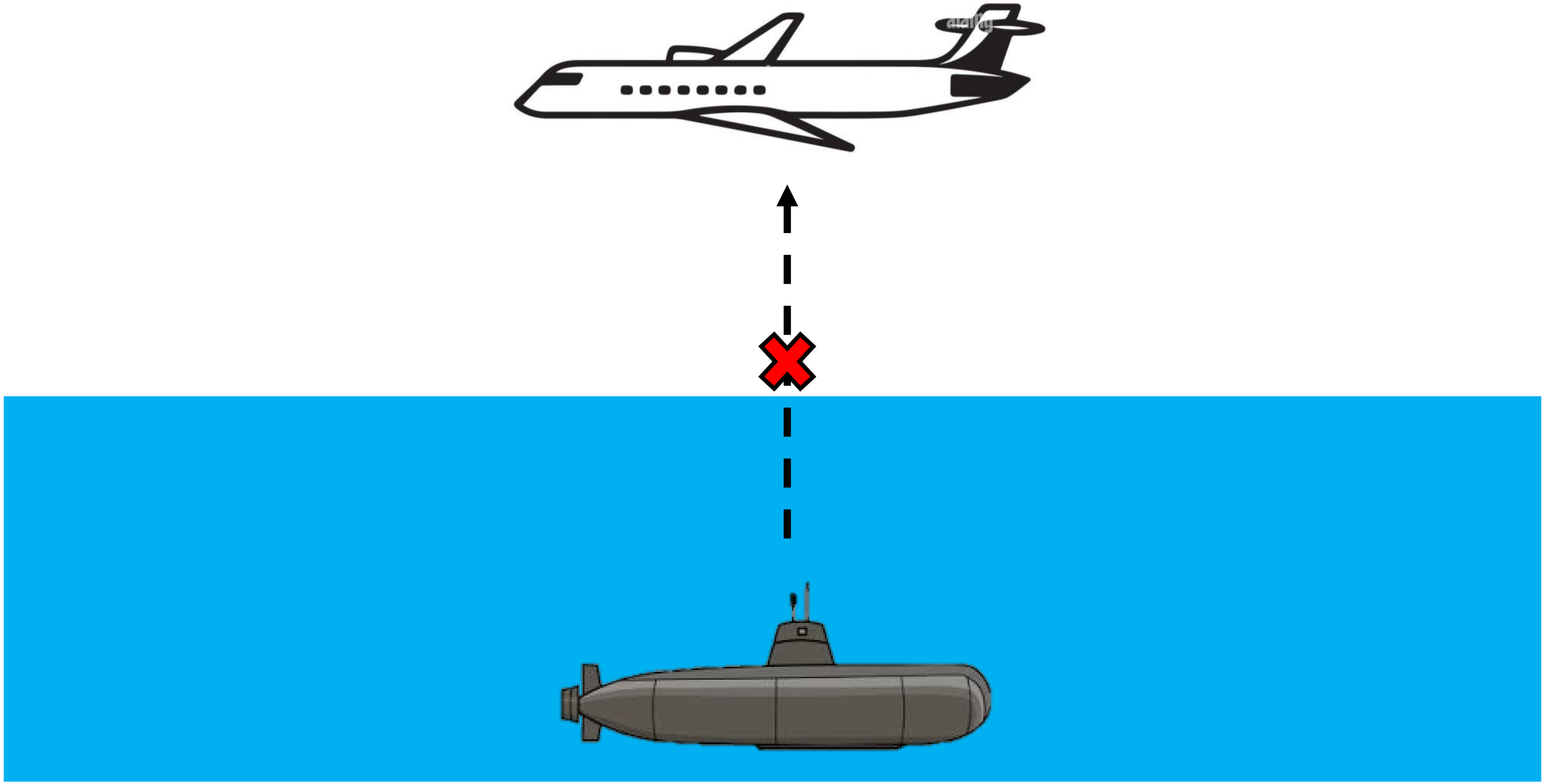
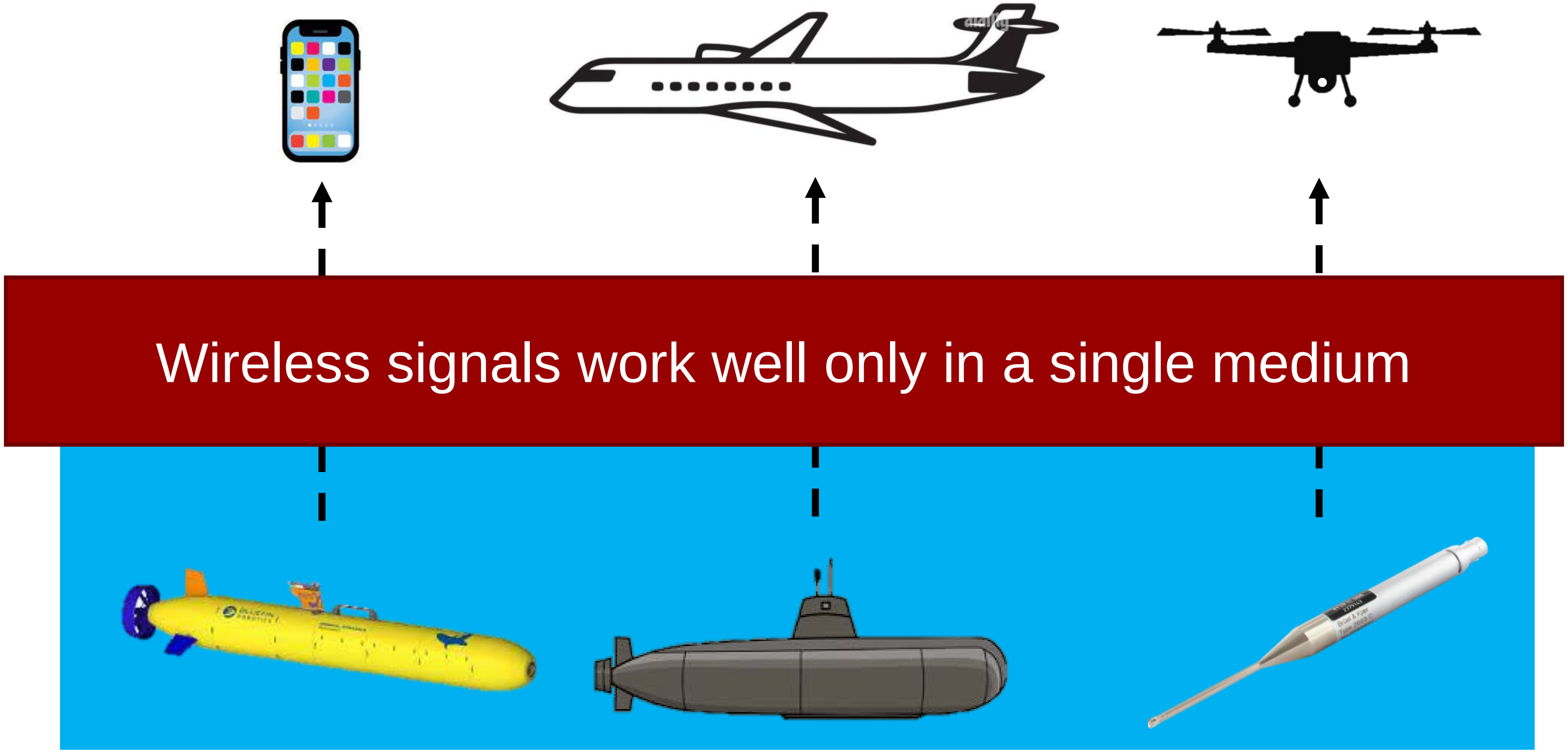
IoT for the climate change

Charalampos Orfanidis (chaorf@dtu.dk)

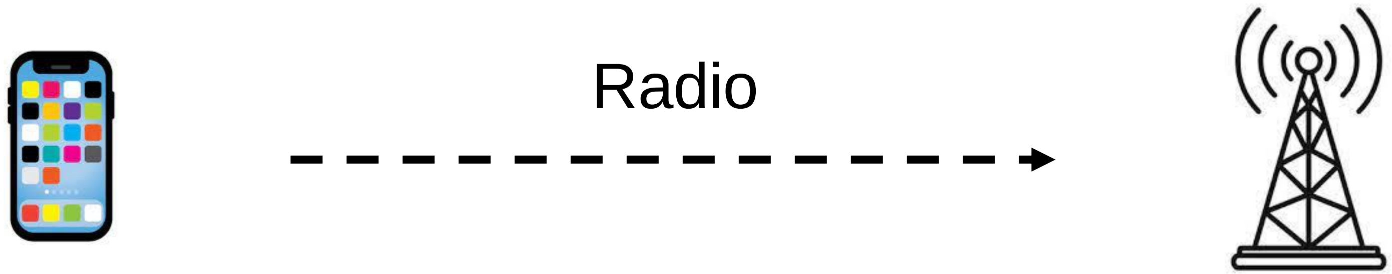
Francesco Tonolini and Fadel Adib. 2018. ***Networking across boundaries: enabling wireless communication through the water-air interface*.** In Proceedings of the 2018 Conference of the ACM Special Interest Group on Data Communication (SIGCOMM '18).

