



6.1820/MAS.453 Mobile and Sensor Computing

aka IoT Systems

<https://6mobile.github.io/>

Lecture 12: Ocean IoT

Course Staff

Lecturers: Fadel Adib (fadel@mit.edu)

TAs: Maisy Lam (mllam@mit.edu)

Laura Dodds (ldodds@mit.edu)

Let's start with some trivia

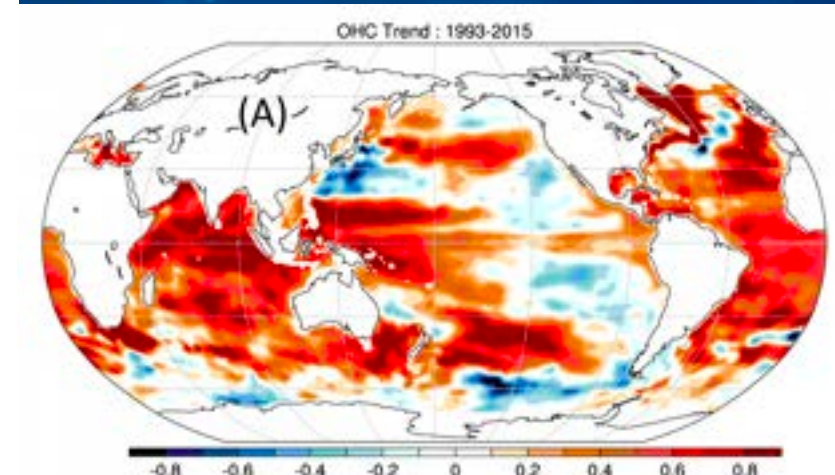
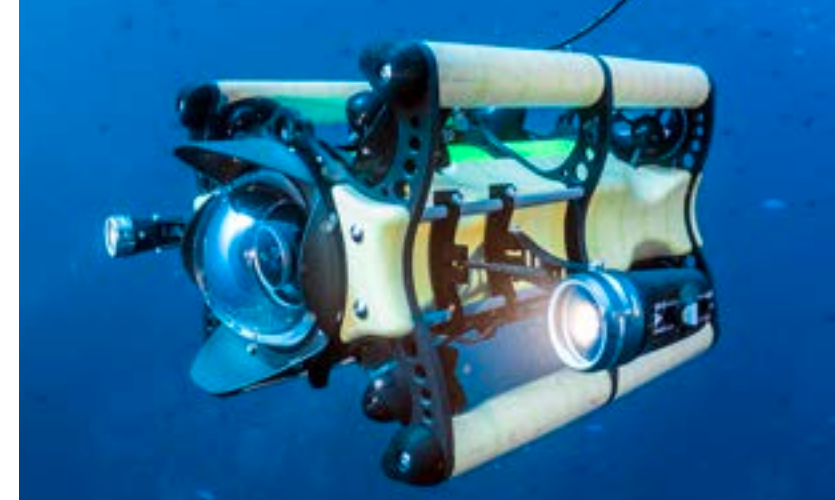
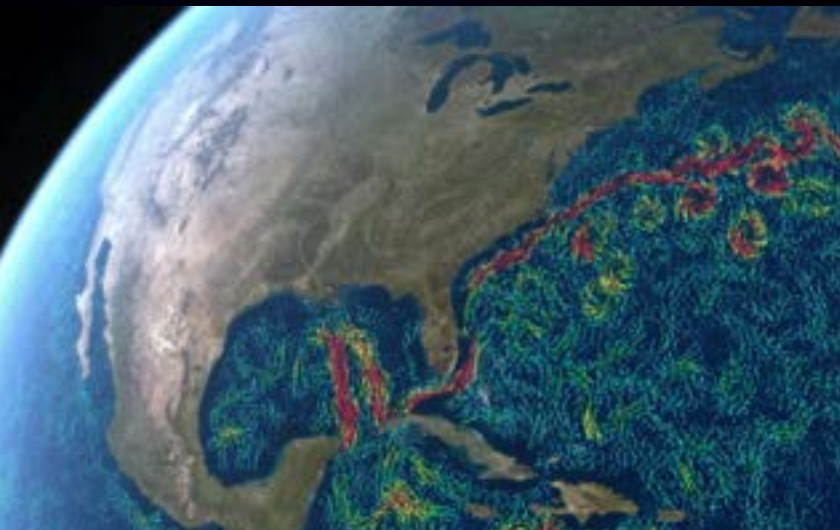
1. What percentage of the ocean floor has never been observed?

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

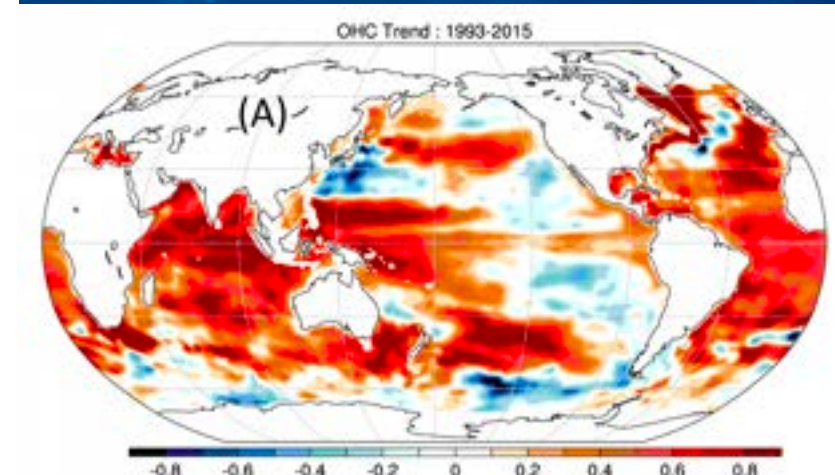
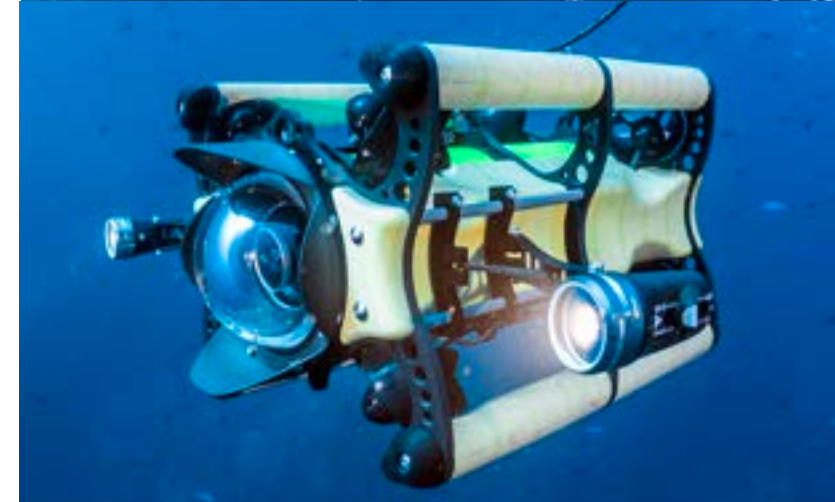
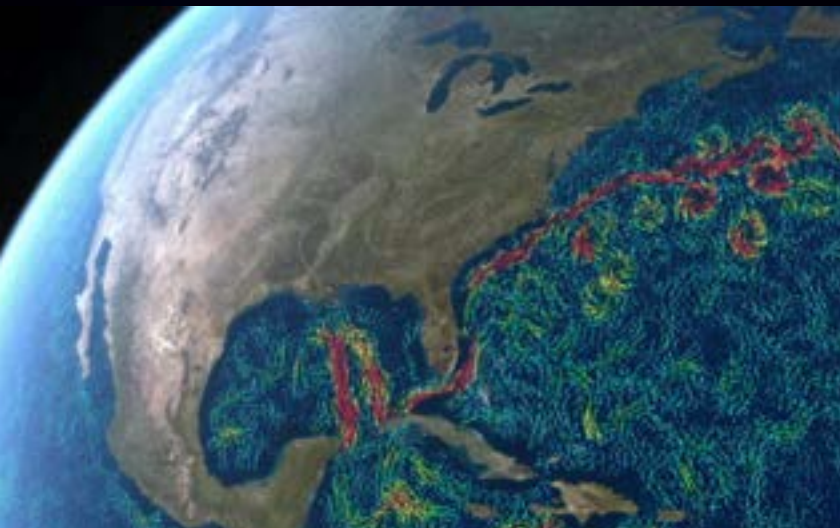
IoT Devices

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.



How Can IoT help?

1. What 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*"?



Importance of Ocean



Maritime IoT Breakthrough Creates a Digital Ocean

Date: November 20, 2025

Maritime IoT Breakthrough Creates a Digital Ocean

South Korea has taken a decisive step towards shaping the future of connected oceans by validating the world's first real-world Maritime Internet of Things communication network. The successful verification of this system marks a remarkable milestone, proving that a dedicated maritime IoT network can reliably collect environmental, navigational and safety data at sea. It also establishes a technical foundation that could redefine how nations manage coastal infrastructure, marine assets and climate intelligence.

Korea's achievement has been led by the [Electronics and Telecommunications Research Institute](#), which built and tested the network across the West and South Seas. The system demonstrated stable communication performance over distances of up to 35 kilometres while connecting 30 devices simultaneously. Notably, this is the first test in a real maritime environment using IoT international standard technologies defined by the 3rd Generation Partnership Project.

ETRI explains that this moment goes beyond technical validation. It confirms that reliable, low-power, standardised IoT communication can now extend far offshore: "The world's first verification of an MIoT communication network in the actual ocean is not just a technology demonstration, but also a foundation for the creation of new industries based on maritime big data and the expansion of national maritime safety infrastructure."



development of [Ocean of Things \(OoT\)](#), a project to seed the seas with thousands of floating sensors, monitoring everything that passes from aircraft to submarines.



Climate Action

Progress With Shipments' All- On The High

Contributor ⓘ ⊕

technology journalist, consultant and

contract for the next phase of

inst climate change



cross the world.

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

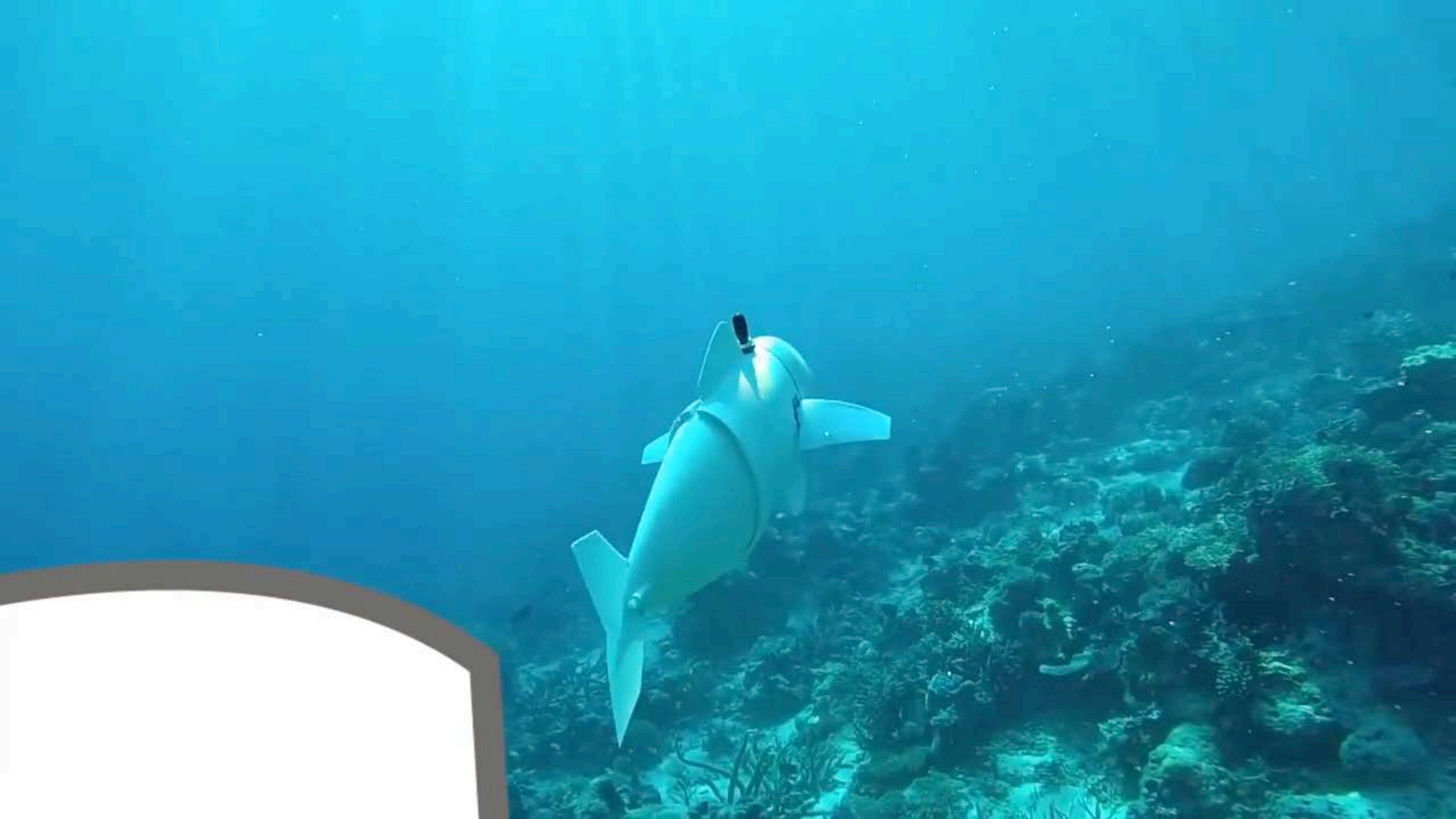


ARGO PROGRAM

BUREAU OF METEOROLOGY







Rest of this Lecture

Underwater Backscatter: Batteryless Underwater communication Technology

- Motivation
- Basic Principles
- Networking
- Localization
- Other applications: Imaging, AI, Robotics, Defense, Space
- Open problems

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)

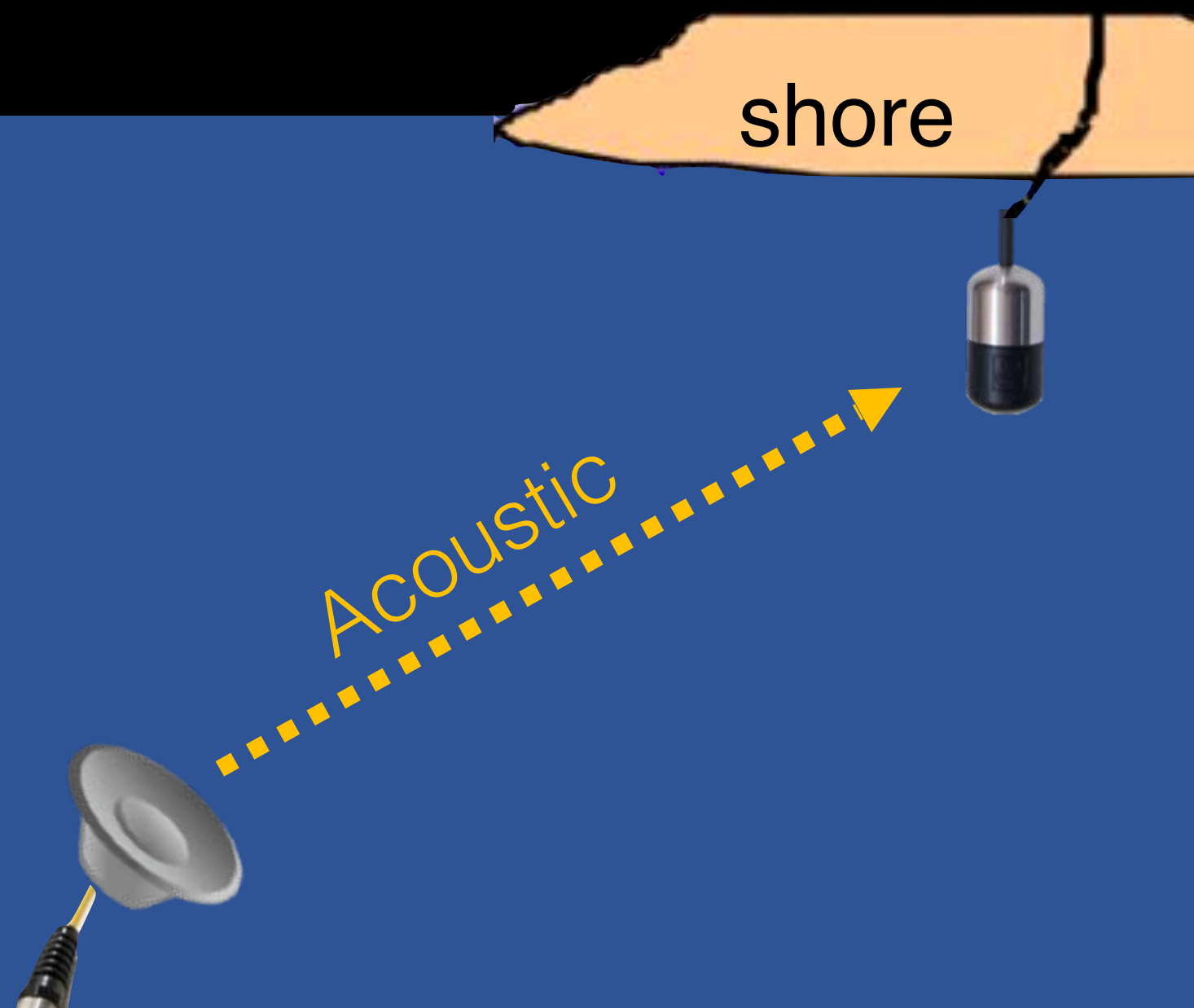


State-of-the-art sensors for tracking marine animals only last for **few hours or days**

