MAS.S62:

Ocean IoT

Technologies, Industries, Sustainability

Lecturer

Fadel Adib fadel@mit.edu

TA

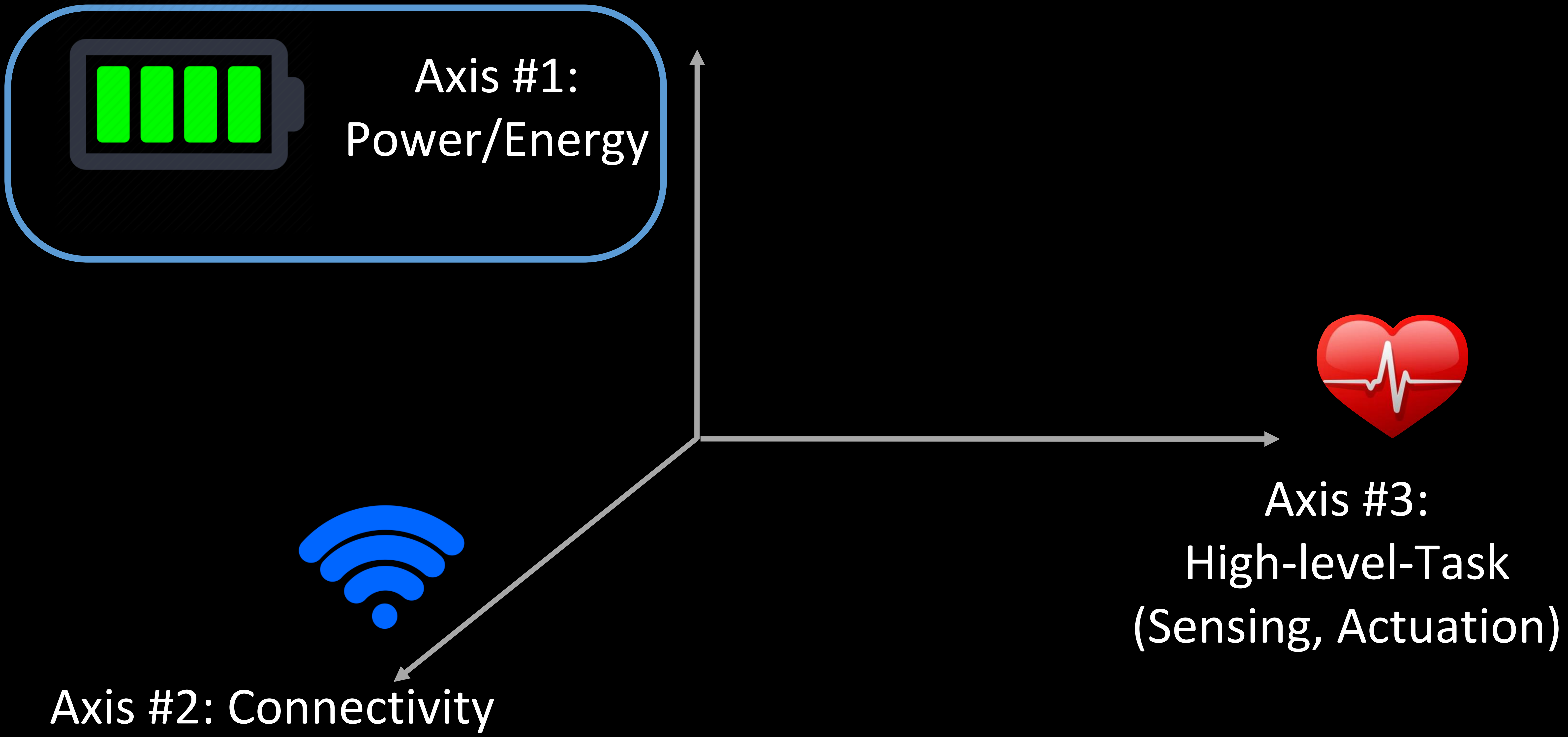
Sayed Saad Afzal afzals@mit.edu

Website

http://www.mit.edu/~fadel/courses/MAS.S62/index.html

Main Components of (Ocean) IoT Systems

This Lecture



Objectives of Today’s Lecture

Learn **fundamentals** of energy harvesting, backscatter, end-to-end system design

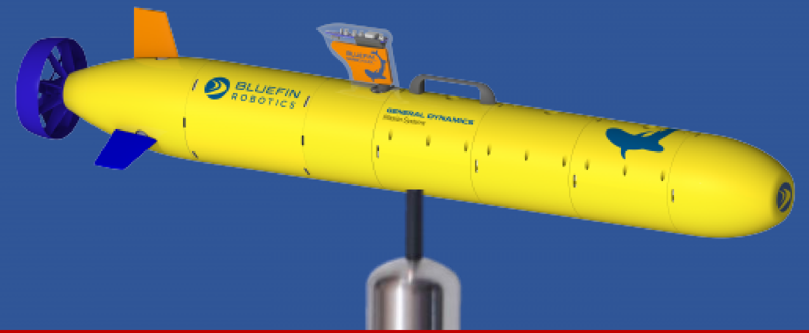
1. Why is it not feasible to use batteries with underwater IoT sensors?

2. What are underwater backscatter systems, why do they consume net-zero power?

3. What are the different components that make an end-to end underwater backscatter system?
   - The physical, mathematical, engineering, and design fundamentals
   - Why are these systems designed the way they are

Traditional Approach

Underwater Drone



Sensor generates its own acoustic signal

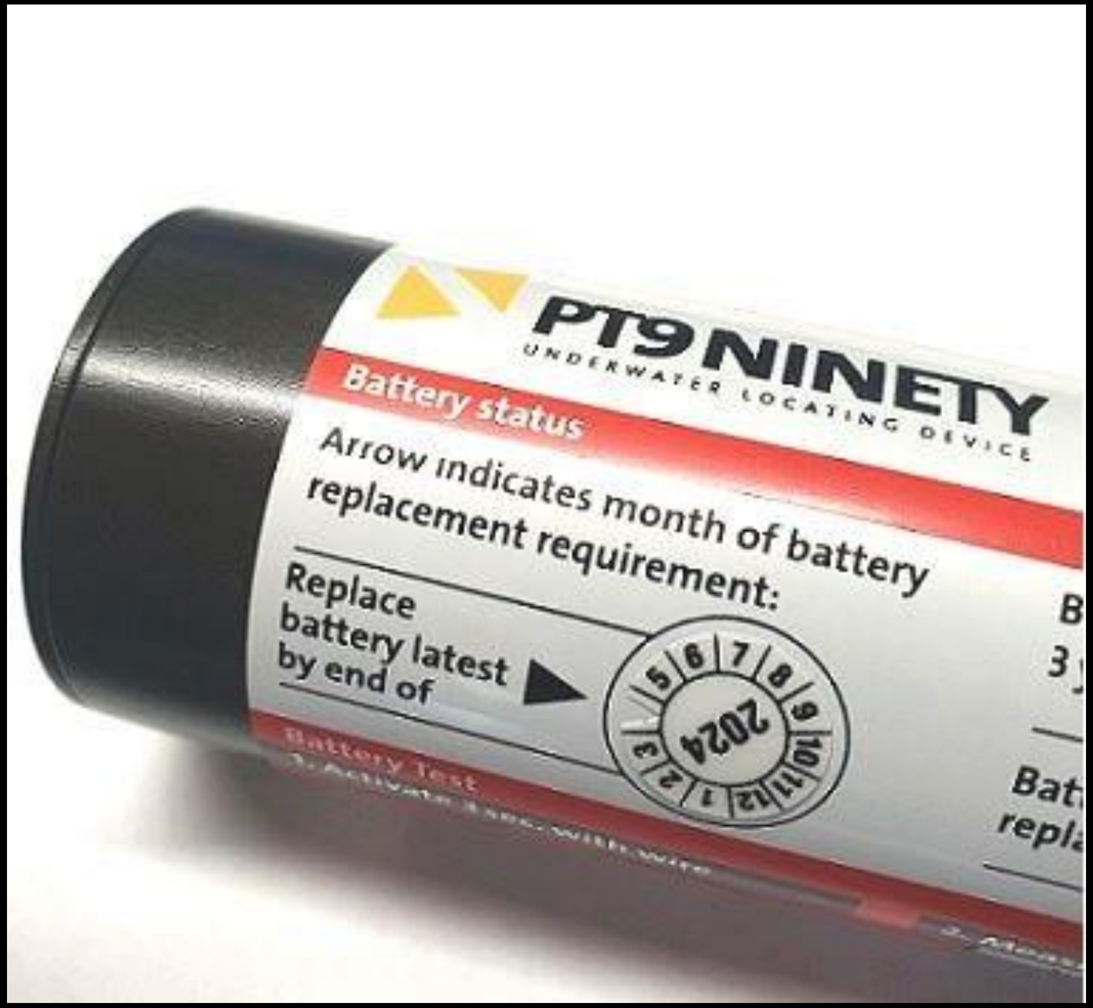
temperature
sensor

Why is it not feasible to use batteries with underwater IoT sensors?

Using batteries with underwater IoT sensors

Pollution via battery leakage

Cost of replacing batteries



Insulation of Batteries/Electrical Shortage

Problem: Battery life of underwater sensors is extremely limited

Low-power underwater transmitters consume 100s of Watts

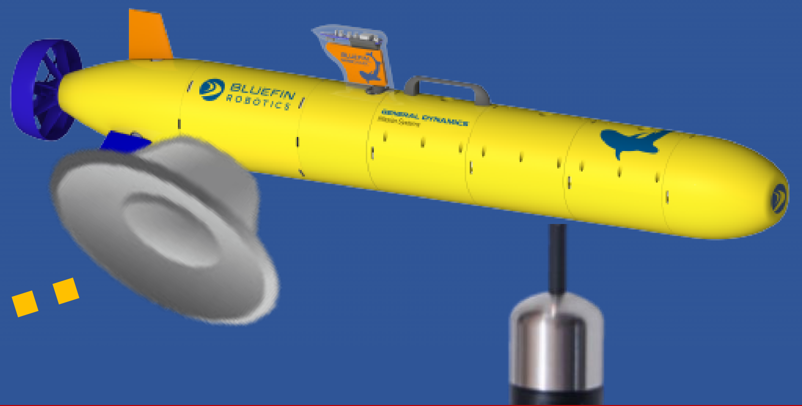
(e.g., WHOI low-power micro-modem 2019)

↓

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

[Animal Biotelemetry'15, Scientific Reports'17]

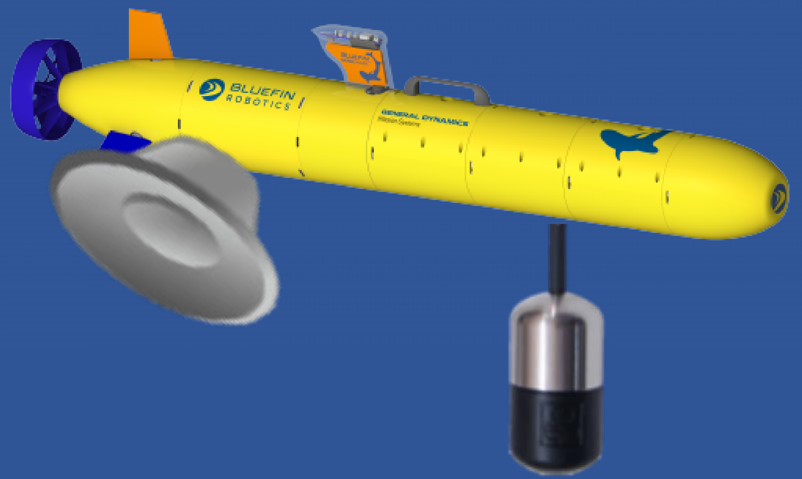
Underwater Backscatter : Basic Principle of Operation

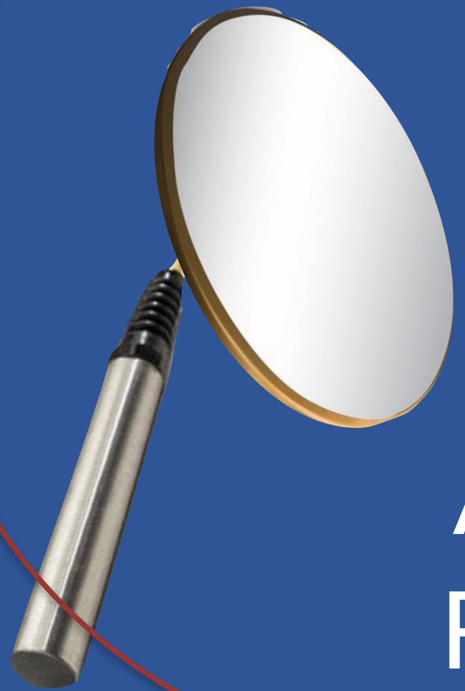


Sensor reflects an existing acoustic signal

How can we control the reflections of acoustic signals?