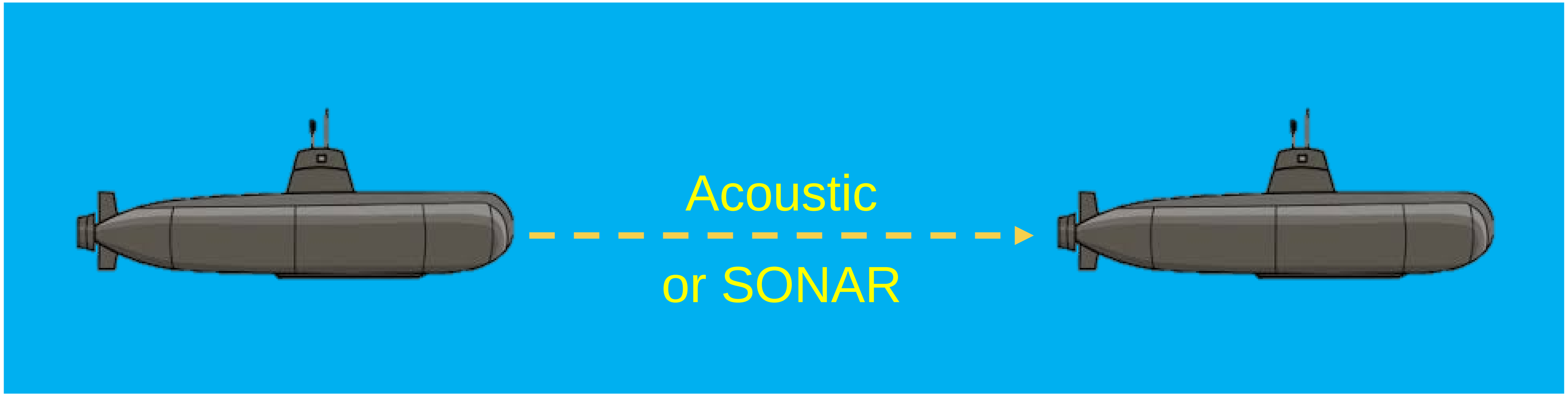


Direct underwater-air communication is infeasible



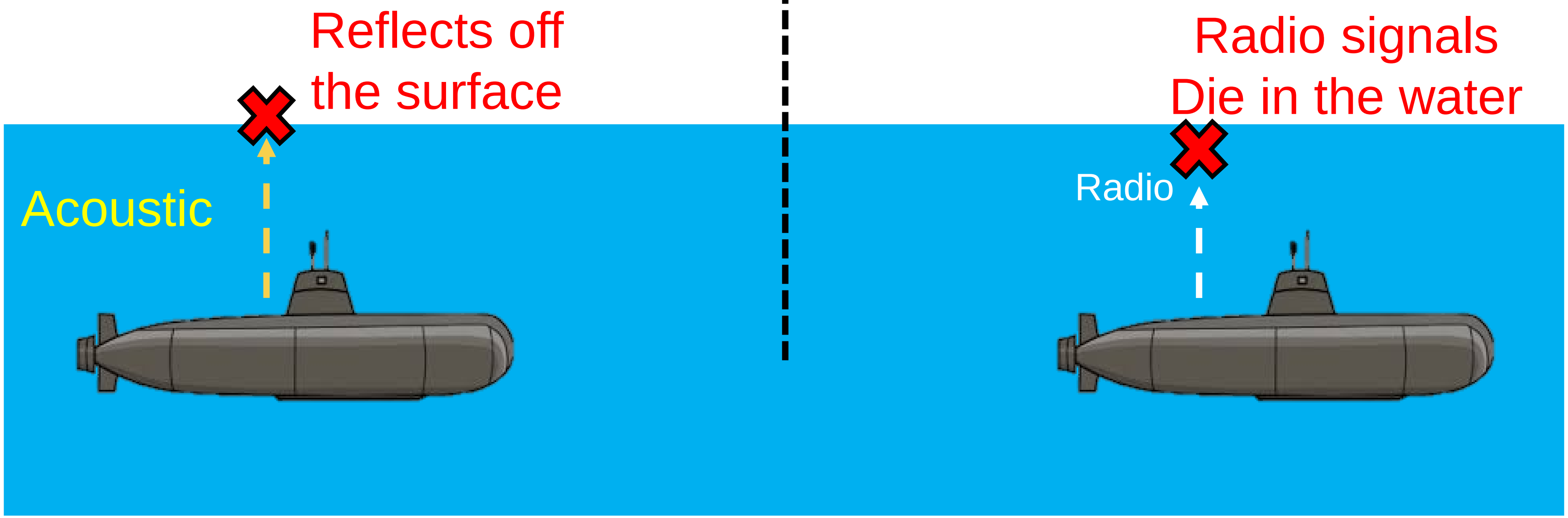
Wireless signals work well only in a single medium



