6.808 Mobile and Sensor Computing

aka IoT Systems

http://6808.github.io

Lecture #15:

Ocean IoT

Course Staff

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Announcements

1- Grades out

2- Lab 4 due March 30

3- PSet 2 due April 4

4- Midterm April 11

Taking the Internet of Things to the Ocean World

30 bn

IoT Devices

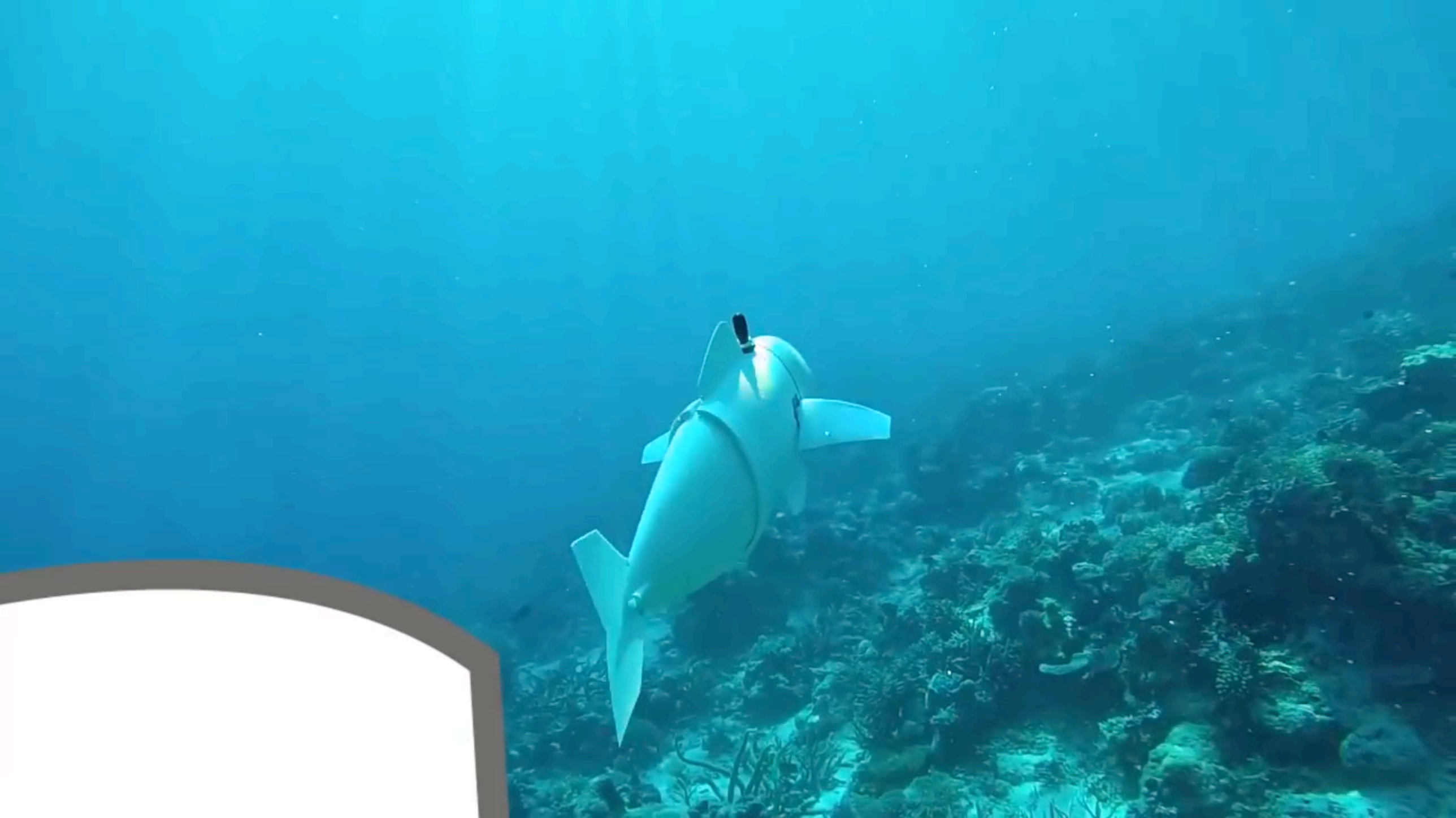
Less than 1 in a million of IoT is in the ocean, even it they covers >70% of the planet and has significant needs for food, climate, etc.

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

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



Rest of this lecture: Underwater Backscatter

- 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)

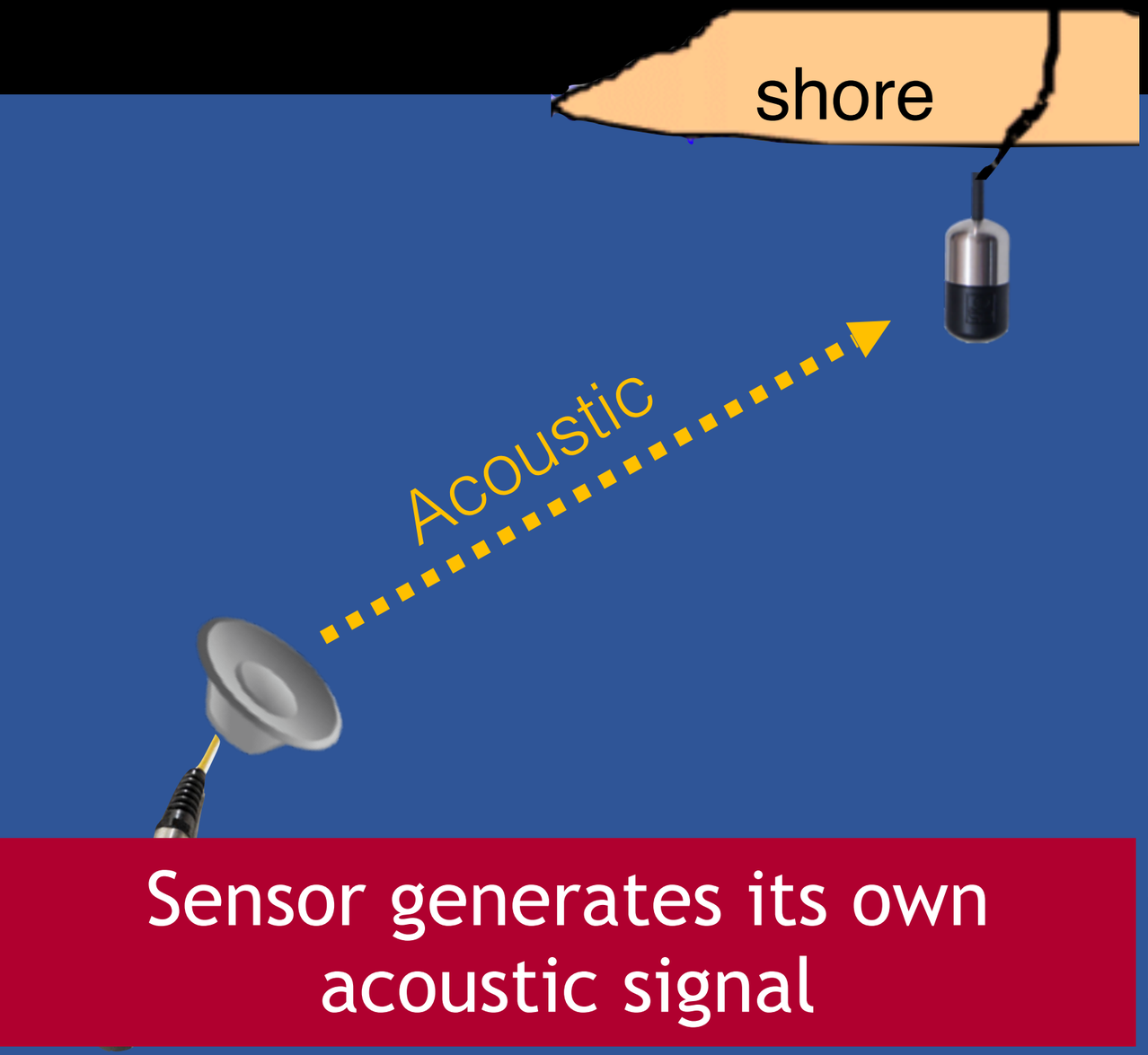
State-of-the-art sensors for tracking marine animals only last for few hours or days

[Animal Biotelemetry'15, Scientific Reports'17]

Technology that Enables Underwater Backscatter (Batteryless) Networking

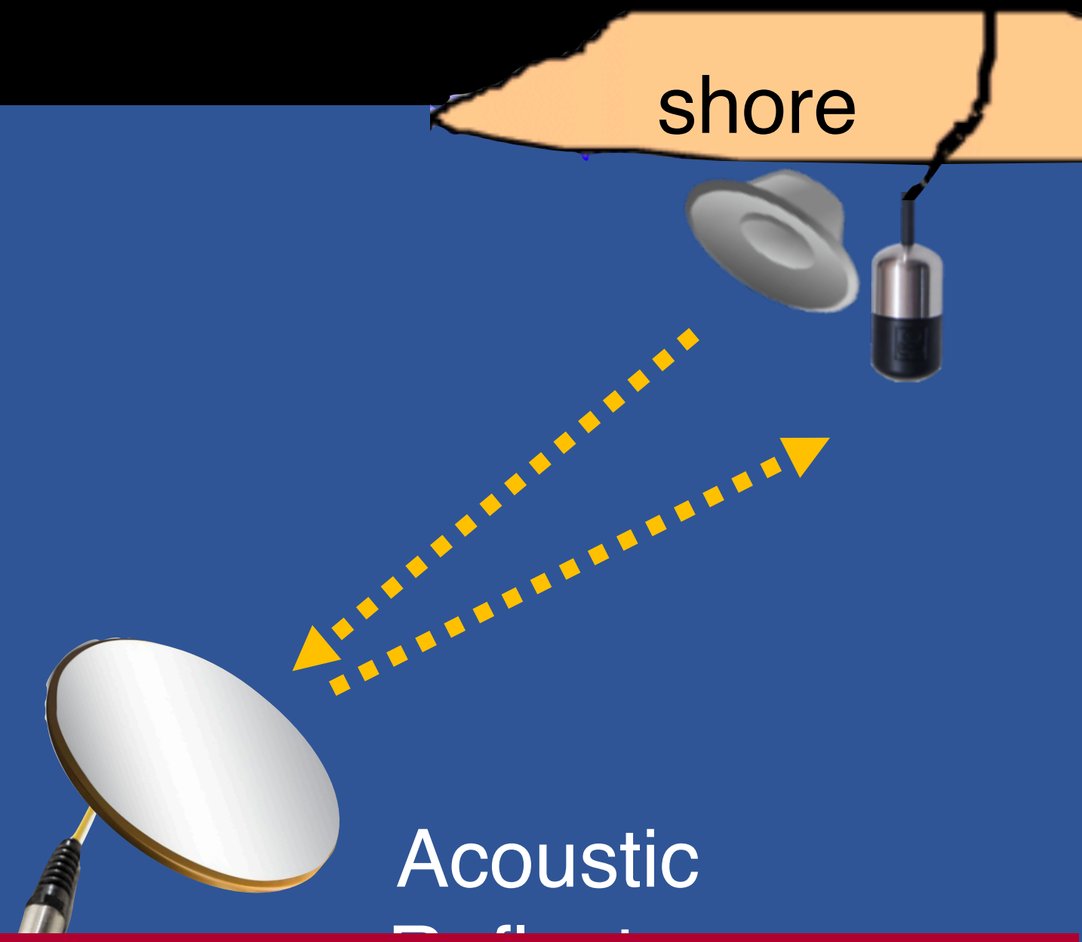
PAB (ACM SIGCOMM'19)

Traditional Approach



Sensor generates its own acoustic signal

Our Technology

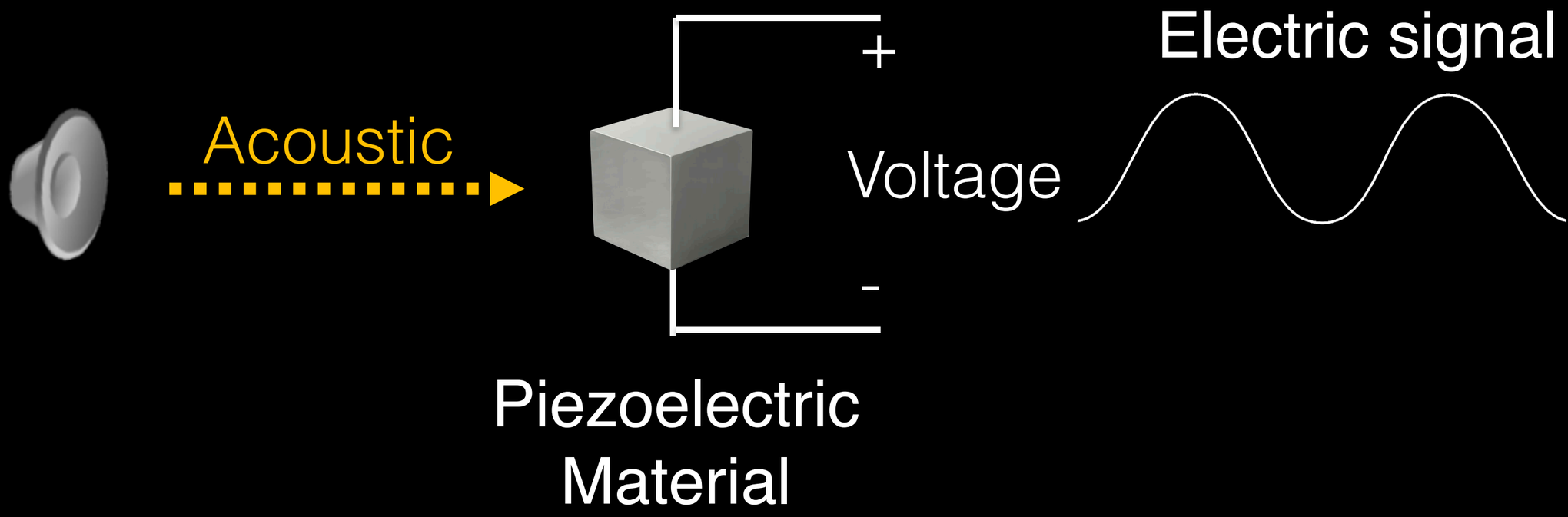


Sensor reflects an existing acoustic signal

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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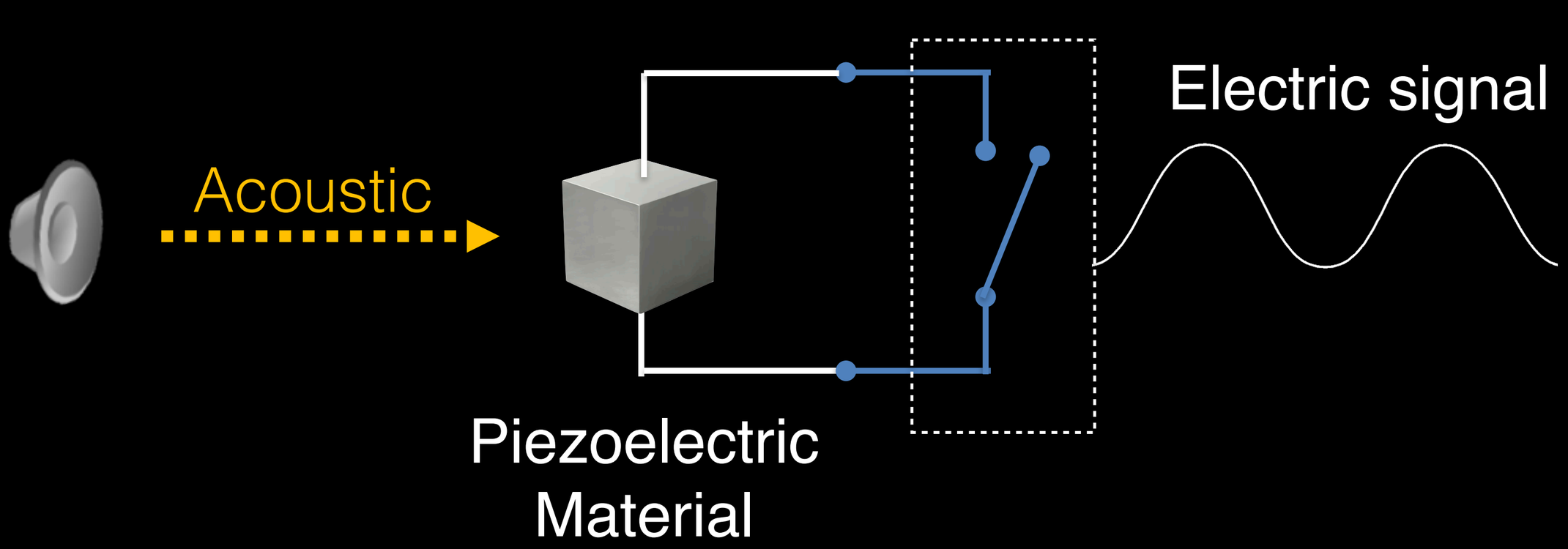