[Animal Biotelemetry'15, Scientific Reports'17]

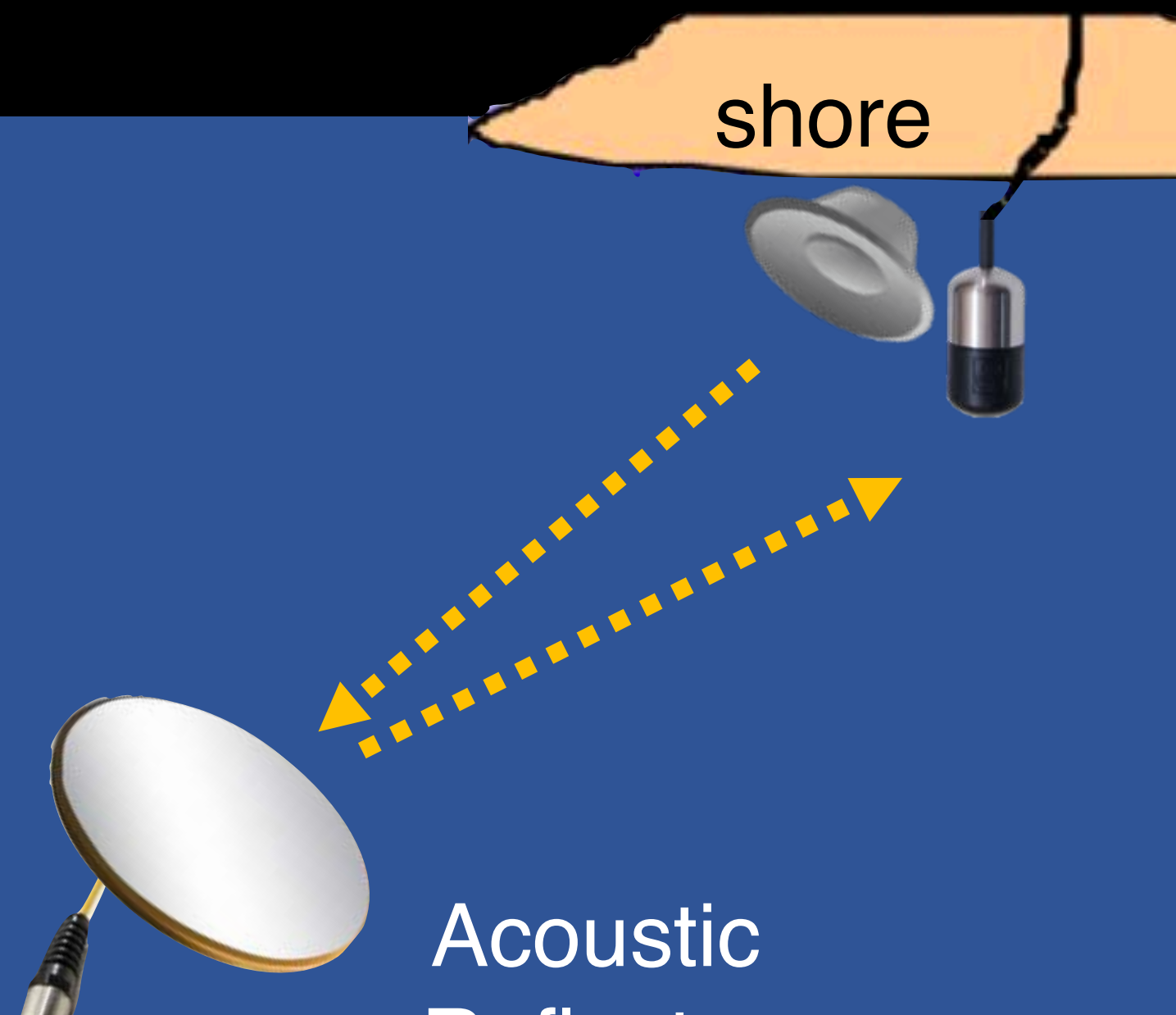
Technology that Enables Underwater Backscatter (**Batteryless**) Networking

Traditional Approach



Sensor generates its own acoustic signal

Underwater Backscatter

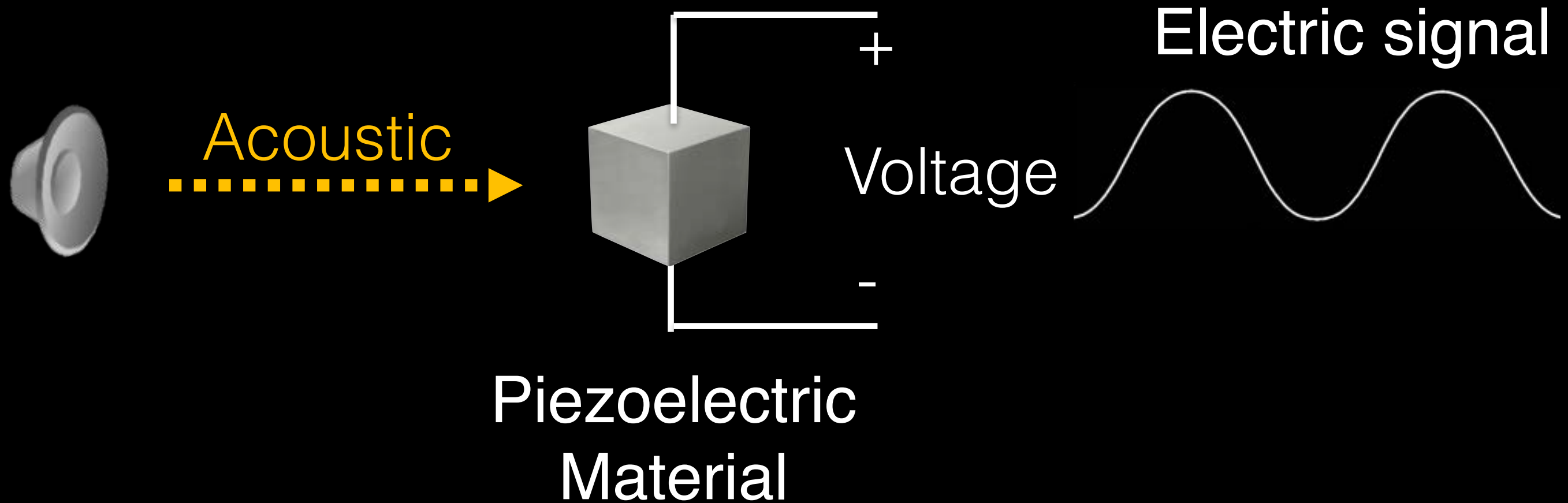


Sensor reflects an existing acoustic signal

How can we control the reflections of
acoustic signals?

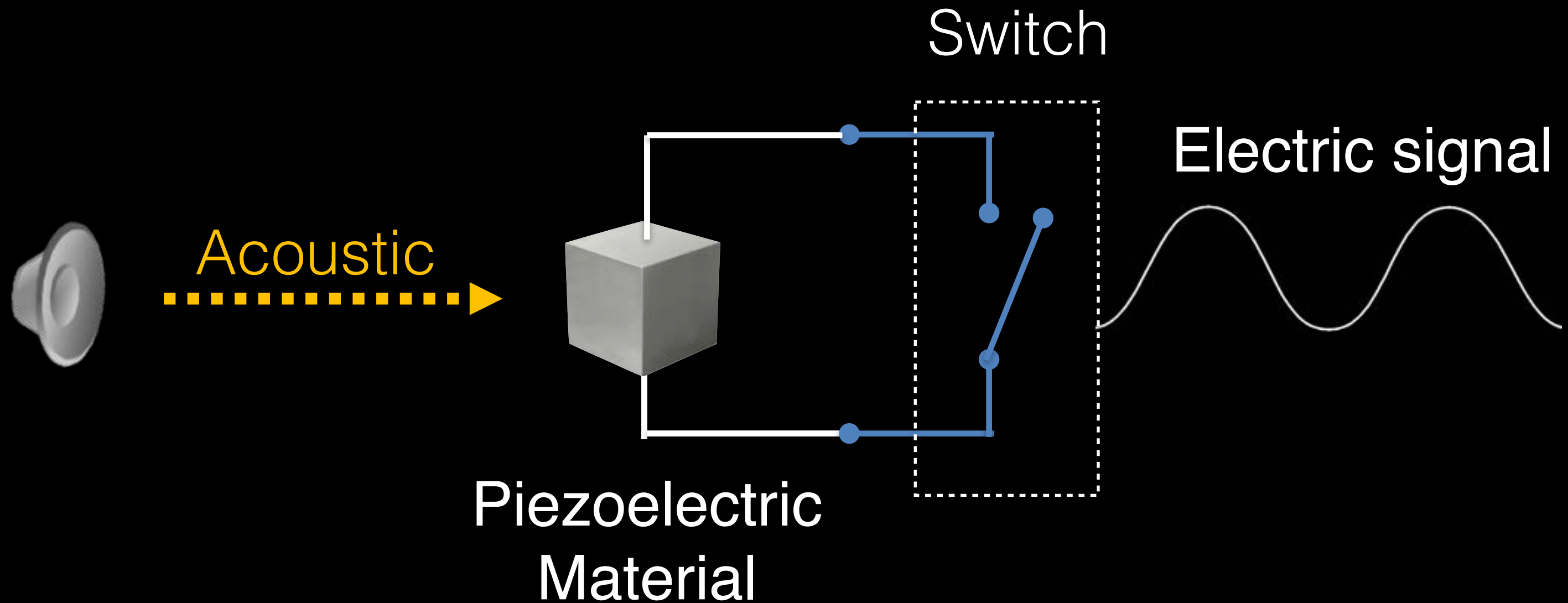
Key Idea: Use piezoelectricity to design programmable acoustic reflectors

Piezoelectric materials transform mechanical to electrical energy



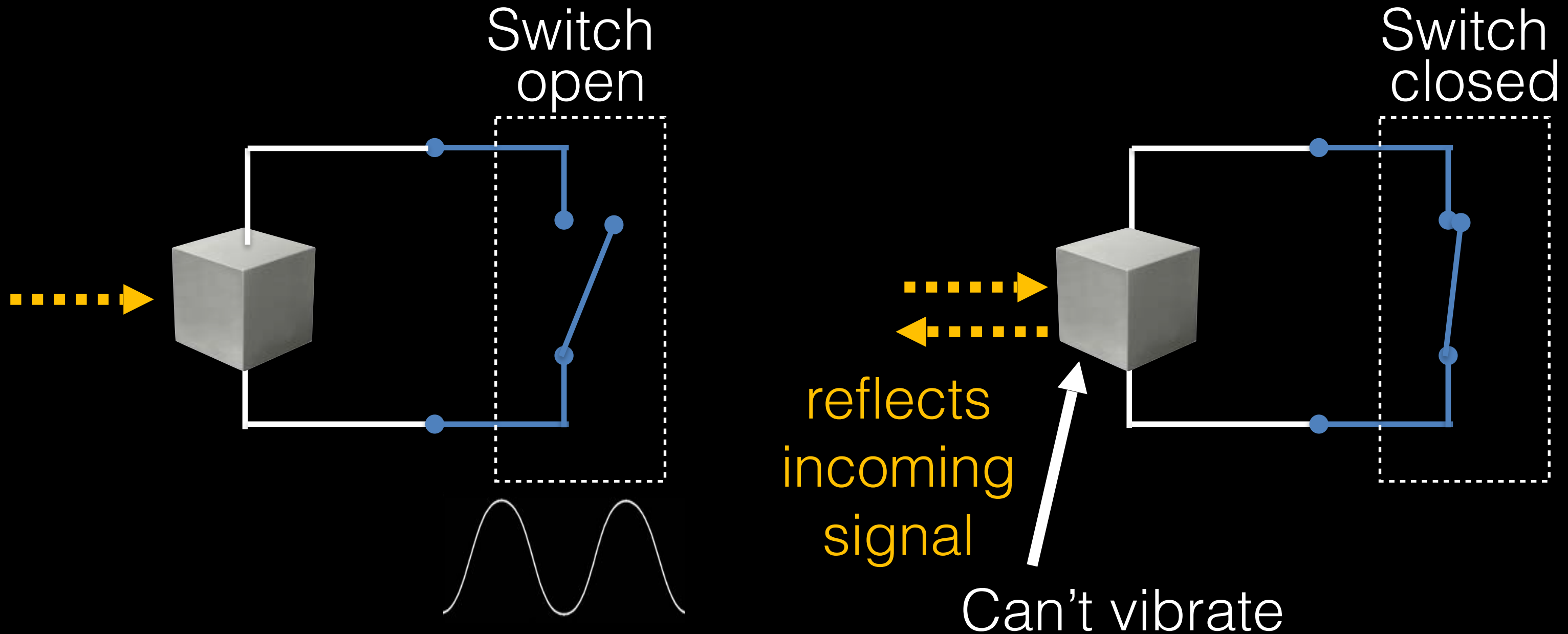
Key Idea: Use piezoelectricity to design programmable acoustic reflectors

Piezoelectric materials transform mechanical to electrical energy

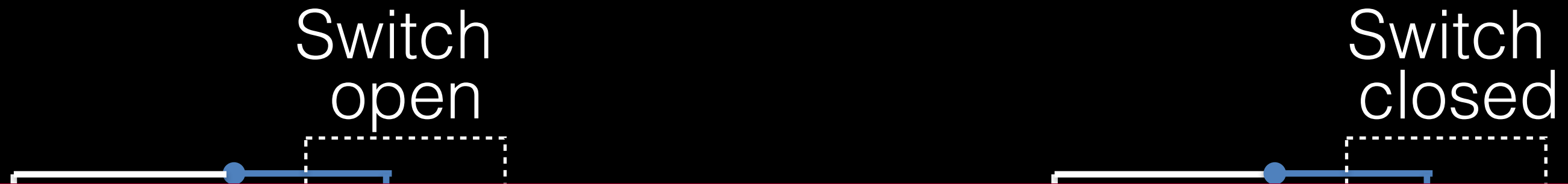


Key Idea: Use piezoelectricity to design programmable acoustic reflectors

Piezoelectric materials transform mechanical to electrical energy



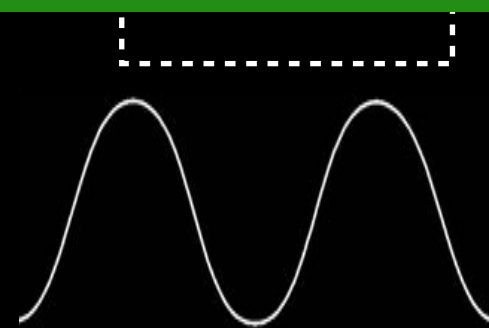
Piezo-Acoustic Backscatter



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



Incoming
signal

Can't vibrate

Hydrophone receiver



Projector (speaker)