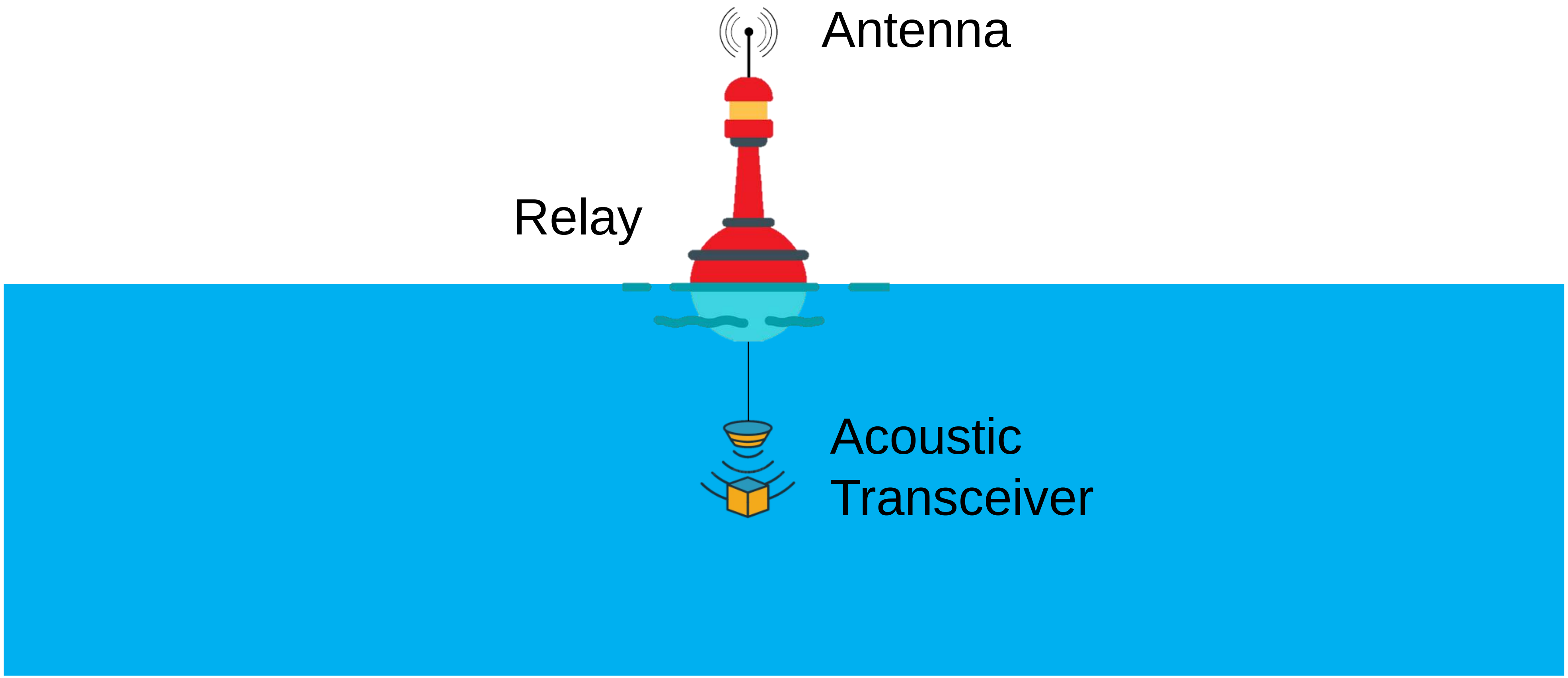


Why we do not use acoustic signals

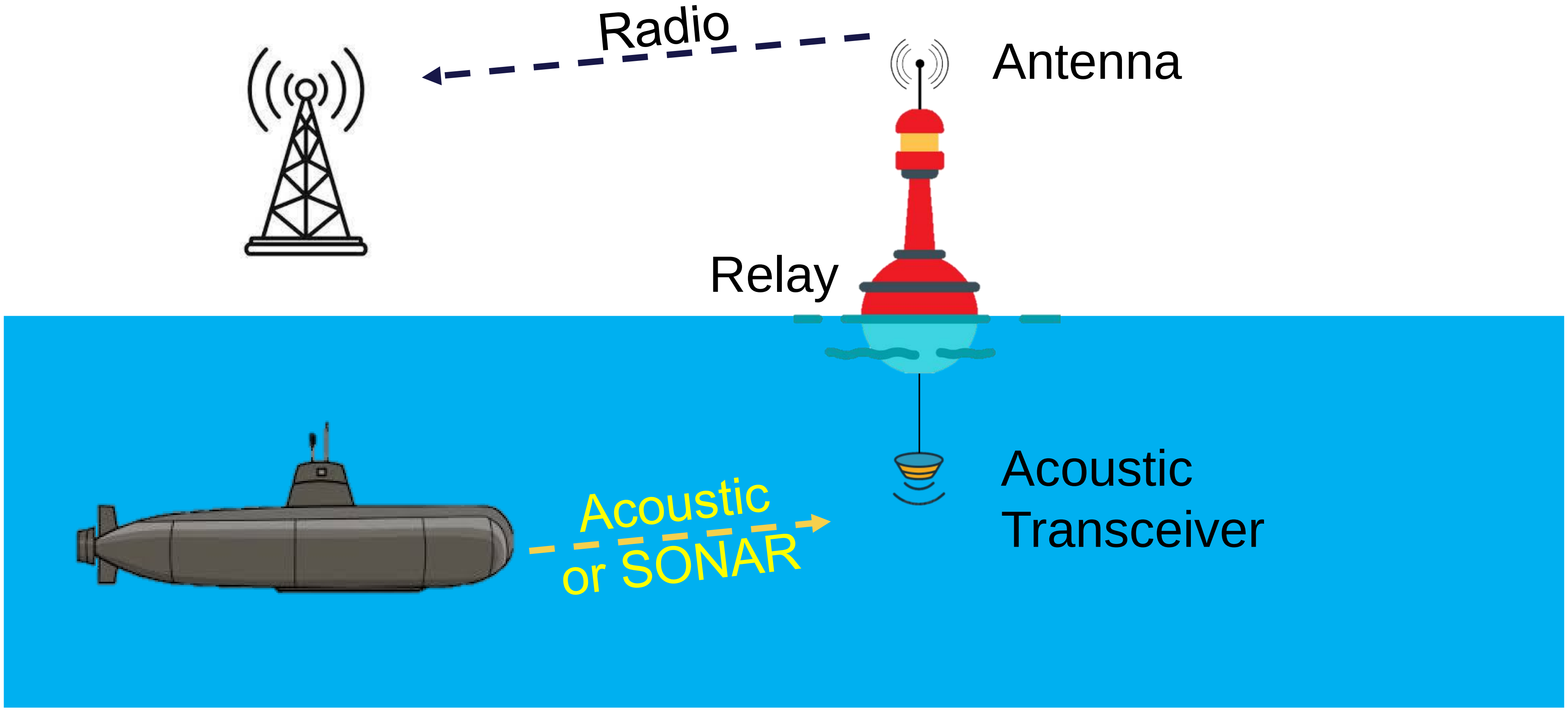
Why we do not use radio signals



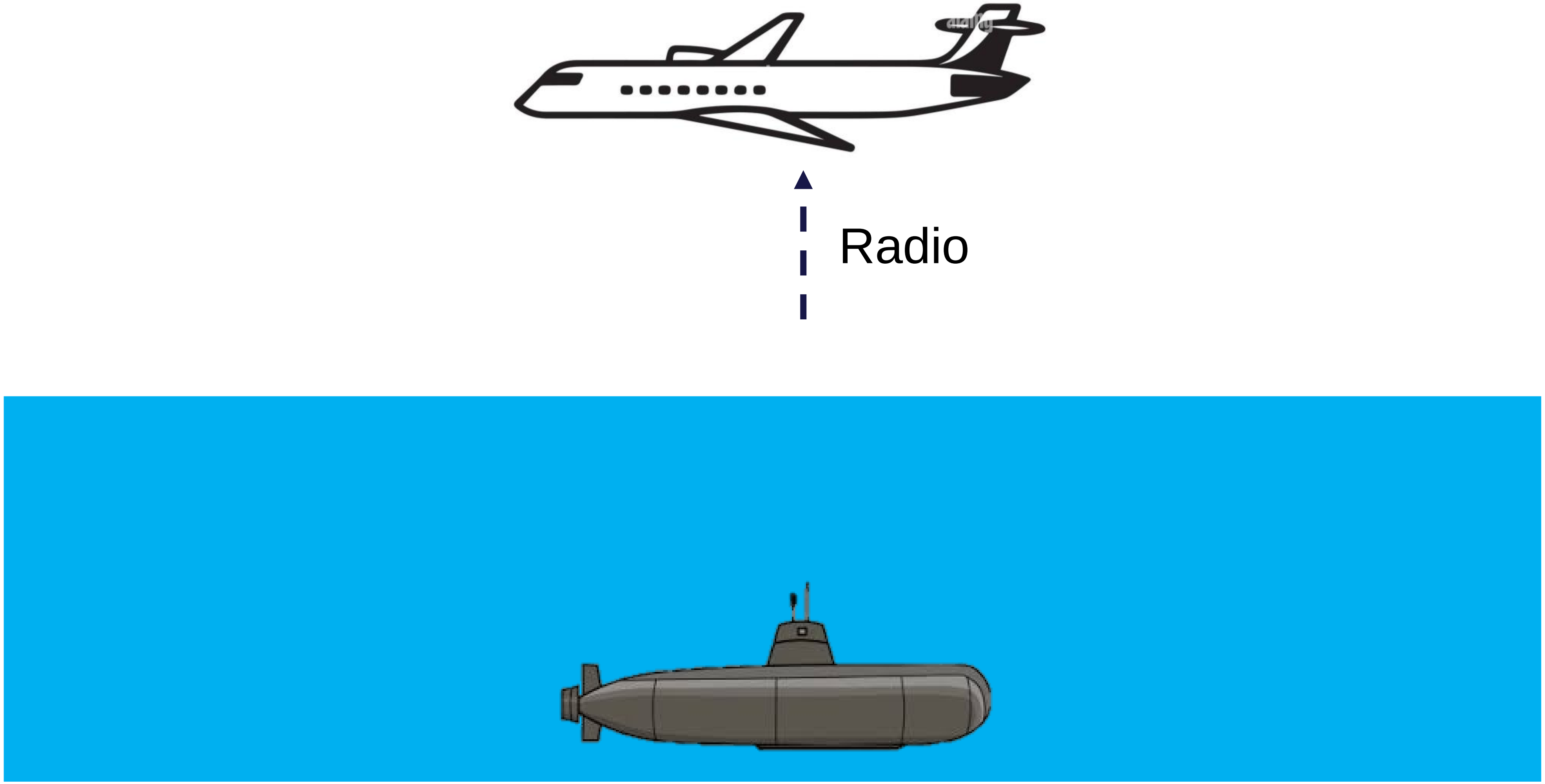
Approach #1: Relay Nodes



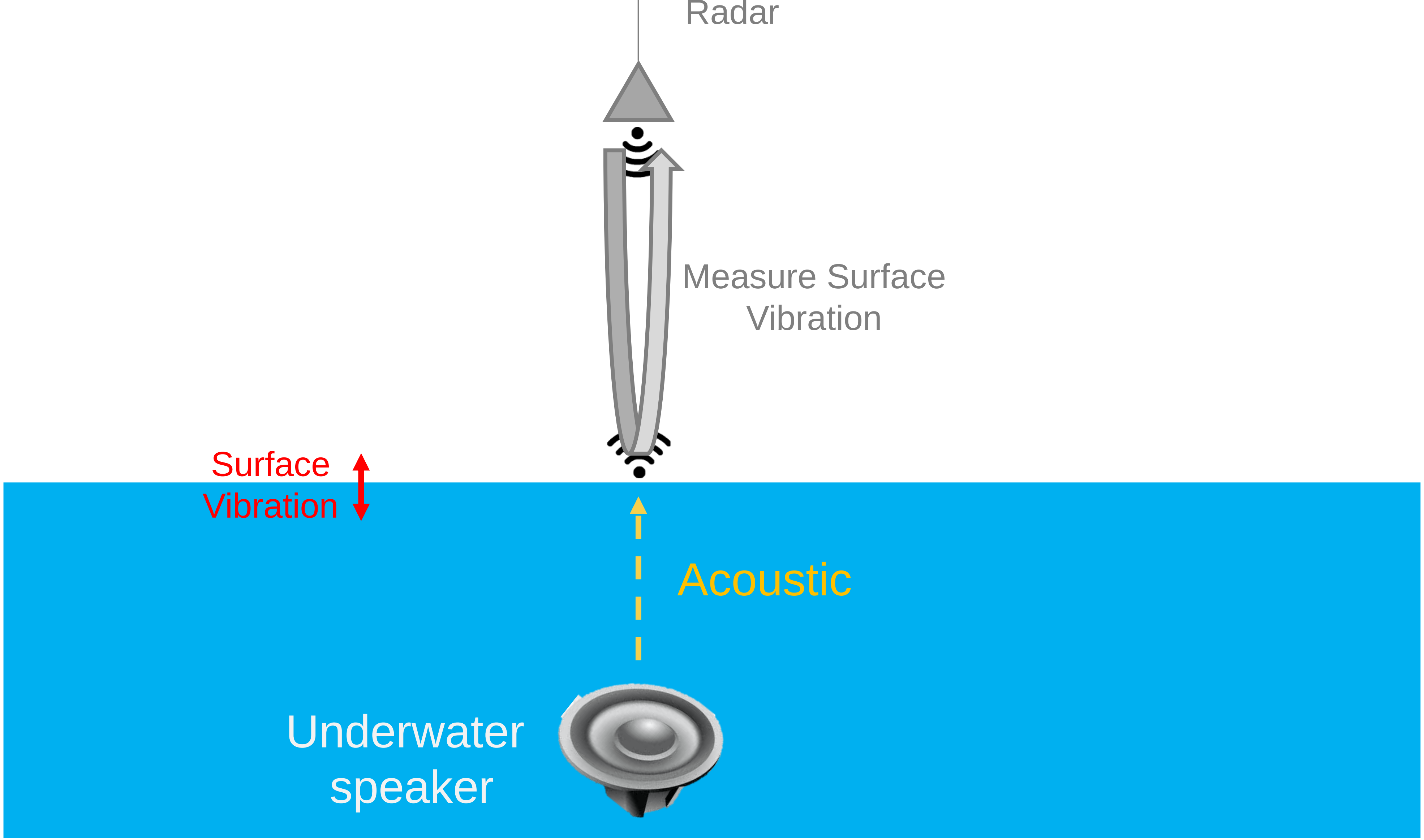
Approach #1: Relay Nodes



Approach #2:Surfacing



Translational Acoustic RF Communication (TARF)



Translational Acoustic RF Communication (TARF)

- First technology that enables wireless communication water-air interface
- Theoretically achieves the best of both RF and acoustic signals in their respective media
- Deals with practical challenges of communicating across water-air interface including natural surface waves
- Implemented and tested in practical environments

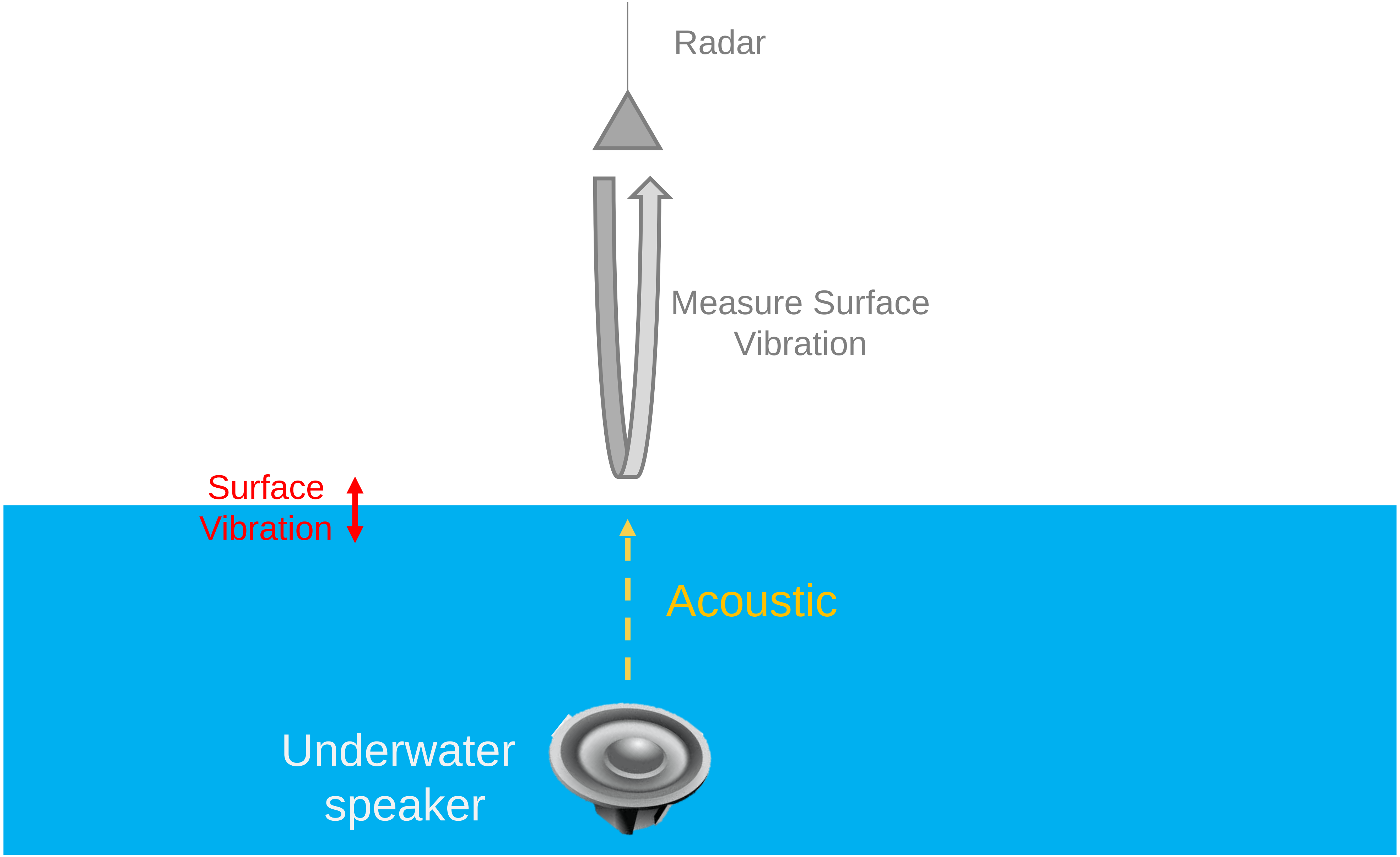
Application scenarios

Submarine - Airplane Communication

Finding missing airplanes

Ocean exploration

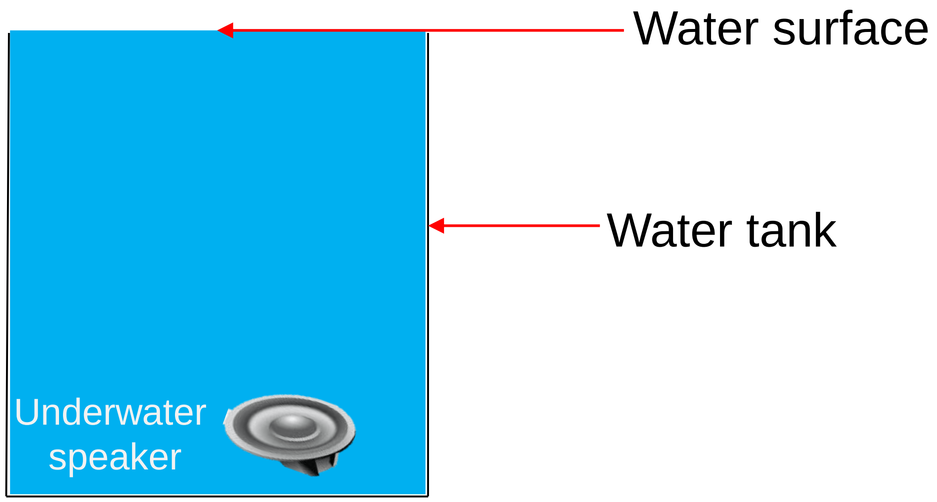
Key idea

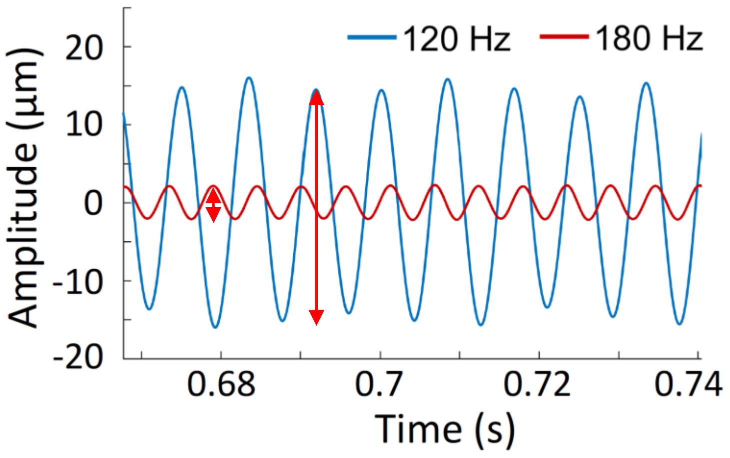

Radar
Measure Surface Vibration
Surface Vibration
Acoustic
Underwater speaker

Can we sense the surface vibration caused by the transmitted the transmitted underwater signal?