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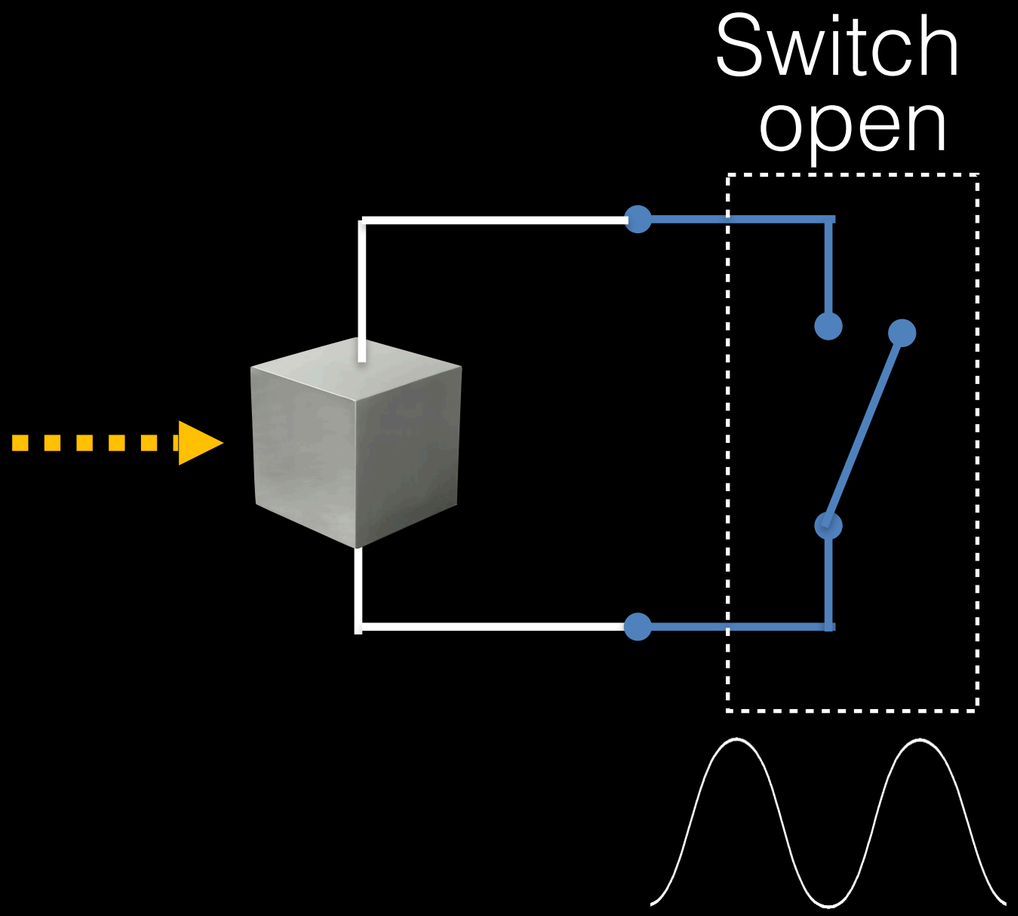
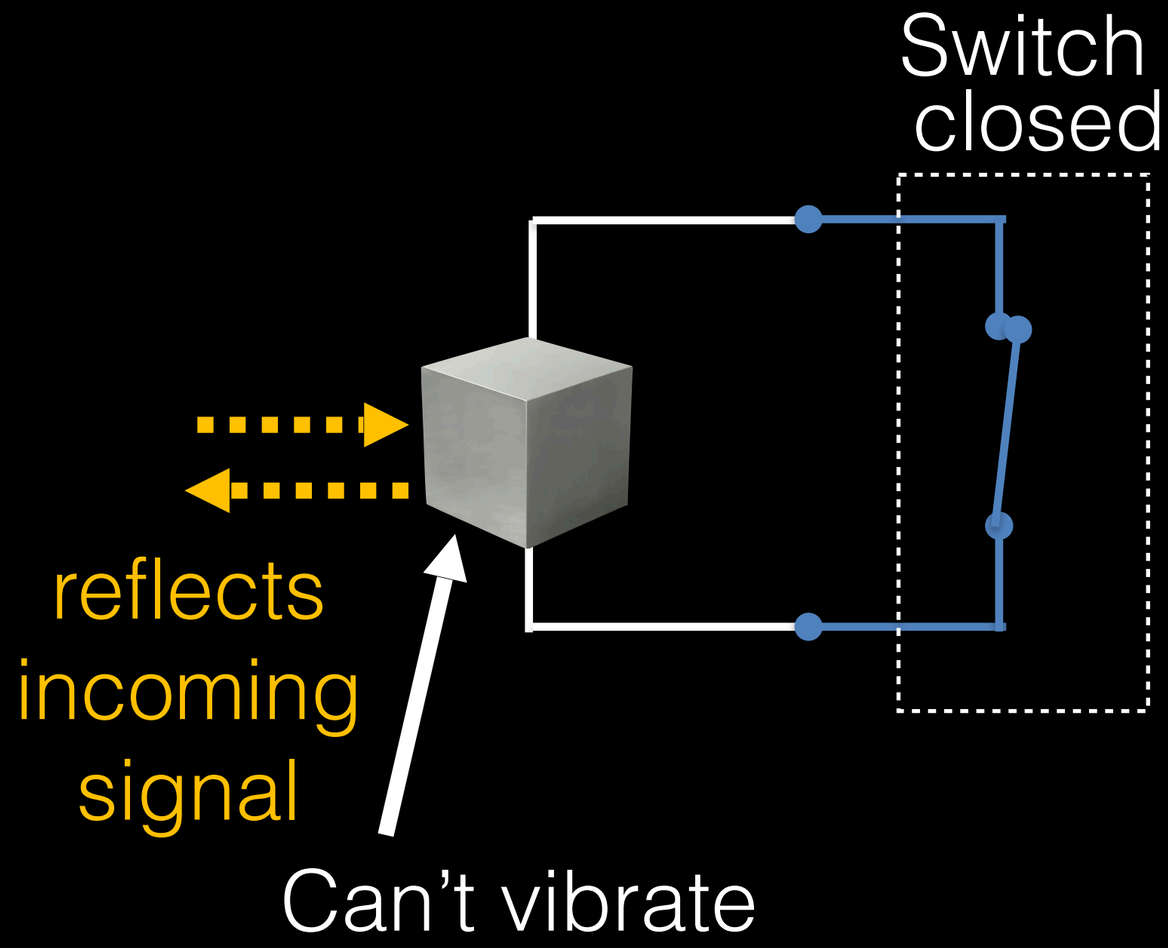
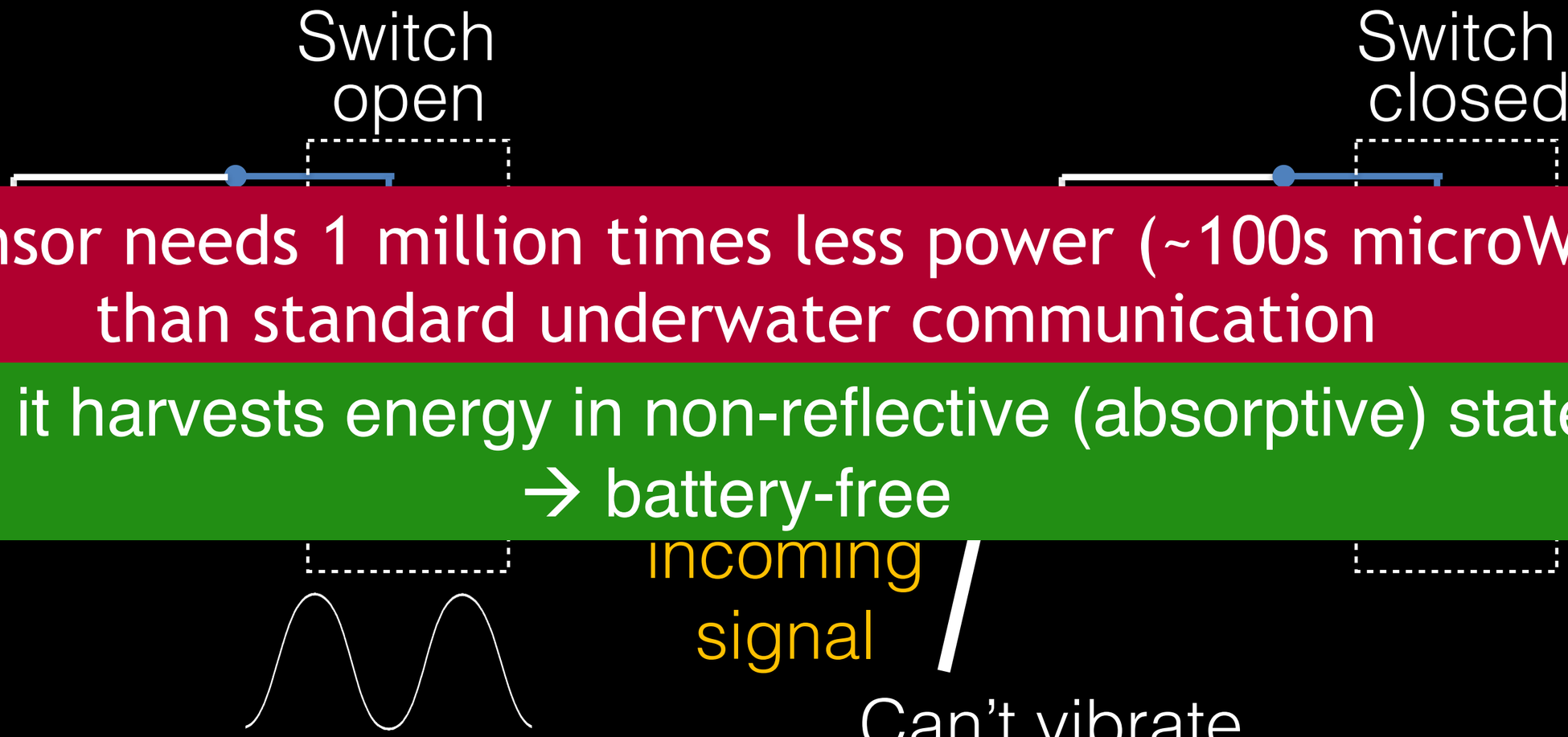