LED



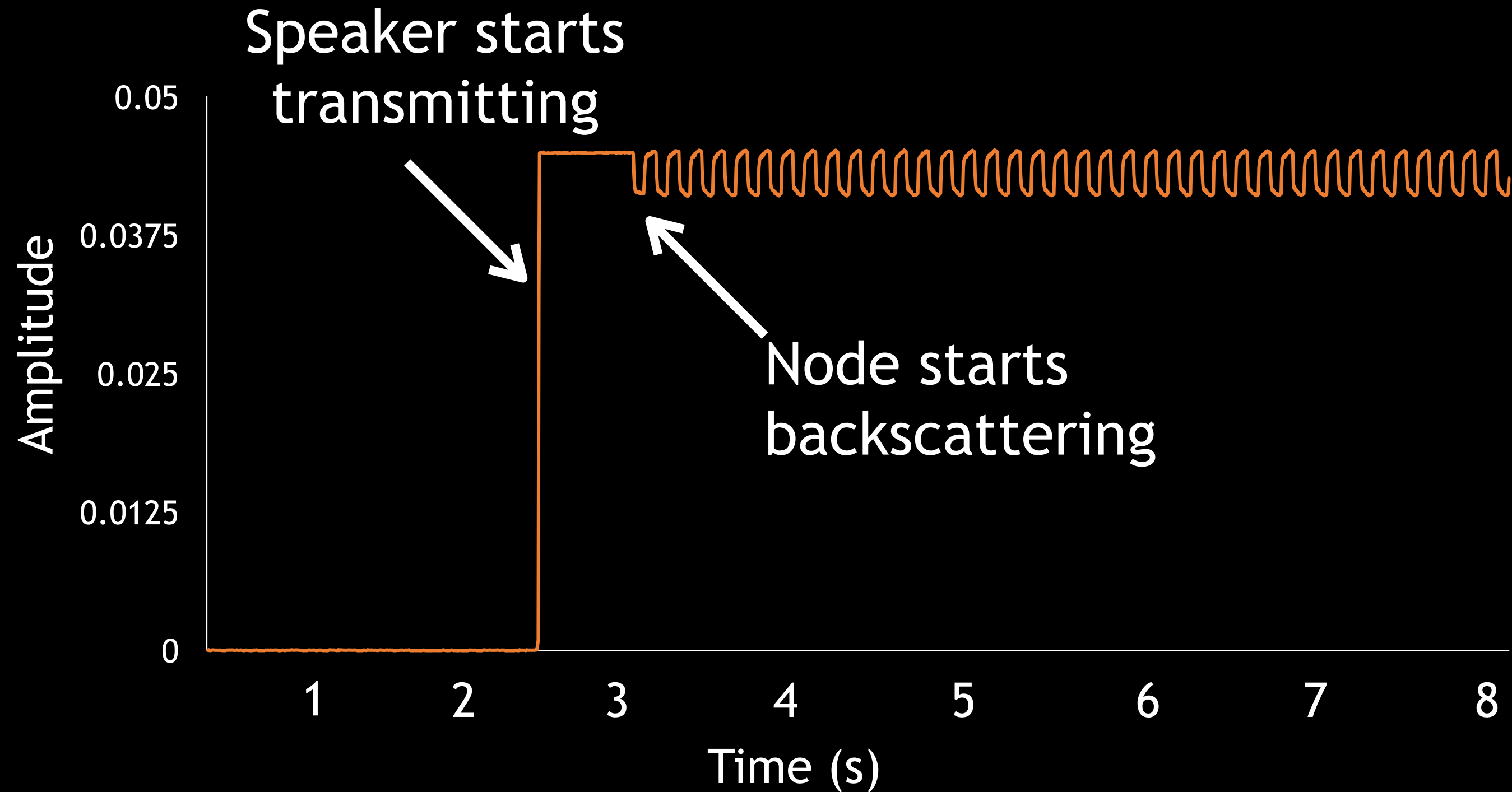
batteryless PAB sensor

connected to circuit



Large Experimental Pool

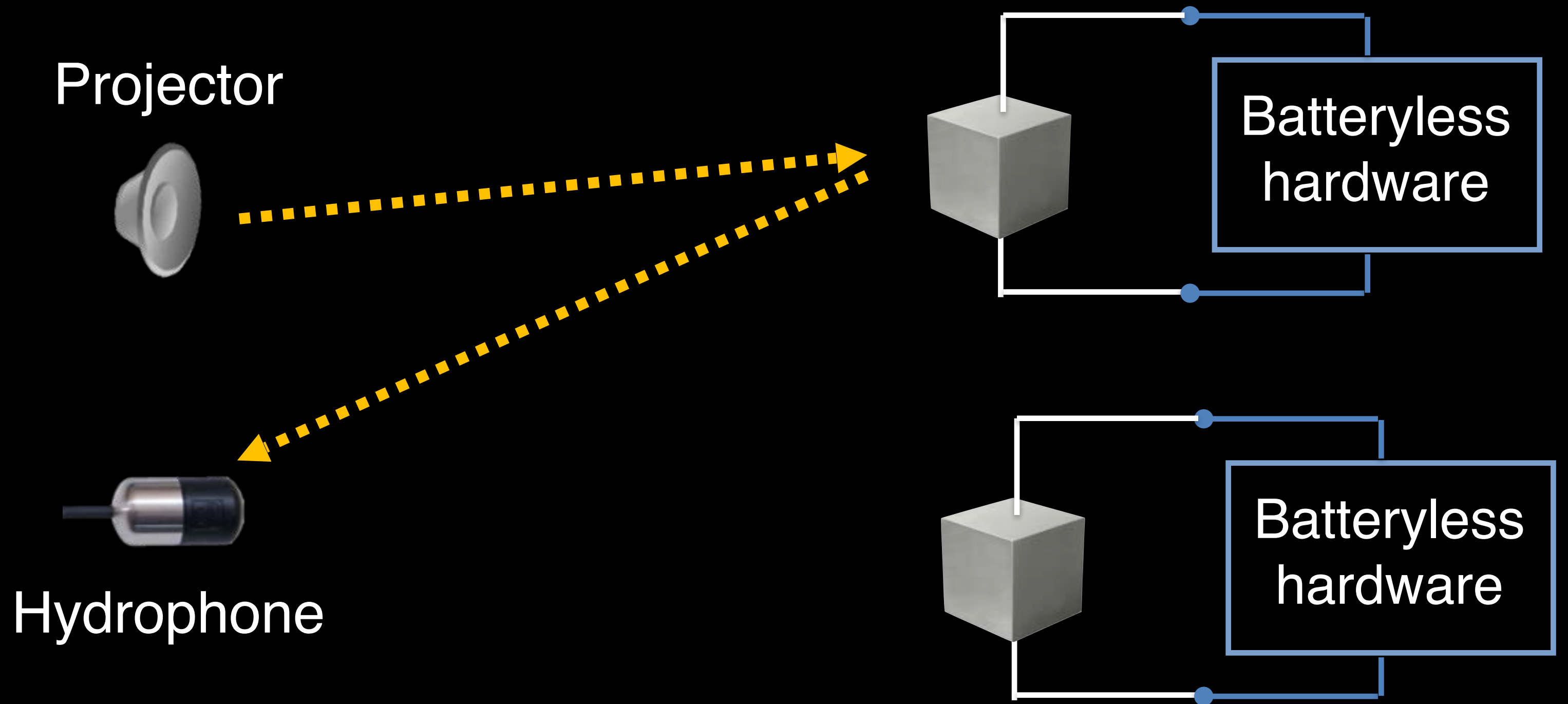
Measuring the Backscatter Signal (by Hydrophone)



How can we extend underwater backscatter to multiple nodes?