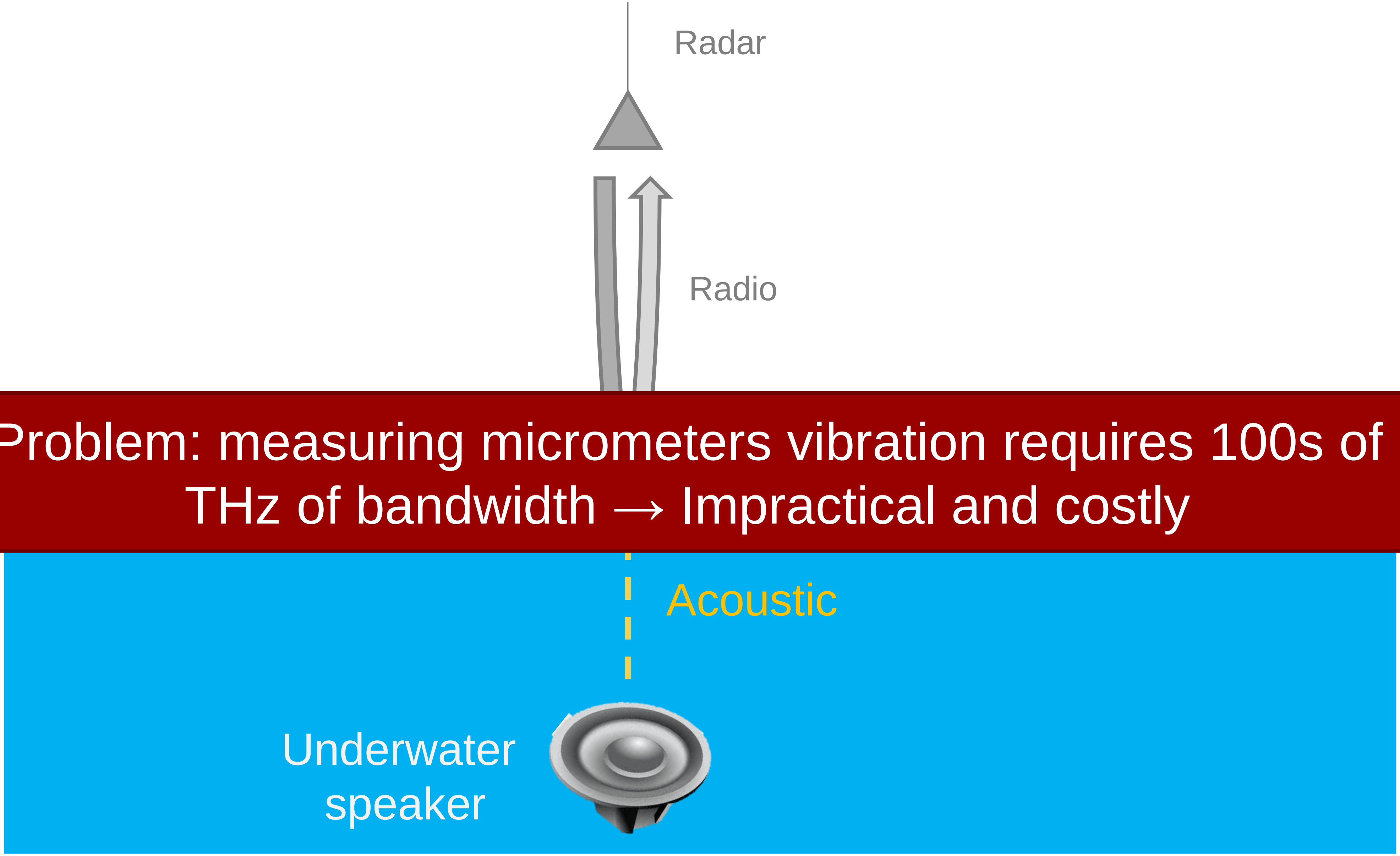
Recording the surface vibration

Experiment: Transmitting acoustic signal at 120 and 180 Hz



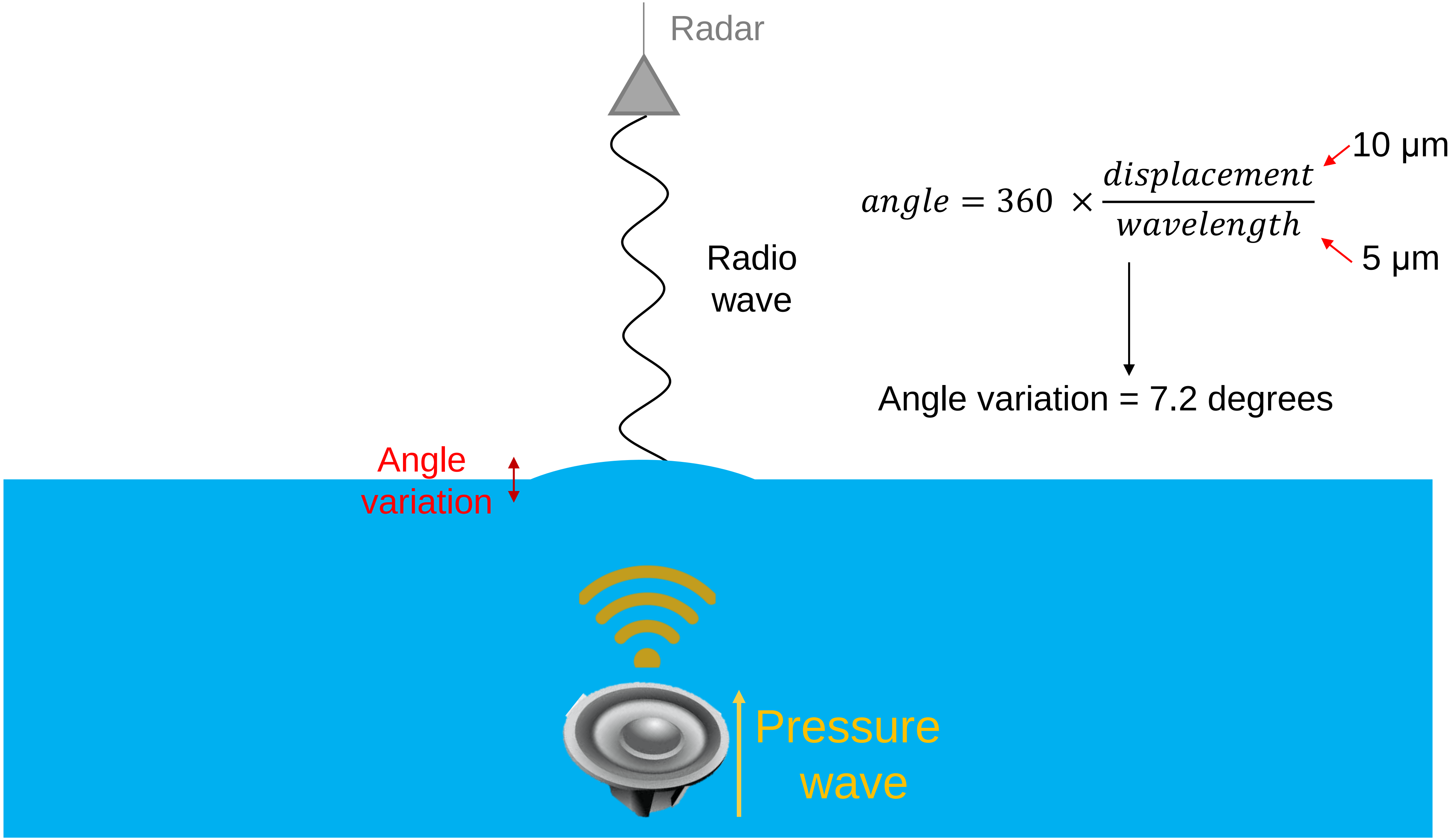


How can we sense microscale vibration



Problem: measuring micrometers vibration requires 100s of THz of bandwidth → Impractical and costly

Solution: Measure changes in displacement using the angle of the millimeter-wave radar



$$angle = 360 \times \frac{displacement}{wavelength}$$

10 μm

5 μm

Angle variation = 7.2 degrees

Natural surface waves mask the signal

On calm days ocean surface ripples (capillary waves) have 2cm peak-to-peak amplitude

↓

1000 larger than surface vibration cause by the acoustic signal

Natural surface waves can be treated as structural interference and filtered out

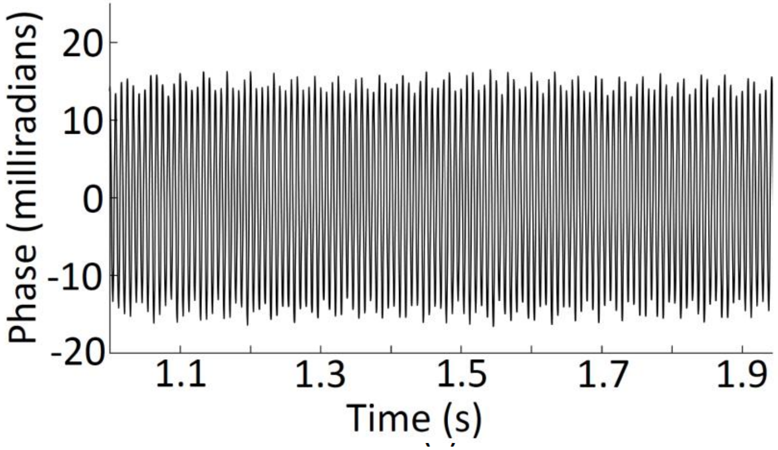
Natural occurring waves (i.e. ocean waves) are relatively slow → 1 – 2 Hz

Acoustic signal are transmitted at higher frequencies → 100 – 200 Hz

Filtering alone does not work!