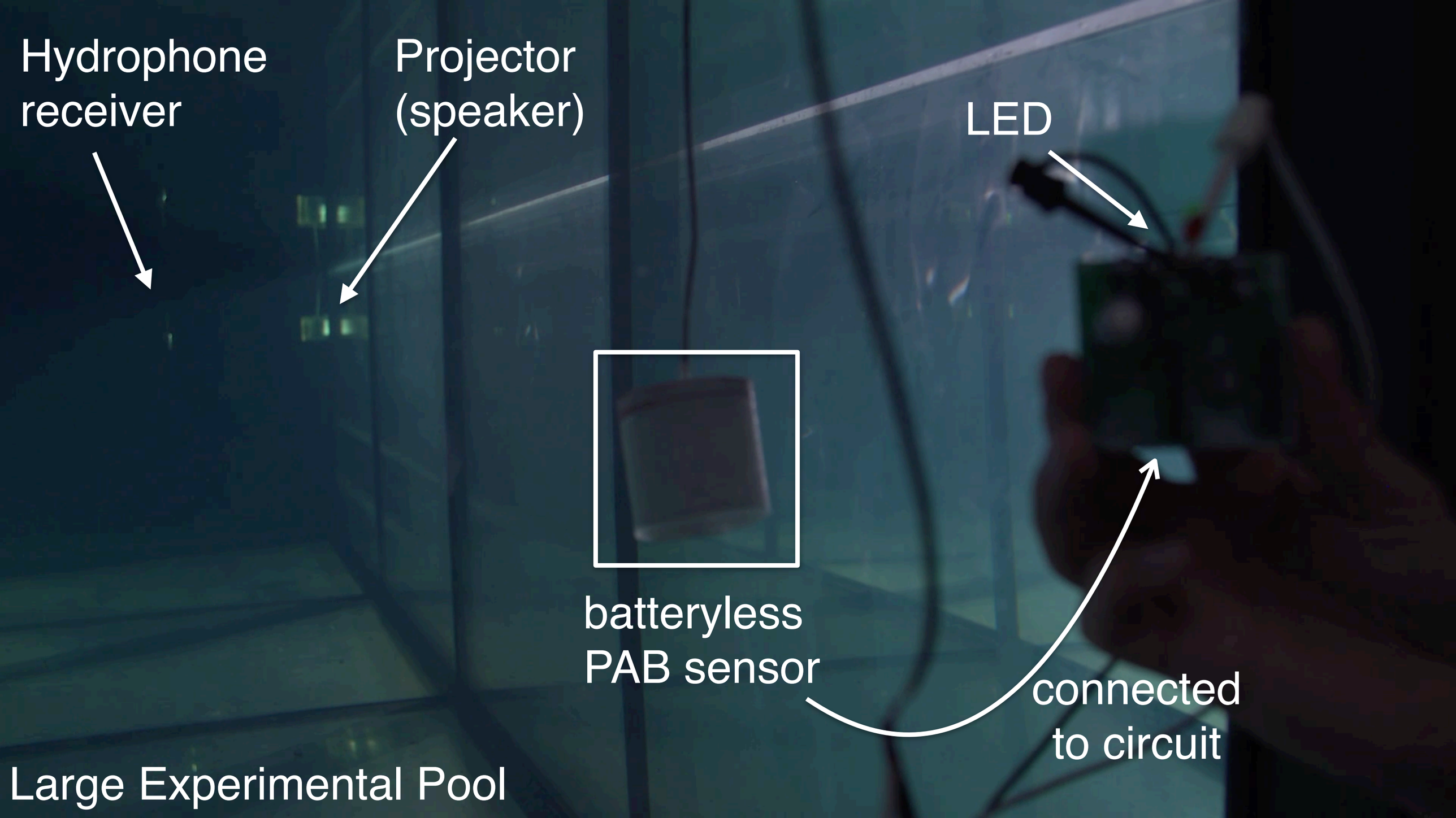


Piezo-Acoustic Backscatter

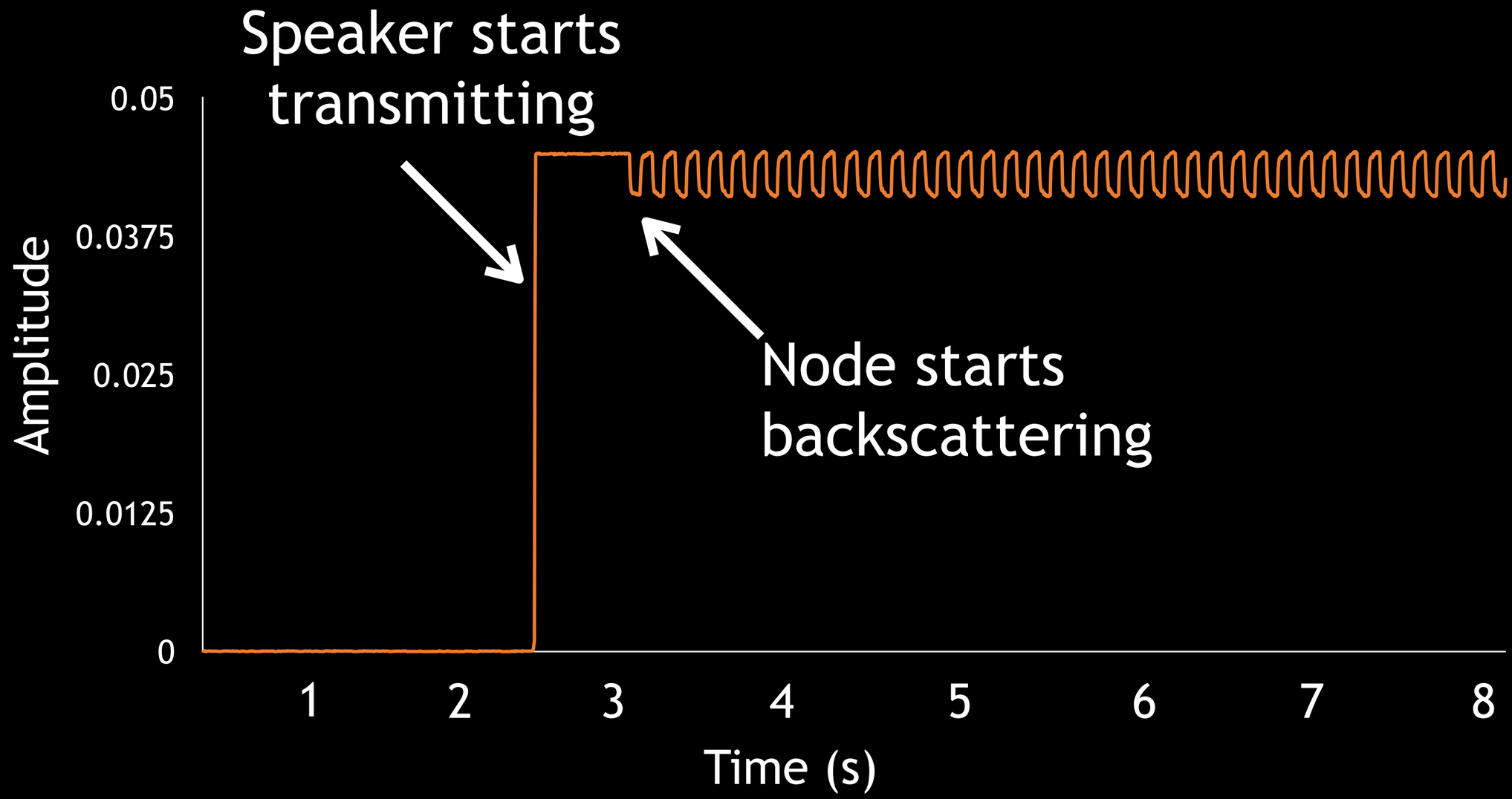


PAB sensor needs 1 million times less power (~100s microWatt) than standard underwater communication

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)

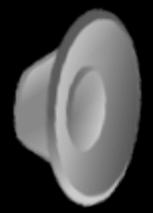


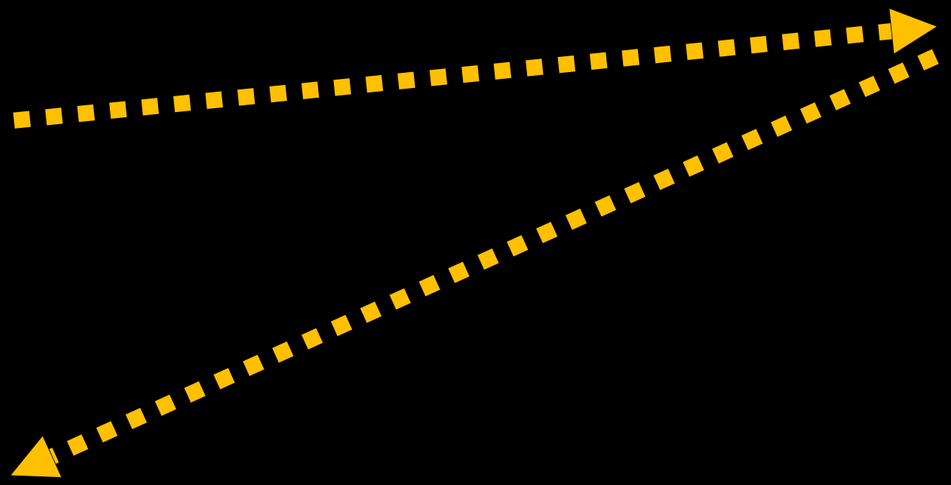
How can we extend underwater backscatter to multiple nodes?

Extending to Multiple Nodes

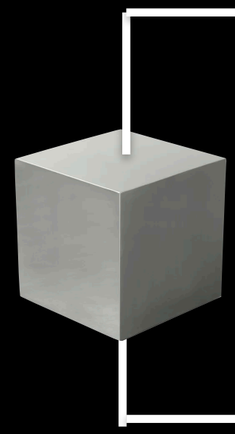
Option 1: Time Division Multiplexing

Projector

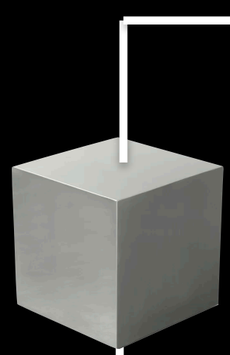




Hydrophone



Batteryless hardware



Batteryless hardware

Extending to Multiple Nodes

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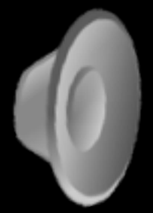

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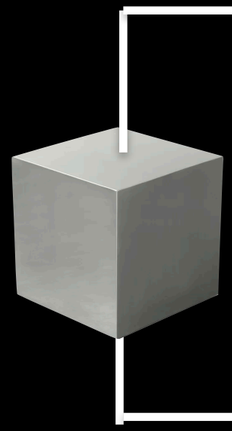
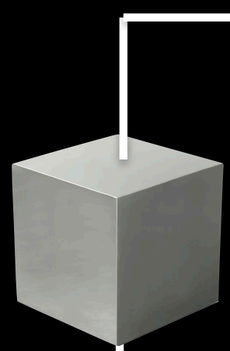


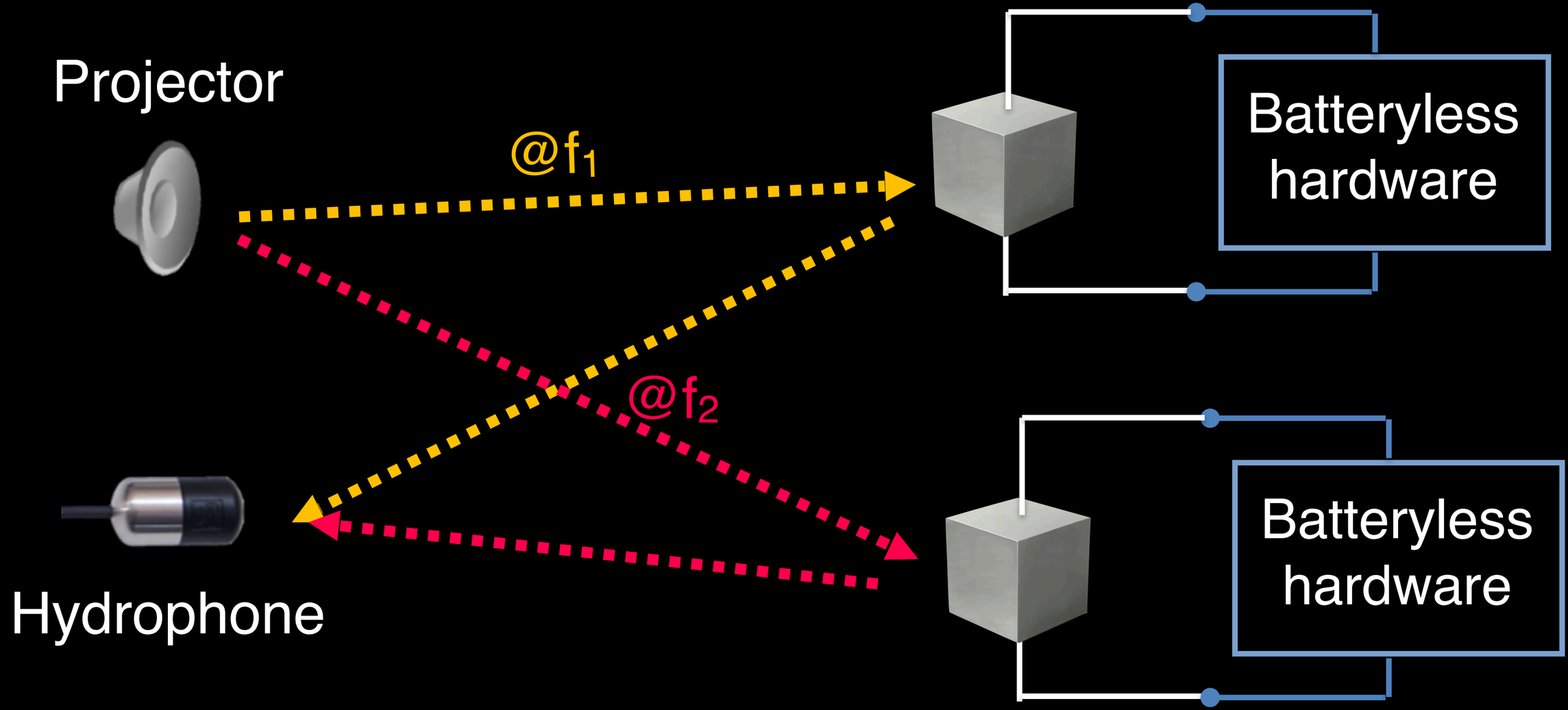
Batteryless hardware



Batteryless hardware

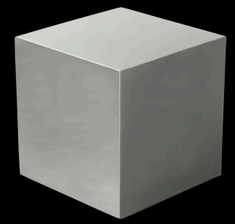
Extending to Multiple Nodes

Option 2: Frequency Division Multiplexing



Extending to Multiple Nodes

Problem: Resonance of piezoelectrics limits their bandwidth



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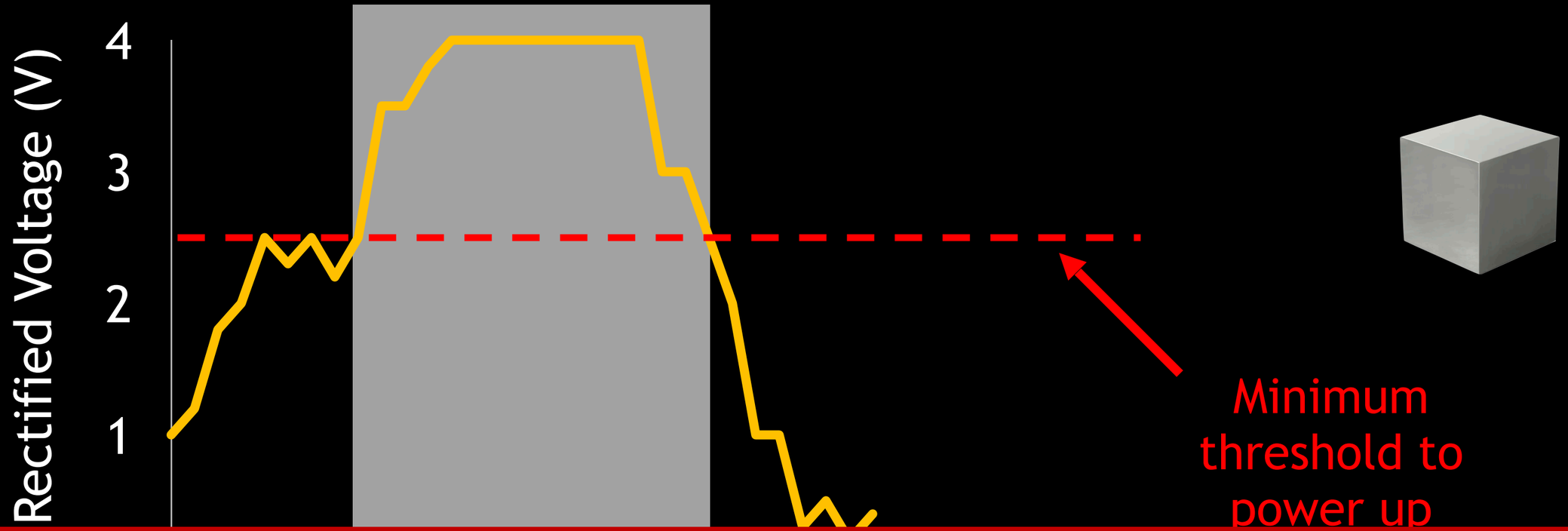

Operating at resonance maximizes energy harvesting but limits concurrent transmissions (and FDMA)

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

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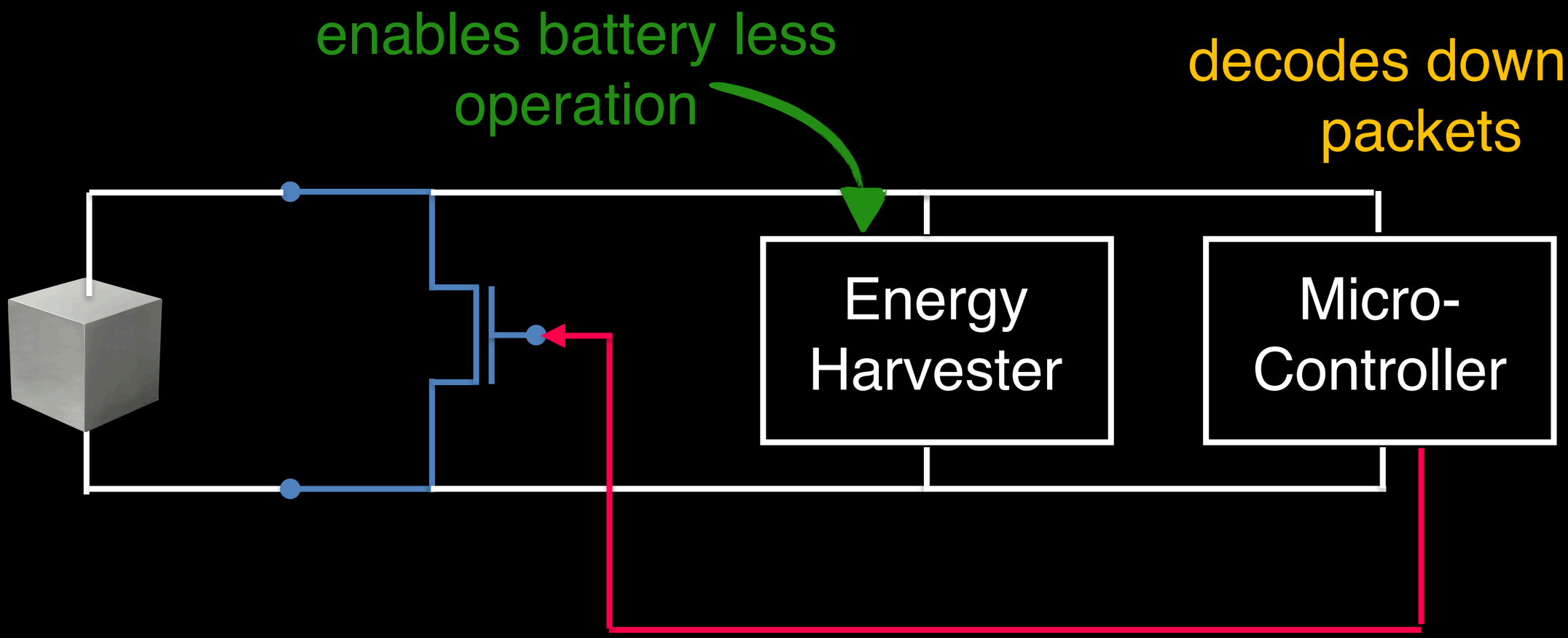