Underwater Backscatter : Backscatter Node

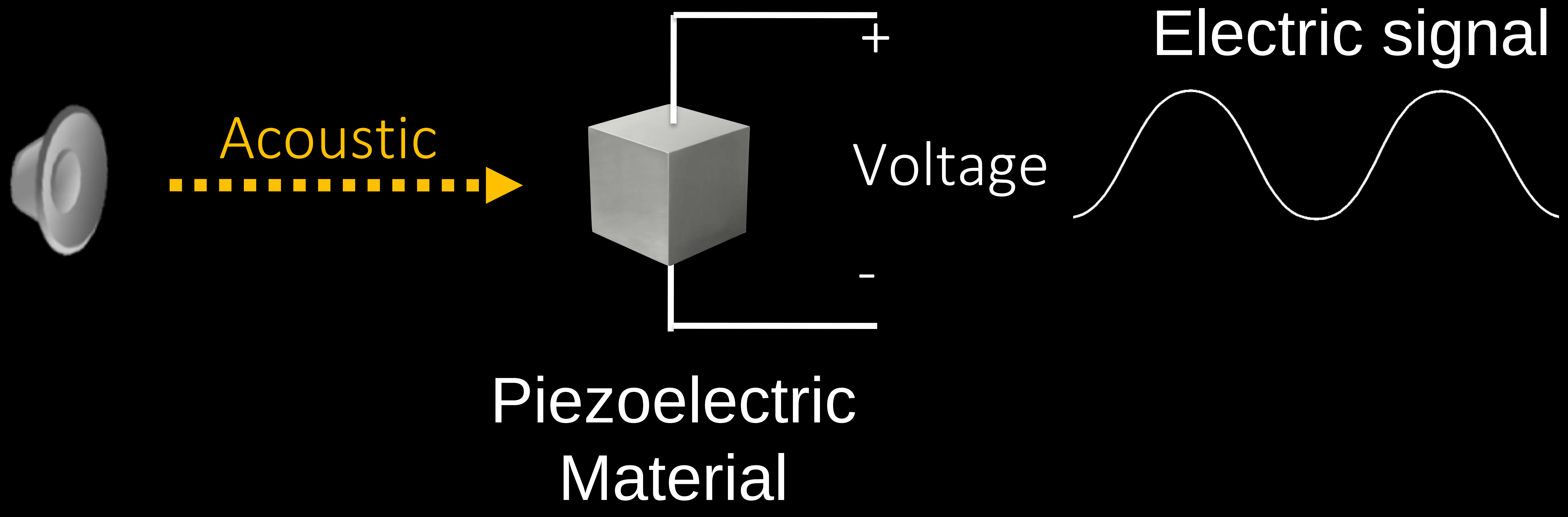




Acoustic
Reflector

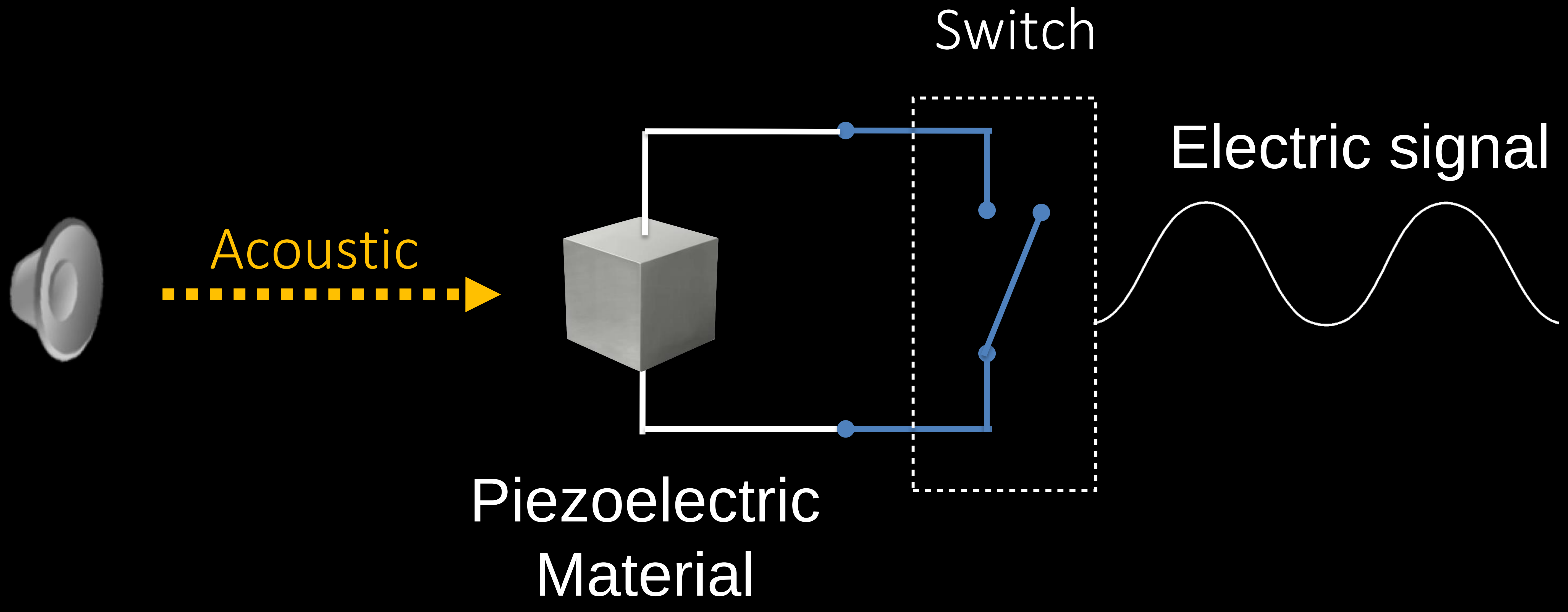
Key Idea: Use piezoelectricity to design programmable acoustic reflectors

Piezoelectric materials transform mechanical to electrical energy



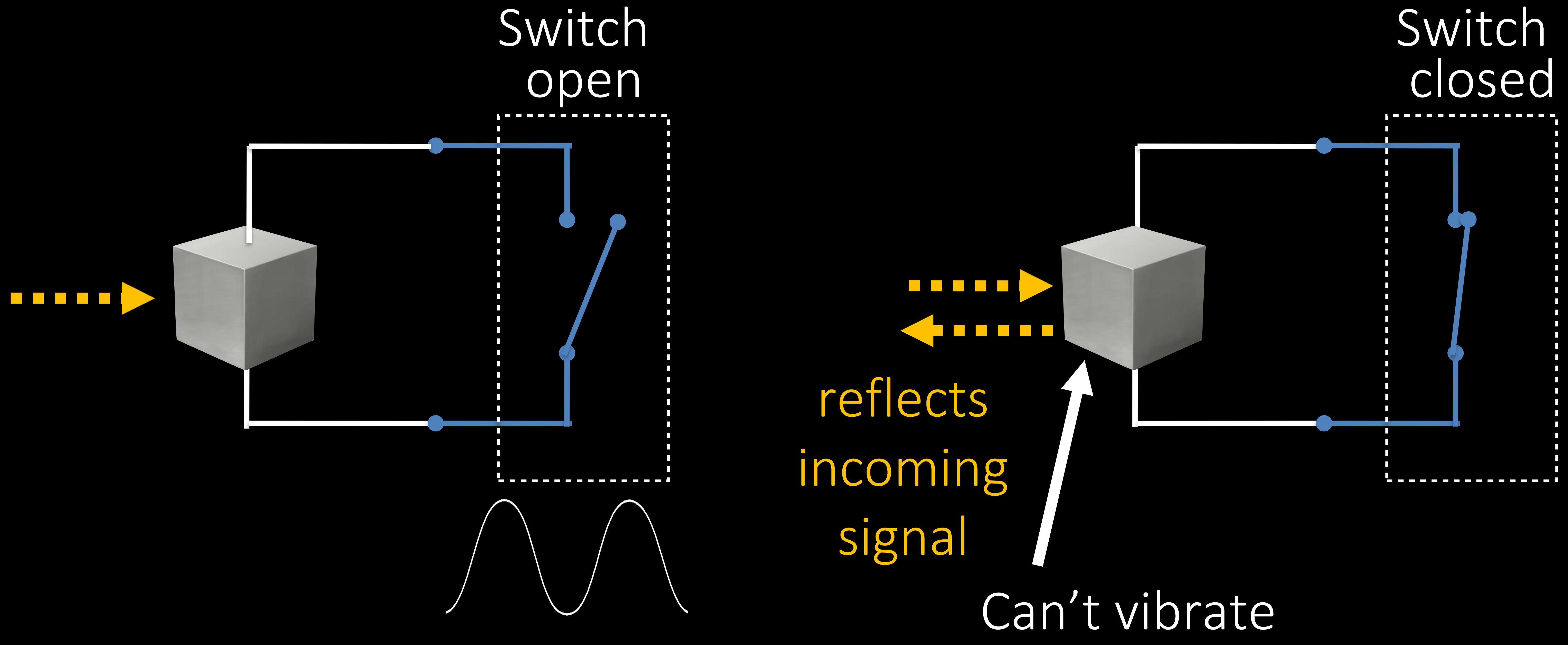
Key Idea: Use piezoelectricity to design programmable acoustic reflectors

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

Switch open

Switch closed

PAB 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

Piezoelectric Transducers (Physics)

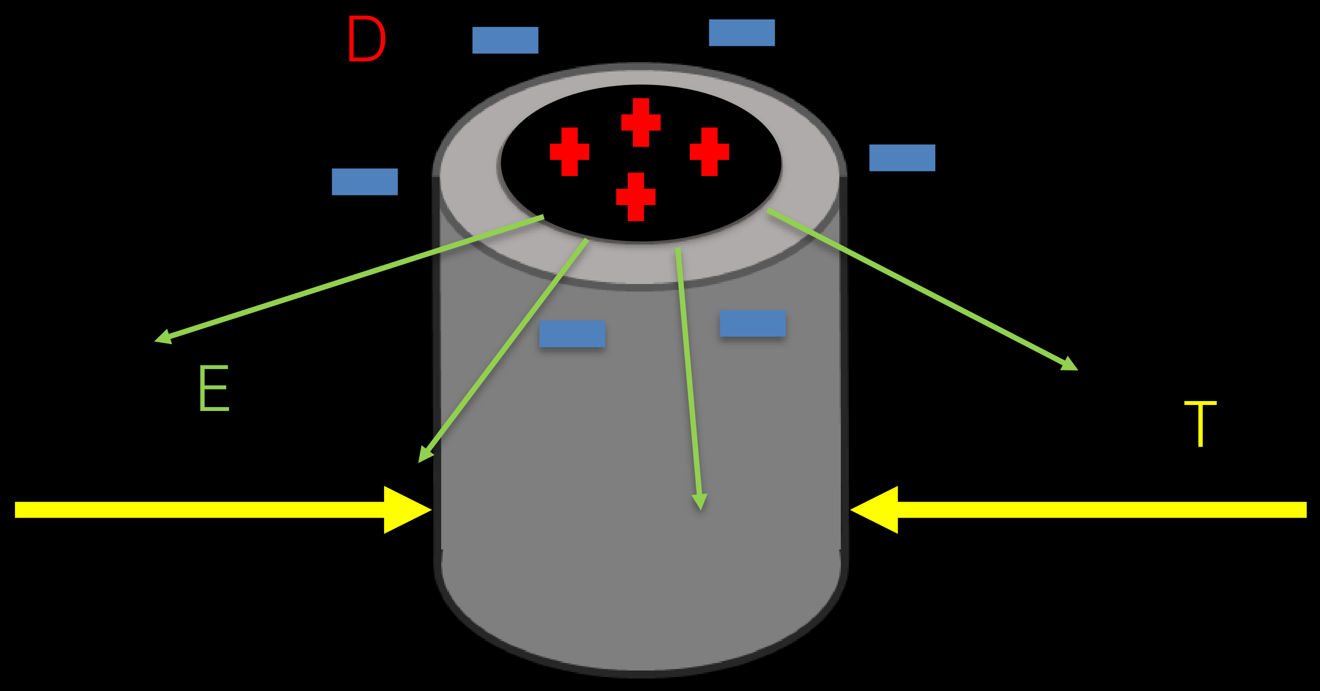
Stress, Strain, Resonance frequency, Impedance matching