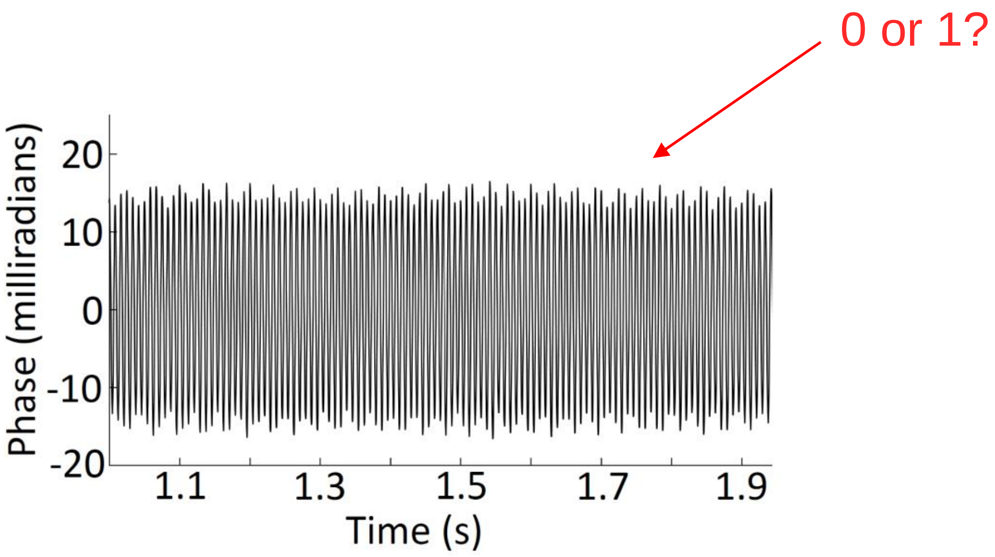
Dealing with waves

$$angle = 360 \times \frac{displacement}{wavelength} \quad \textcolor{red}{mod 360}$$

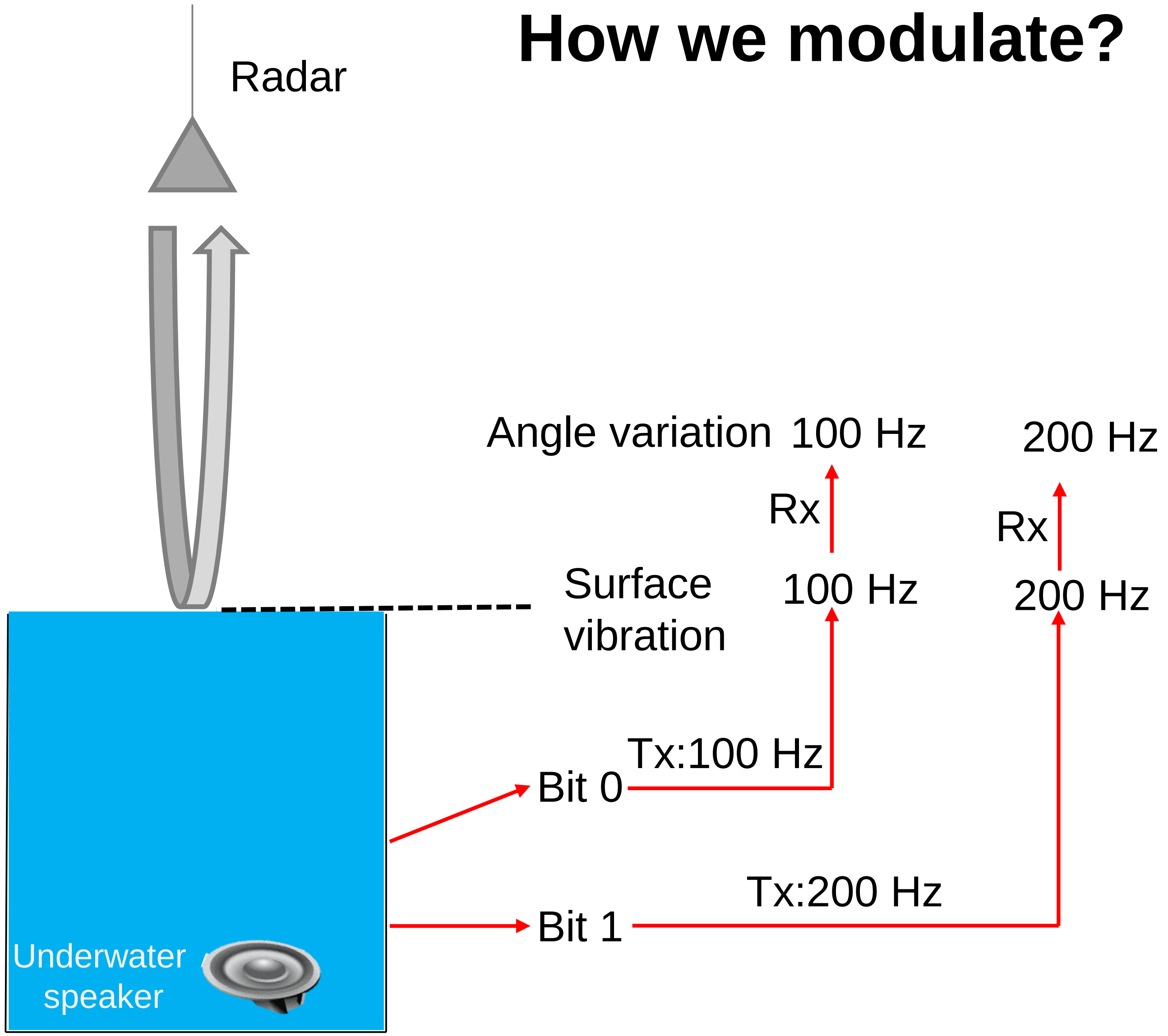


By treating natural surface waves as structured interference, they are able to track and eliminate their impact on our signal.

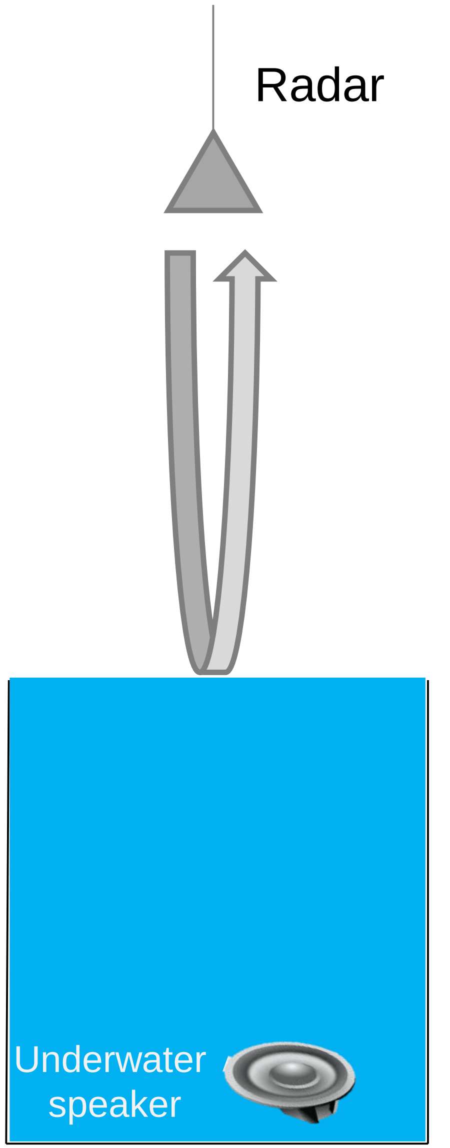
How we modulate?



How we modulate?



Implementation



<u>Receiver</u>

Custom made FMCW Millimeter-Wave RADAR

- Center frequency: 60GHz
- Bandwidth: 3GHz
- Antennas: 3dBi Gain Horn Antennas

Radar acts as daughter board to USRP(N210) software defined radio

<u>Transmitter</u>

Electro-Voice UW30 Underwater loudspeaker

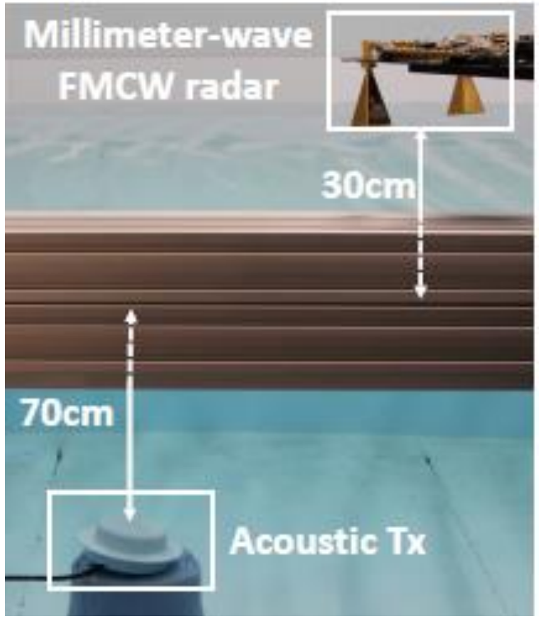
- Center frequency: 150GHz
- Bandwidth: 100GHz
- Antennas: 3dBi Gain Horn Antennas

Pre-amplifiers

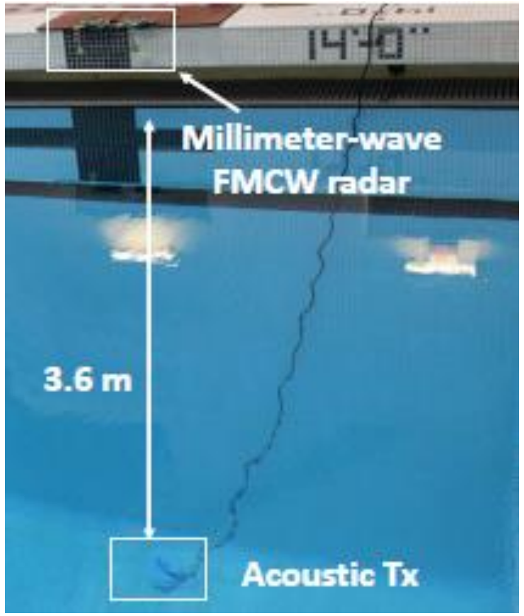
- OSD 75W Compact subwoofer amplifier
- Pyle 300W Stereo Receiver