Solution Idea: Shift the resonance frequency *itself* to a different channel

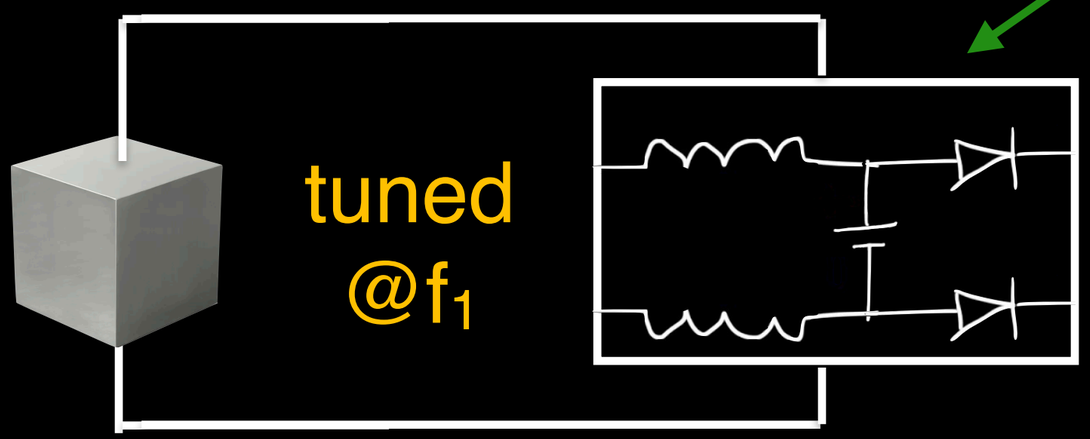
resonance frequency determined by interaction between piezo & the batteryless circuit

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

frequency dependent

→Tune the circuit to a different frequency

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



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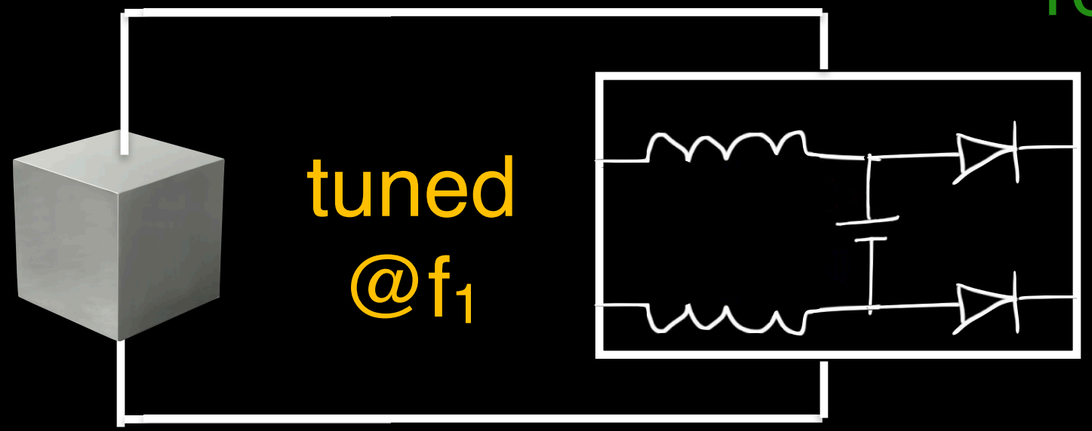

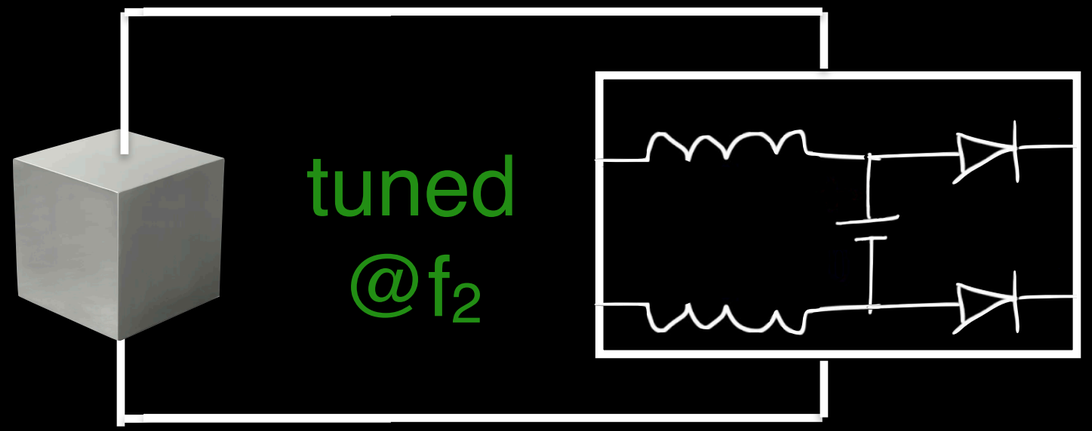

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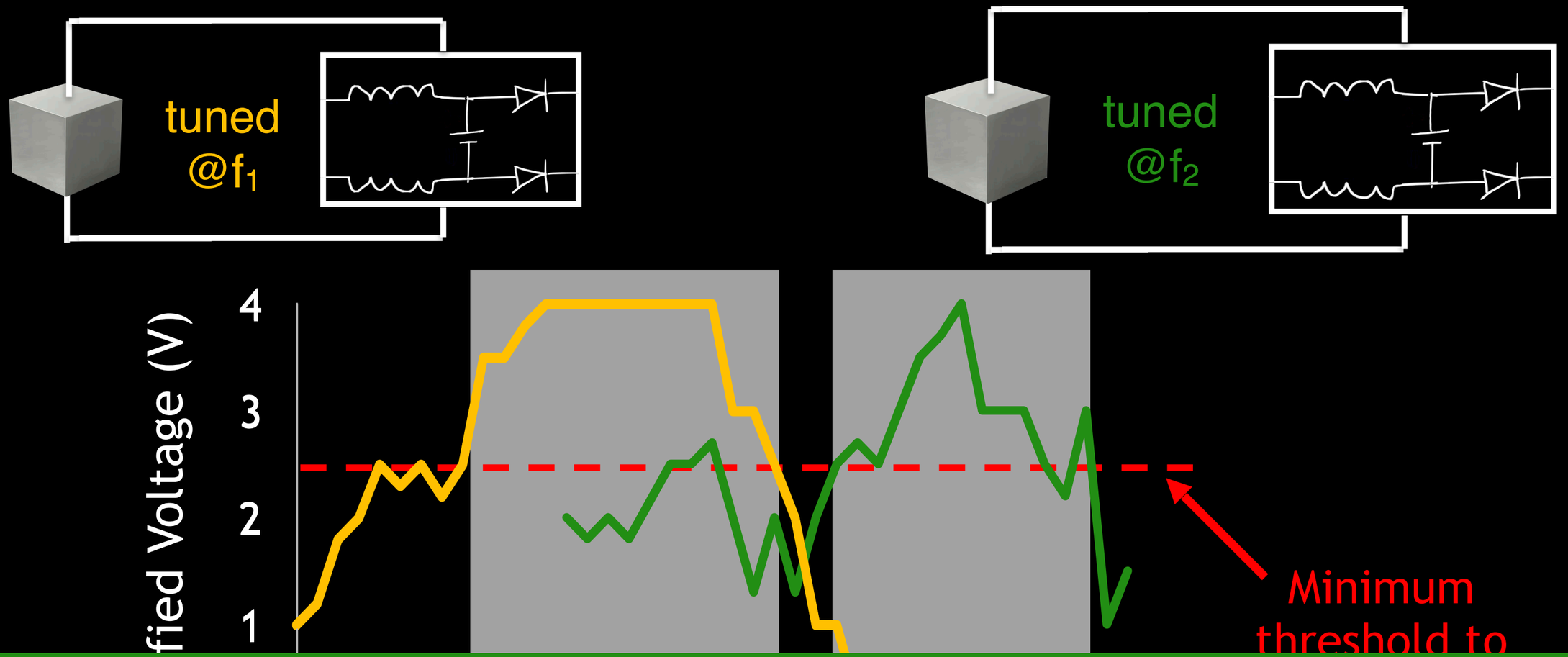
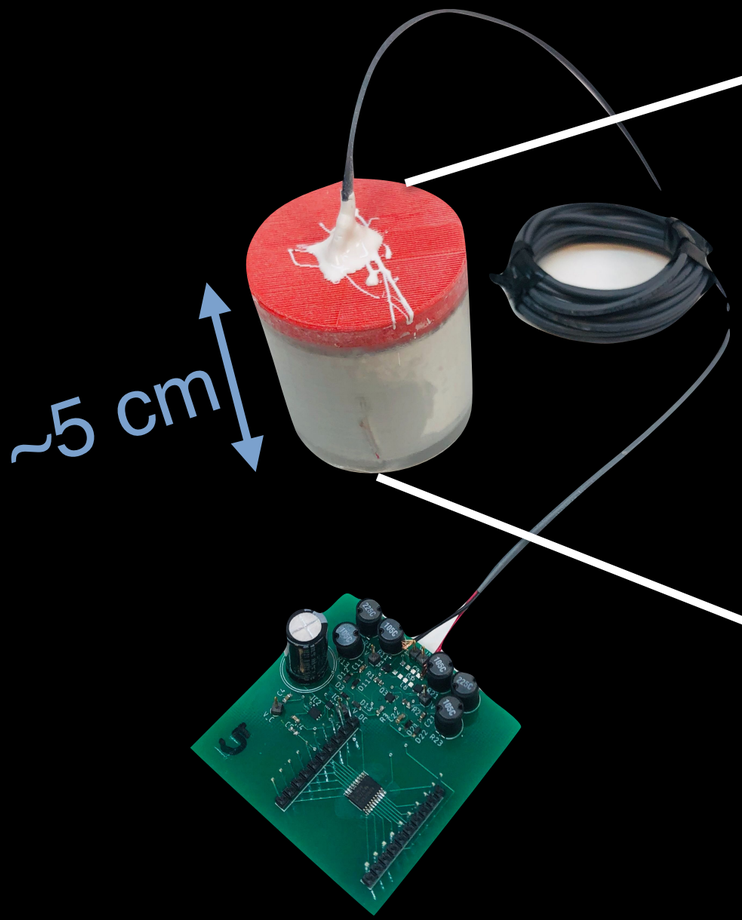


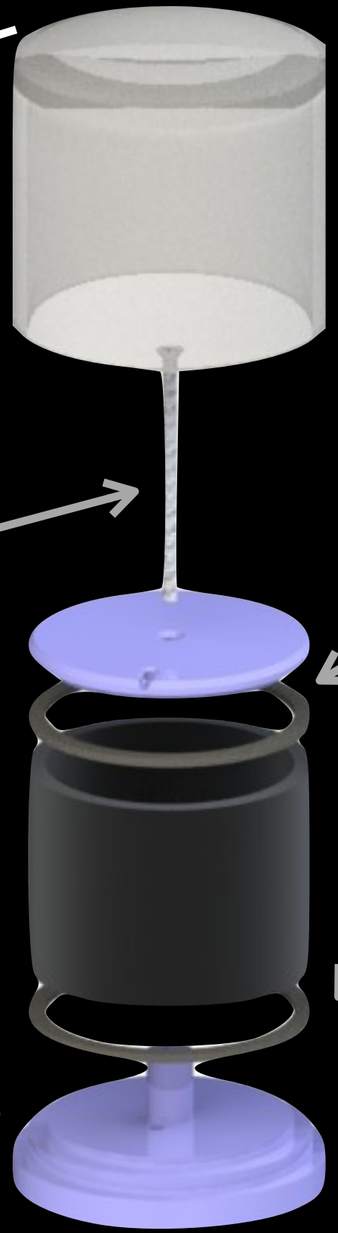
Extend the idea to uplink communication using a MIMO-style decoder adapted to backscatter resonance modes

Implementation

Batteryless PAB sensor

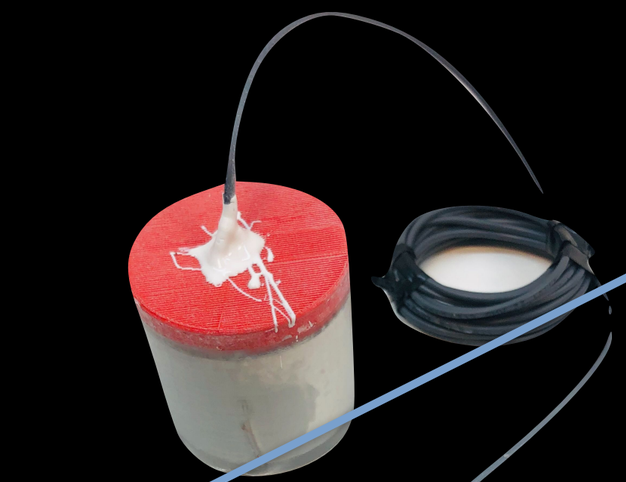


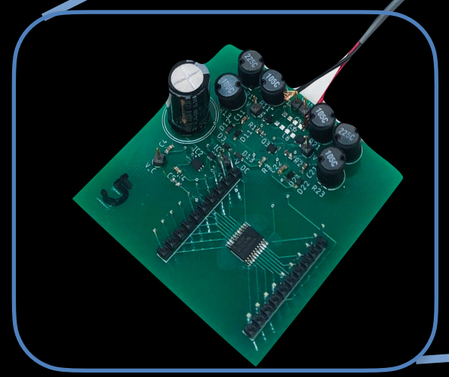
Exploded transducer view

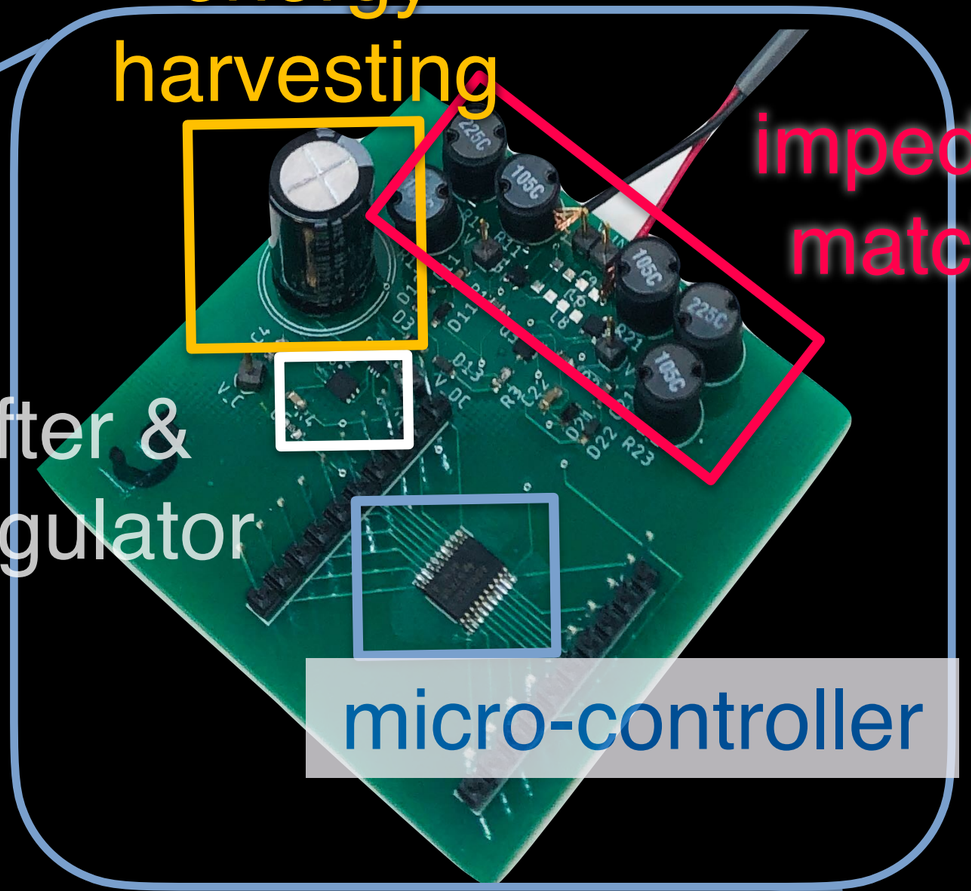


Implementation

Batteryless PAB sensor







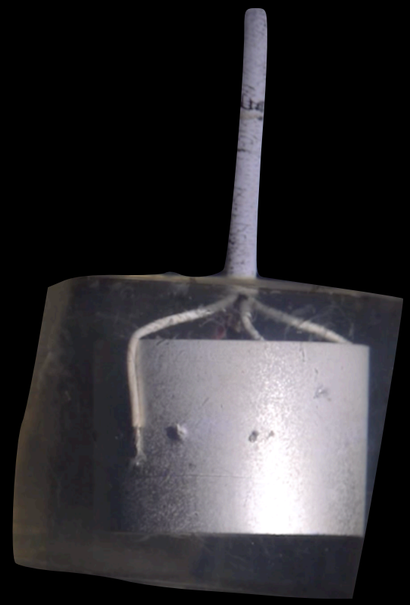
Open Source Code+Schematics:

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

Implementation

Batteryless PAB sensor

Projector

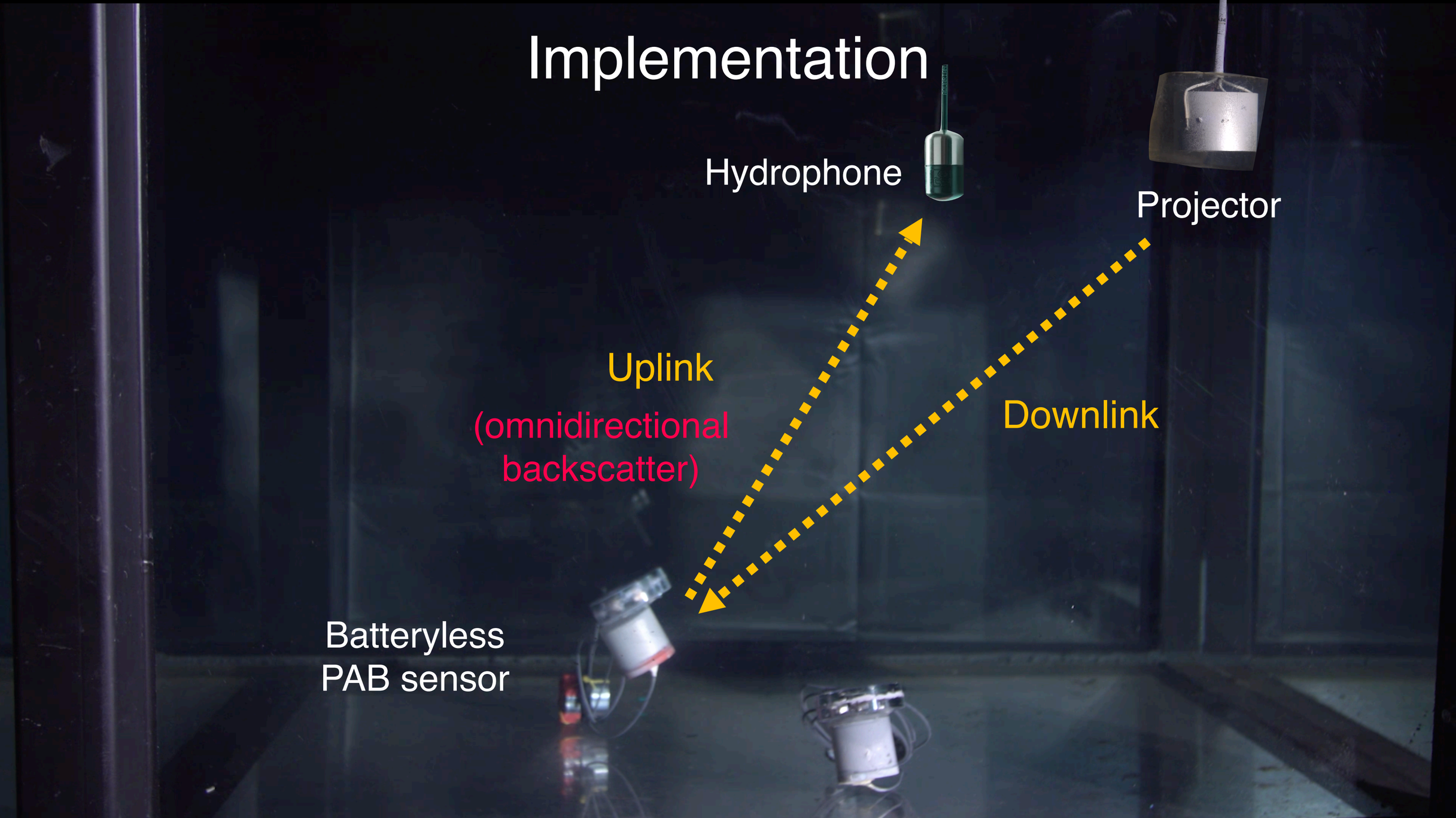


fabricated in-house

Hydrophone

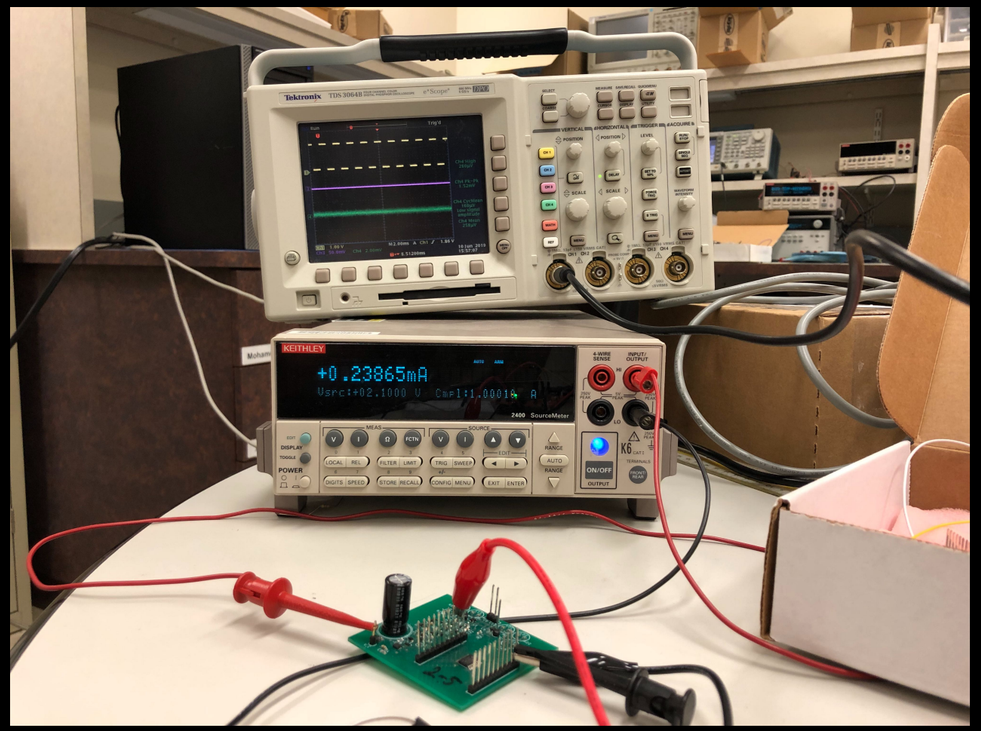
Aquarian H2A

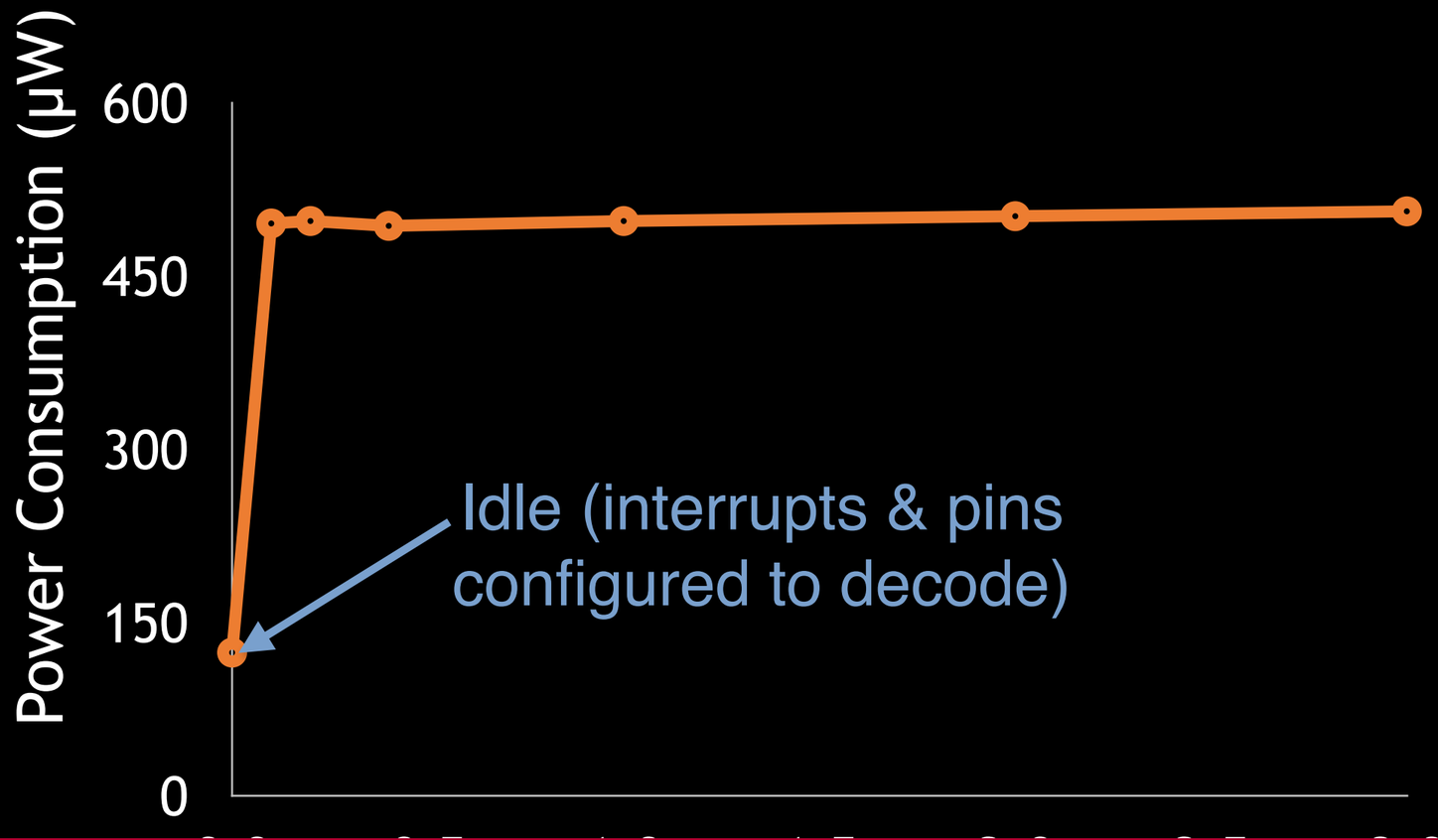
Implementation



Power Consumption

Empirically measured using Keithley 2400 source meter

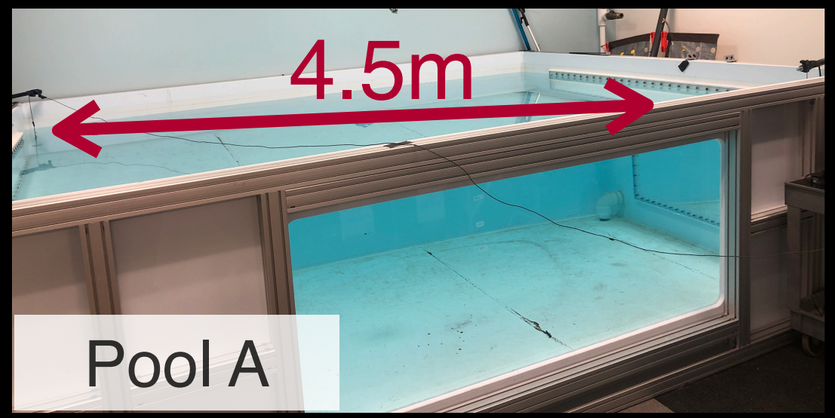


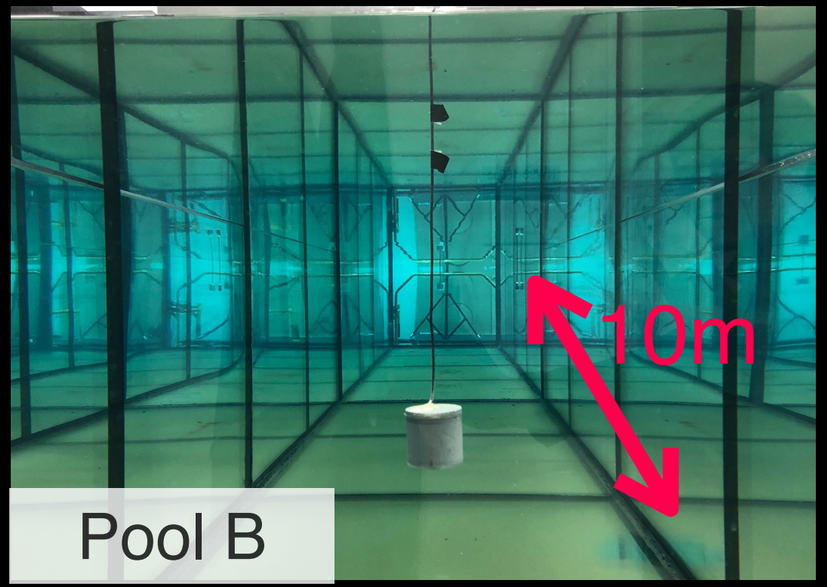


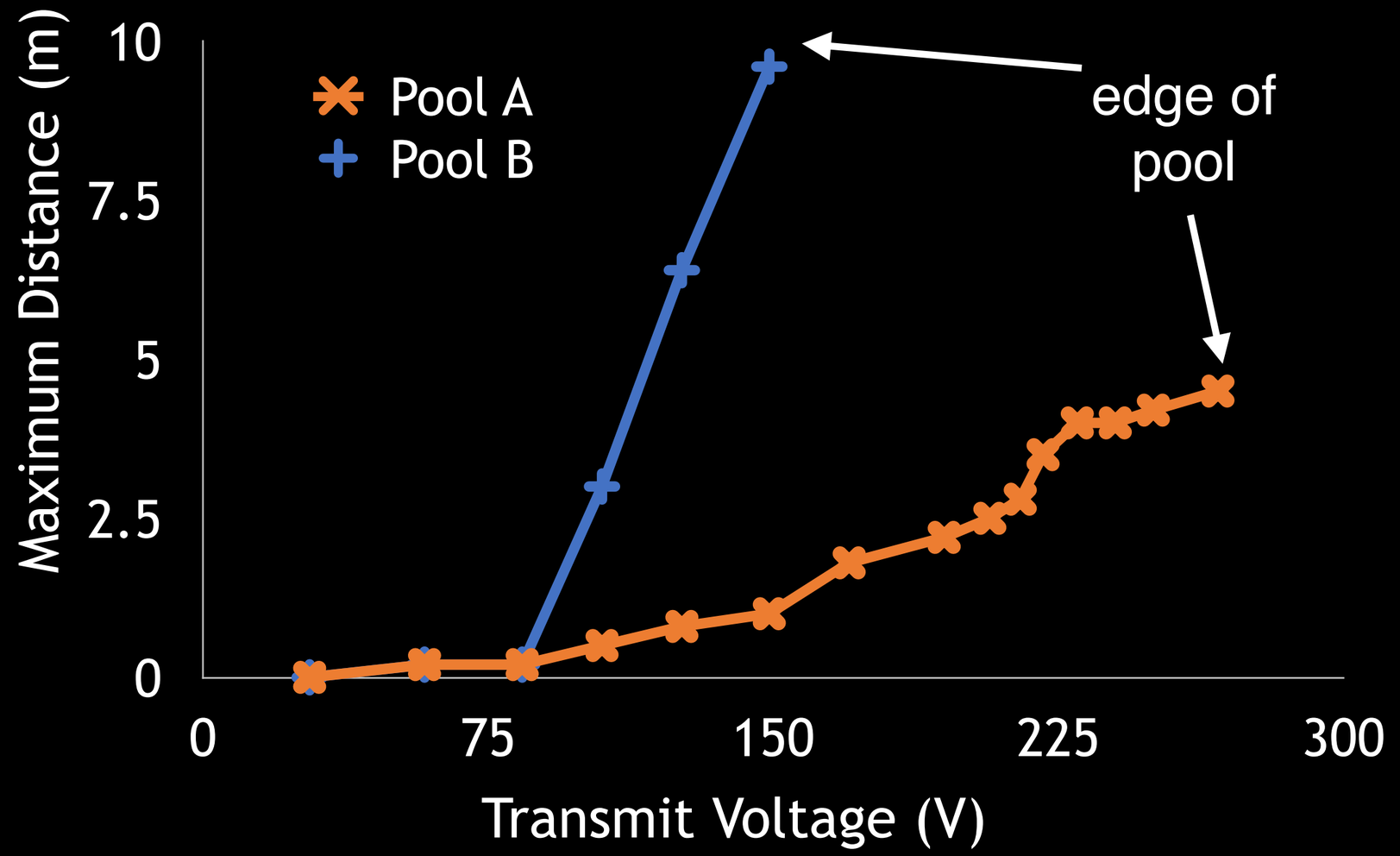
1 million times less power than state-of-the-art low-power underwater sensors [WHOI micro-modem 2019]

Power-up Range

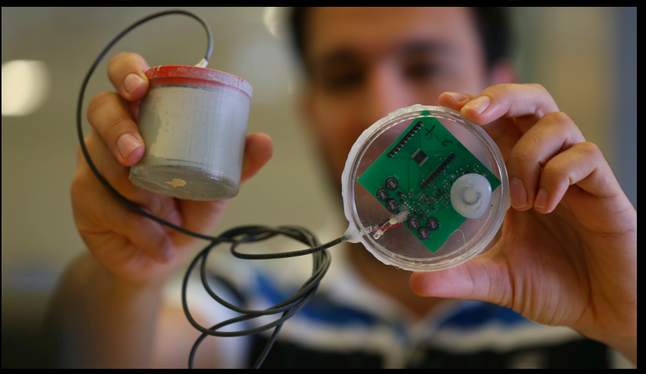
Experiment: Vary power and distance to sensor







Batteryless Ocean Sensing
[ACM SIGCOMM'19]



Fabrication
[ACM SIGCOMM'20]

Metamaterials for UWB (40 kHz)