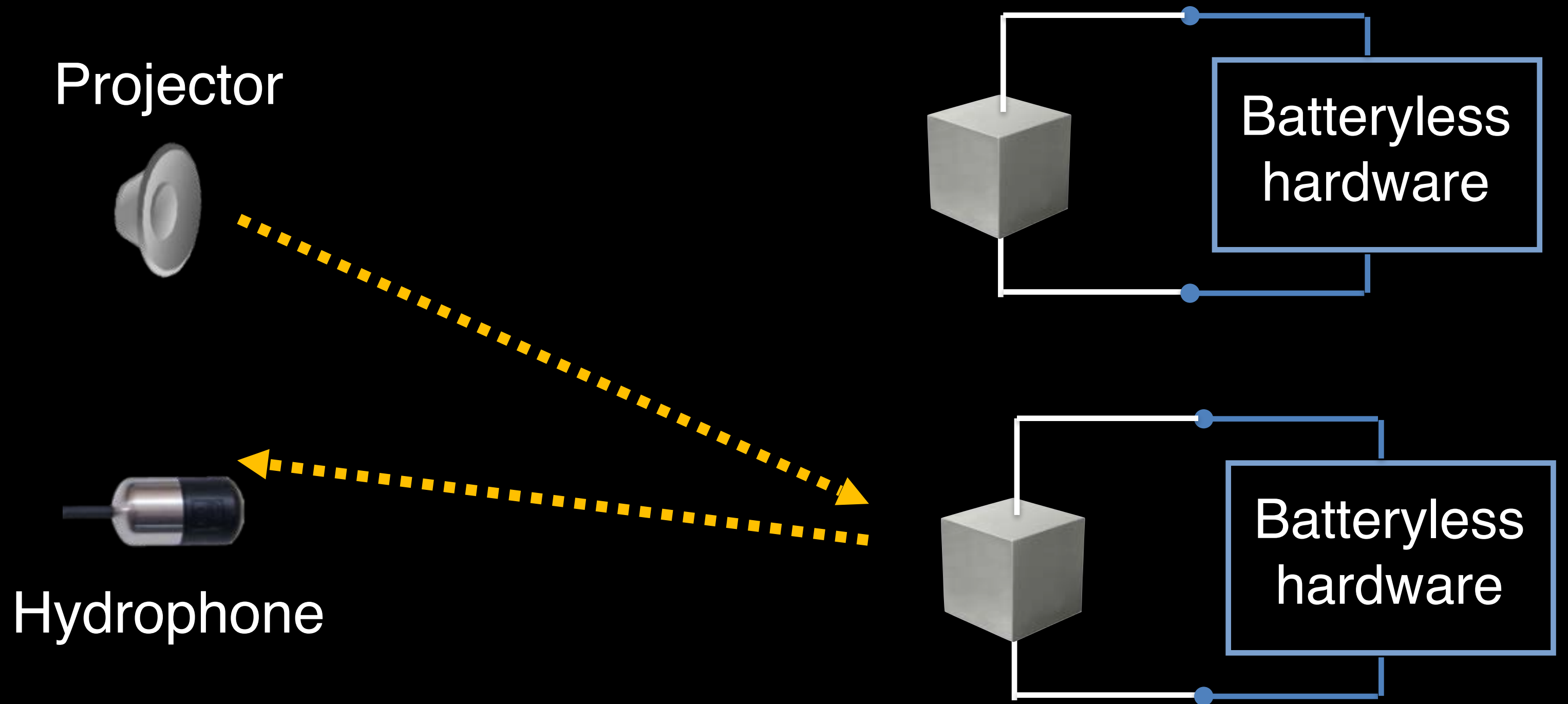
Extending to Multiple Nodes

Option 1: Time Division Multiplexing



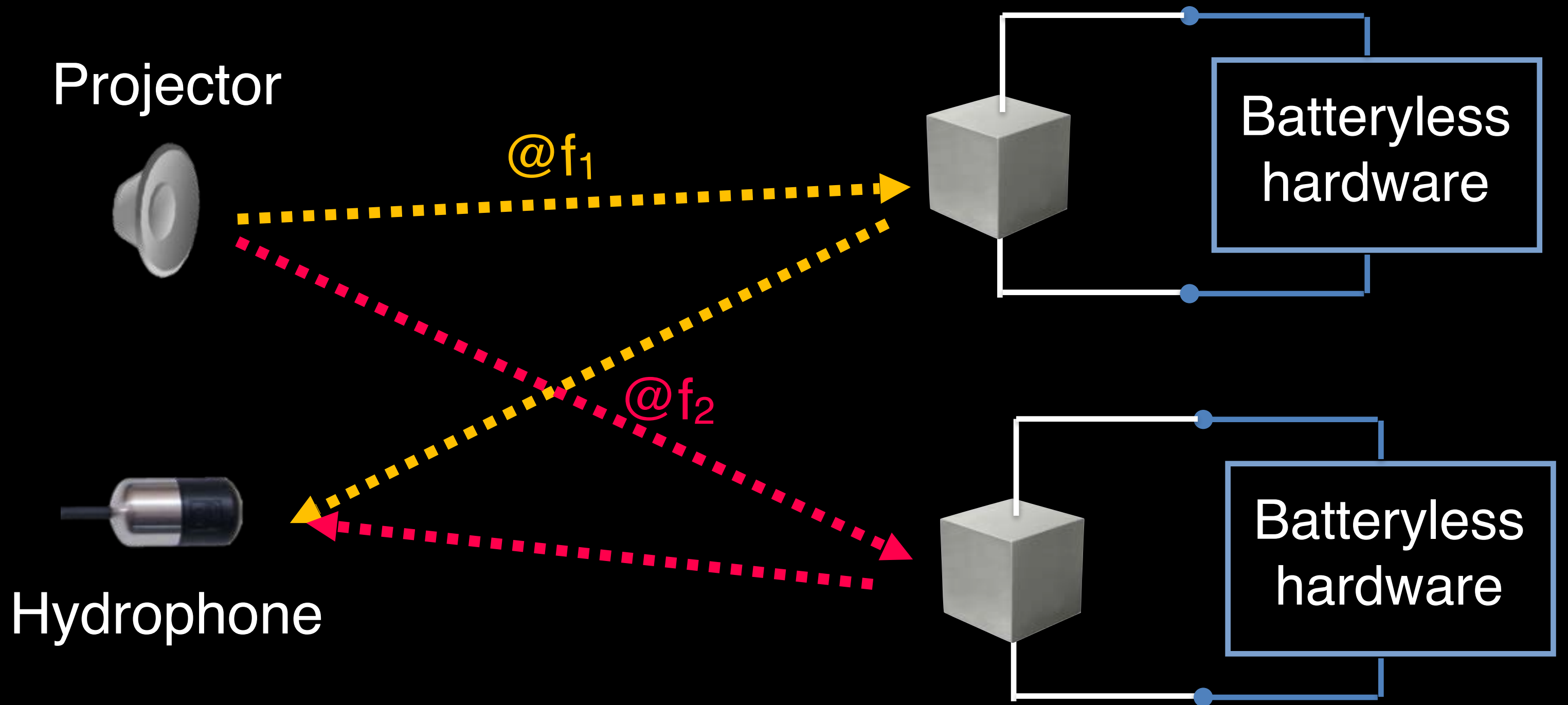
Extending to Multiple Nodes

Option 1: Time Division Multiplexing



Extending to Multiple Nodes

Option 2: Frequency Division Multiplexing



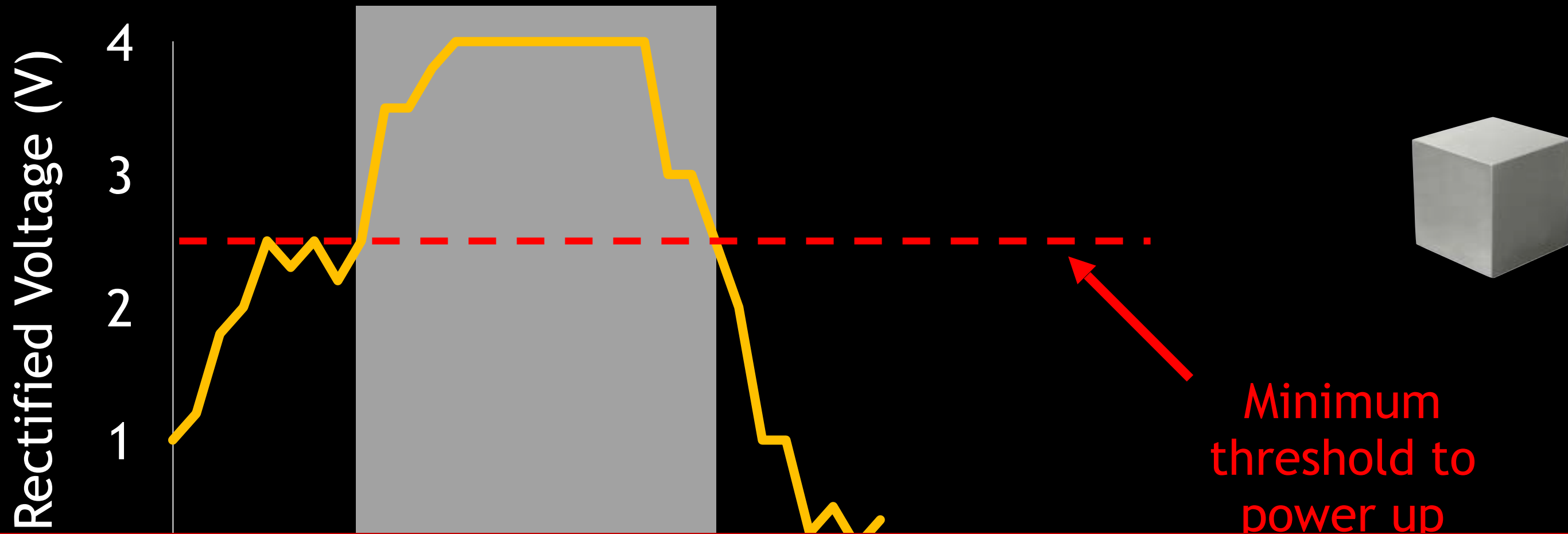
Extending to Multiple Nodes

Problem: Resonance of piezoelectrics limits their bandwidth



Extending to Multiple Nodes

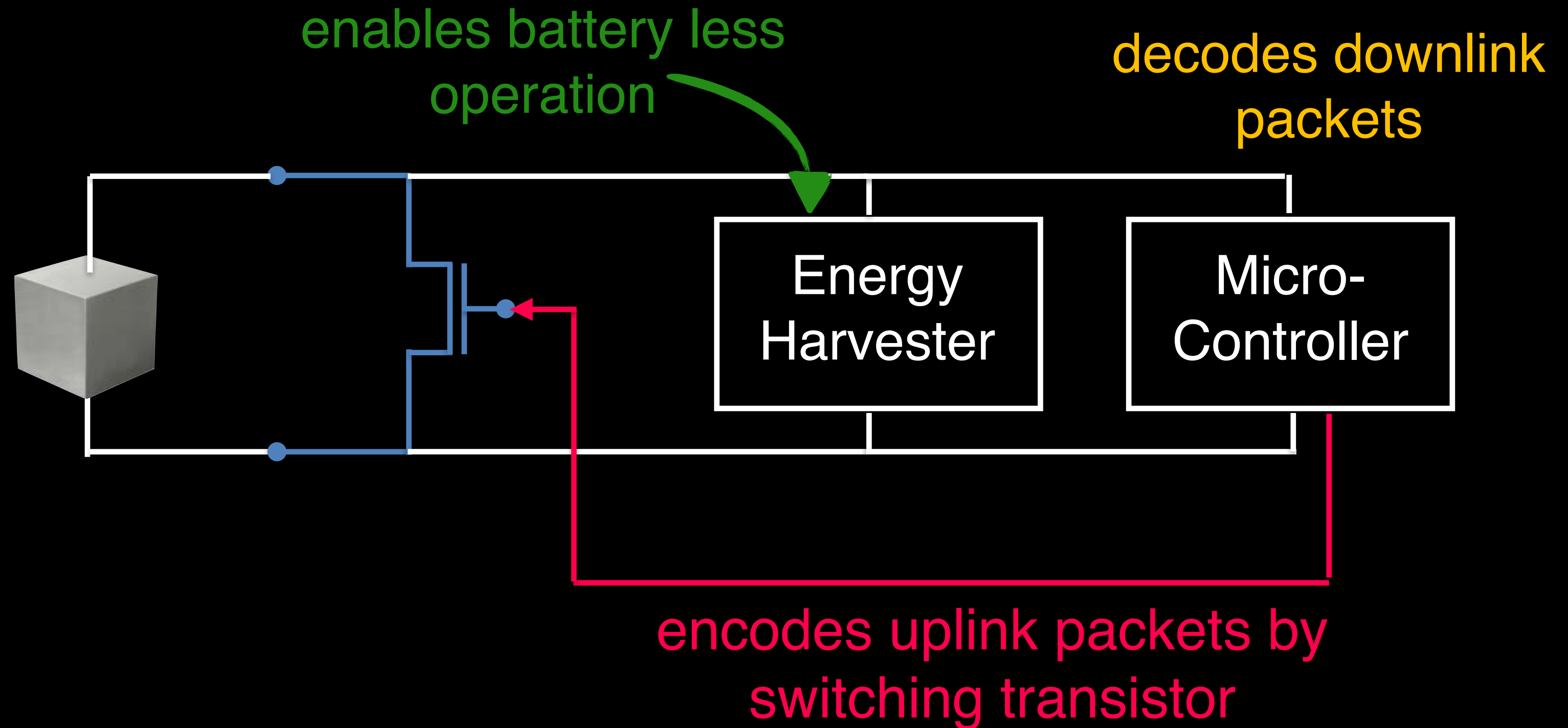
Problem: Resonance of piezoelectrics limits their bandwidth



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



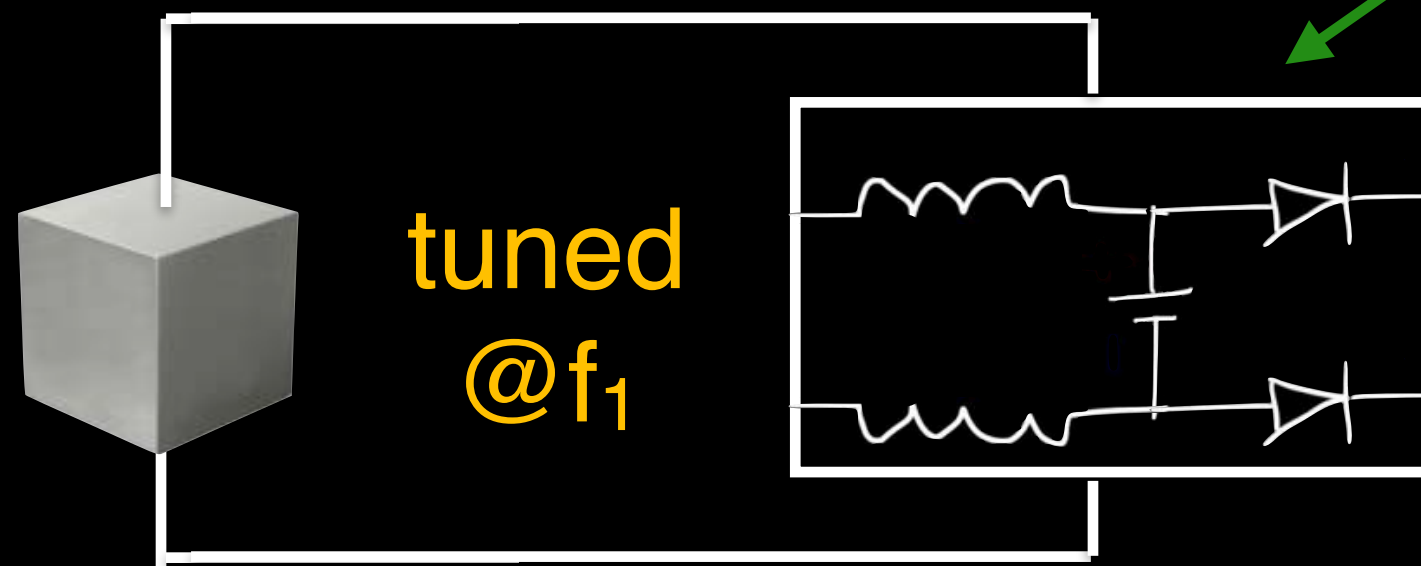
$$Z_{circuit}(f) = Z_{piezo}^*(f)$$

frequency dependent

→ Tune the circuit to a different frequency

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

resonance frequency determined by interaction between piezo & the batteryless circuit

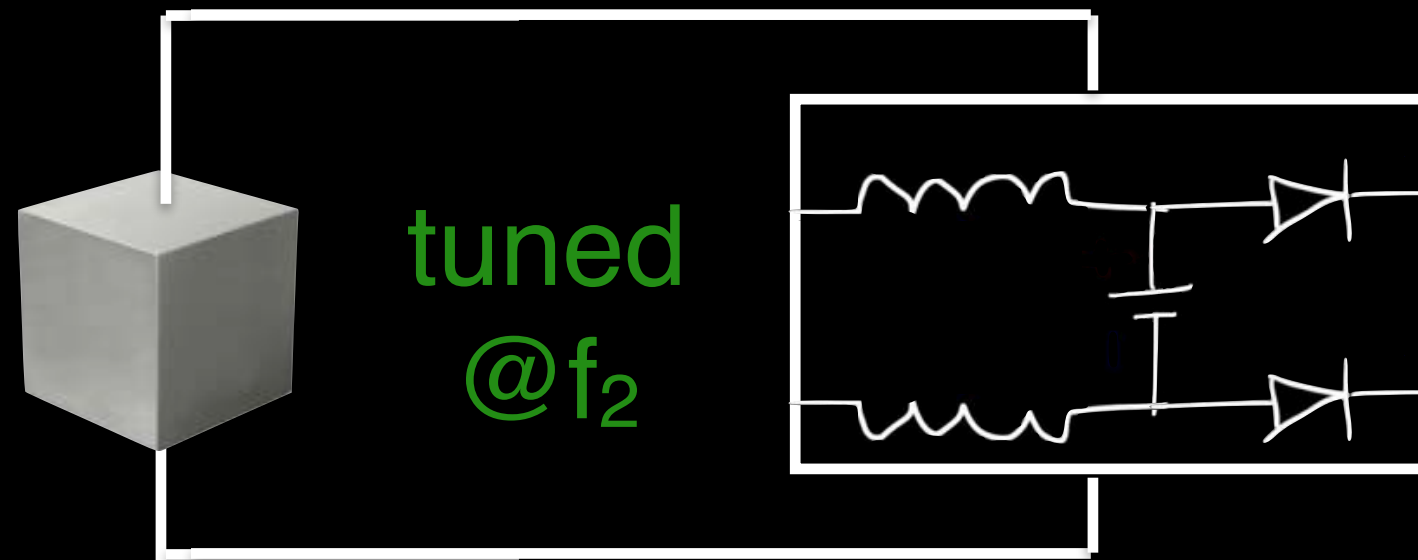
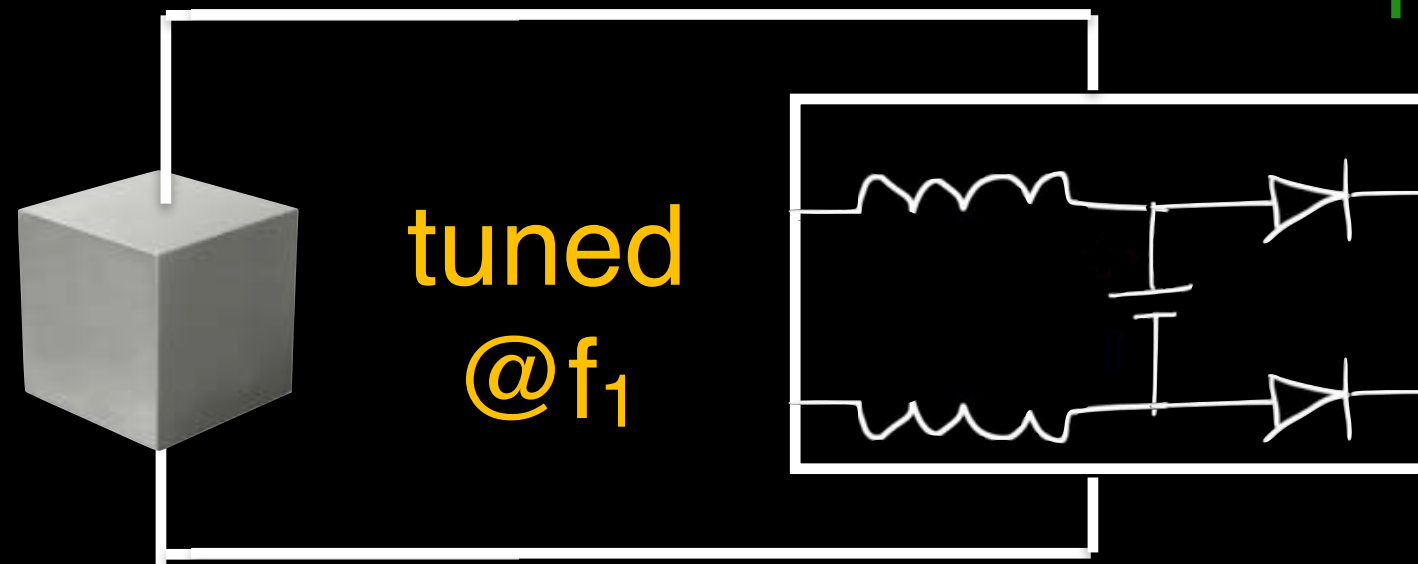


$$Z_{circuit}(f) = Z_{piezo}^*(f)$$

frequency dependent

→ Tune the circuit to a different frequency

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



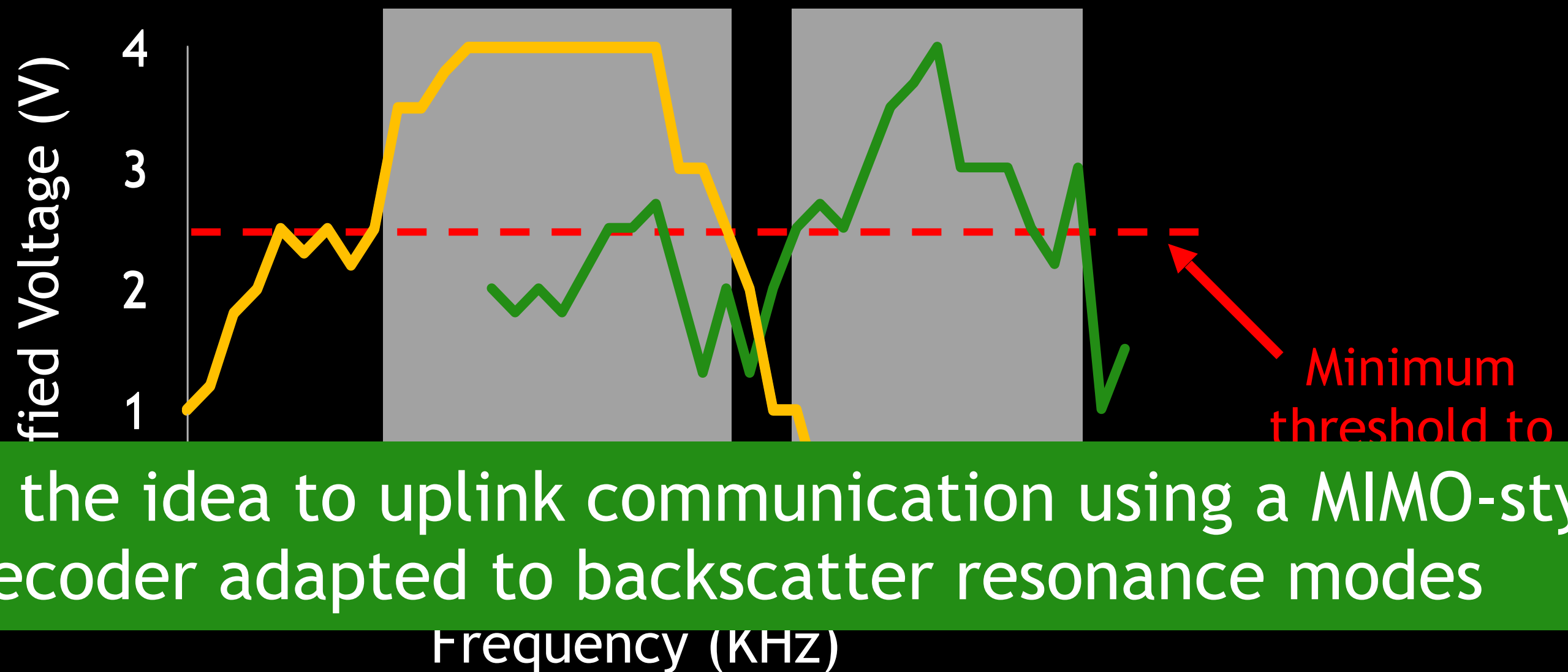
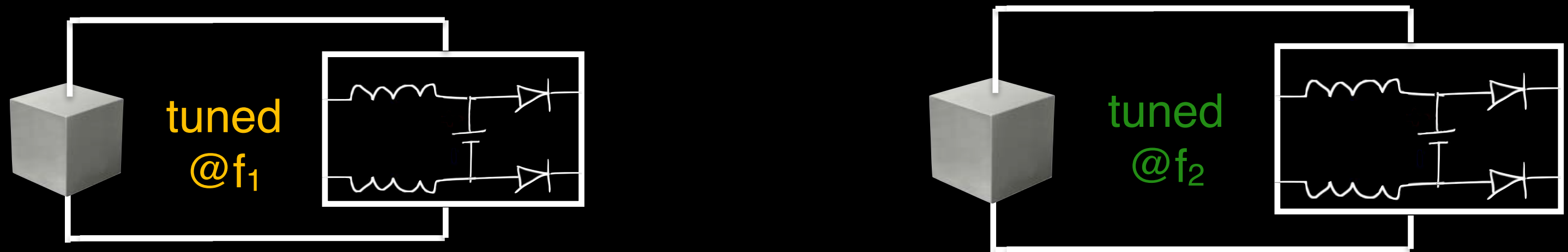
resonance frequency determined by interaction between piezo & the batteryless circuit