$$D = dT + \epsilon^T E$$

Charge Displacement

Stress

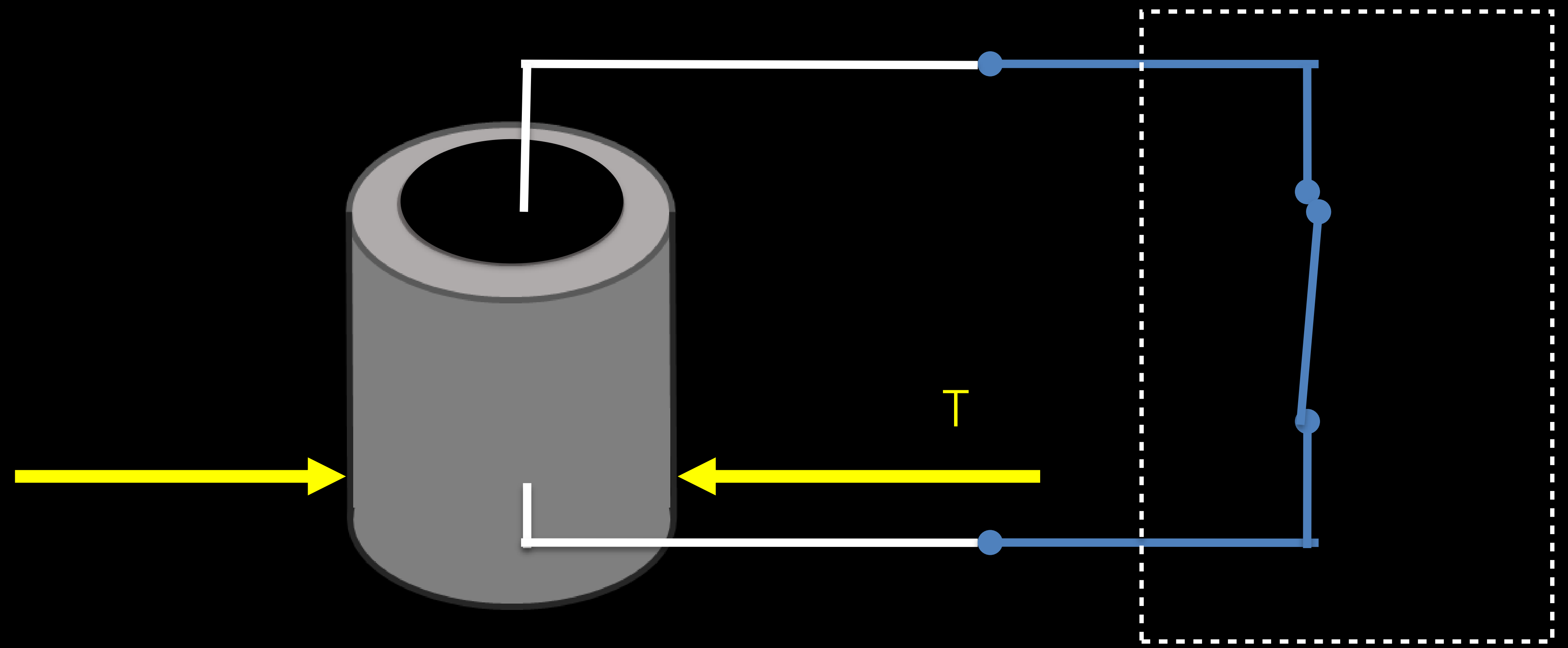
Electric Field



Piezoelectric Transducers (Physics)

Stress, Strain, Resonance frequency, Impedance matching

$$D = dT + \epsilon^T E$$



$T = 0$

Piezoelectric Transducers (Physics)

Stress, Strain, Resonance frequency, Impedance matching

$$D = dT + \epsilon^T E$$

$T = 0 \longleftarrow$ Net Stress

$T = P_{ref} + P_{in}$

$P_{in} = P_o \sin(2\pi f t)$

$P_{ref} = -P_o \sin(2\pi f t) \longleftarrow$ The same signal gets reflected back

Piezoelectric Transducers (Physics)

Stress, Strain, Resonance frequency, Impedance matching

$$D = dT + \epsilon^T E$$

$$S = s^E T + dE$$

Total Deformation (strain)

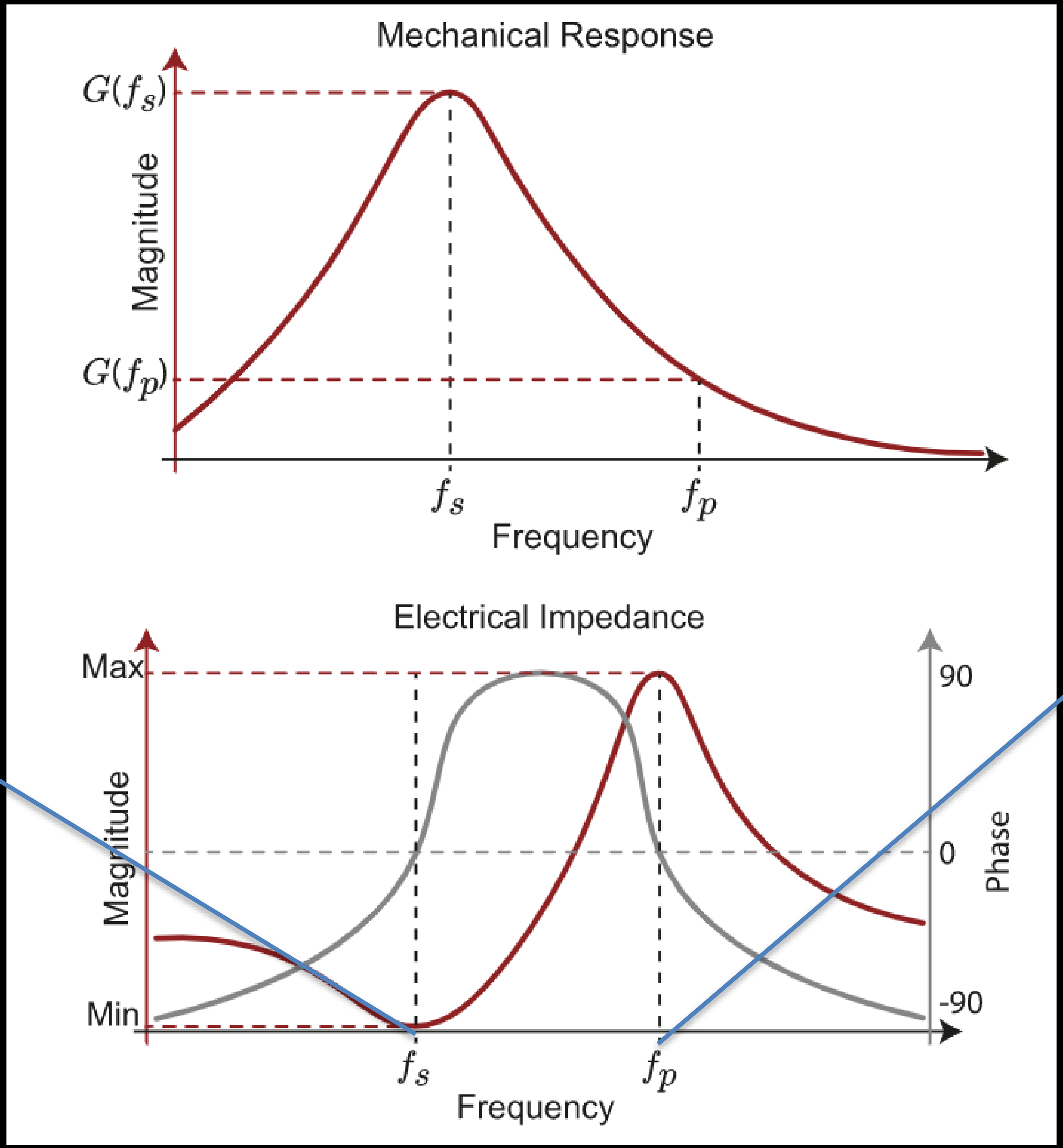
Compliance coefficient

$T = 0, E = 0$ ← Strain = 0, the material cannot deform

Piezoelectric Transducers (Physics) -- Continued

Stress, Strain, **Resonance frequency**, Impedance matching

Resonance



Anti-Resonance

Piezoelectric Transducers (Physics) -- Continued

Stress, Strain, Resonance frequency, **Impedance matching**

- Resonance is a function of frequency, to get maximum power transfer, we need to match impedance of our circuit to the impedance of the piezo transducer (at resonance)

$$Z_L = Z_s^*$$

- Impedance matching can also improve SNR, reflected power:

$$P_r = \left| \frac{Z_L - Z_s^*}{Z_L + Z_s} \right|^2$$

Piezoelectric Transducers (Physics) -- Continued

Stress, Strain, Resonance frequency, **Impedance matching**

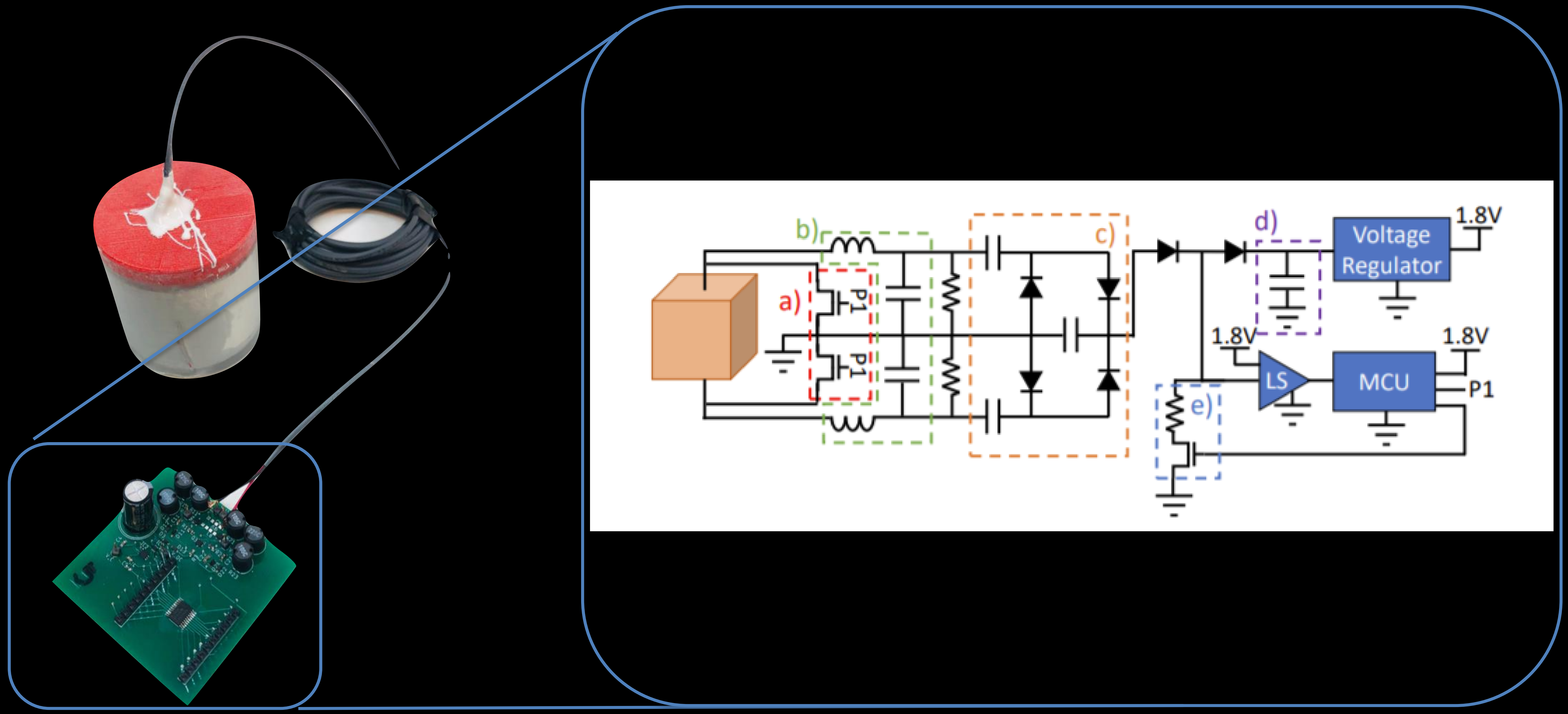
- Resonance is a function of frequency, to get maximum power transfer, we need to match impedance of our circuit to the impedance of the piezo transducer (at resonance)