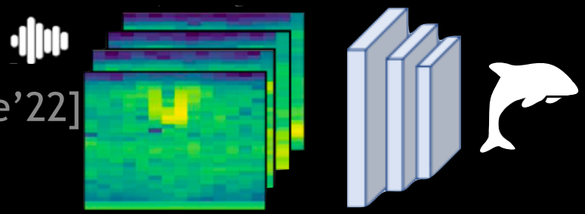
Communication
[MITS/IEEE OCEANS'20]

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

Localization
[ACM HotNets'20]

Battery-free GPS (~10cm)

AI
[ACM HotMobile'22]

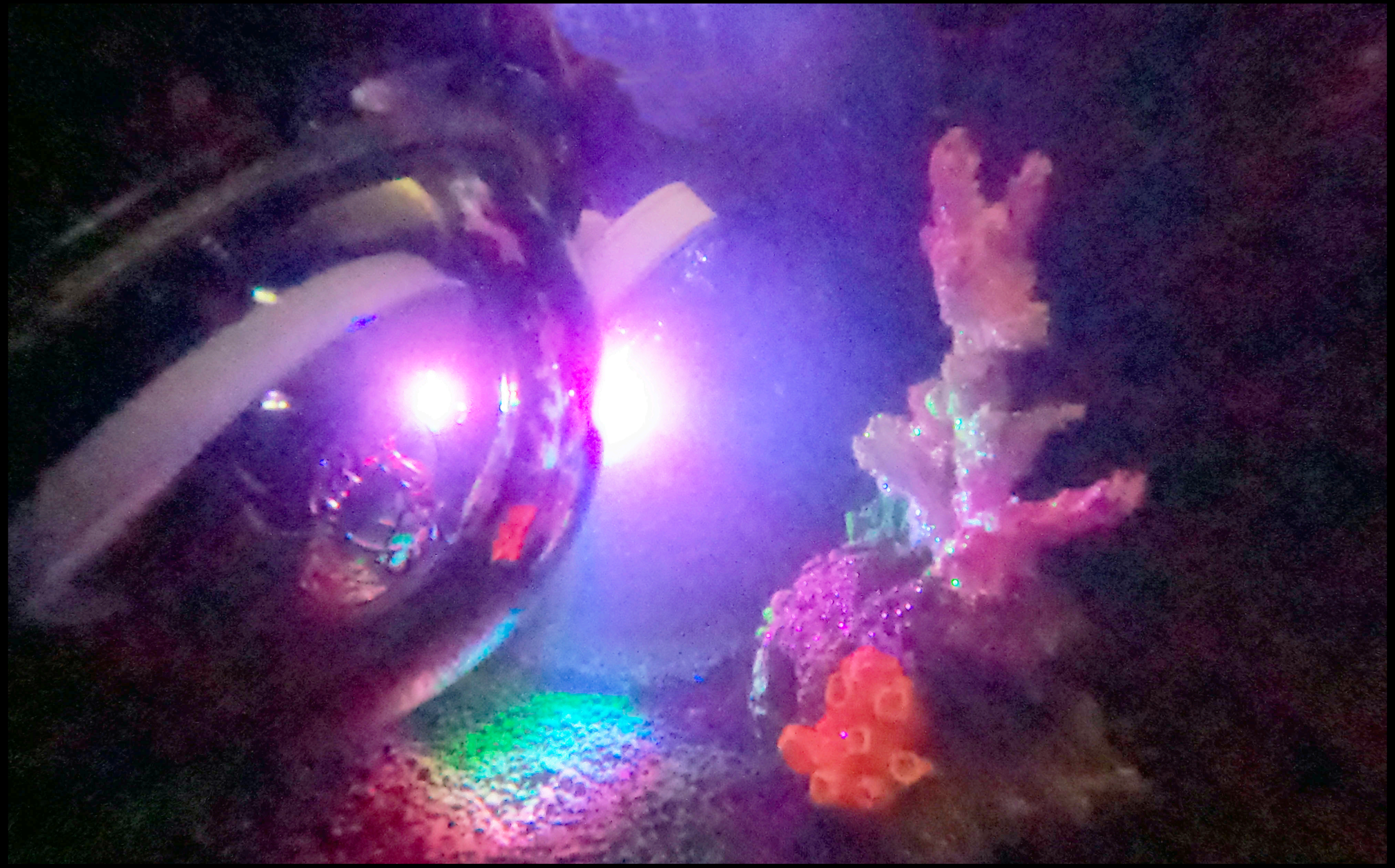


Bioacoustics (animal/climate sensing)

Imaging

Monitoring for climate, ecology, defense

Can we enable battery-free underwater imaging?



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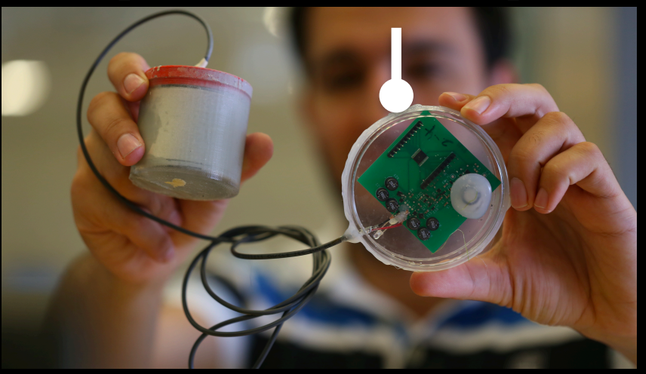

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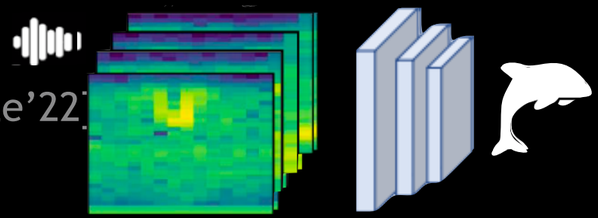

Bioacoustics (animal/climate sensing)

Imaging

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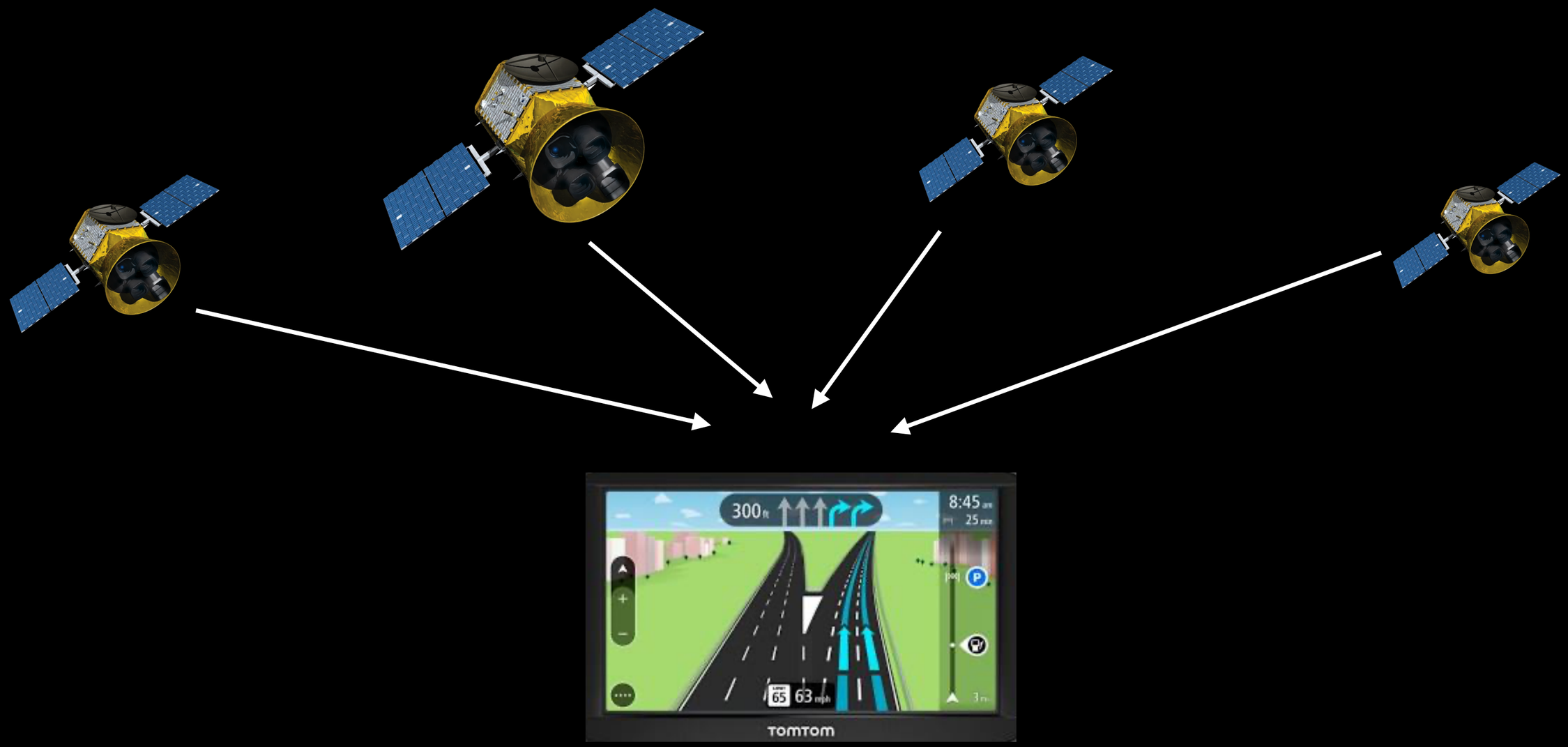
Can we enable battery-free underwater localization?

Global Positioning System (GPS)