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

frequency dependent

→ Tune the circuit to a different frequency

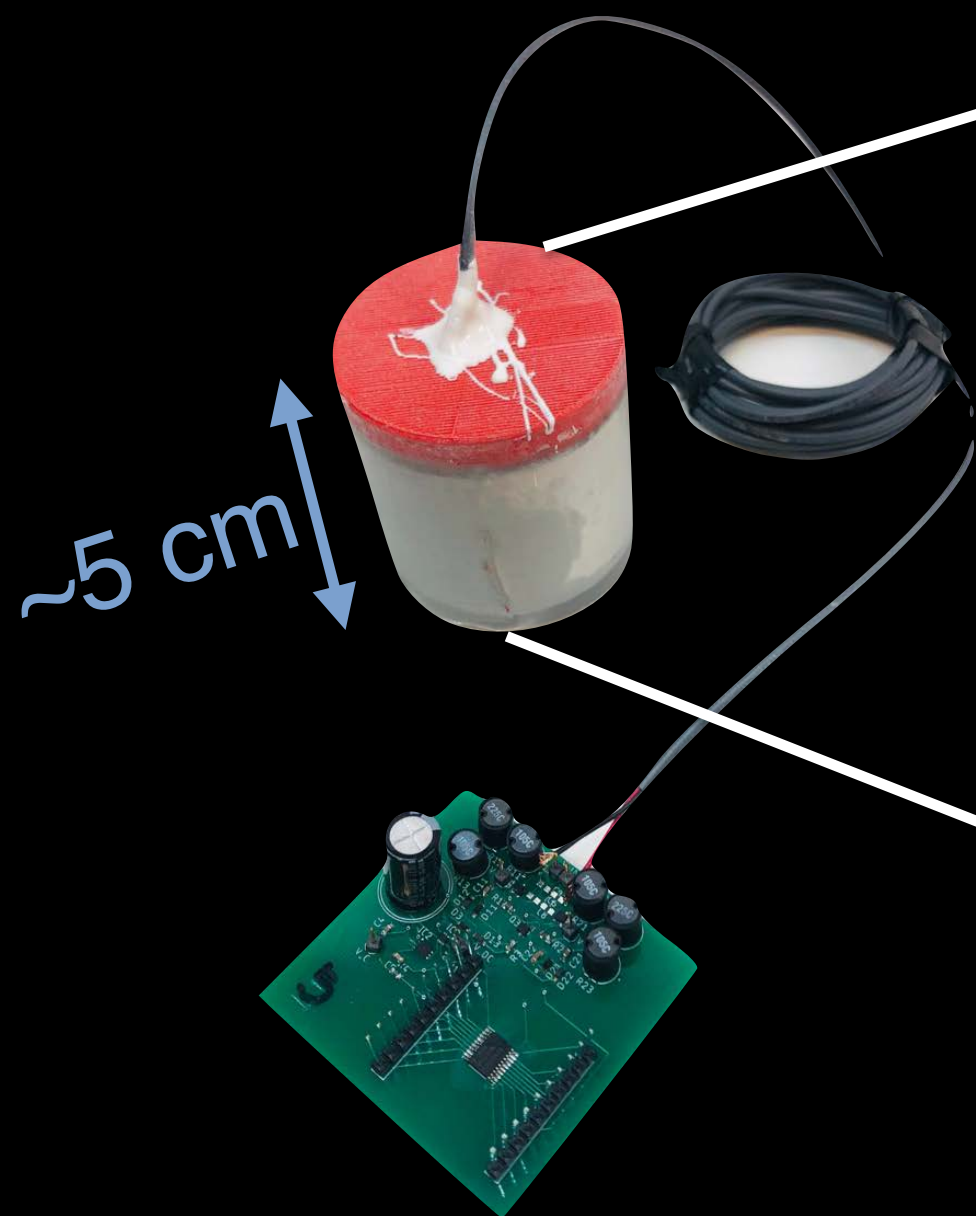
Solution Idea: Shift the resonance frequency *itself* to a different channel



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

Implementation

Batteryless PAB sensor

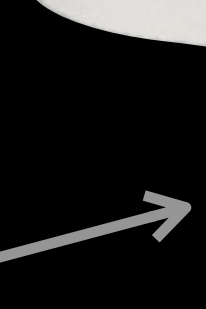


Exploded
transducer view



polyurethane
encapsulation

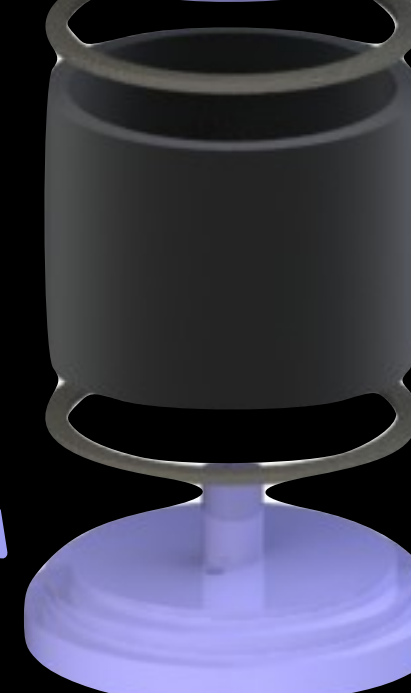
bolt



washers



3D printed
end-caps

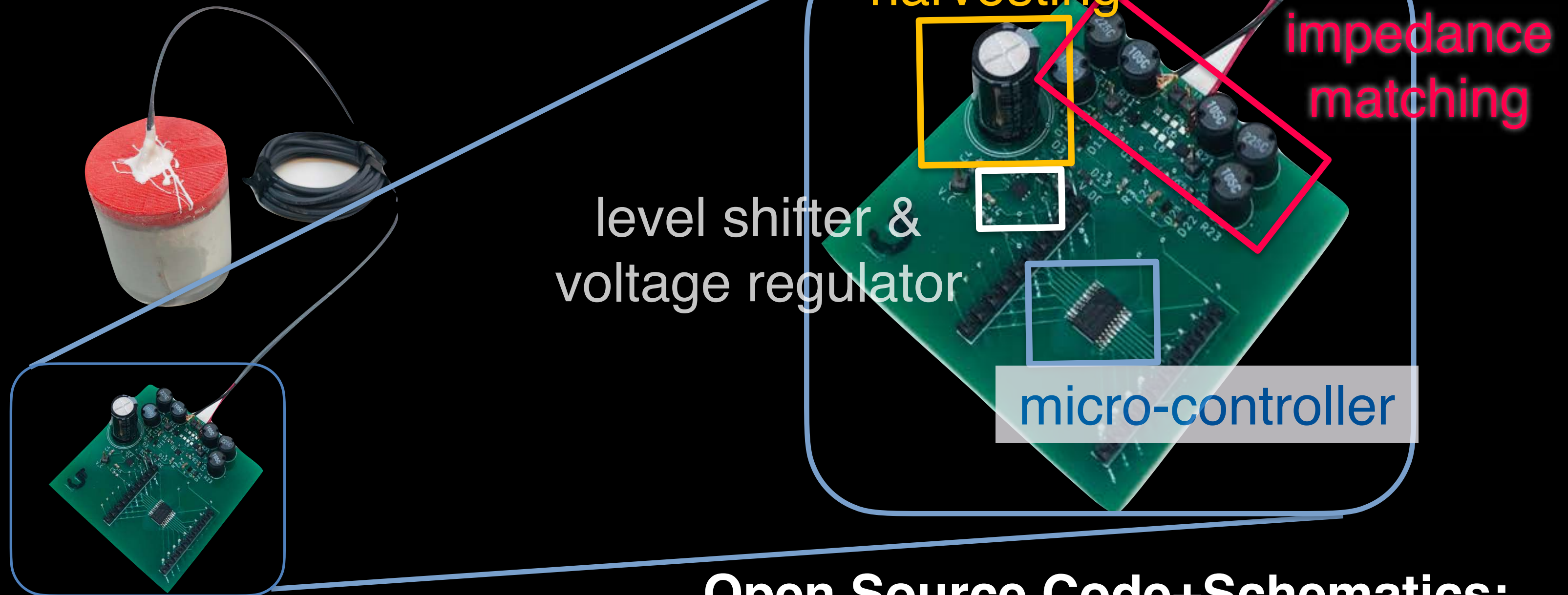


piezoceramic
cylinder



Implementation

Batteryless PAB sensor



Open Source Code+Schematics:

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

Implementation

Batteryless PAB sensor



Projector



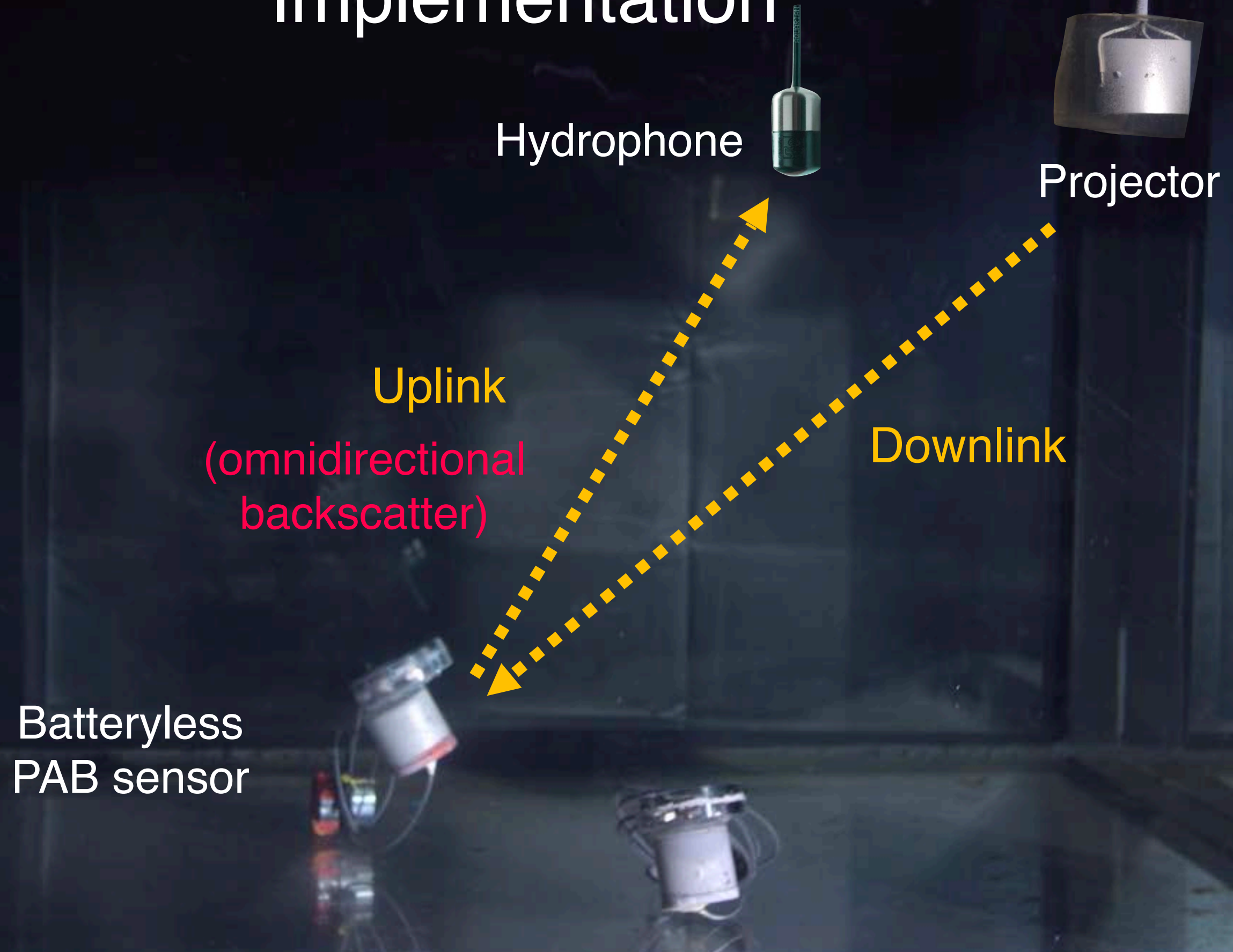
fabricated in-house

Hydrophone



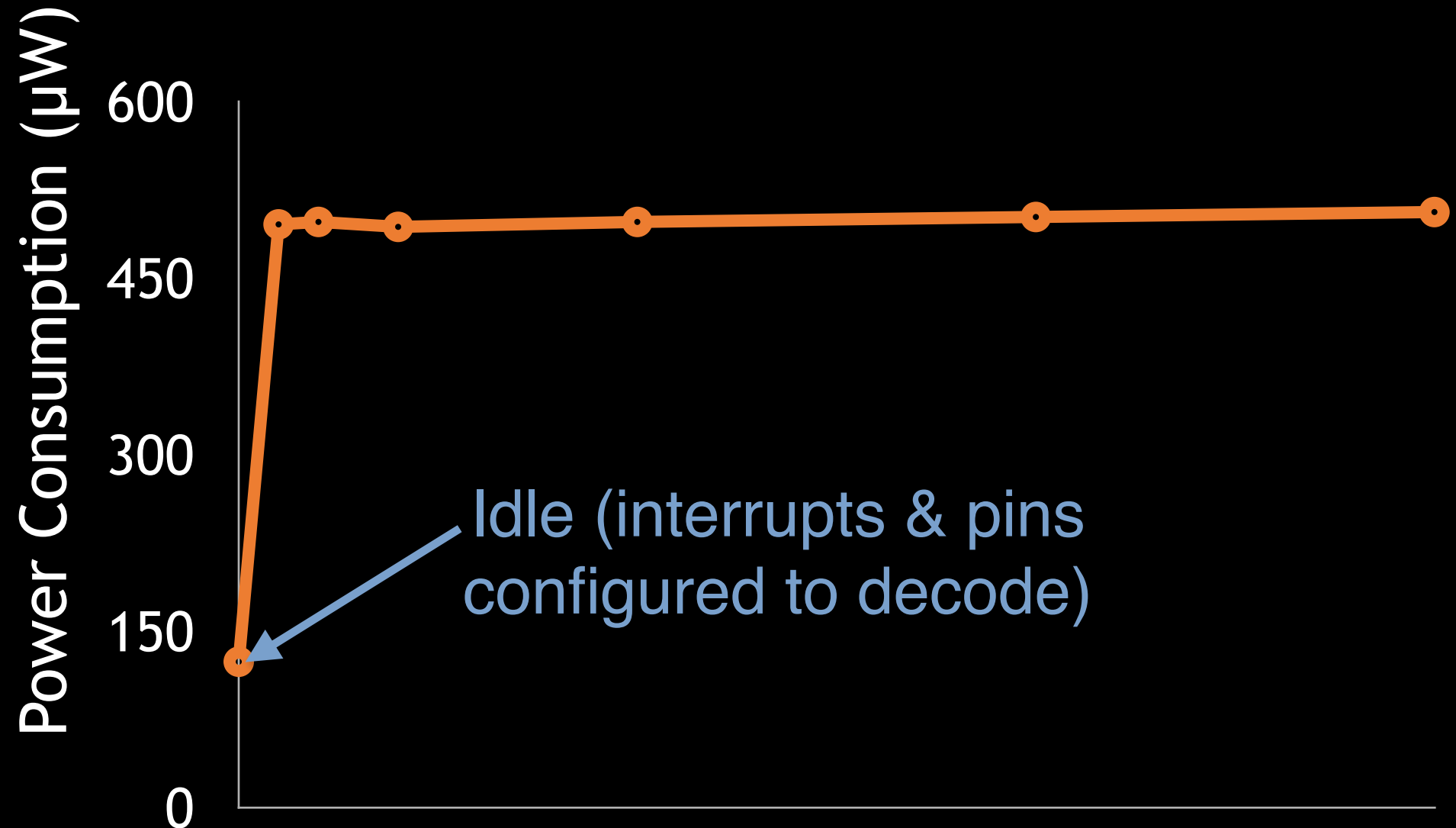
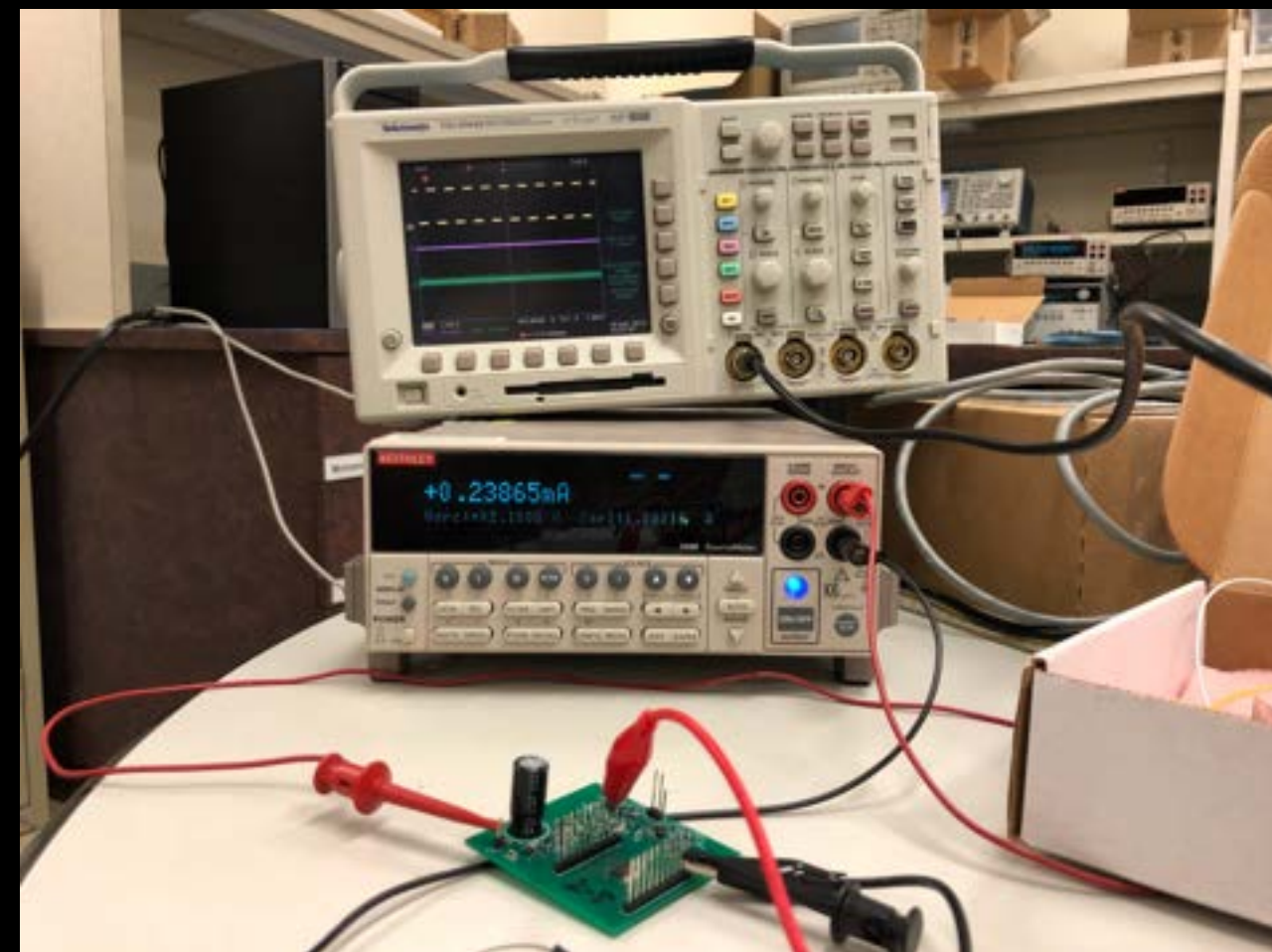
Aquarian H2A