$$Z_L = Z_s^*$$

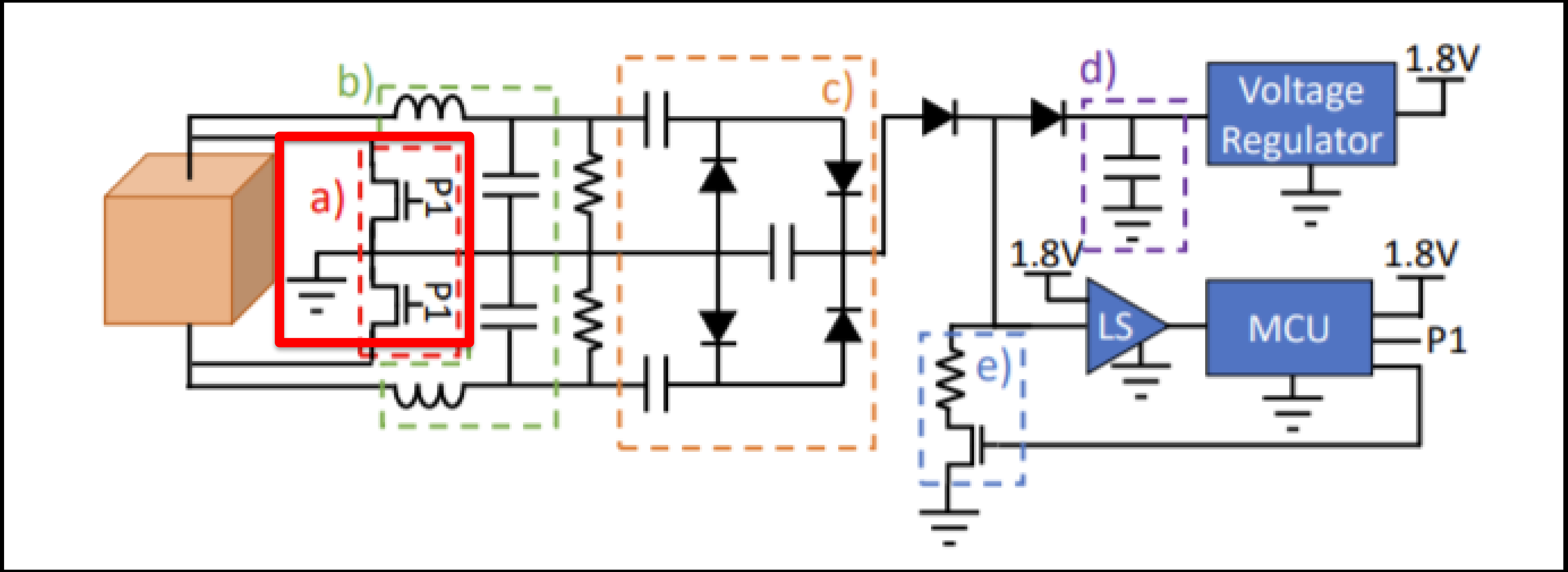
- Impedance matching can also improve SNR, reflected power:

$$P_r = \left| \frac{Z_L - Z_s^*}{Z_L + Z_s} \right|^2$$

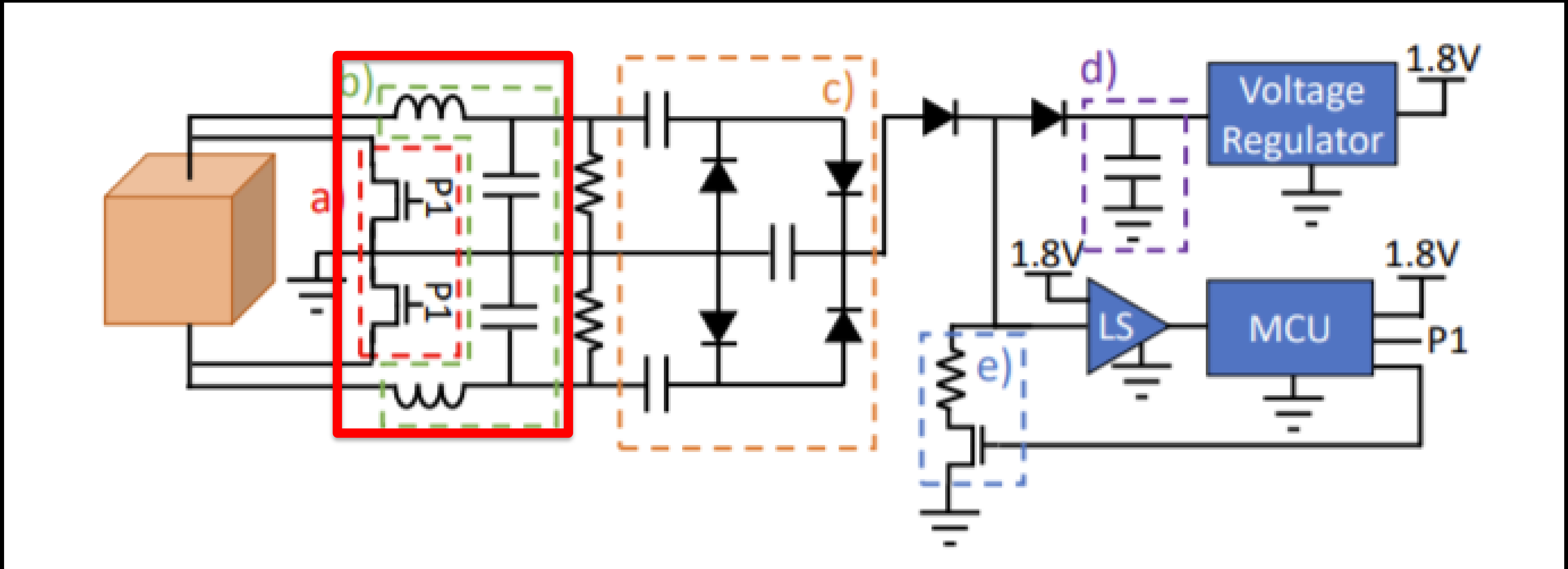
Piezo Acoustic Backscatter -- Circuit Design



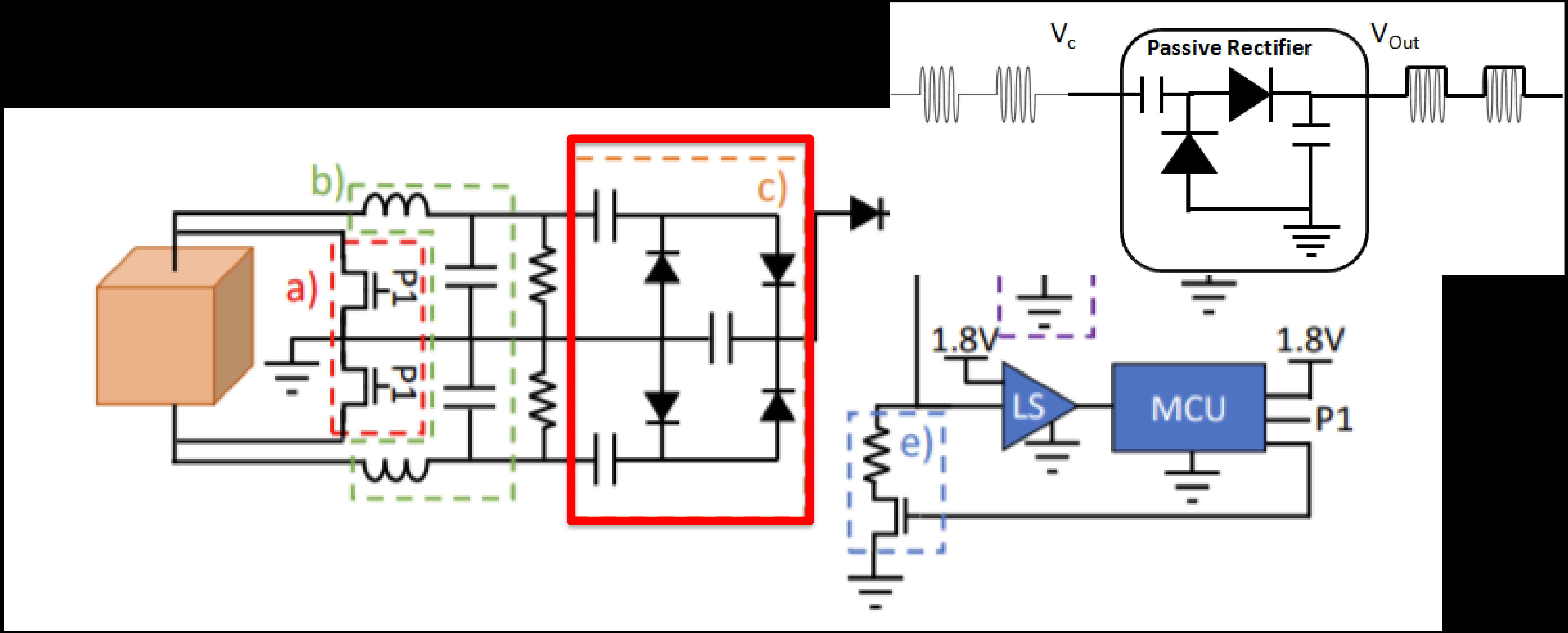
Piezo Acoustic Backscatter -- Circuit Design (Continued)



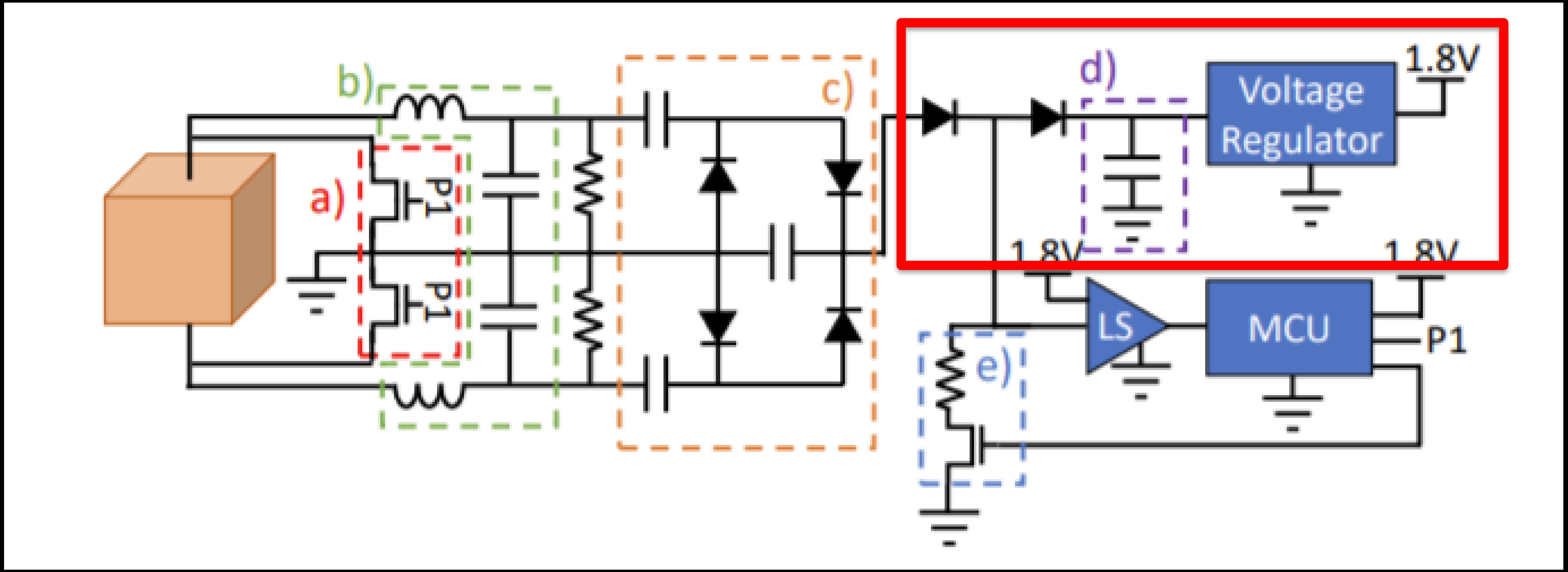
Piezo Acoustic Backscatter -- Circuit Design (Continued)



