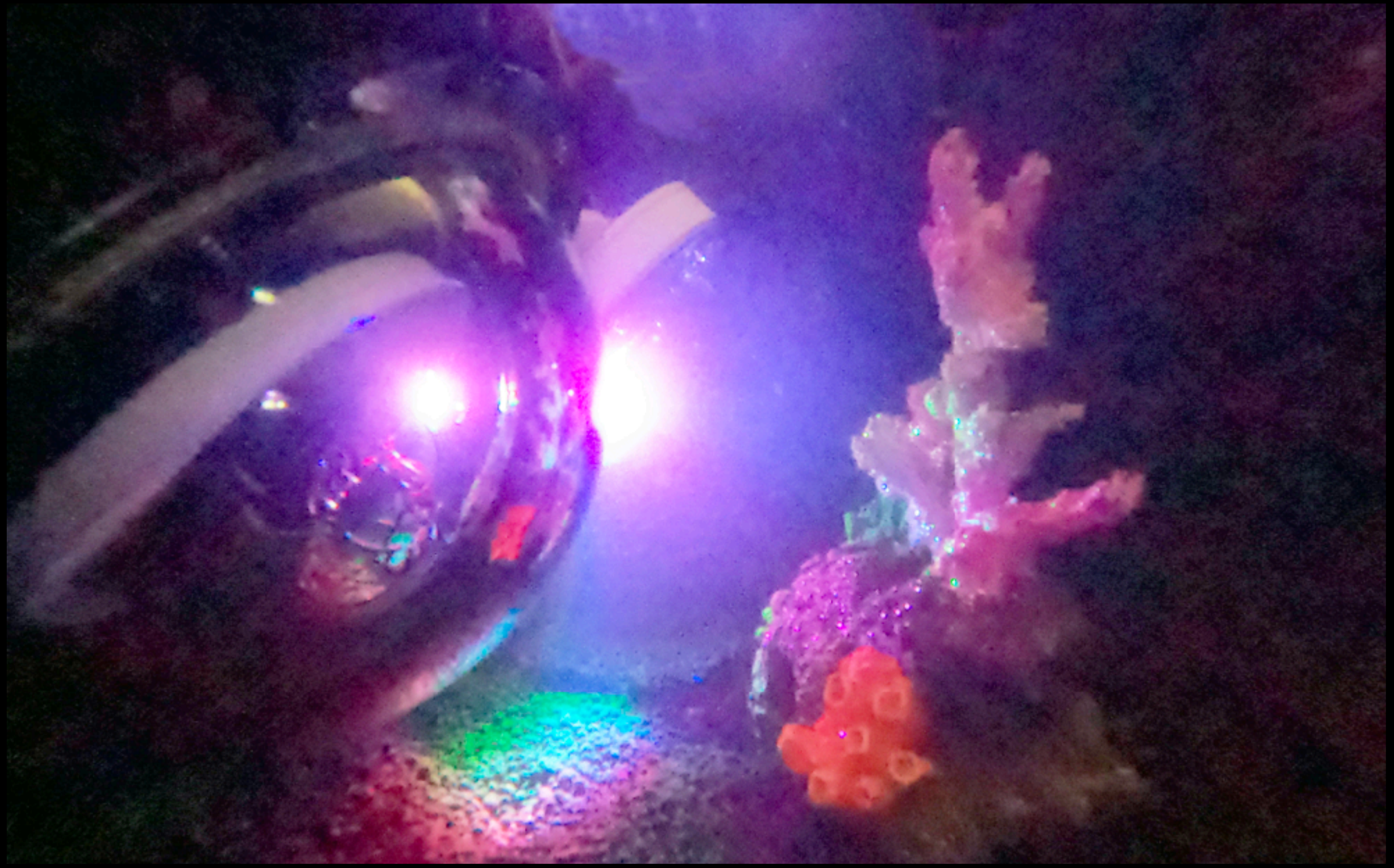
End-to-End Battery-Free Camera Operation