Implementation



Power Consumption

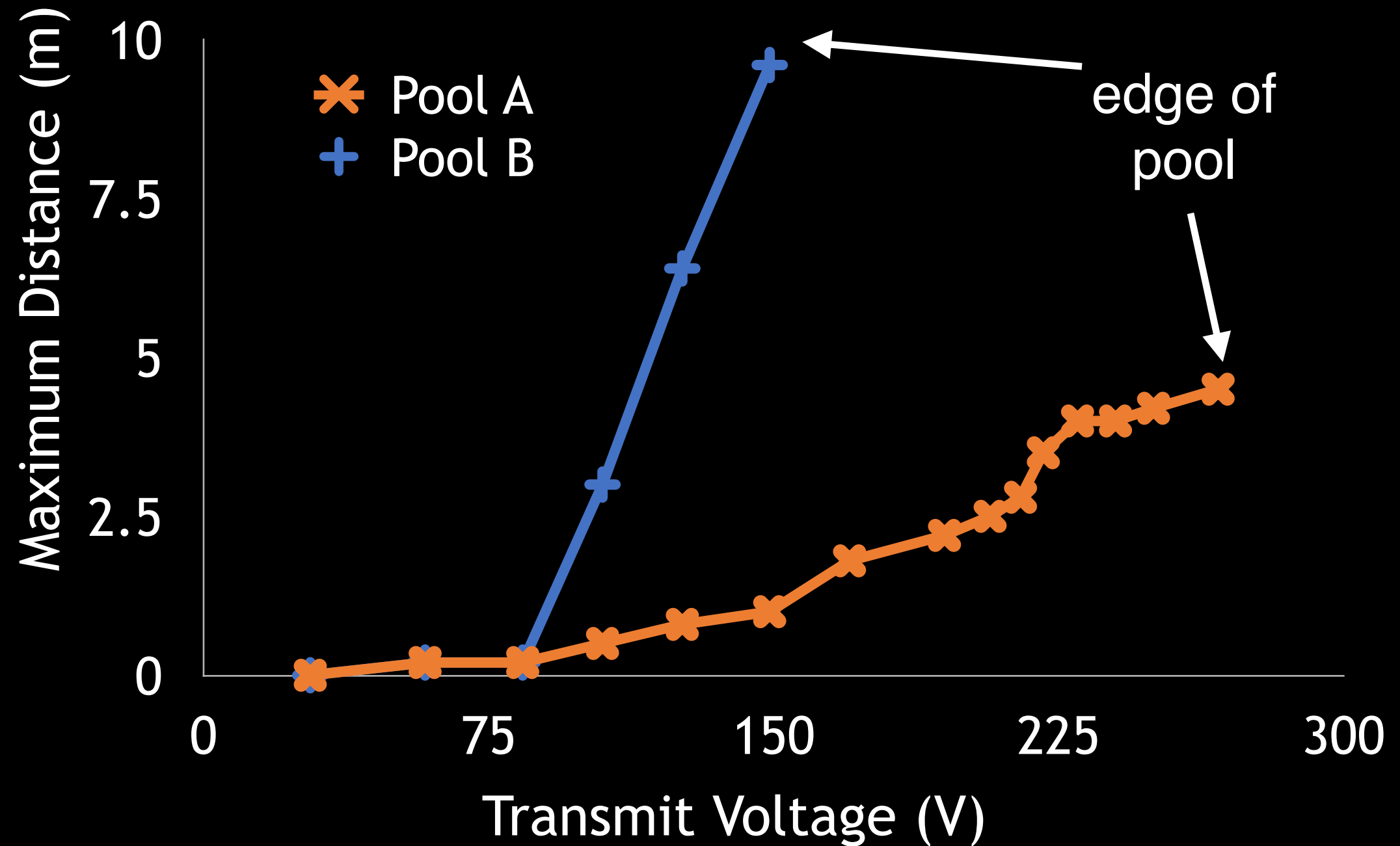
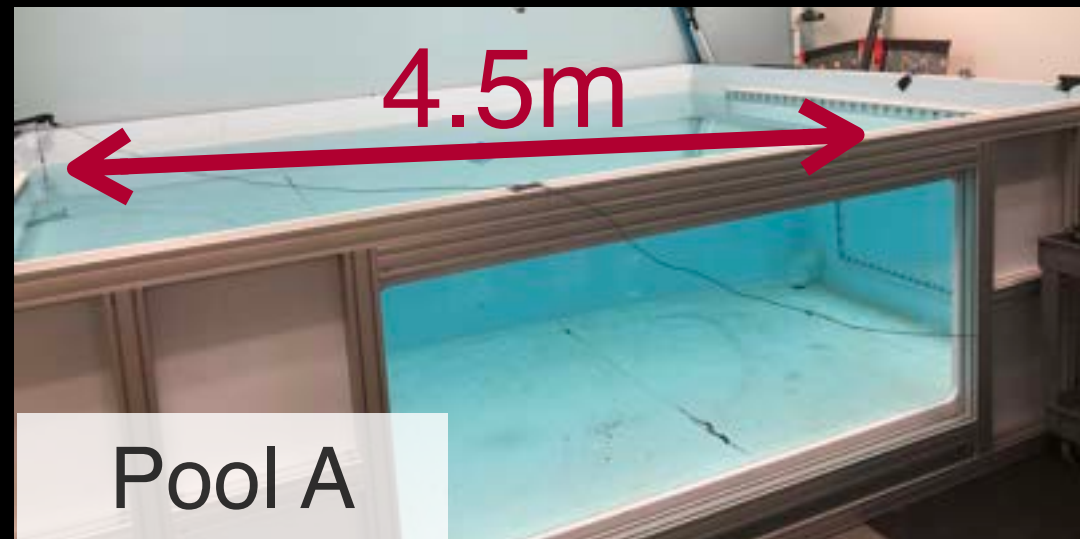
Empirically measured using Keithley 2400 source meter



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

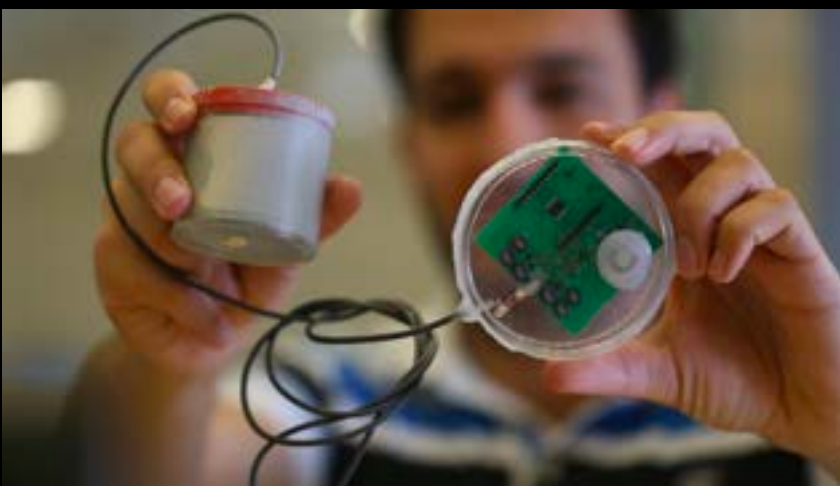
Power-up Range

Experiment: Vary power and distance to sensor



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

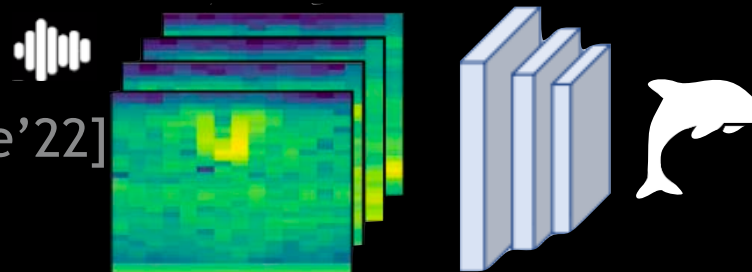
[ACM HotNets'20]



Battery-free GPS
(~10cm)

AI

[ACM HotMobile'22]



Bioacoustics
(animal/climate
sensing)

Imaging

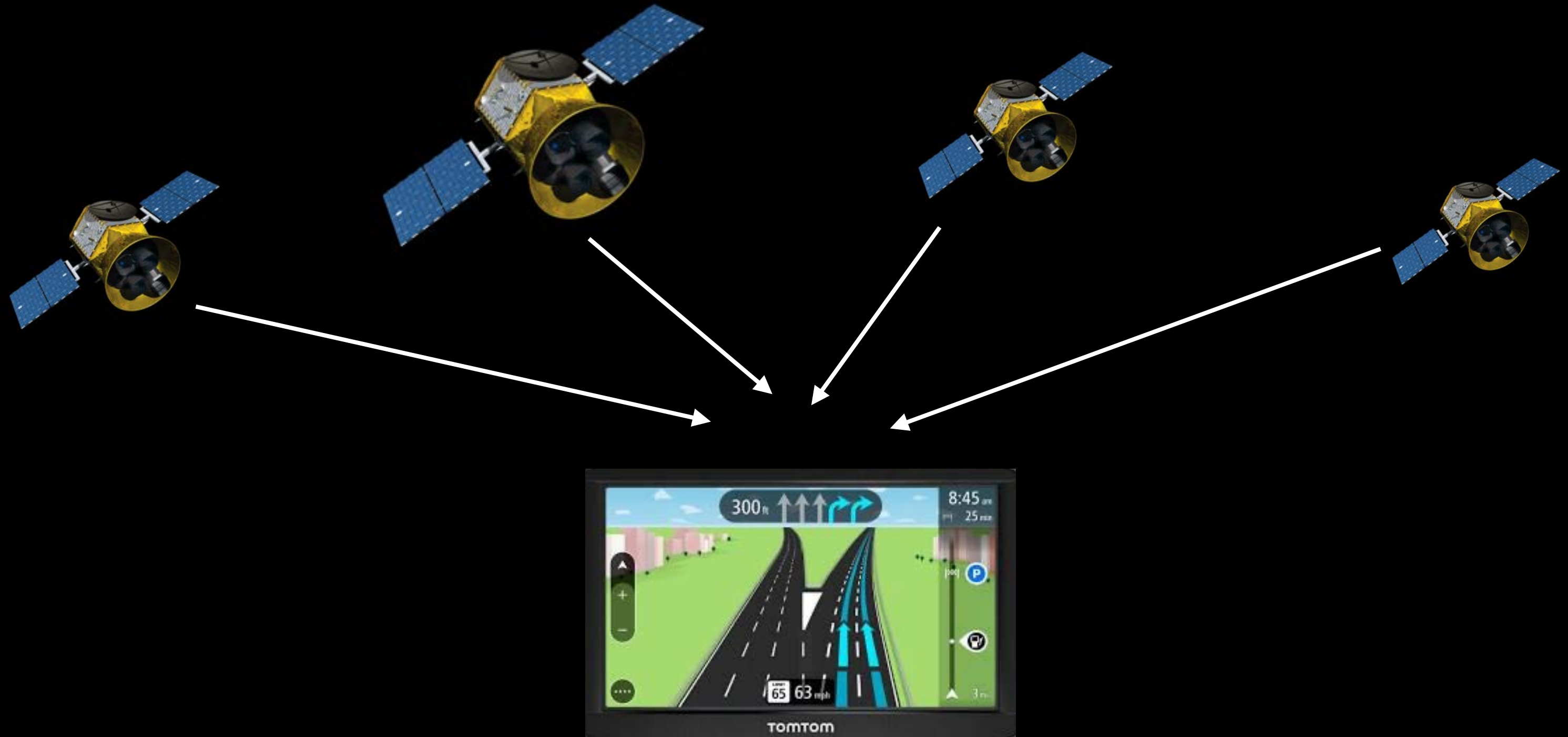


Monitoring for
climate, ecology,
defense

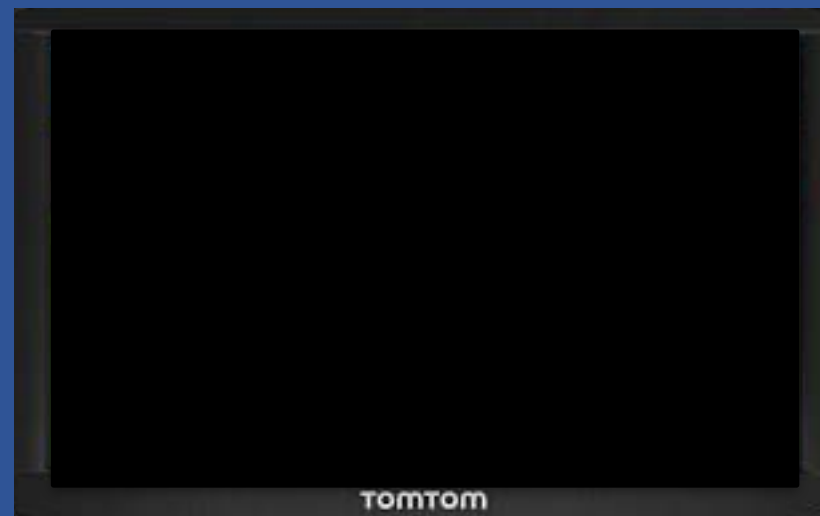
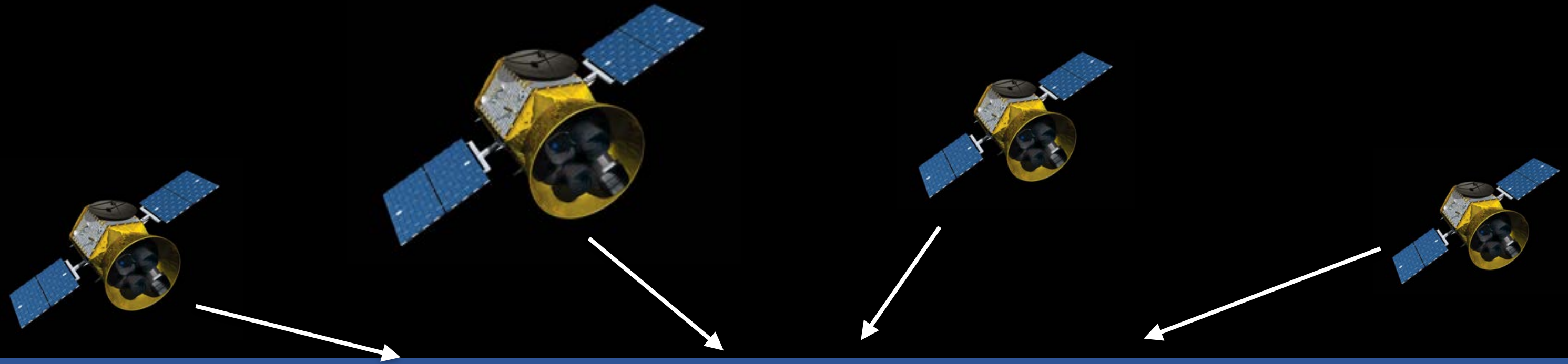
Can we enable battery-free underwater localization?