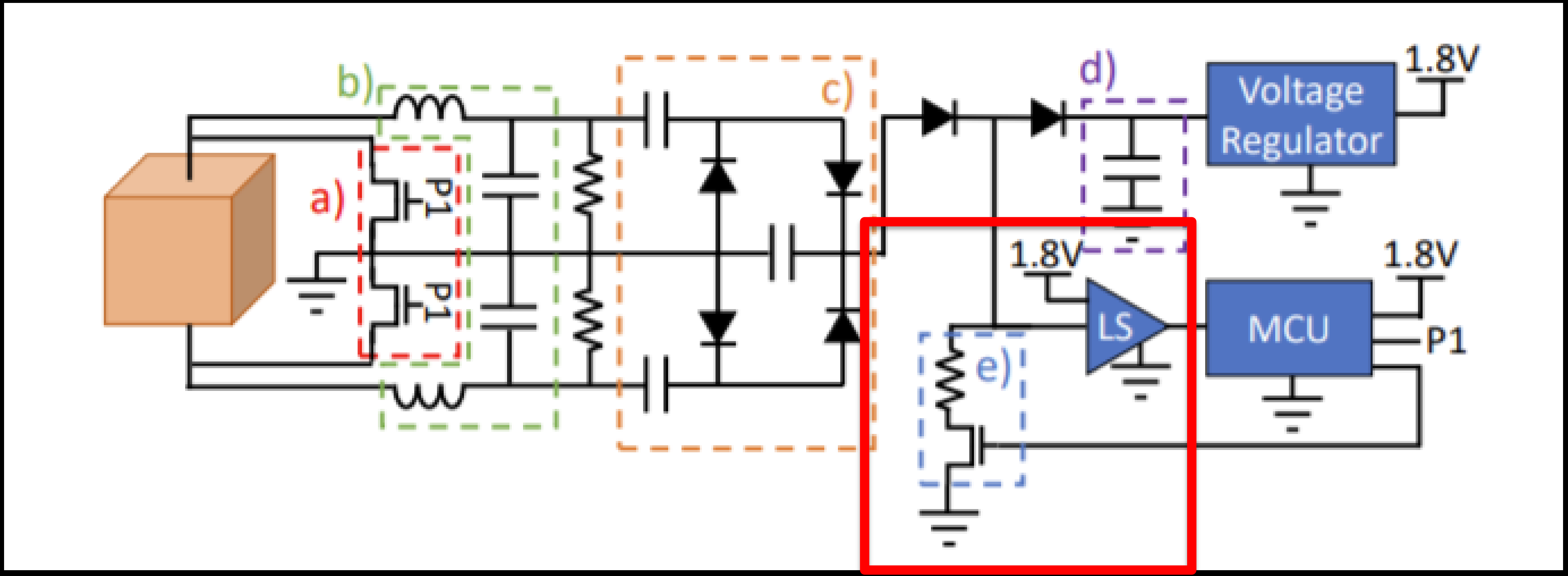
Piezo Acoustic Backscatter -- Circuit Design (Continued)



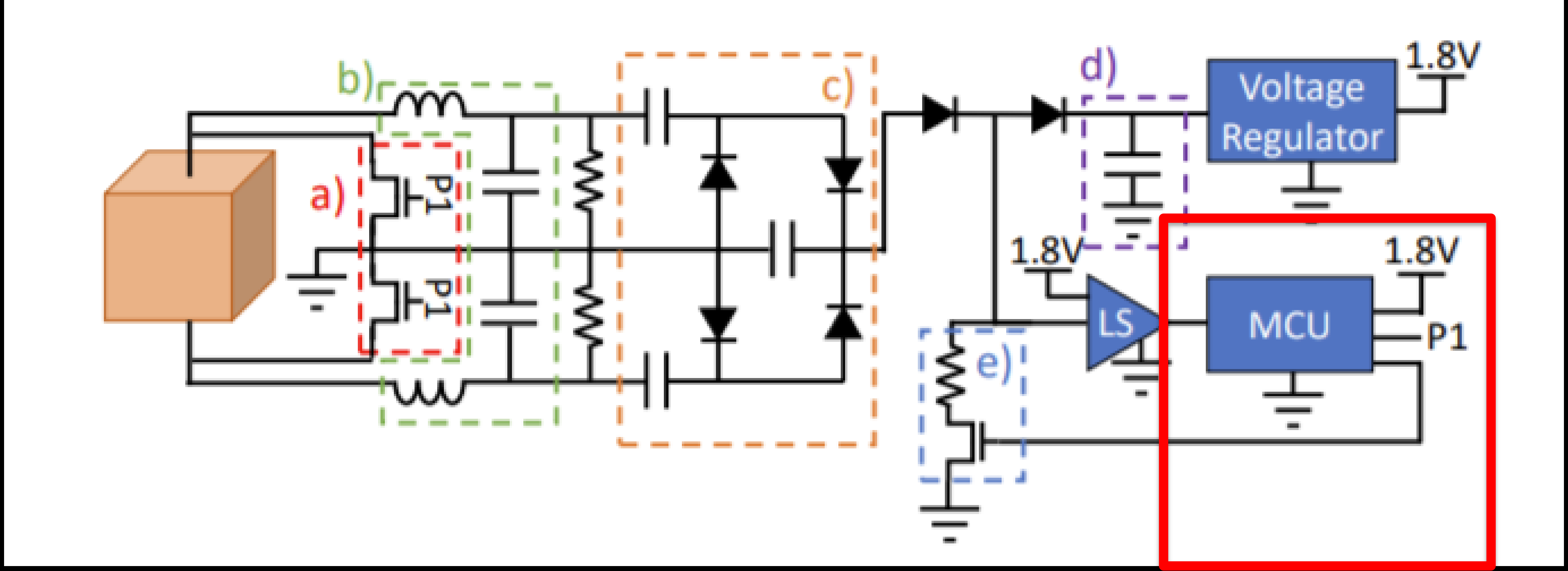
Piezo Acoustic Backscatter -- Circuit Design (Continued)



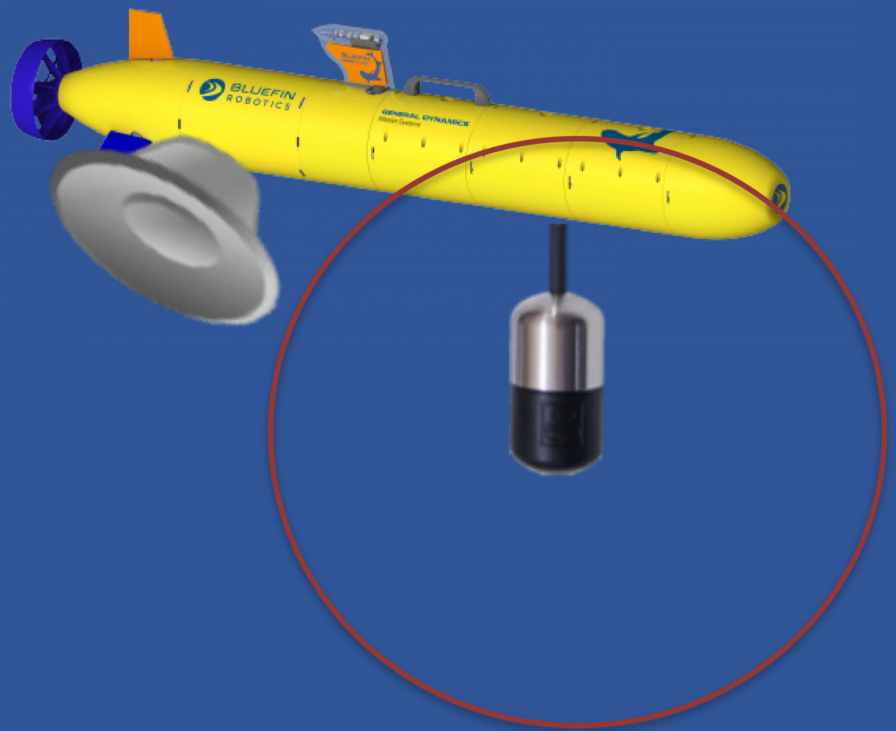
Piezo Acoustic Backscatter -- Circuit Design (Continued)



Piezo Acoustic Backscatter -- Circuit Design (Continued)

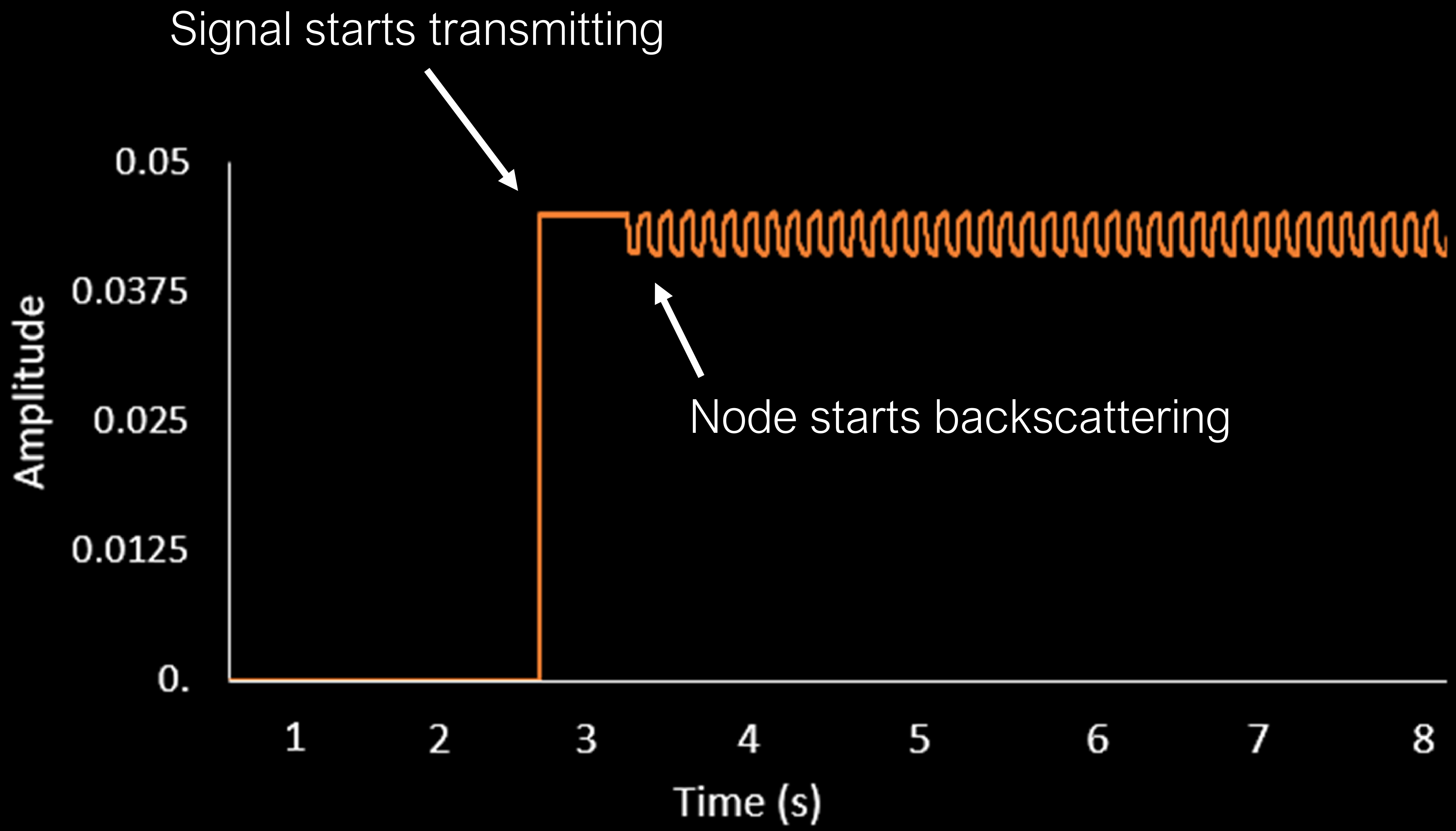


Underwater Backscatter : Hydrophone



Acoustic Reflector

Measuring the Backscatter Signal (by Hydrophone)