Evaluation

Water tank

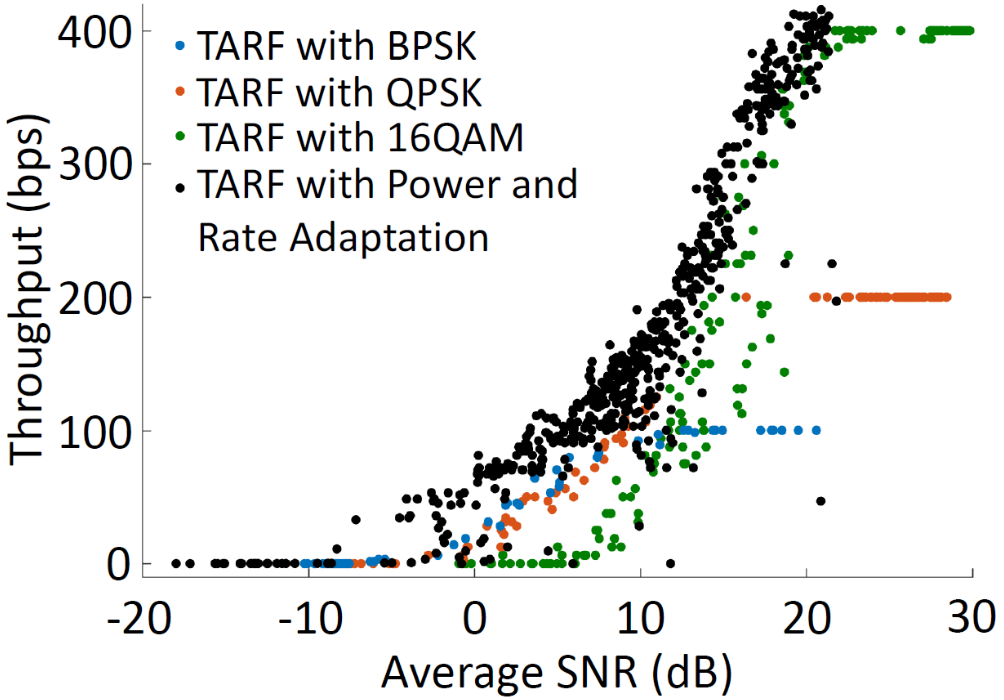


Pool setup

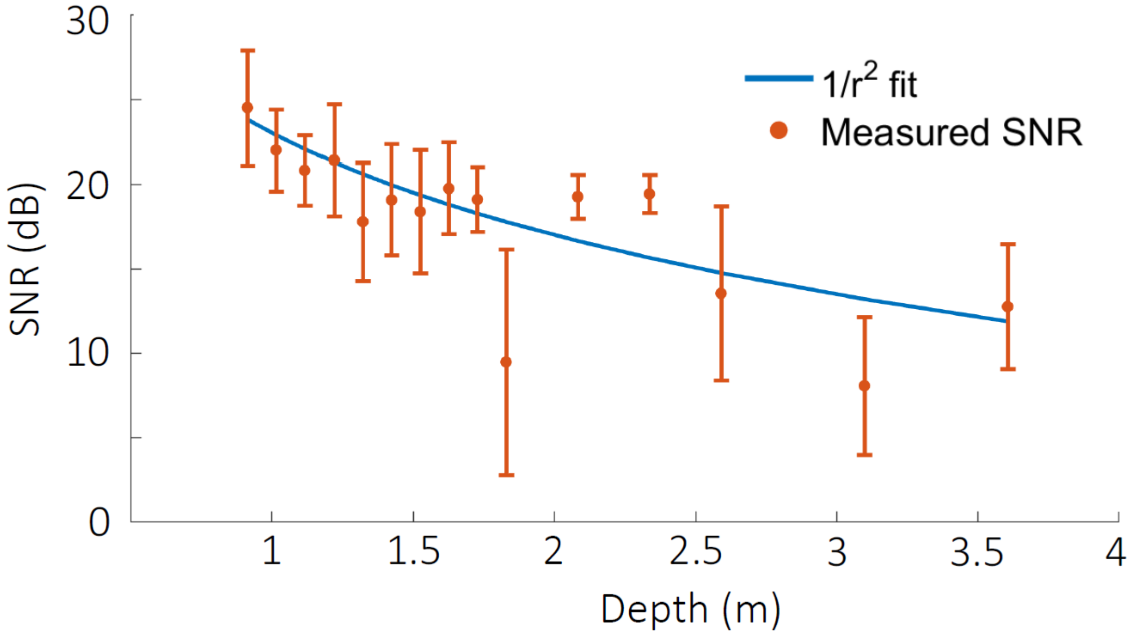


Throughput

Experiment: Vary the power and depth of the underwater transmission

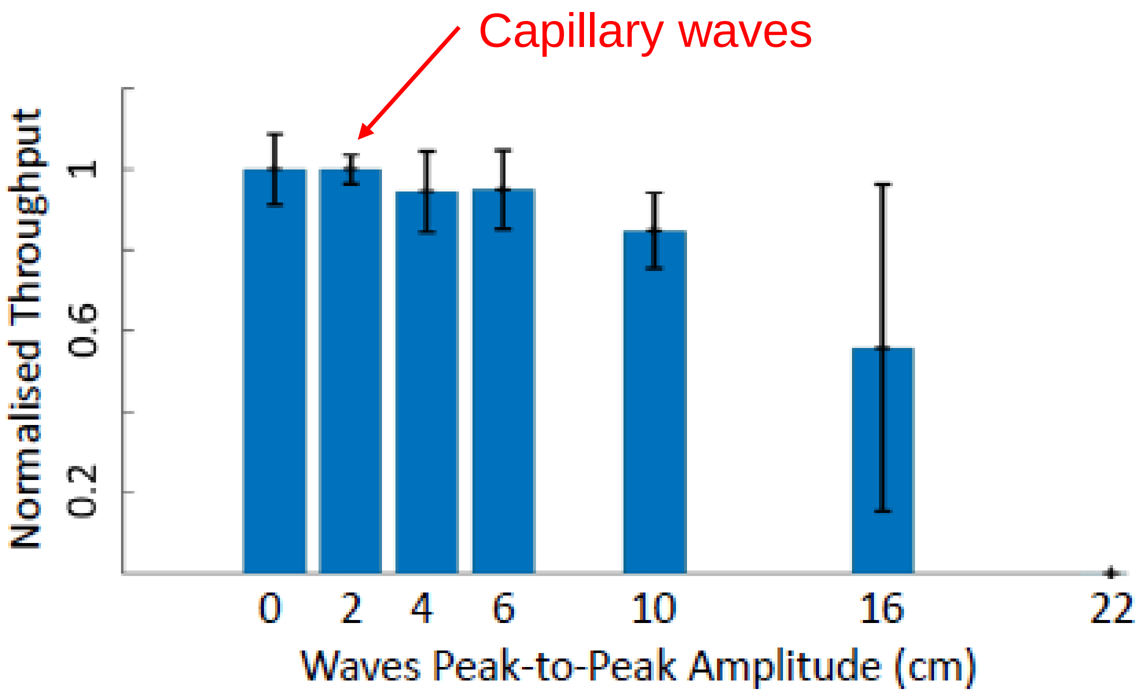


SNR Vs Depth



Dealing with waves

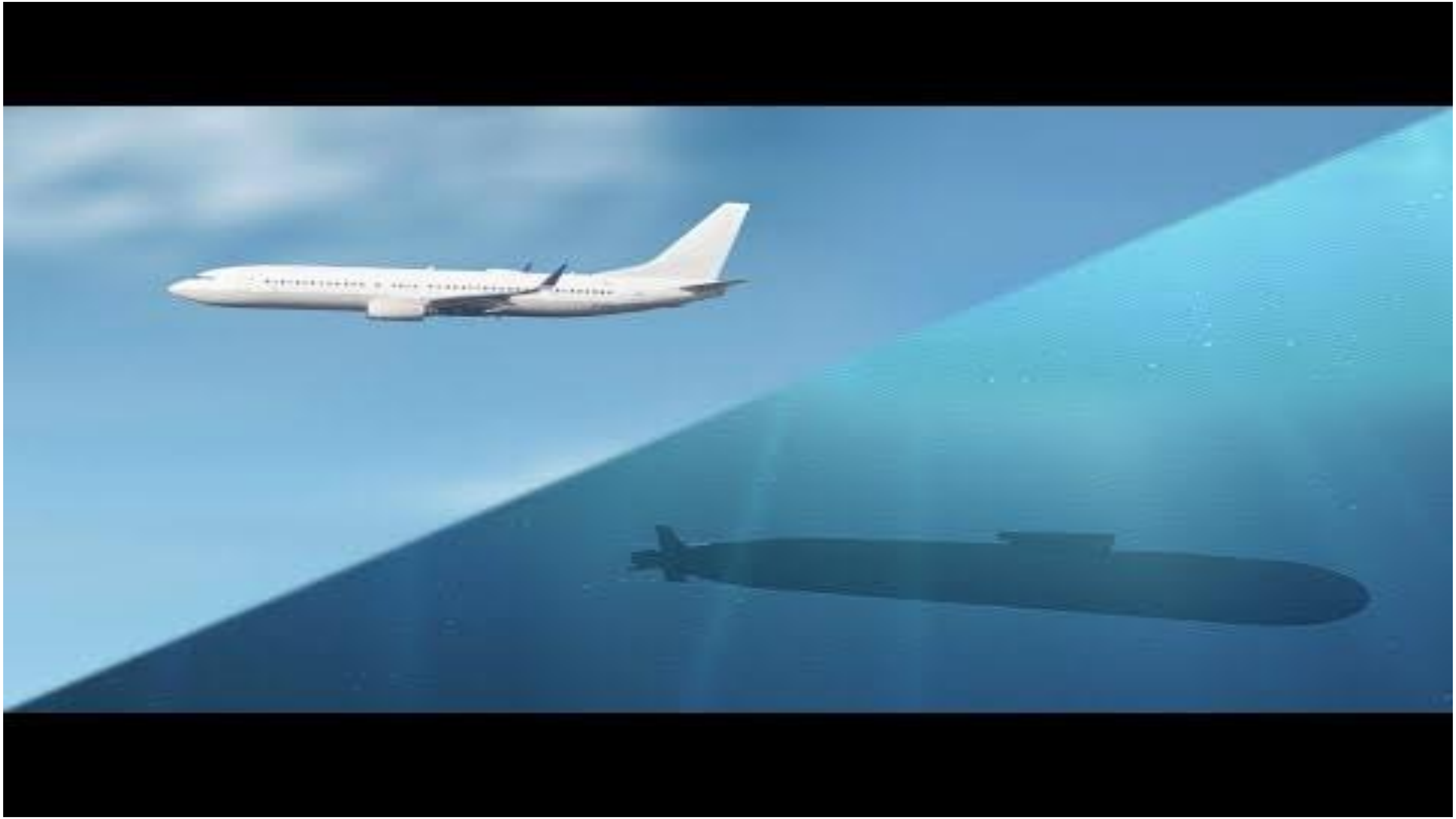
Experiment: Generate waves of peak-to-peak amplitude



Conclusions

- TARF (Translational Acoustic-RF) Communication
  - The first communication modality that enables wireless transmissions through the water-air interface
  - A prototype system that demonstrates uplink communication and deals with practical challenges

- Transform the water surface from and obstacle to a communication medium
  - Paves way for many applications like submarine-airplane communication and ocean exploration



Open research questions

Downlink communication?

Reza Ghaffarivardavagh, Sayed Saad Afzal, Osvy Rodriguez, and Fadel Adib. 2020. ***Ultra-Wideband Underwater Backscatter via Piezoelectric Metamaterials*.** In Proceedings of the Annual conference of the ACM Special Interest Group on Data Communication on the applications, technologies, architectures, and protocols for computer communication (SIGCOMM '20).