Global Positioning System (GPS)

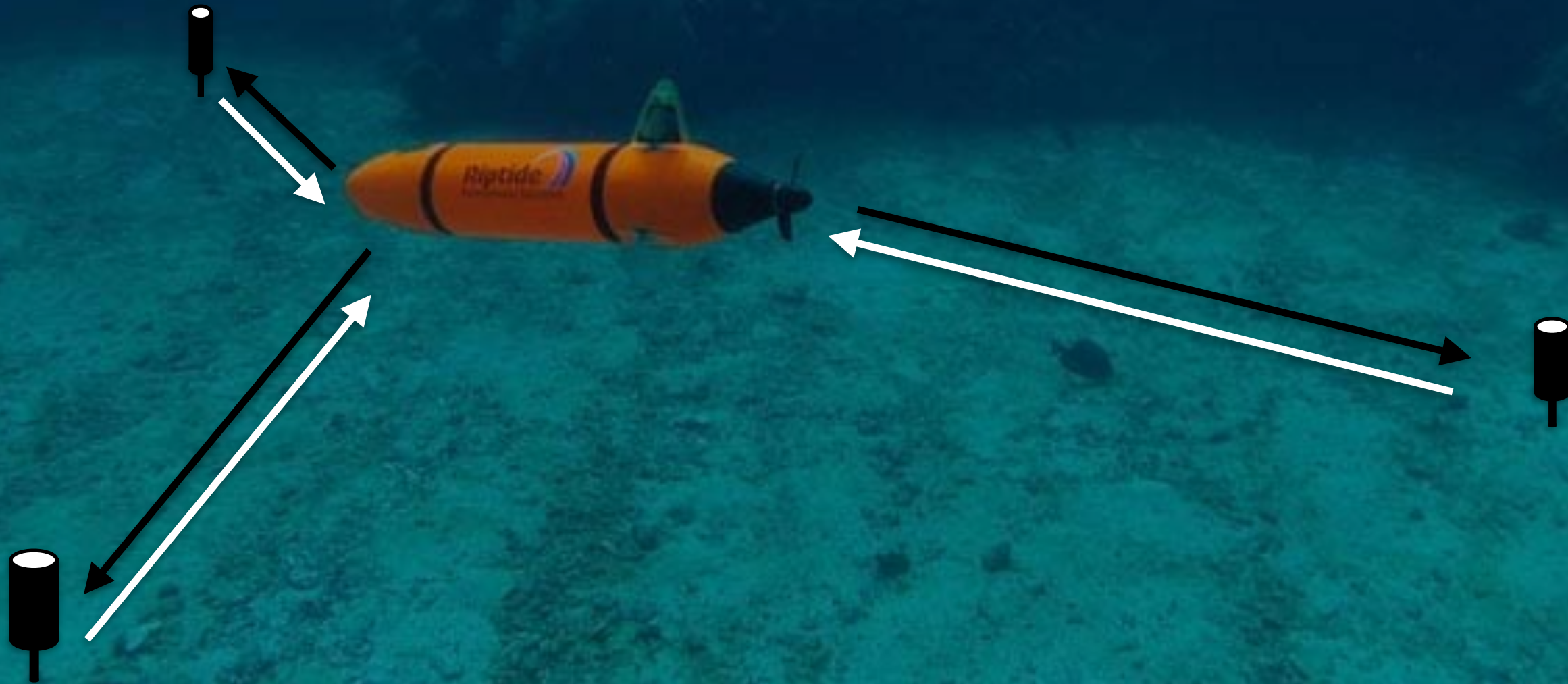


Global Positioning System (GPS)



Conventional Underwater Positioning

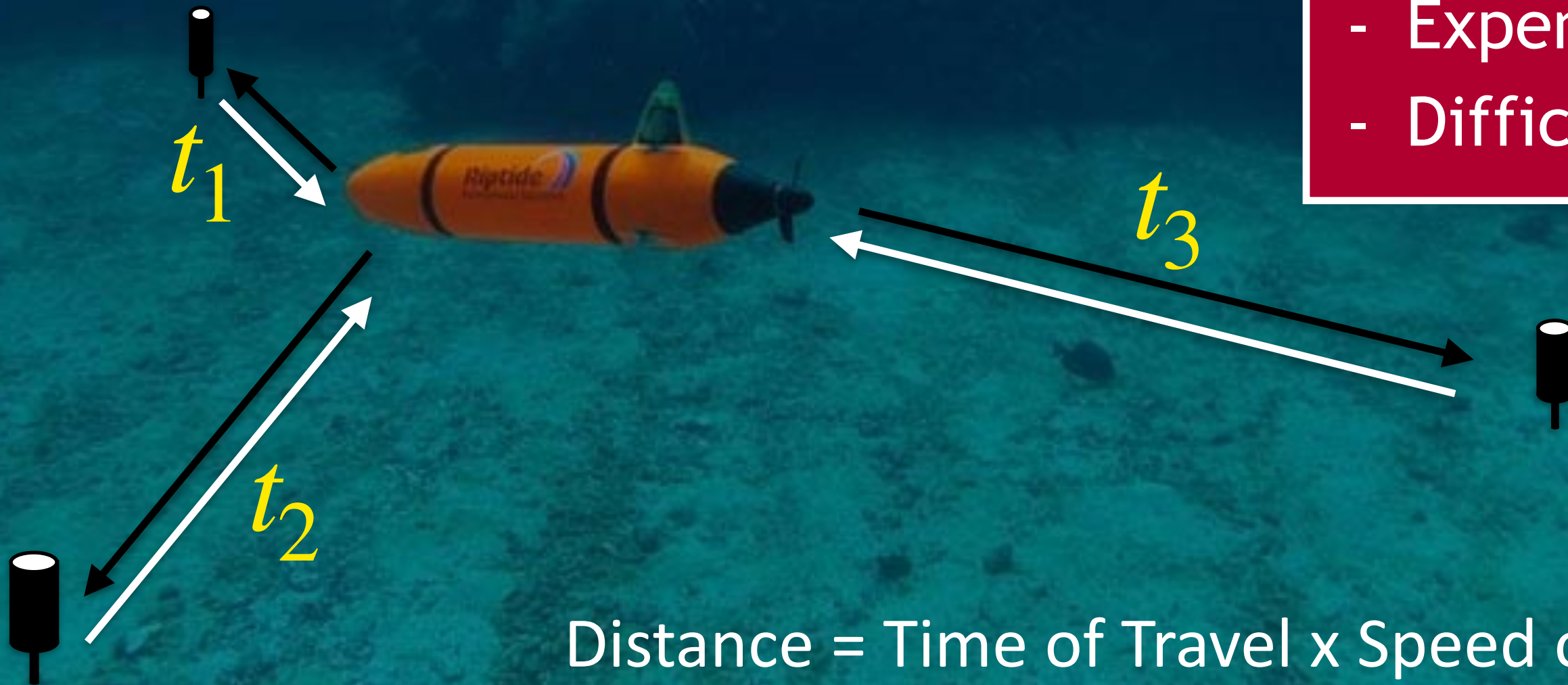
Works by measuring distances to deployed anchors



Conventional Underwater Positioning

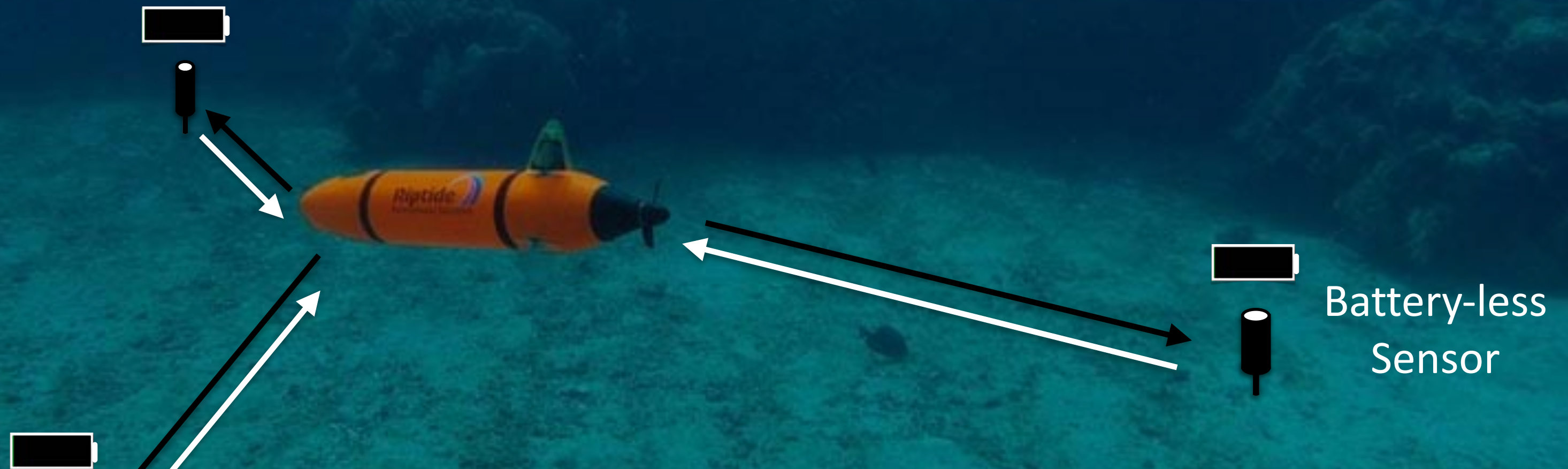
Works by measuring distances to deployed anchors

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



Distance = Time of Travel x Speed of Sound

Batteryless Underwater Positioning



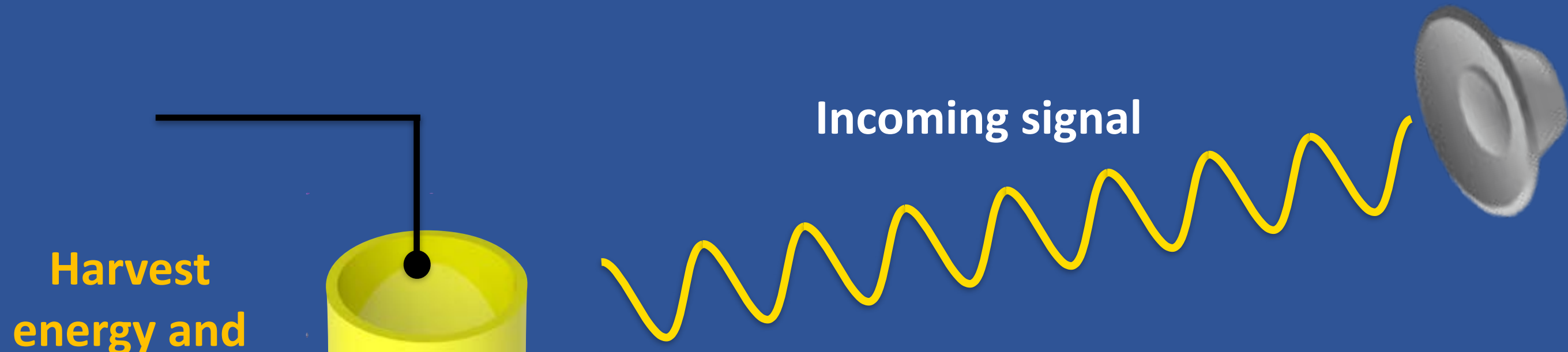
Random wake-up lag makes it extremely hard to localize

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

Key Idea: Underwater positioning using backscatter sensor

Key Idea: Underwater positioning using backscatter sensor

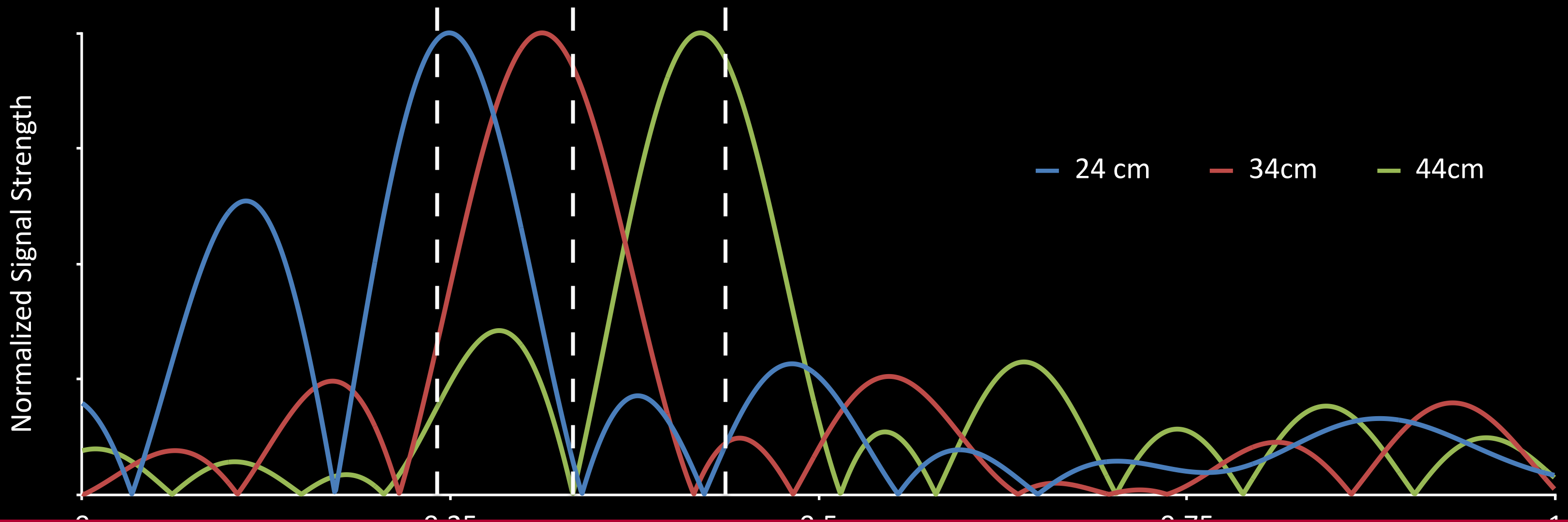
Measure “phase” instead of measuring time



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



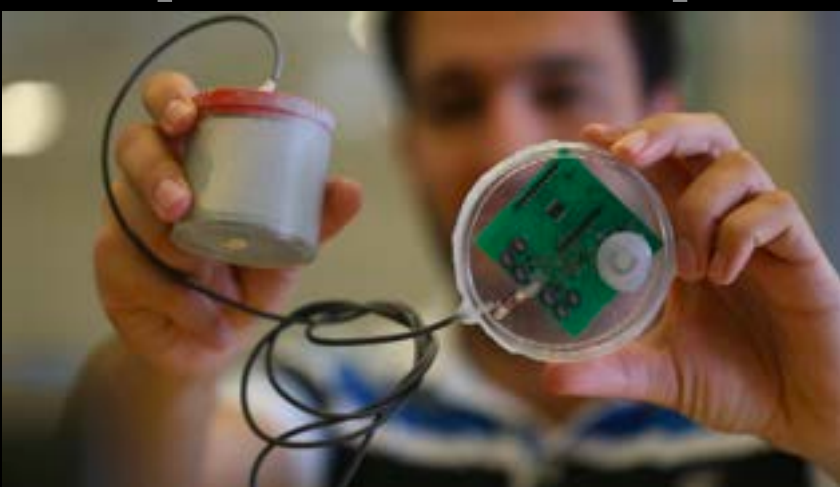
Early results show localization accuracy of ~10 cm

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

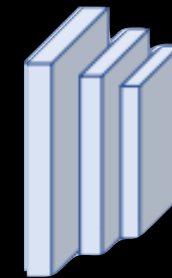
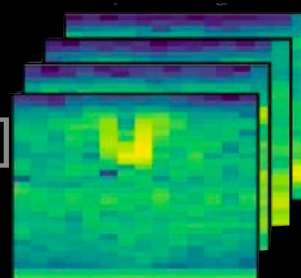
[ACM HotNets'20]



Battery-free GPS
(~10cm)

AI

[ACM HotMobile'22]



Bioacoustics
(animal/climate
sensing)