Channel Estimation (Math)

$$y = h_2 \sin(2\pi f t) + h_1 h_3 p \sin(2\pi f t)$$

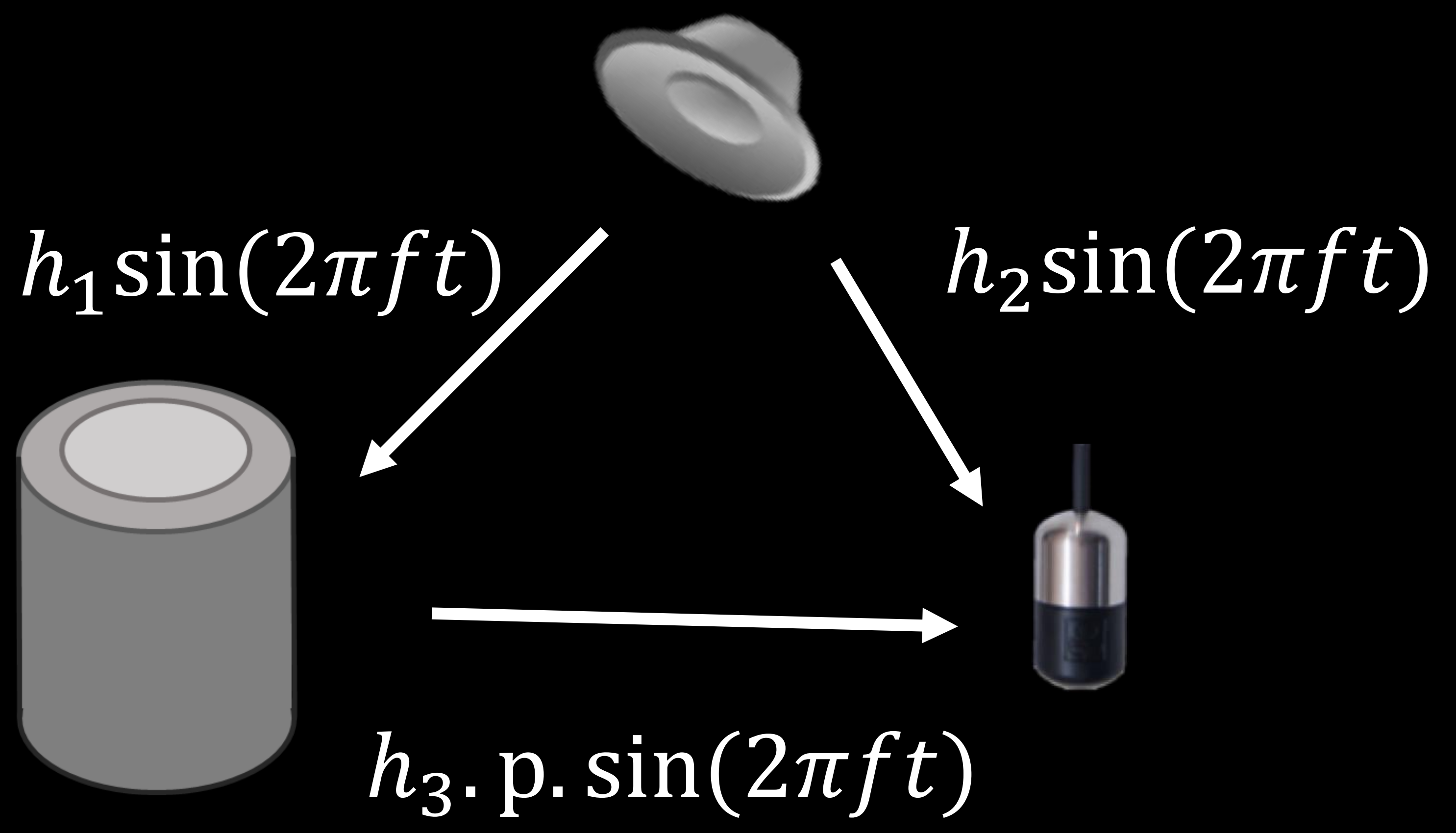
$$y = h_2 \sin(2\pi f t) + h.p.\sin(2\pi f t)$$

$$yd = LPF(y * \sin(2\pi f t))$$

$$yd = h_2 + h.p$$

If preamble is zero mean then:

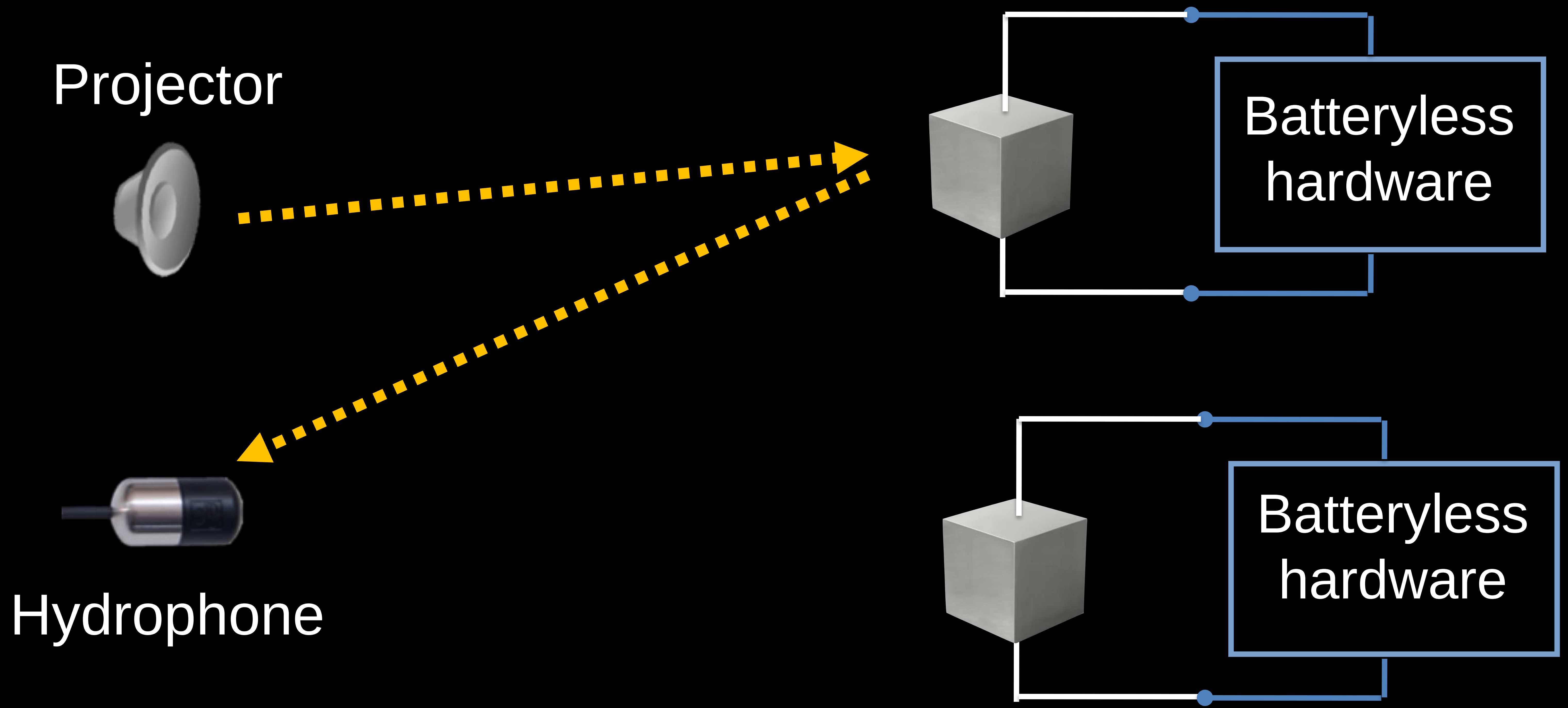
$$h = \frac{\sum(h_2 + h.p)p}{\|p\|^2}$$