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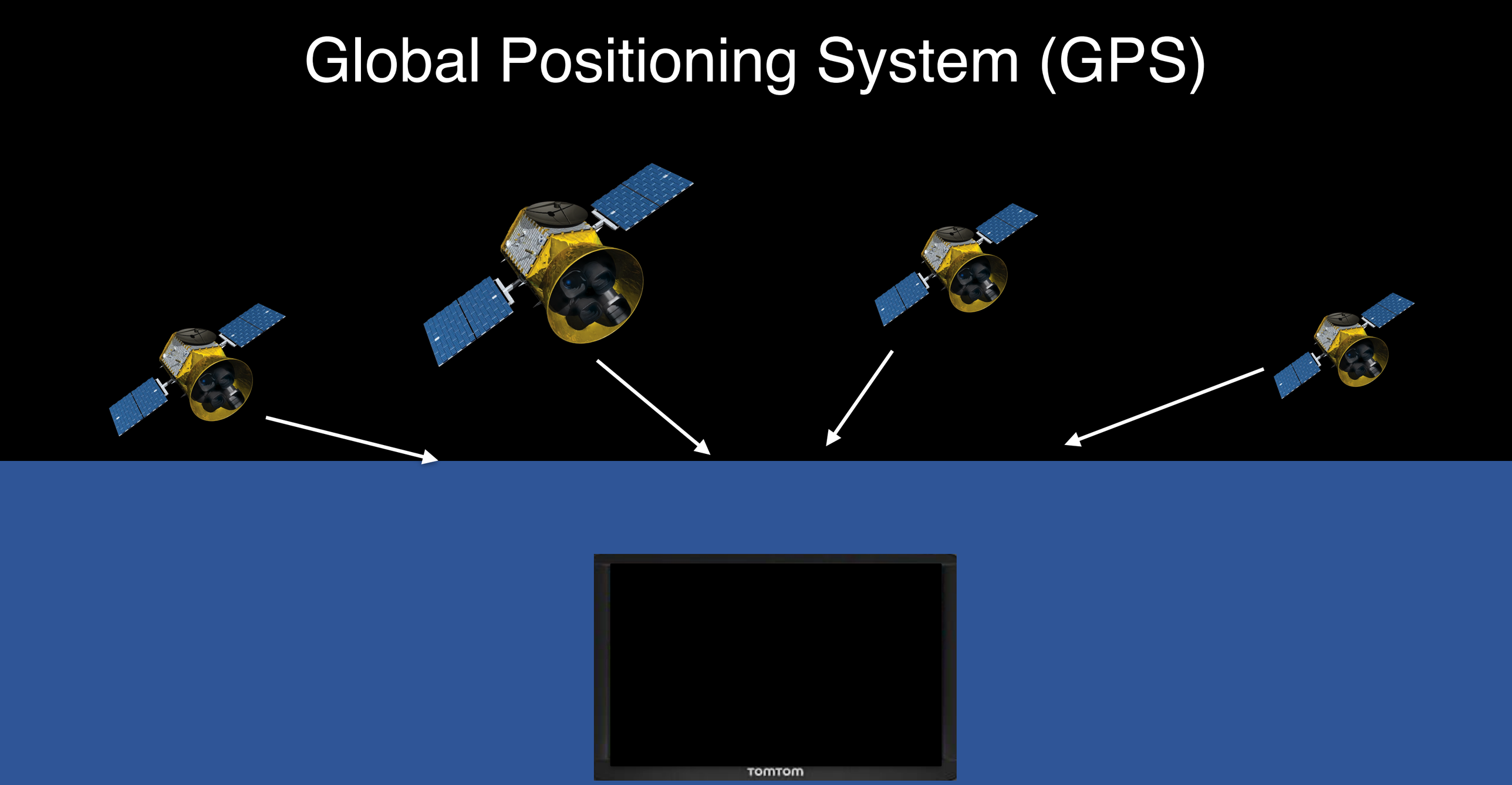
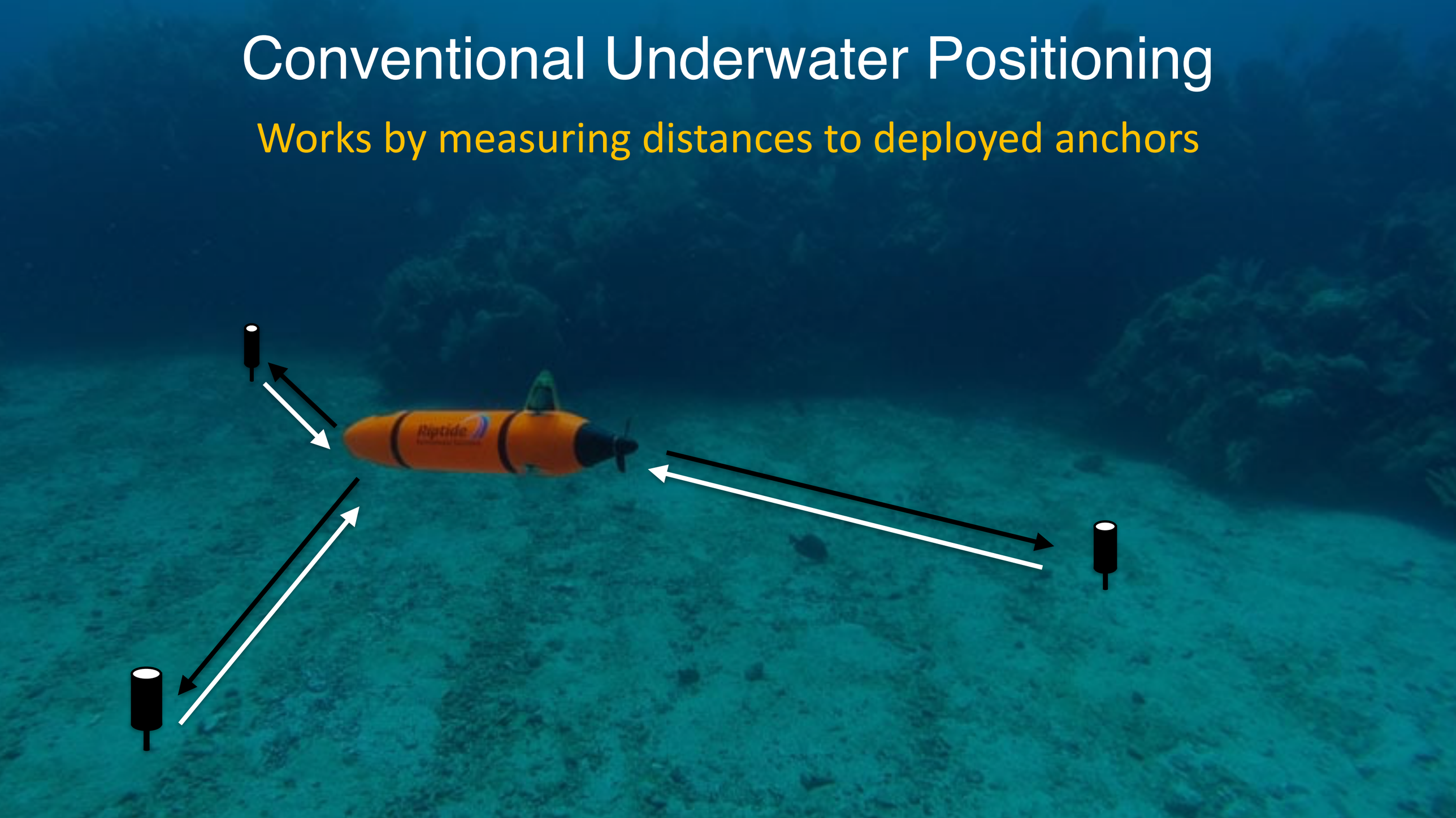


Conventional Underwater Positioning

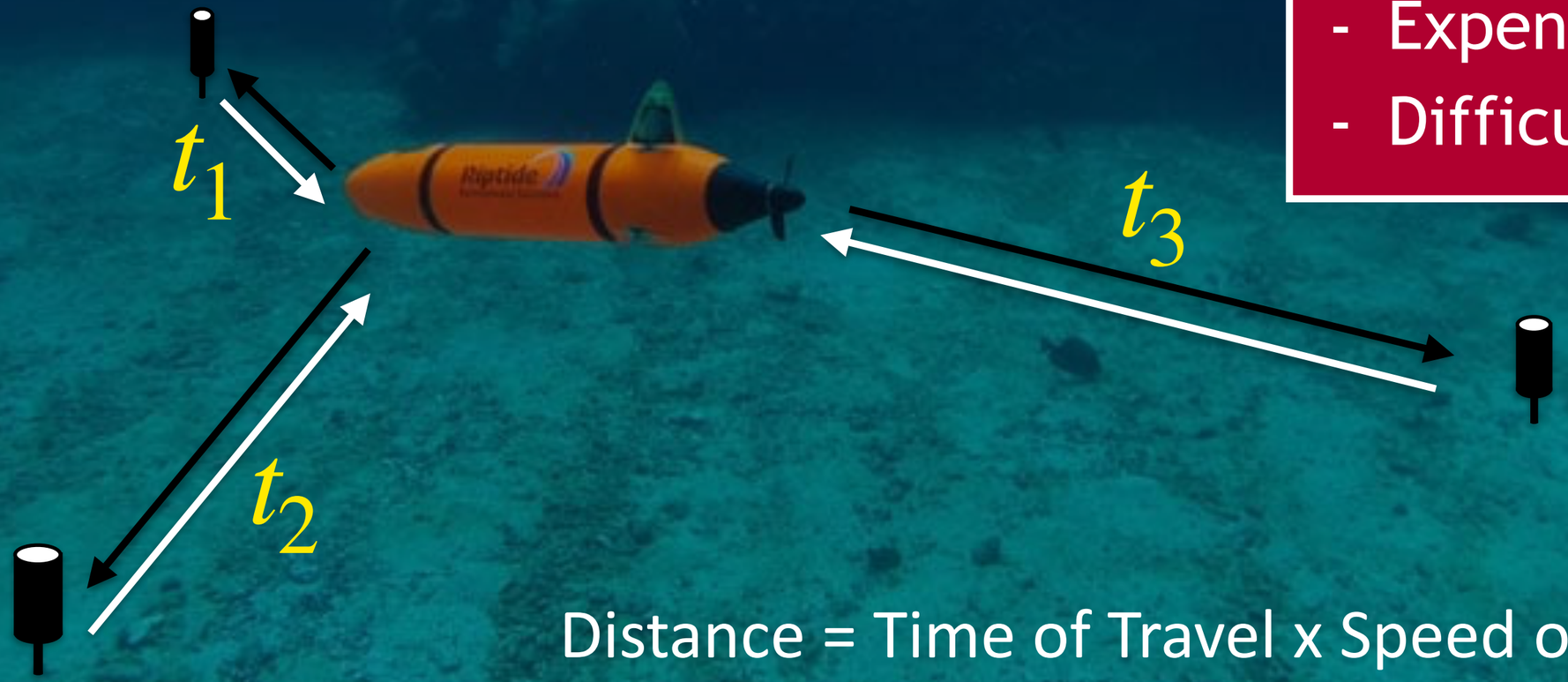
Works by measuring distances to deployed anchors



Conventional Underwater Positioning

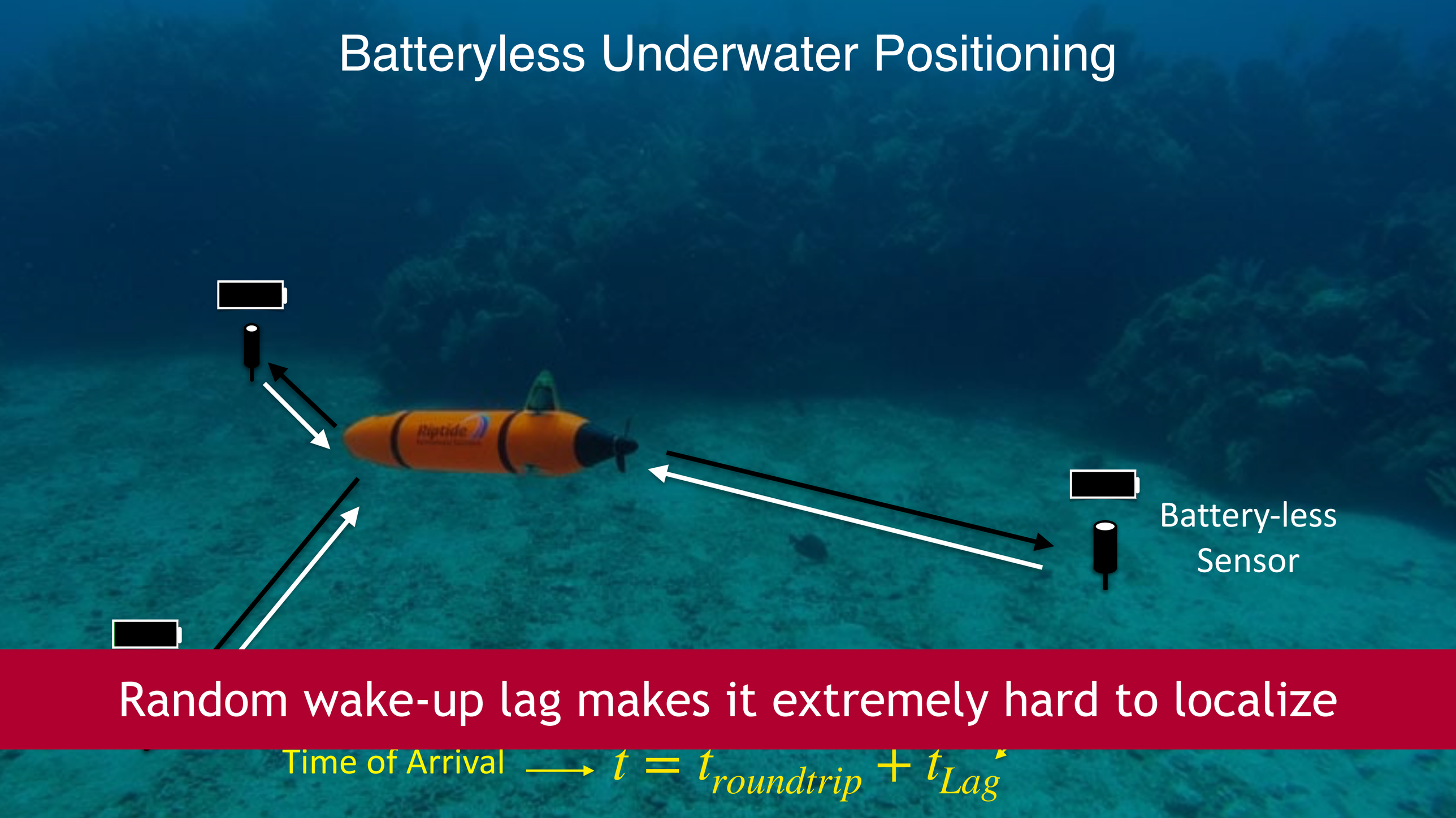
Works by measuring distances to deployed anchors

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



Distance = Time of Travel x Speed of Sound

Batteryless Underwater Positioning



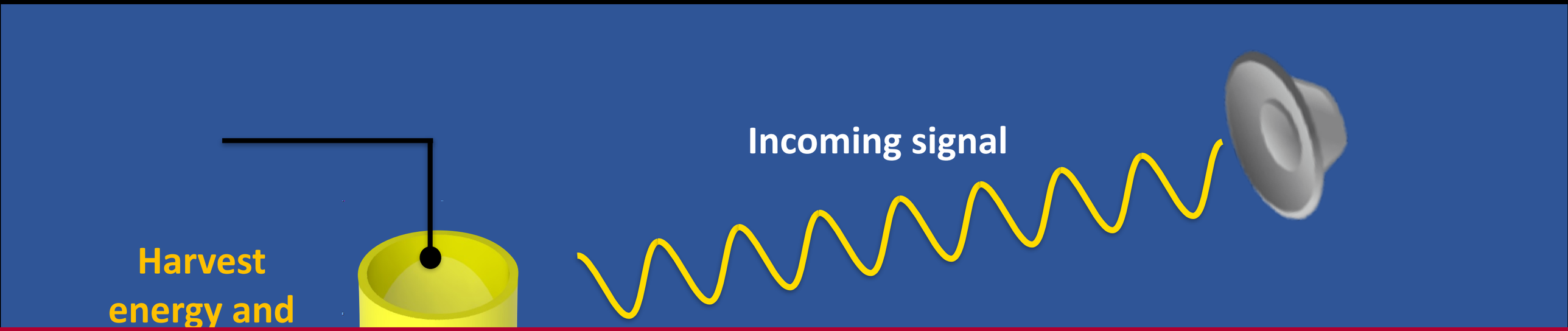
Random wake-up lag makes it extremely hard to localize

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

Key Idea: Underwater positioning using backscatter sensor

Key Idea: Underwater positioning using backscatter sensor

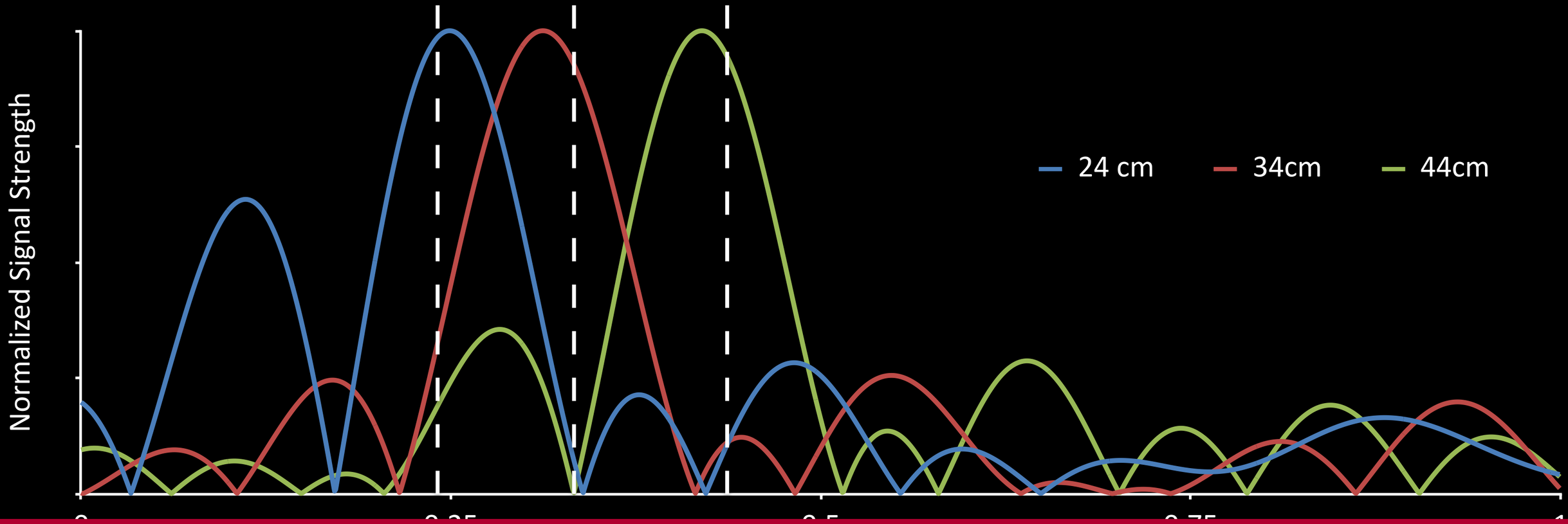
Measure “phase” instead of measuring time