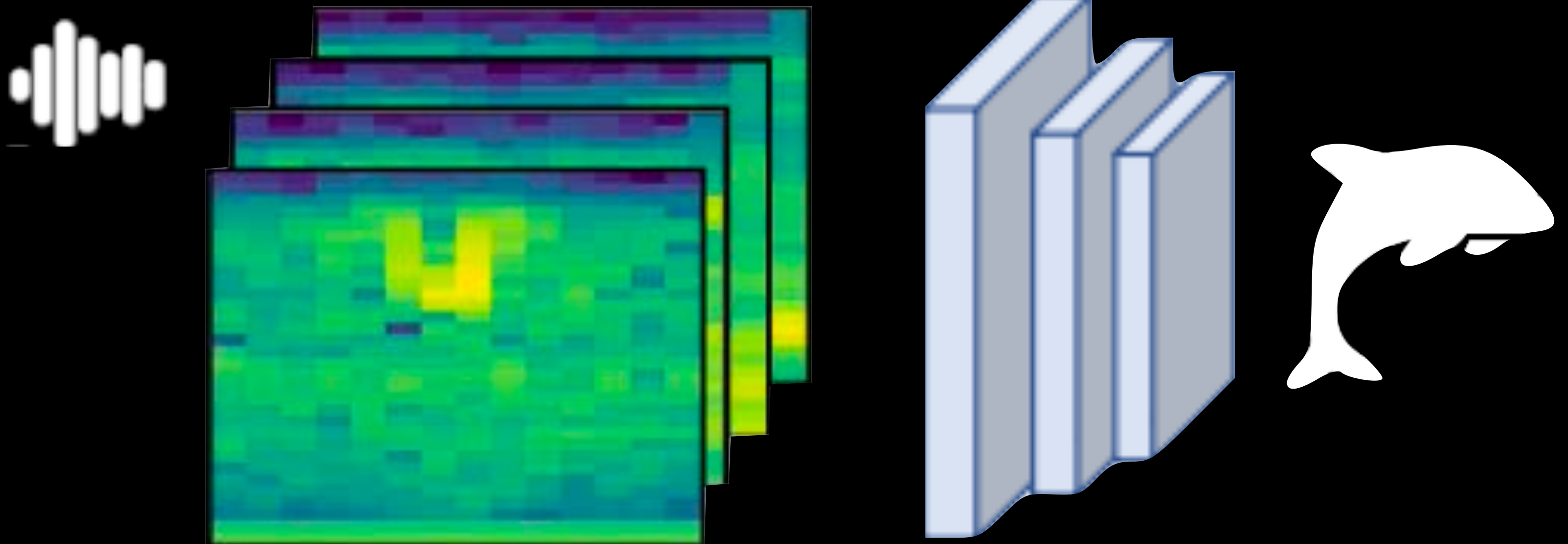
Imaging



Monitoring for
climate, ecology,
defense

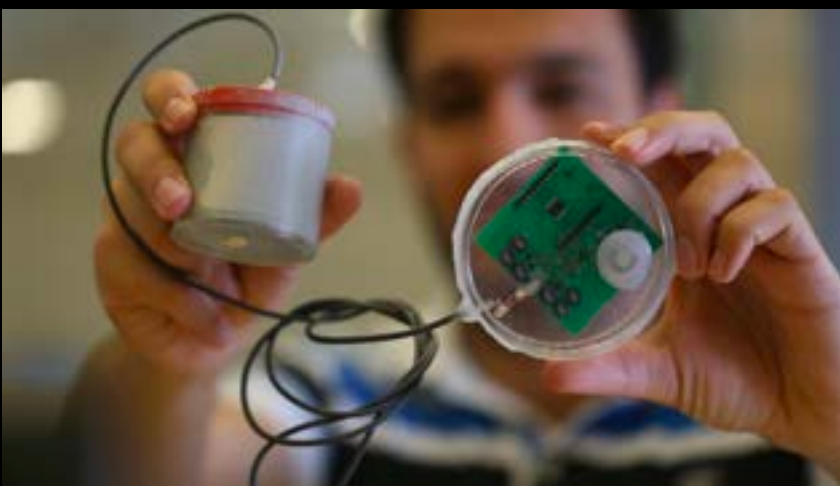
Can we enable battery-free underwater AI?

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



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

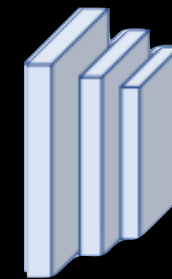
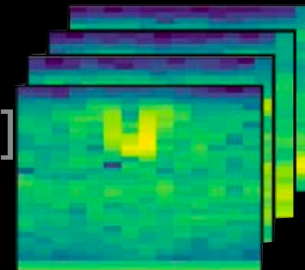
[ACM HotNets'20]



Battery-free GPS
(~10cm)

AI

[ACM HotMobile'22]



Bioacoustics
(animal/climate
sensing)

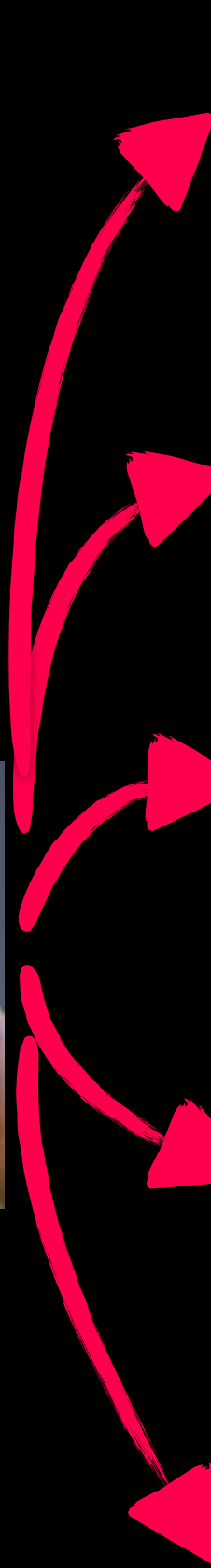
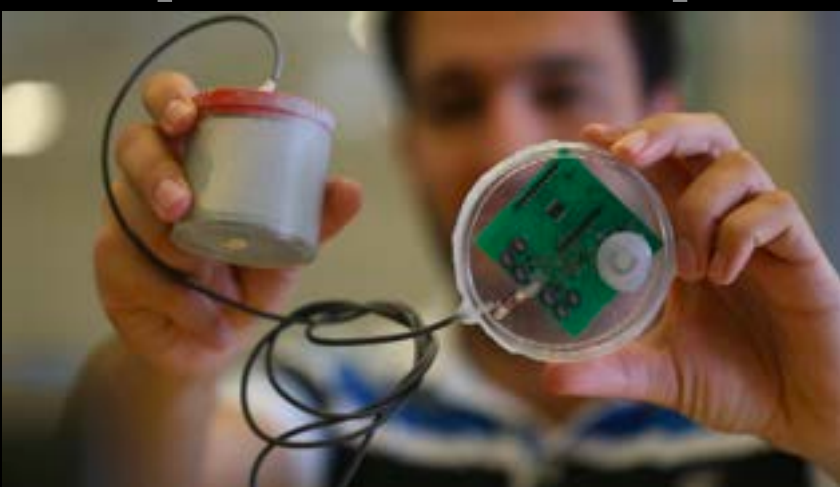
Imaging



Monitoring for
climate, ecology,
defense

Batteryless Ocean Sensing

[ACM SIGCOMM'19]

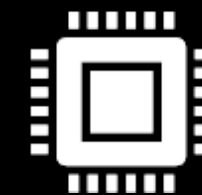


Fabrication

[ACM SIGCOMM'20]



nanoWatt power levels



Communication

[MITS/IEEE OCEANS'20]



Toward km-scale comms

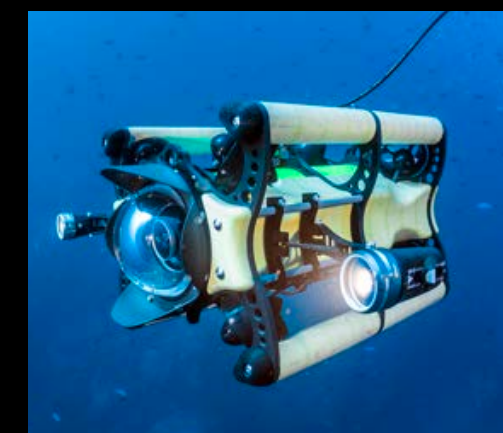


Localization

[ACM HotNets'20]

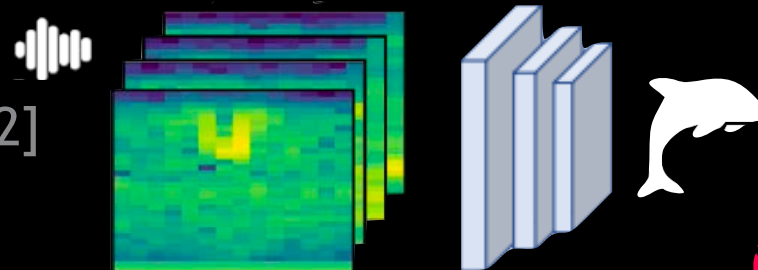


Robotic exploration



AI

[ACM HotMobile'22]



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

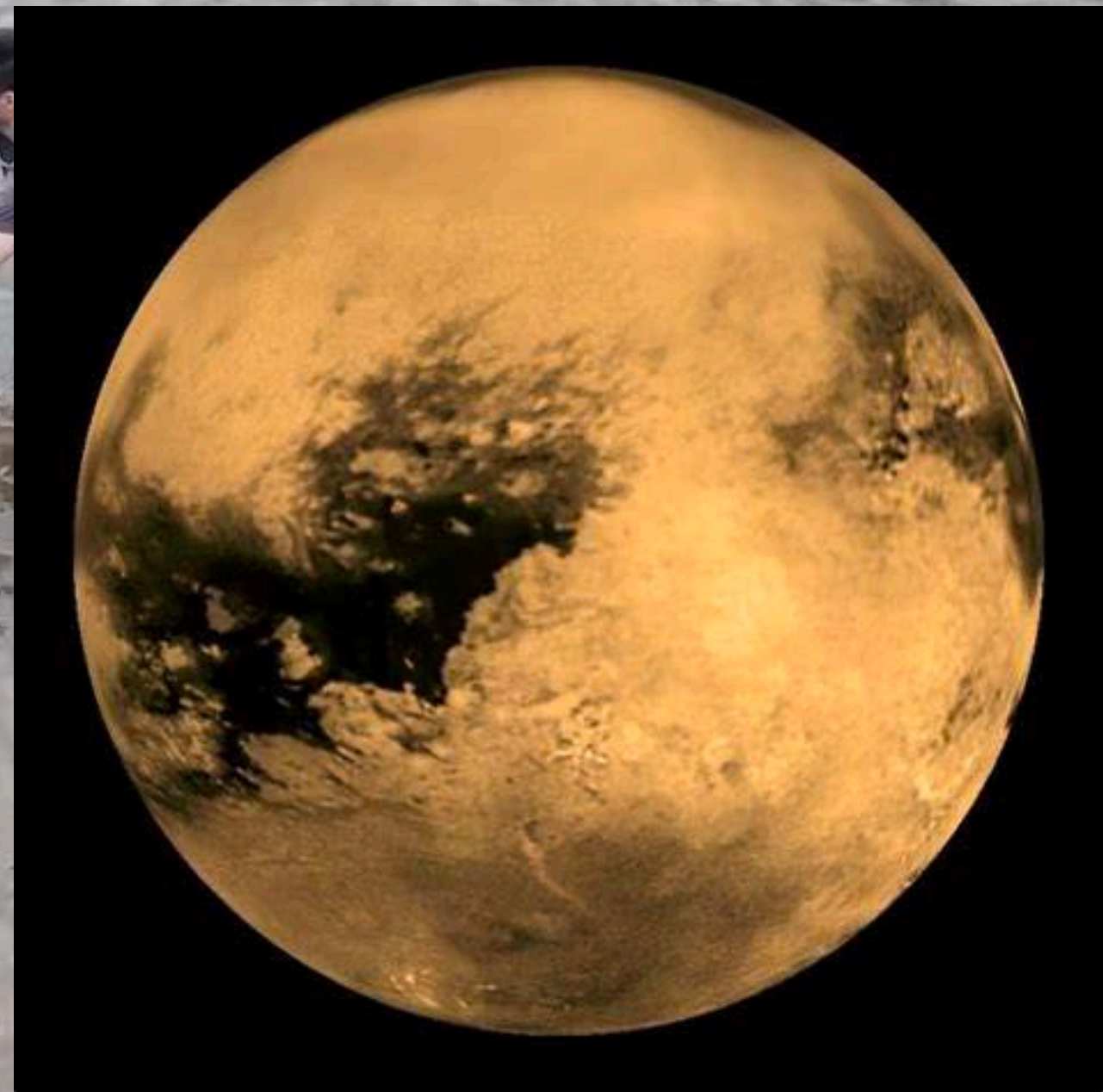
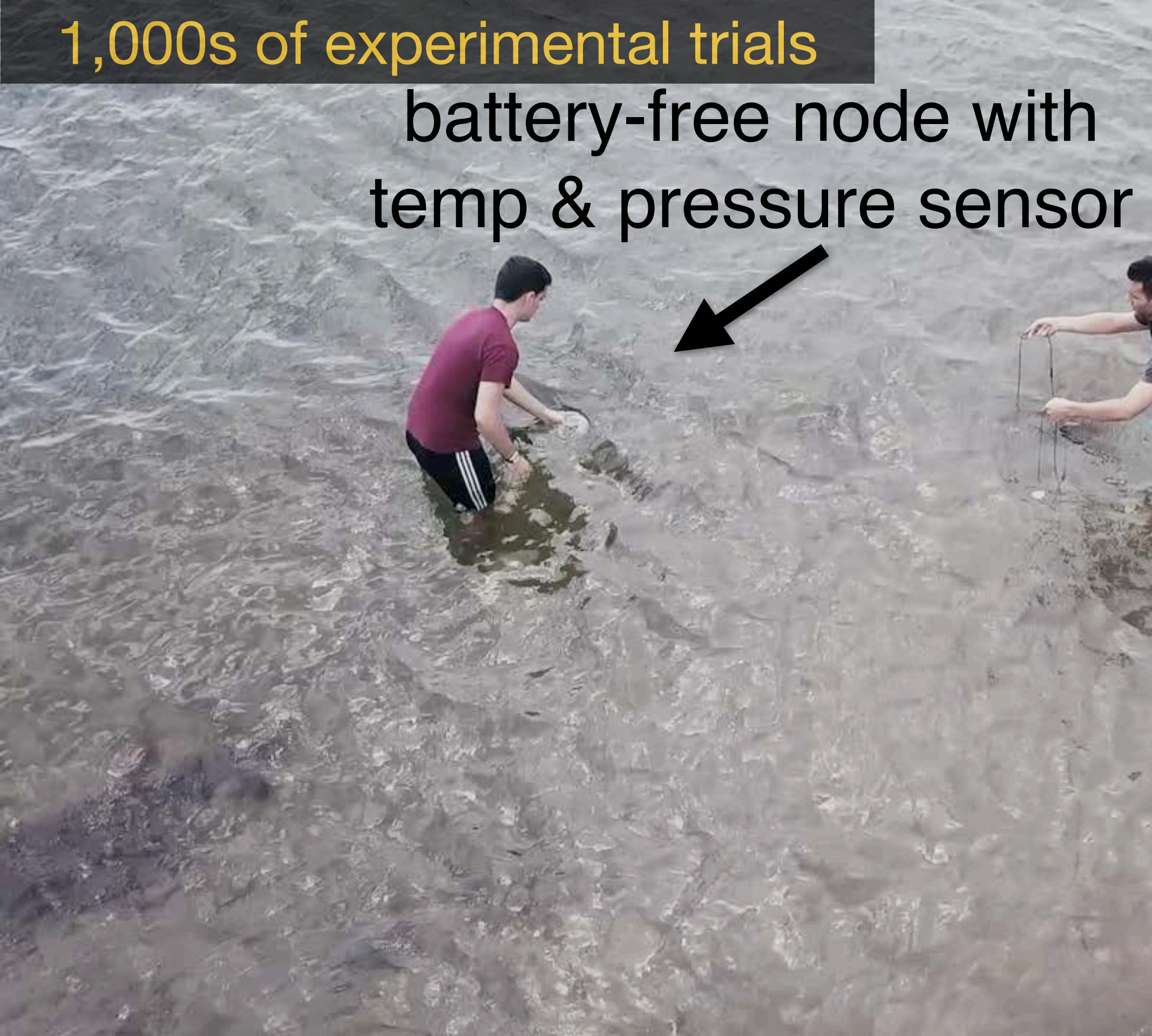
Imaging



1,000s of experimental trials

battery-free node with
temp & pressure sensor

Extraterrestrial
oceans (e.g., Titan)



Summary of this Lecture

- Motivation of Ocean IoT & Existing Systems
- Basic Principles of Underwater backscatter
 - Networking
 - Localization
 - Other applications: Imaging, AI, Robotics, Defense, Space
 - Open problems