Extending to Multiple Nodes

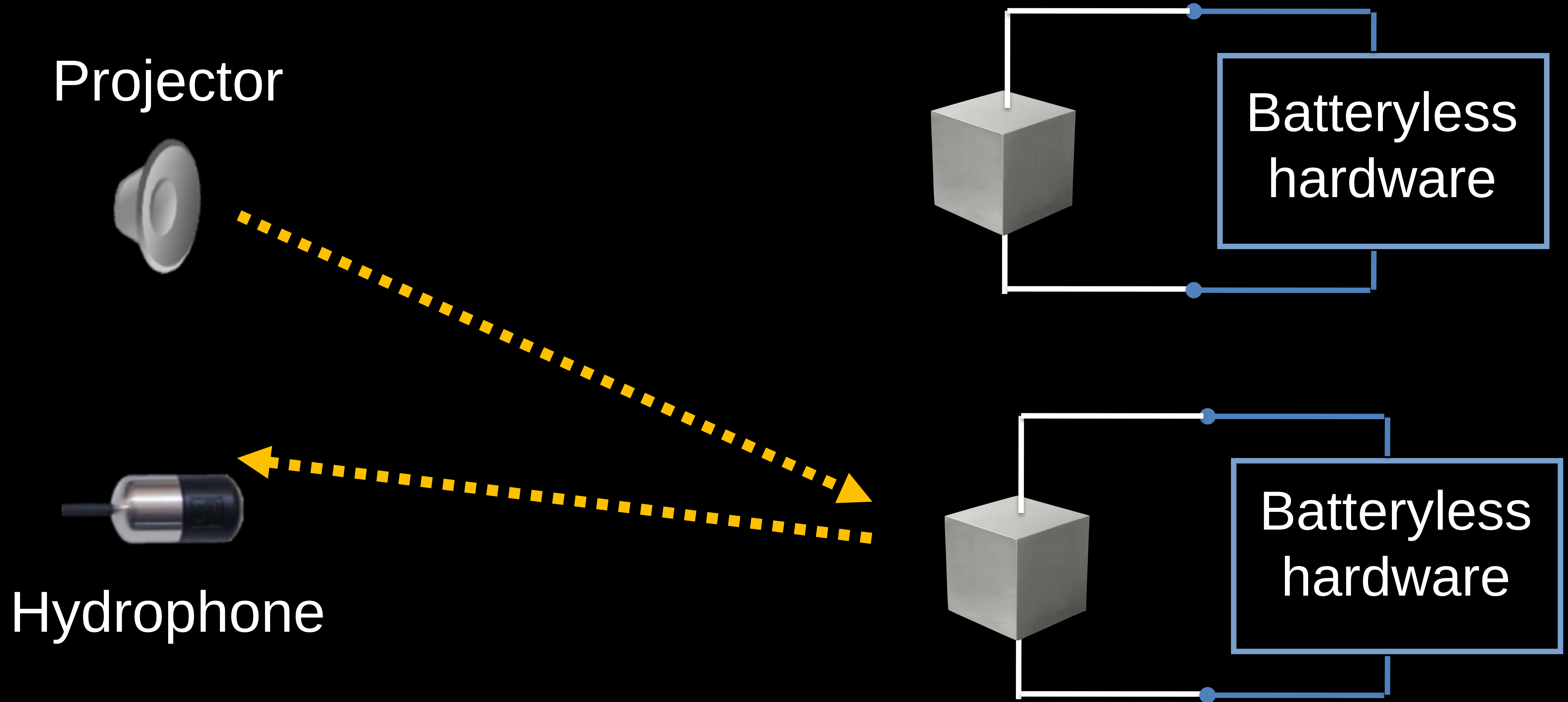
Extending to Multiple Nodes

Option 1: Time Division Multiplexing



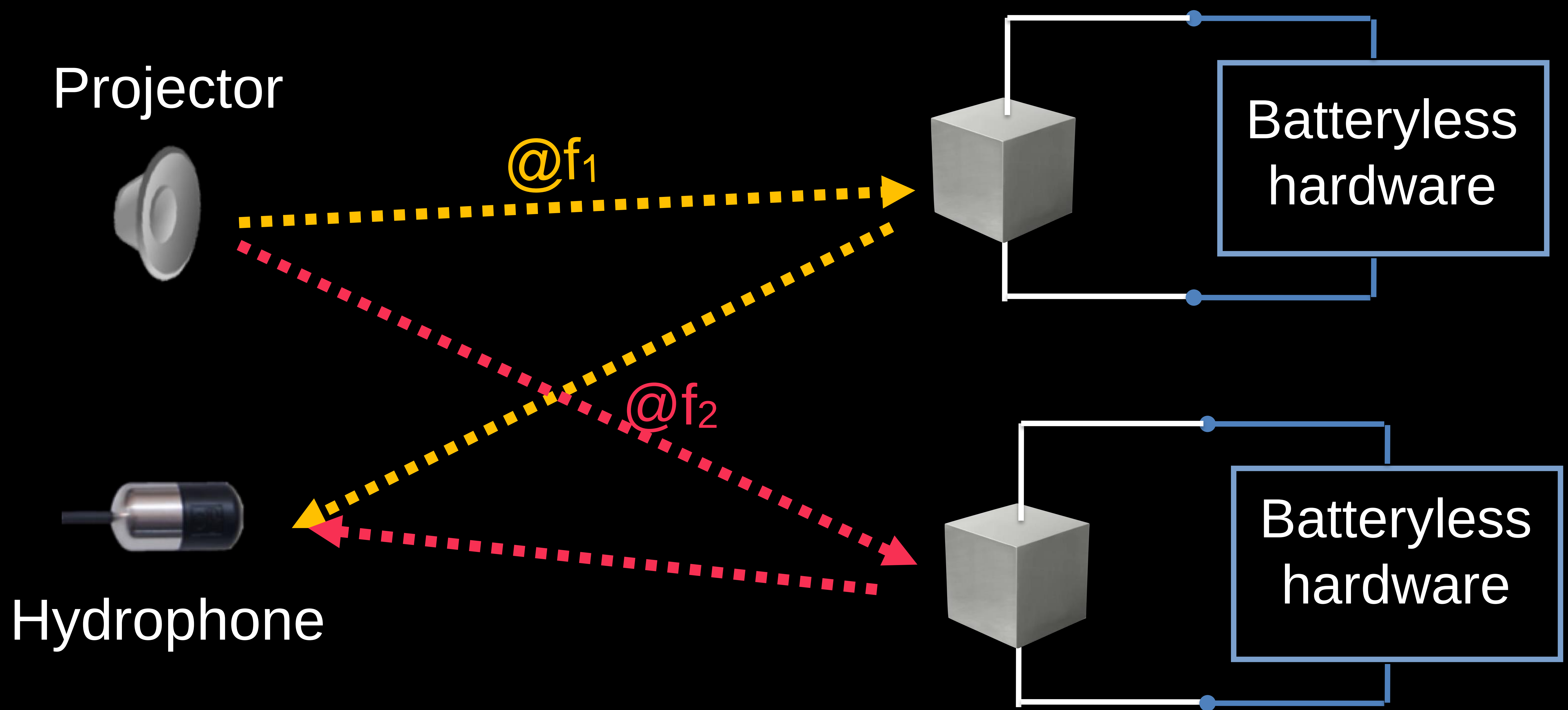
Extending to Multiple Nodes

Option 1: Time Division Multiplexing



Extending to Multiple Nodes

Option 2: Frequency Division Multiplexing

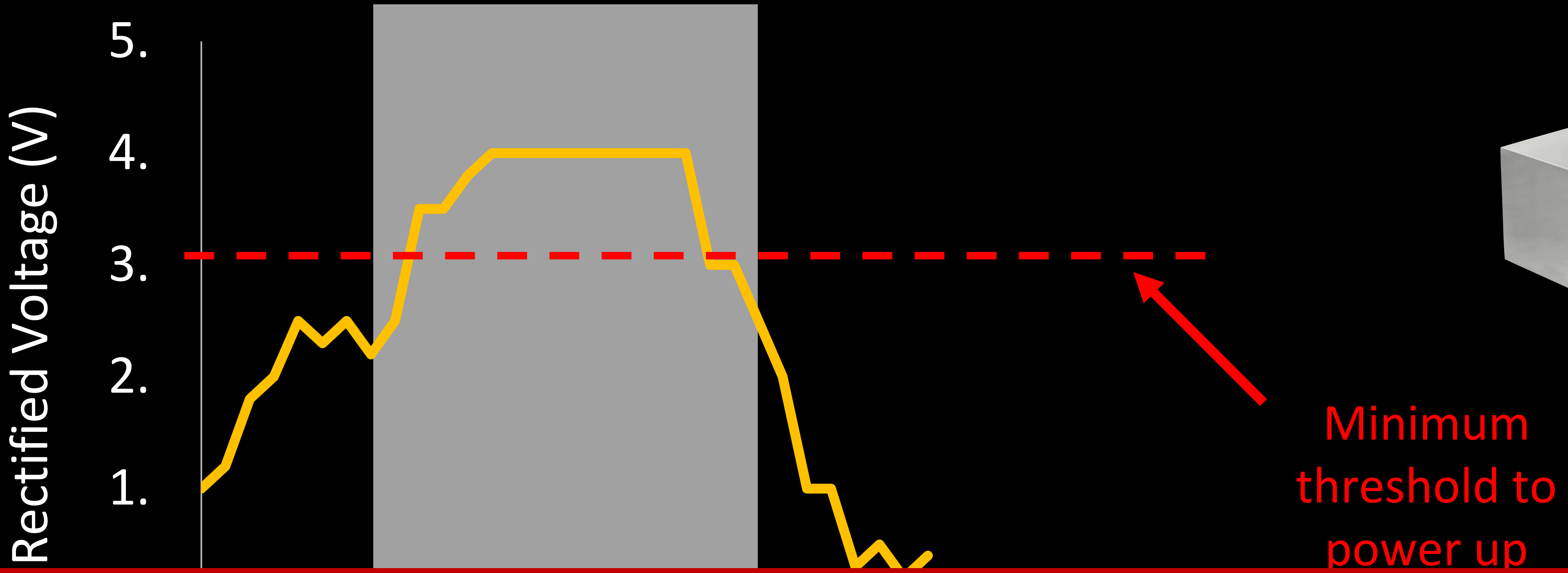


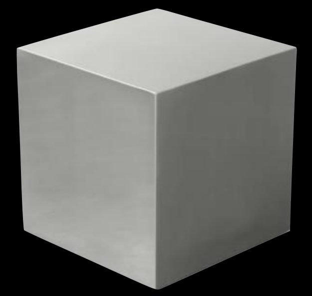
Extending to Multiple Nodes

Problem: Resonance of piezoelectrics limits their bandwidth

Extending to Multiple Nodes

<u>Problem:</u> 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

<u>Solution Idea:</u> Shift the resonance frequency *itself* to a different channel

resonance frequency determined by interaction between piezo & the batteryless circuit