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]

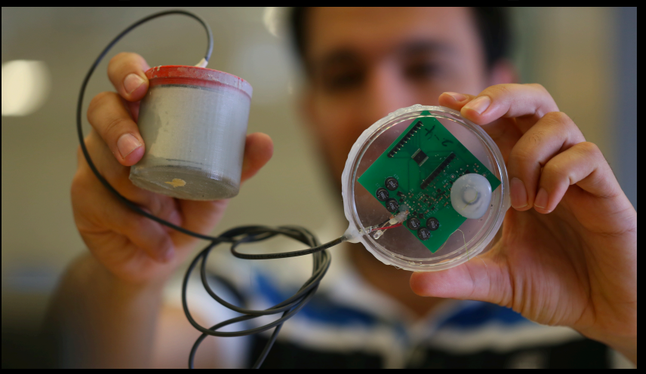
Experimental Evaluation in the River



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)

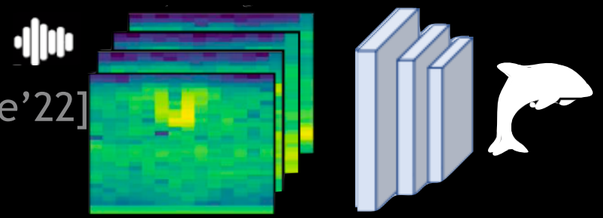
Communication
[MITS/IEEE OCEANS'20]

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

Localization
[ACM HotNets'20]

Battery-free GPS (~10cm)

AI
[ACM HotMobile'22]



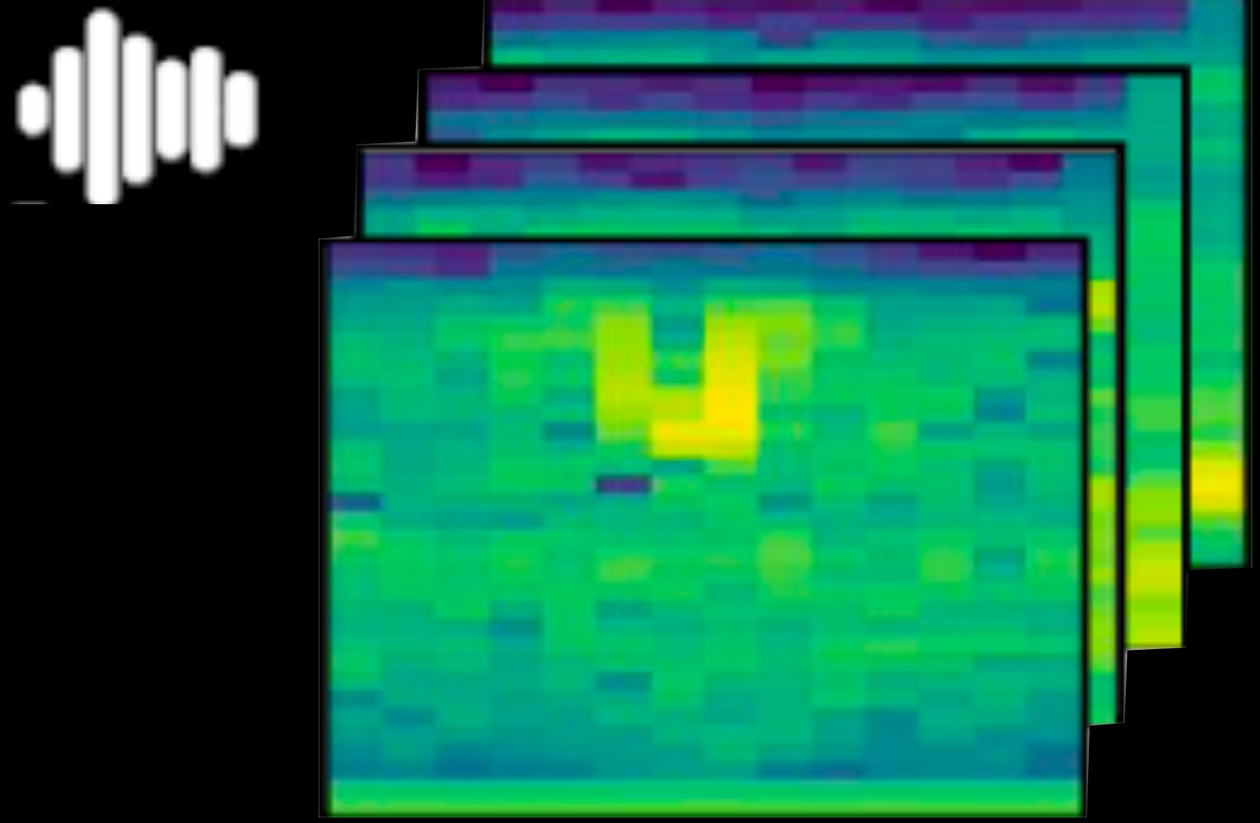
Bioacoustics (animal/climate sensing)

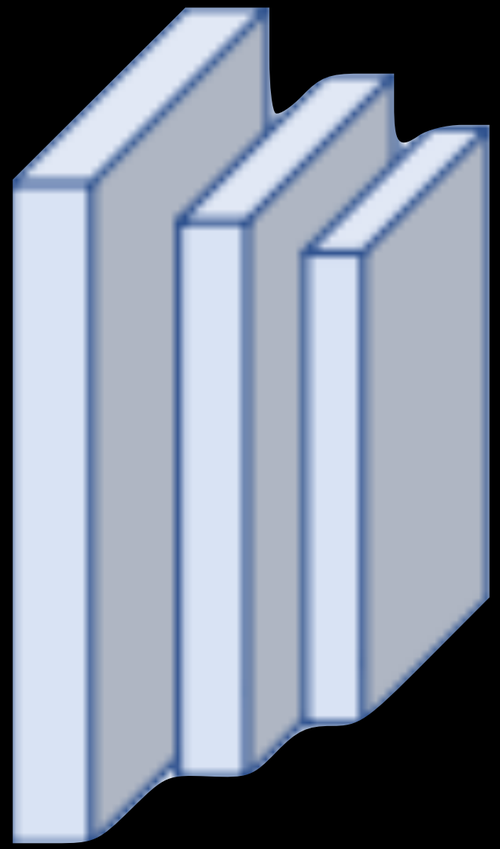
Imaging

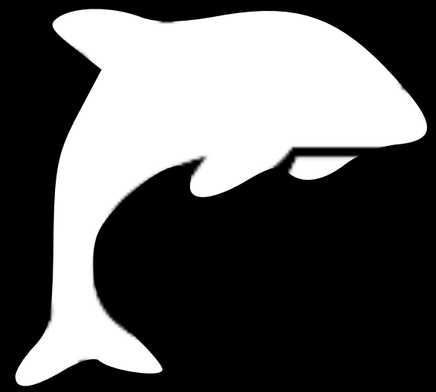
Monitoring for climate, ecology, defense

Can we enable battery-free underwater AI?

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



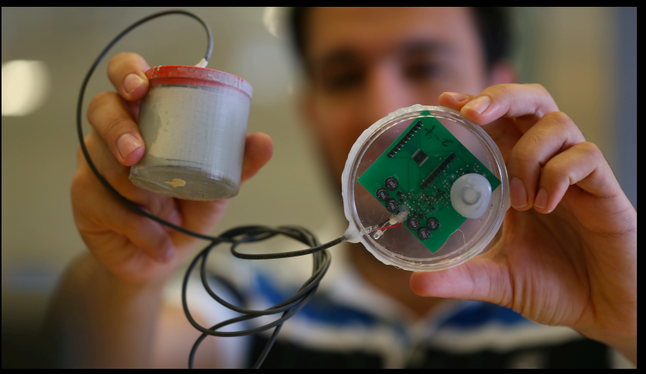




[ACM HotMobile'22]

Imperial College London

Batteryless Ocean Sensing
[ACM SIGCOMM'19]



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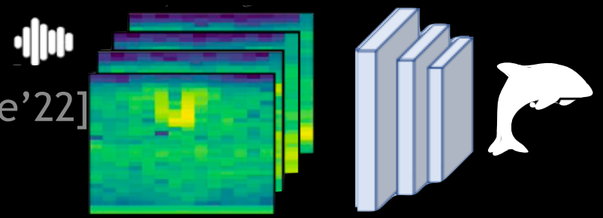

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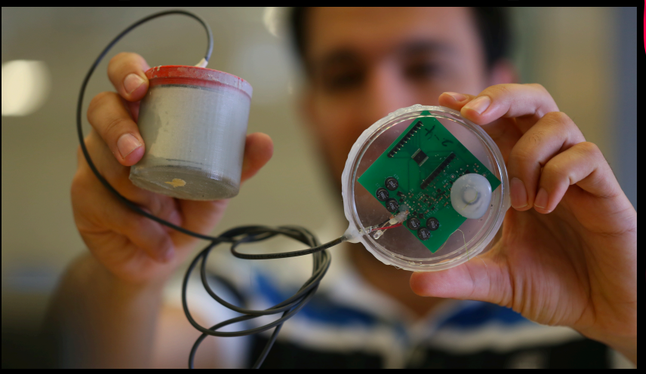
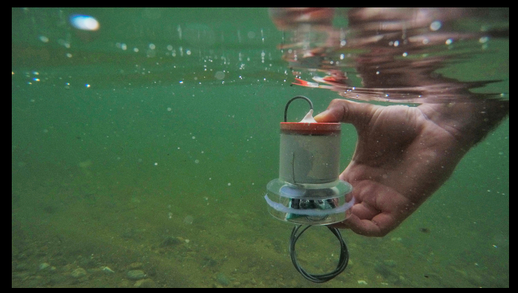
[ACM SIGCOMM'19]



Fabrication
[ACM SIGCOMM'20]

nanoWatt power levels

Communication
[MITS/IEEE OCEANS'20]

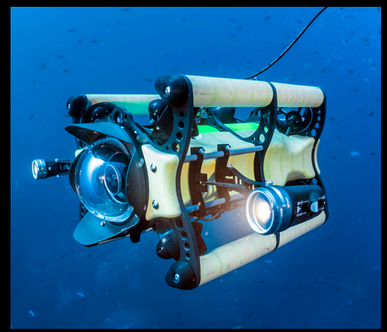


Toward km-scale comms

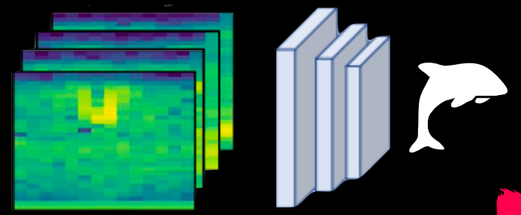
Woods Hole Oceanographic Institution

Localization
[ACM HotNets'20]

Robotic exploration



AI
[ACM HotMobile'22]



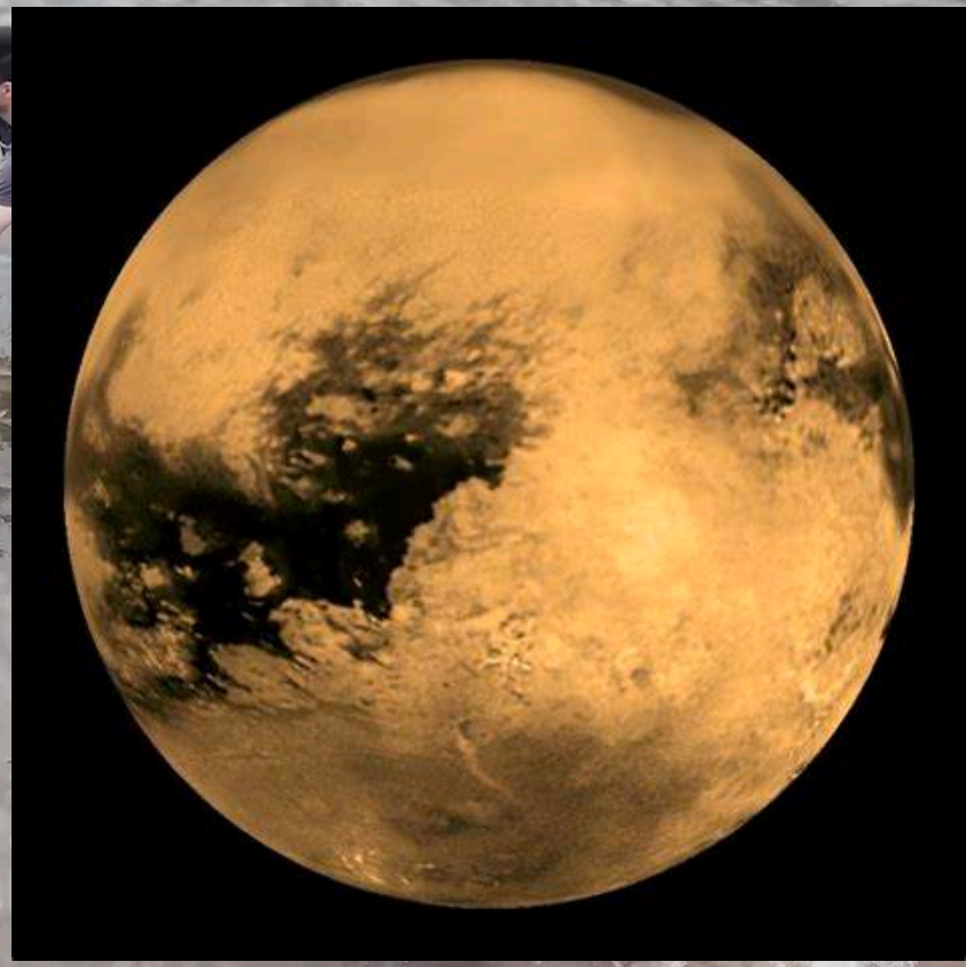
Imaging

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

1,000s of experimental trials

battery-free node with
temp & pressure sensor

Extraterrestrial
oceans (e.g., Titan)



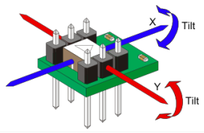
Summary of this Lecture

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

Remainder of the Class

IoT Fundamentals
(9 lectures)

Sensing

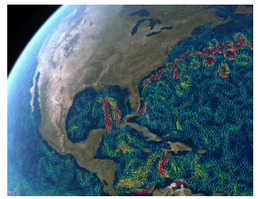


Computation

Power/Energy

Connectivity

Emerging & Cross-Cutting Topics
(6 lectures)



Project Meetings + Hacking

1. **Labs 0-4**
2. **PSets 1-2**

PSet 2 Due April 4

Midterm April 11

1. Will meet teams weekly
2. Presentations + Q&A on last day of class