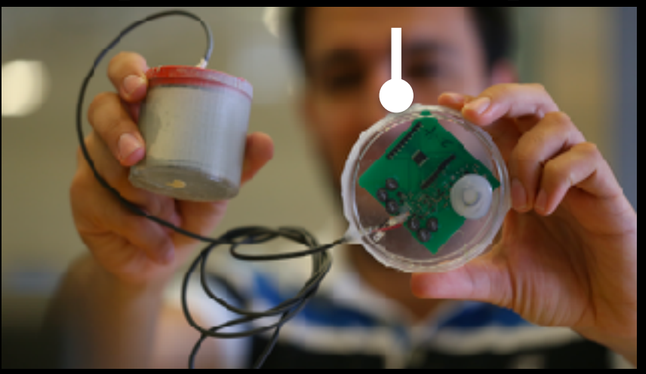
End-to-End Battery-Free Camera Schematic



Can we enable battery-free underwater imaging?



Batteryless Ocean Sensing
[ACM SIGCOMM'19]



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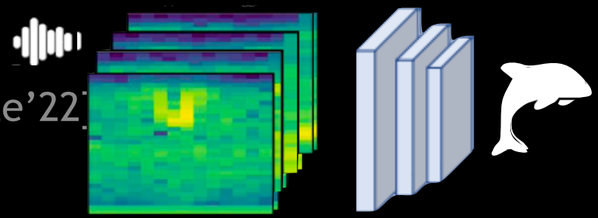

Bioacoustics (animal/climate sensing)

Imaging

Monitoring for climate, ecology, defense

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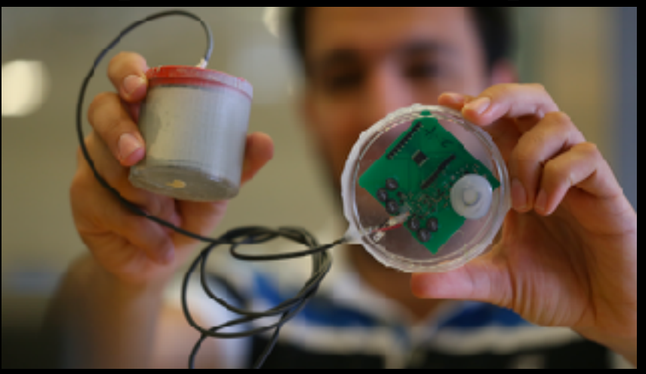

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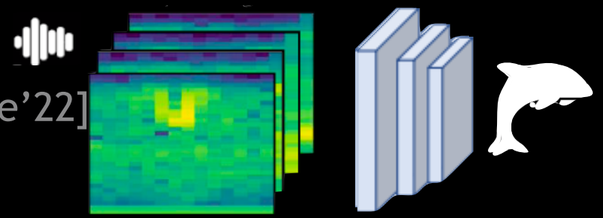

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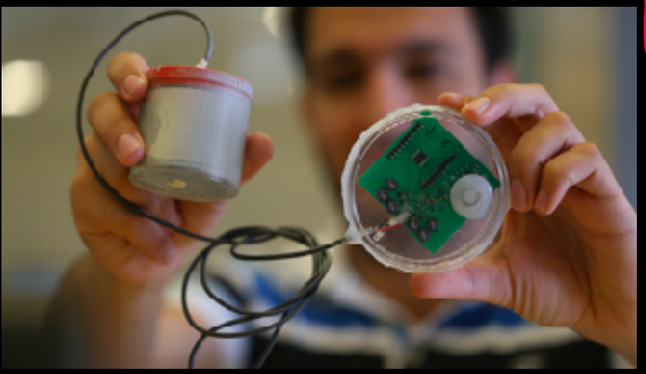


Fabrication
[ACM SIGCOMM'20]

nanoWatt power levels

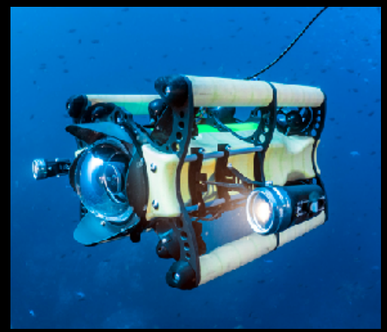
Communication
[MITS/IEEE OCEANS'20]

Toward km-scale comms

Woods Hole Oceanographic Institution

Localization
[ACM HotNets'20]