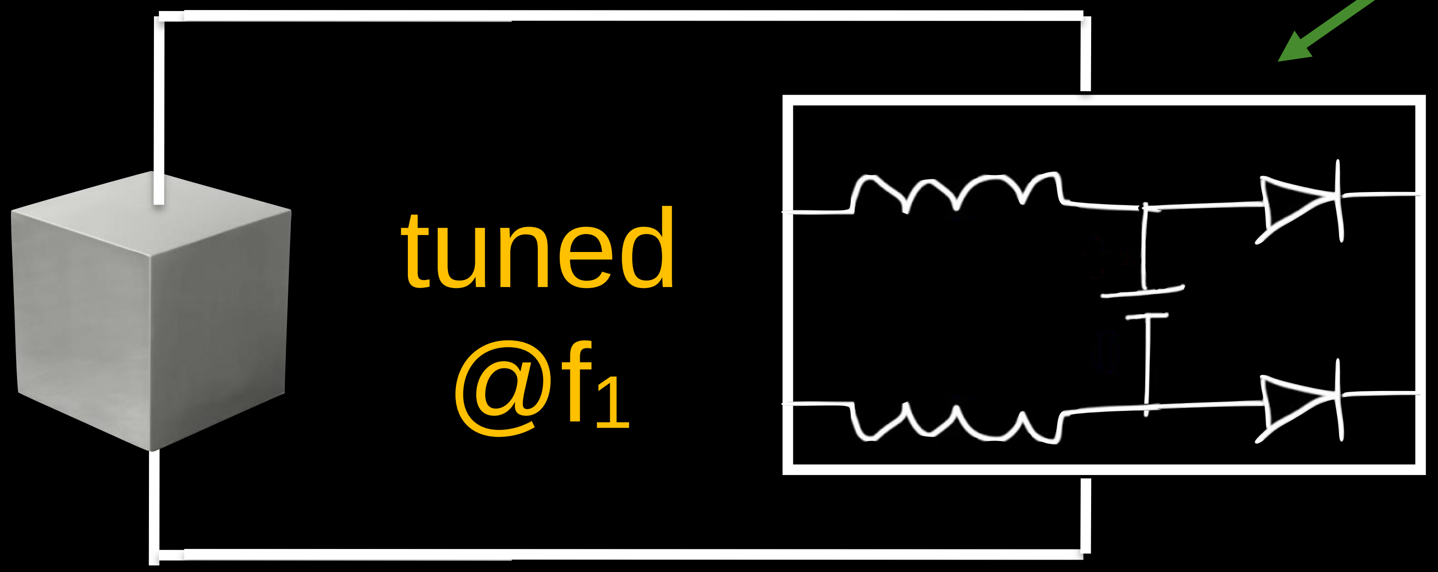
$$Z_{circuit}(f) = Z^{*}_{piezo}(f)$$

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

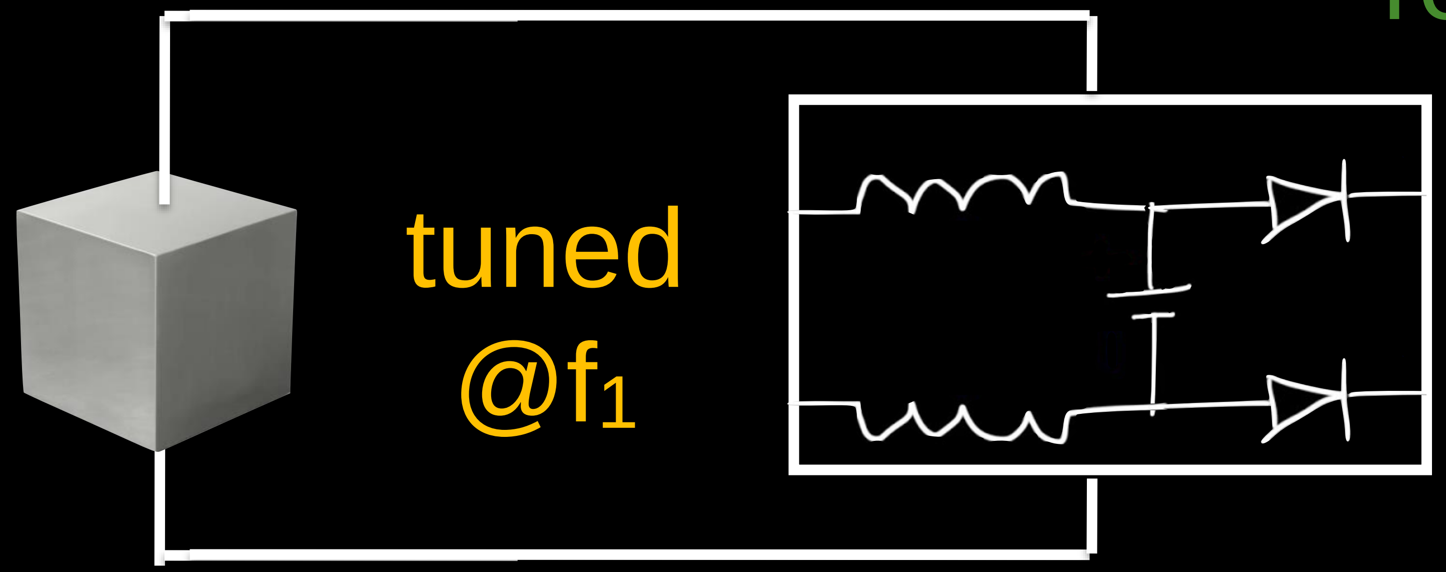


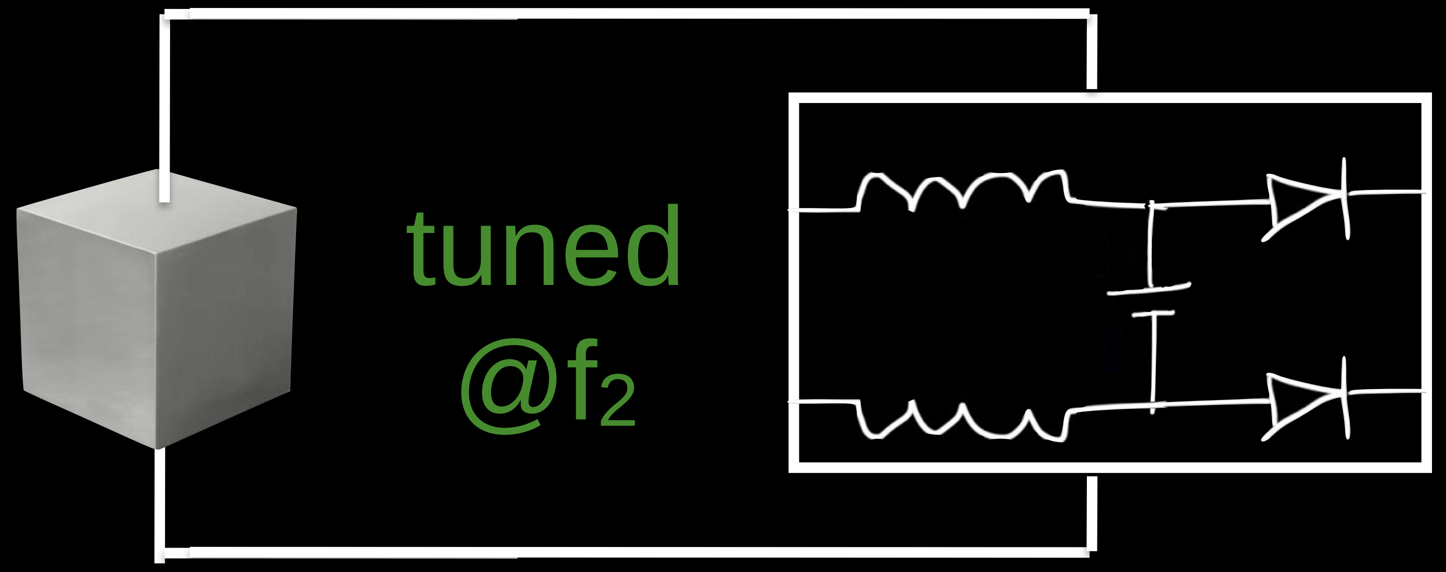
$$Z_{circuit}(f) = Z^{*}_{piezo}(f)$$

frequency dependent

→Tune the circuit to a different frequency

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





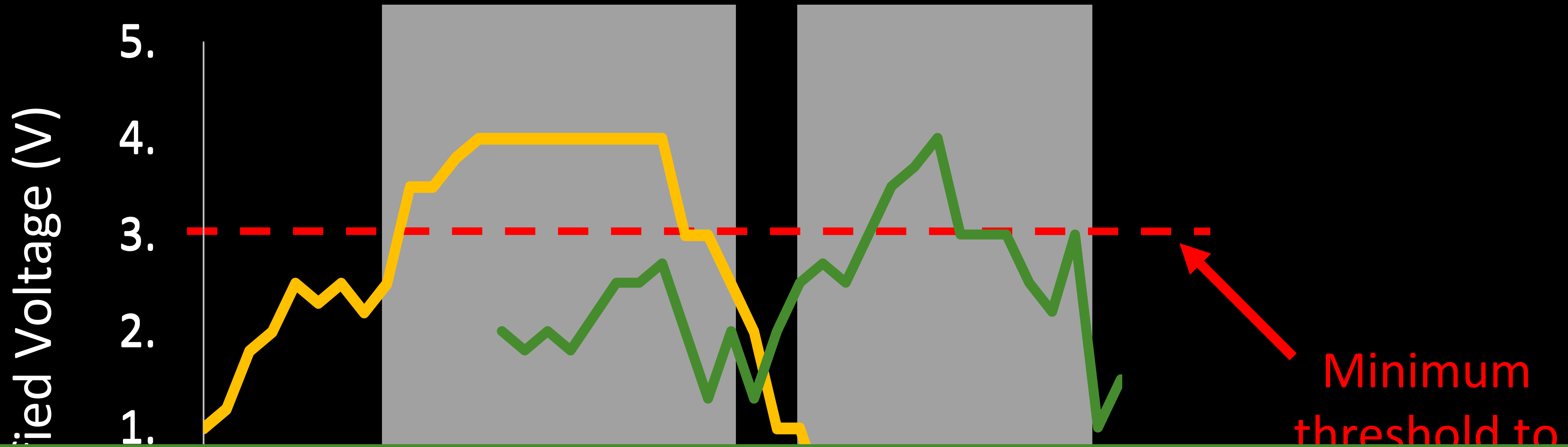
resonance frequency determined by interaction between piezo & the batteryless circuit

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

frequency dependent

→Tune the circuit to a different frequency

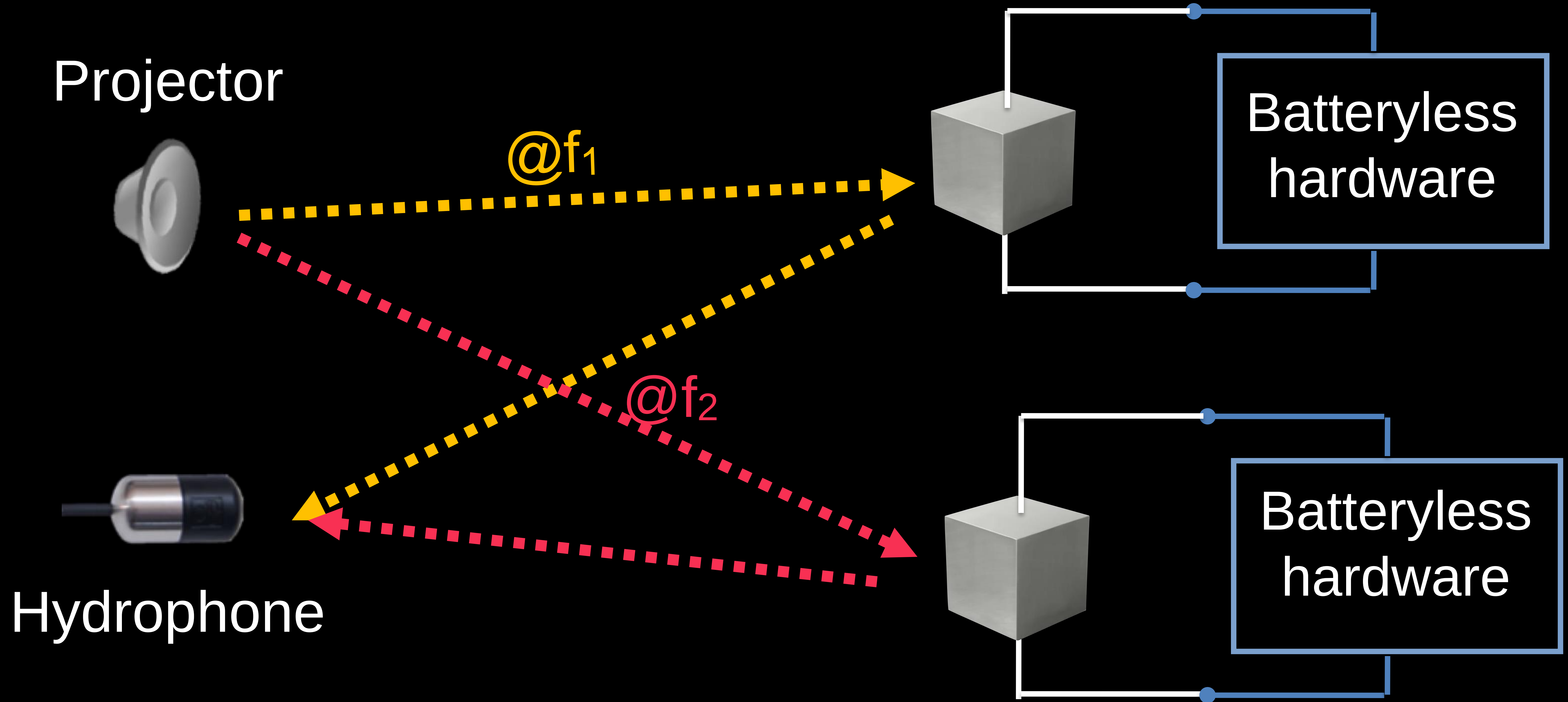
Solution Idea: Shift the resonance frequency *itself* to a different channel



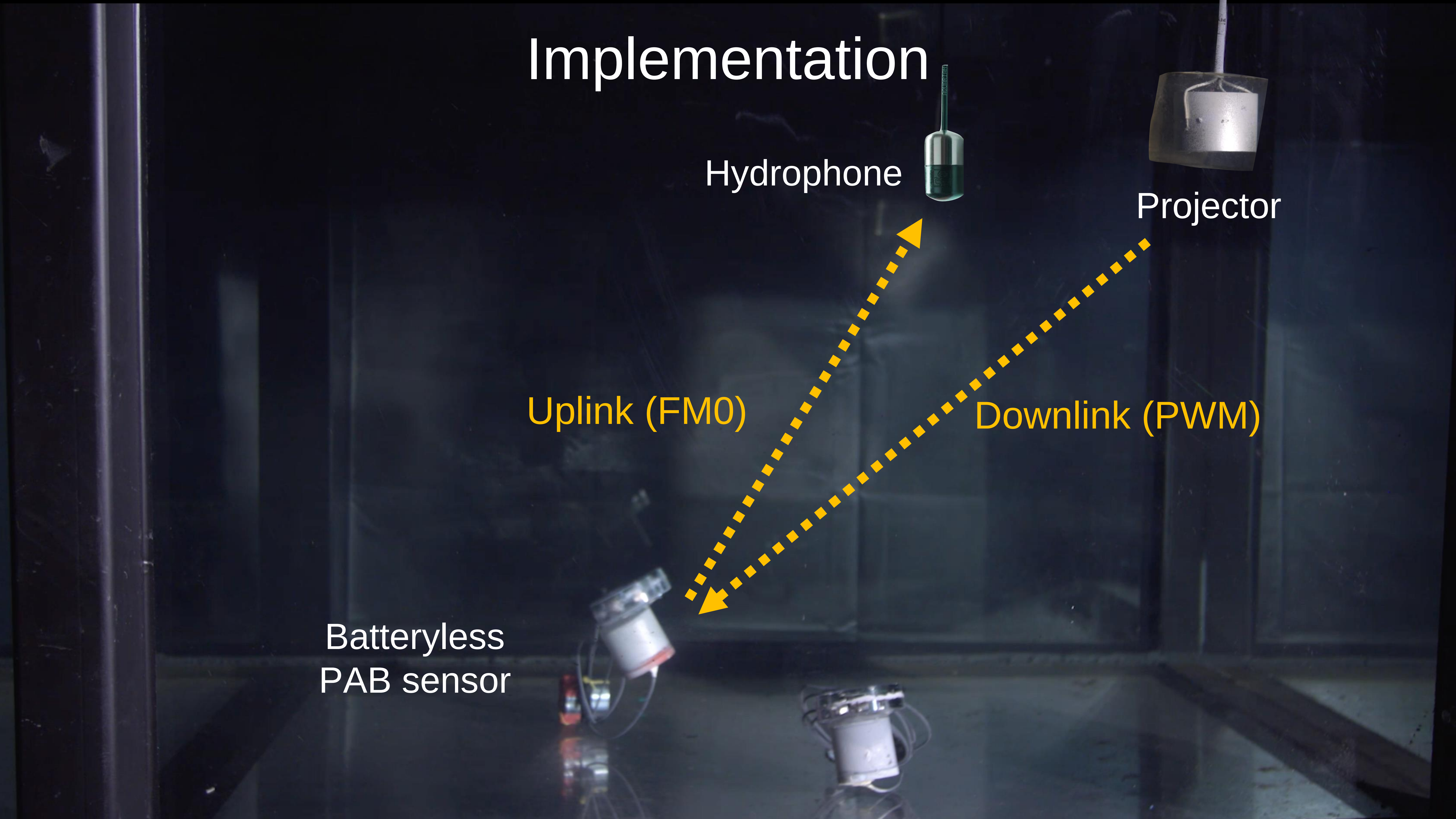
Extend the idea to uplink communication using a MIMO-style decoder adapted to backscatter resonance modes

Extending to Multiple Nodes

Option 2: Frequency Division Multiplexing



Implementation



Objectives of Today's Lecture

Learn **fundamentals** of energy harvesting, backscatter, end-to-end system design

1. Why is it not feasible to use batteries with underwater IoT sensors?

2. What are underwater backscatter systems, why do they consume net-zero power?

3. What are the different components that make an end-to end underwater backscatter system?
   - The physical, mathematical, engineering, and design fundamentals
   - Why are these systems designed the way they are

Next Class (Underwater Localization)

1) Required (Reviews)

- Inverted Ultra-short baseline Localization

2) Optional Readings

- Underwater backscatter localization

Following week pitch projects in the class (slack)

Feedback on Reviews