Significant interest in Ocean IoT

“More than 95% of ocean remains unobserved and unexplored.“

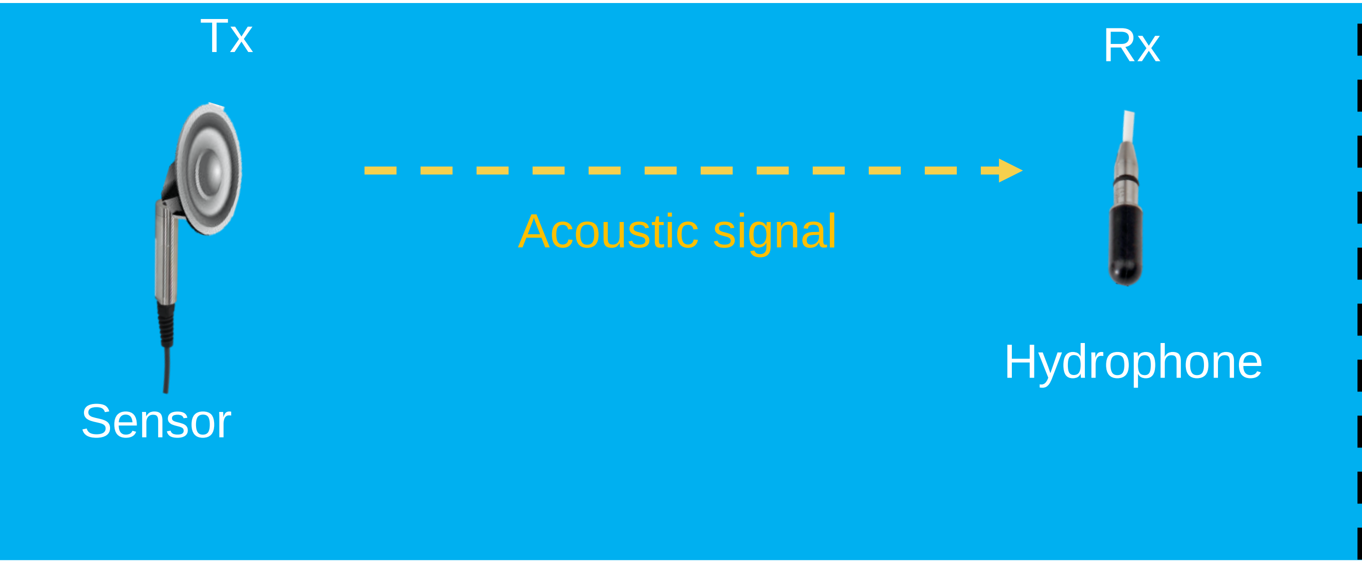
- NOAA, 2018

Ocean exploration

Climate monitoring

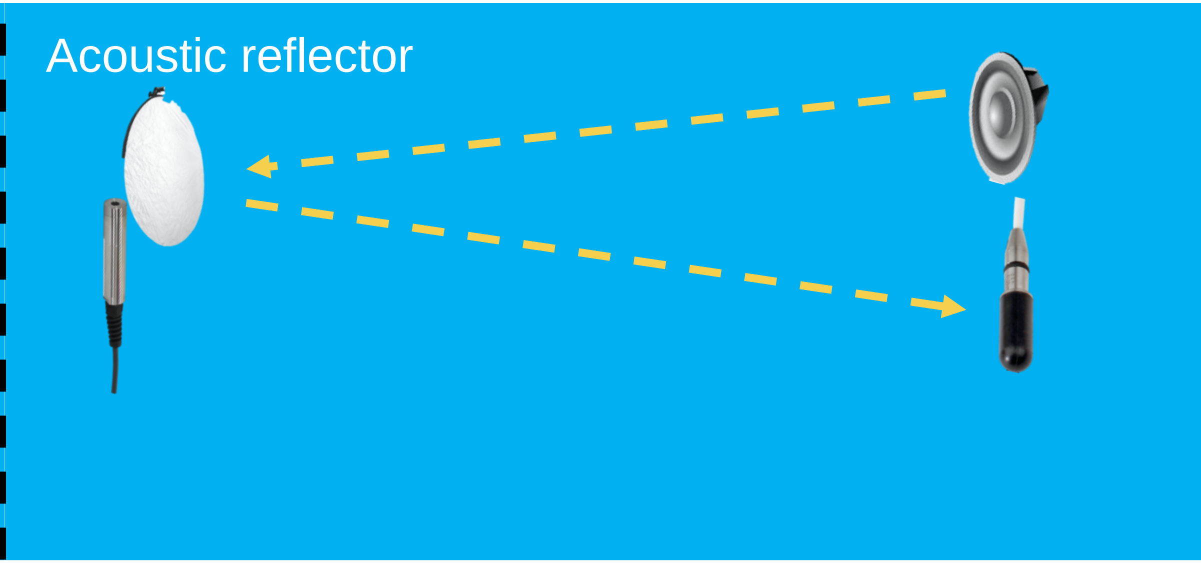
Aquaculture

Underwater communication



- Sufficient throughput (~10-50 kbps)
- Long range (~50 – 100 m)
- High power consumption
- Costly to scale

Underwater backscatter



- Limited throughput (2-3 kbps)
- Short range (5-10 m)
- Ultra-low power consumption
- Very cost-efficient

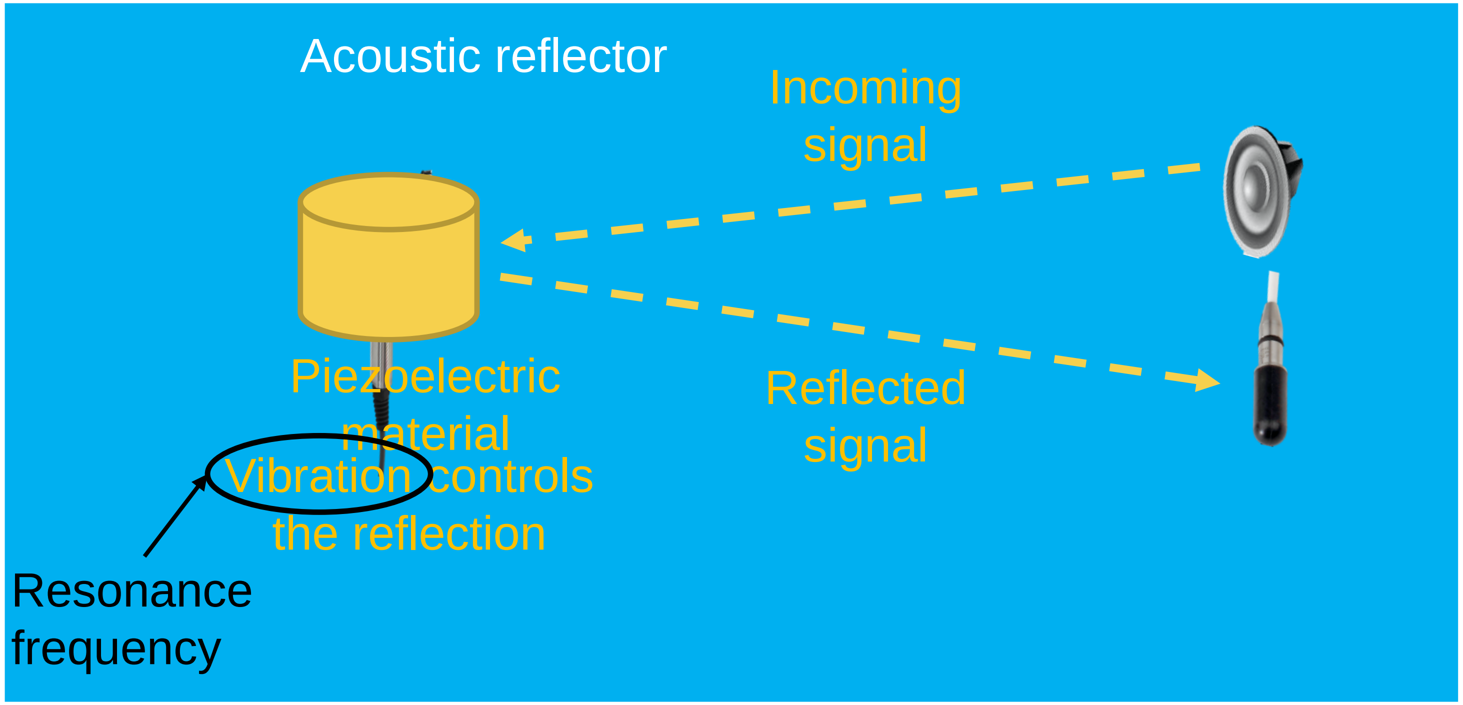
Ultra-Wideband Underwater Backscatter via Piezoelectric Metamaterials (U^2B)

- Enables scalable, ultra-low-power and low-cost ocean IoT

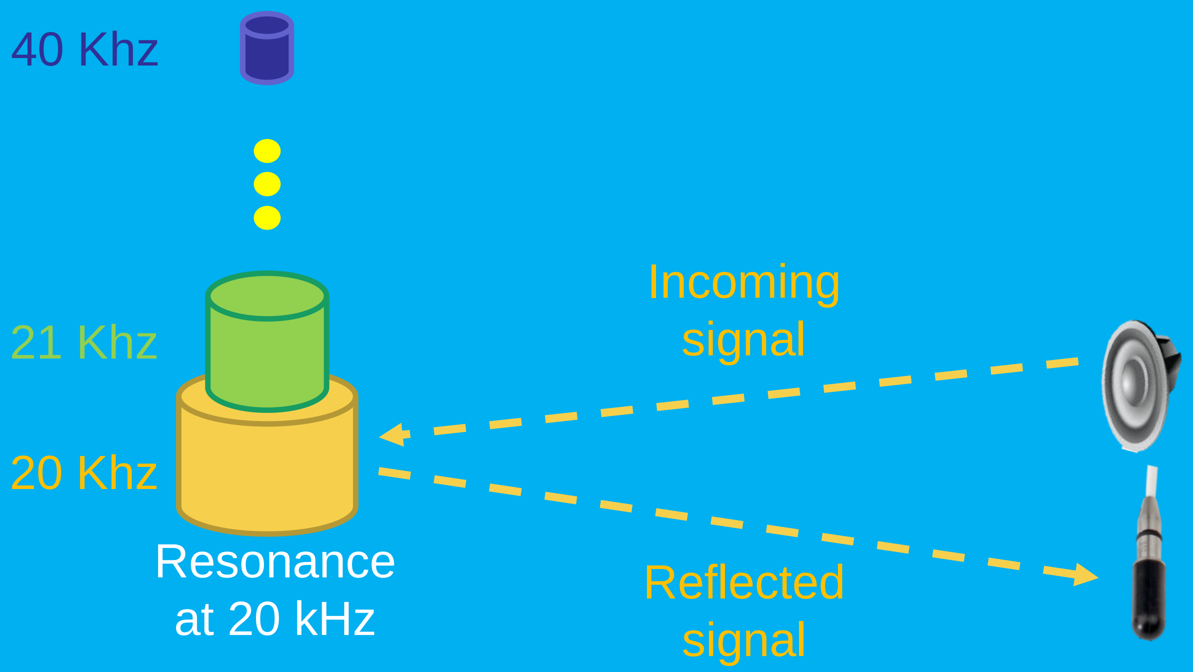
- Introduces a novel metamaterial design for underwater backscatter
  - Higher throughput
  - Longer range
  - Low-power and low-cost

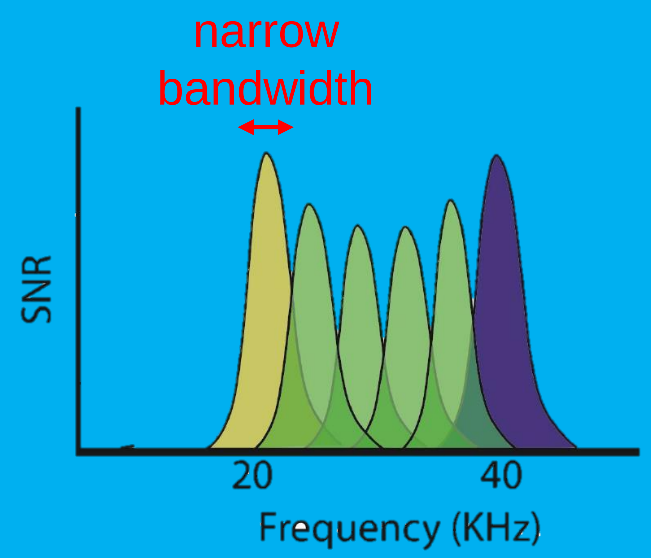
- First demonstration of underwater backscatter in-the-wild

Problem: Underwater backscatter exploits resonant materials which limits their throughput



Problem: Underwater backscatter exploits resonant materials which limits their throughput