Robotic exploration



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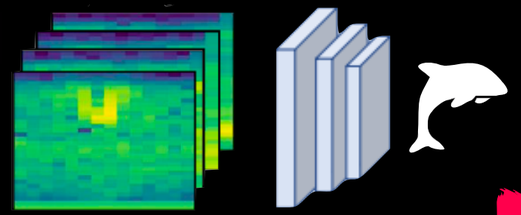


Imaging

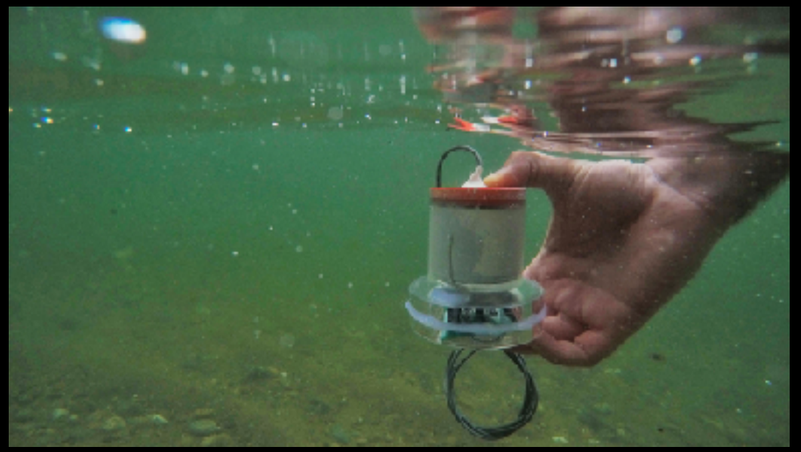
- Discovering marine species
- Aquaculture
- Climate change monitoring
- Defense
- …

Objectives of Today's Lecture

Learn the **fundamentals, emerging technologies, and applications** of ocean IoT

1. What makes underwater IoT different from in-air IoT?
2. What are the applications of underwater IoT?
3. What are the fundamental principles of underwater backscatter?
4. How do battery-free underwater localization and imaging work?

This Class: Ocean IoT



1) Required

- Underwater Backscatter
- Battery-Free Underwater Camera

2) Optional Reading List

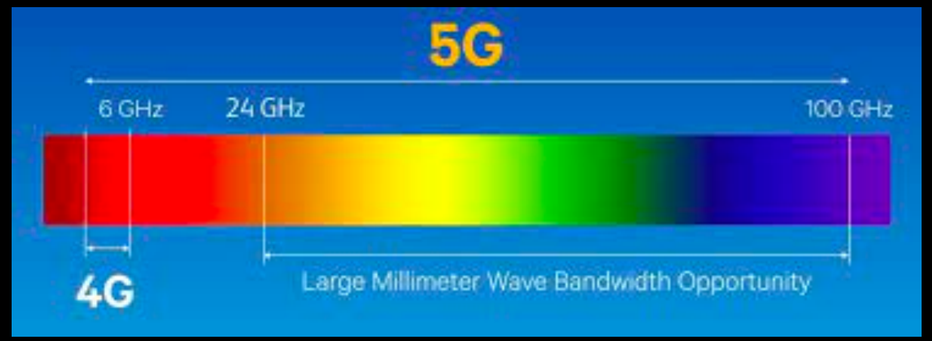
Class on Ocean IoT: http://www.mit.edu/~fadel/courses/MAS.S62/lectures.html

- Underwater Drones, Remote Sensing Localization, Imaging, Mobile Sensing, SMART cables

Next Class: Millimeter Waves

1) Required

- Automotive Radar
- Millimetero



2) Optional

- 5G as a wireless power grid
- Through Fog High Resolution Imaging Using Millimeter Wave Radar
- Practical Null Steering in Millimeter Wave Networks
- Listeer: Mmwave beam acquisition and steering by tracking indicator leds on wireless aps
- Single-shot link discovery for terahertz wireless networks

3) Reminders/Announcements

- Class feedback survey
- Any equipment needs (asap + needs)
- Readings for next week
- Project meetings - today // end of lectures + Nov. 14 & Dec. 5