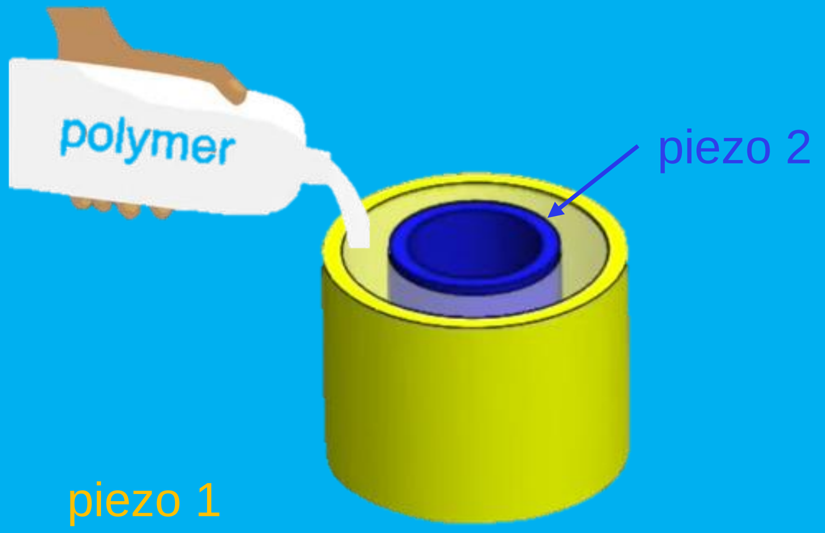
Resonance → Narrow bandwidth → Limited throughput

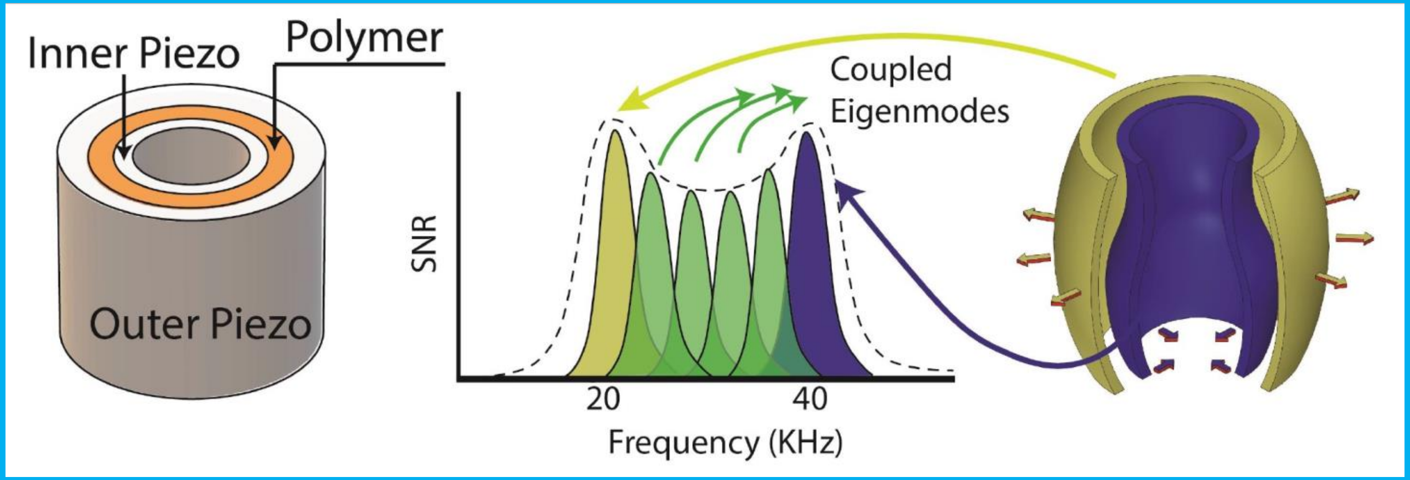
This approach is costly, bulky and adds unwanted directionality

How can we overcome the resonance problem while maintaining low-cost, low-power backscatter?

Introduce a novel metamaterial design that enables ultra-wideband backscatter.

Key idea: create coupling only between two piezos to synthesize many resonances





Ultra-Wideband Underwater Backscatter

Higher throughput
Higher backscatter bitrate

Longer range
Out-of-band Full-Duplex

Scale to more nodes
FDMA

Evaluation

400 experimental trials at different ranges, throughputs and number of nodes

Throughput: 20kbps (↑ by 5x)

Range: 62m (↑ by 6x)

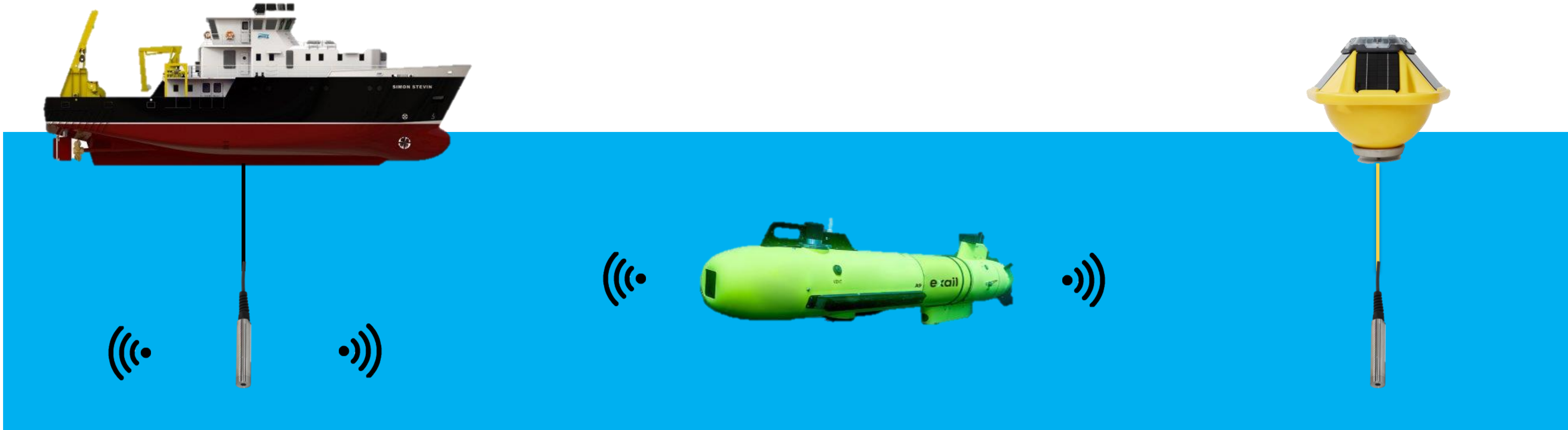
Concurrent nodes: 10 (↑ by 5x)

Code + Tutorials

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

Zhao, Y., Afzal, S. S., Akbar, W., Rodriguez, O., Mo, F., Boyle, D., … Haddadi, H. (2022). ***Towards battery-free machine learning and inference in underwater environments***. 29–34. Presented at the Proceedings of the 23rd Annual International Workshop on Mobile Computing Systems and Applications, Tempe, Arizona.

Existing approaches for underwater sensing are not scalable



Vessels with subsea sensor

❌ Expensive

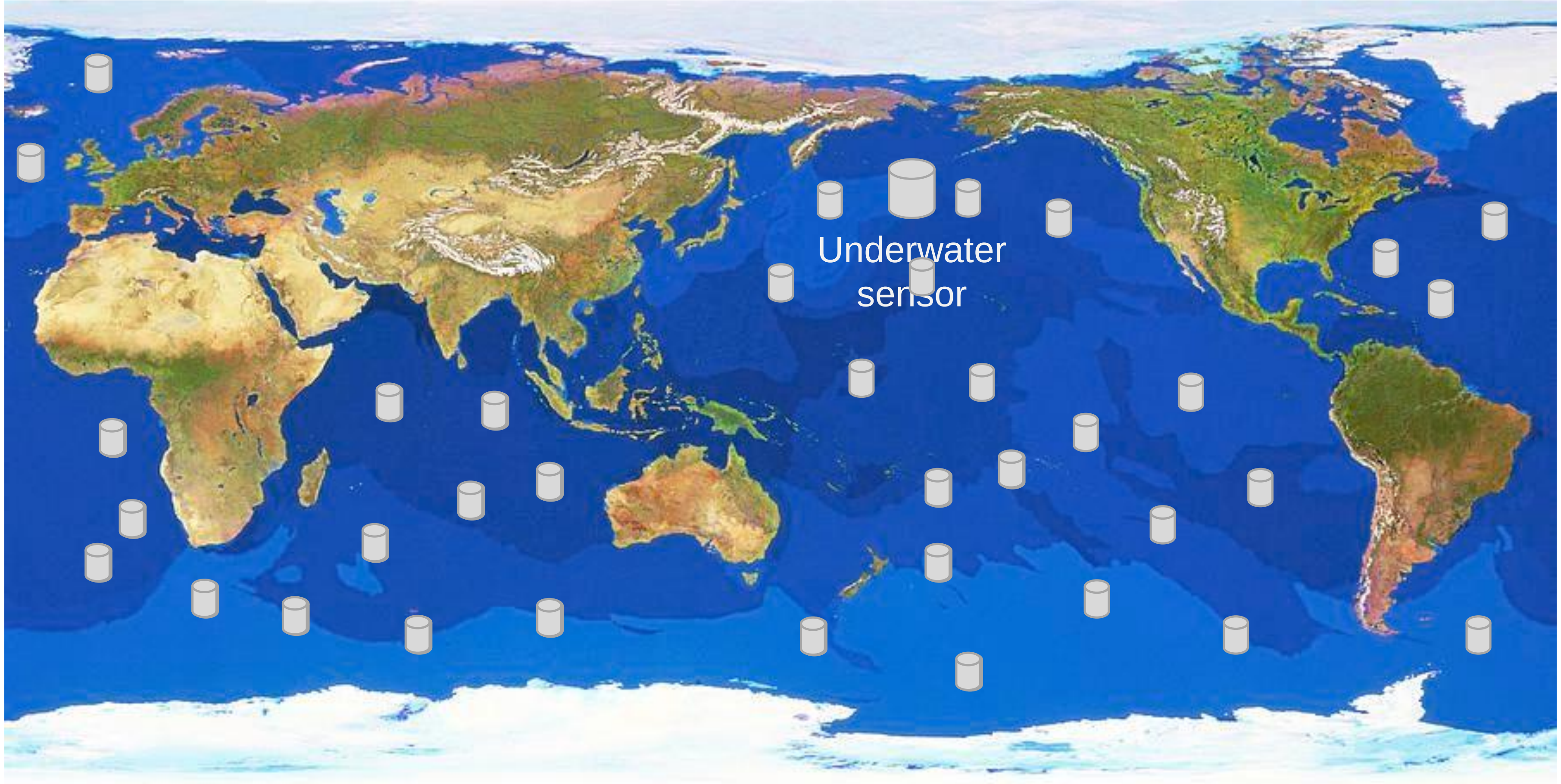
Underwater robots

❌ Low spatial-temporal accuracy

Floats

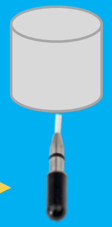
❌ Ocean surface only

Vision: Scalable Underwater IoT for Sensing the Ocean



Bio-acoustics application to detect animal sounds

Underwater sensor



Sound

Hydrophone

Underwater drone

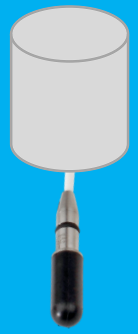
❌ Memory constrained

❌ Compute constrained

The sensor (with a standard low-power MSP430 MCU) can only store <u>less than 10s of audio if it stores the entire raw signal!</u>

How to enable long-term sensing within the memory and compute constraints of ultra-low power nodes?

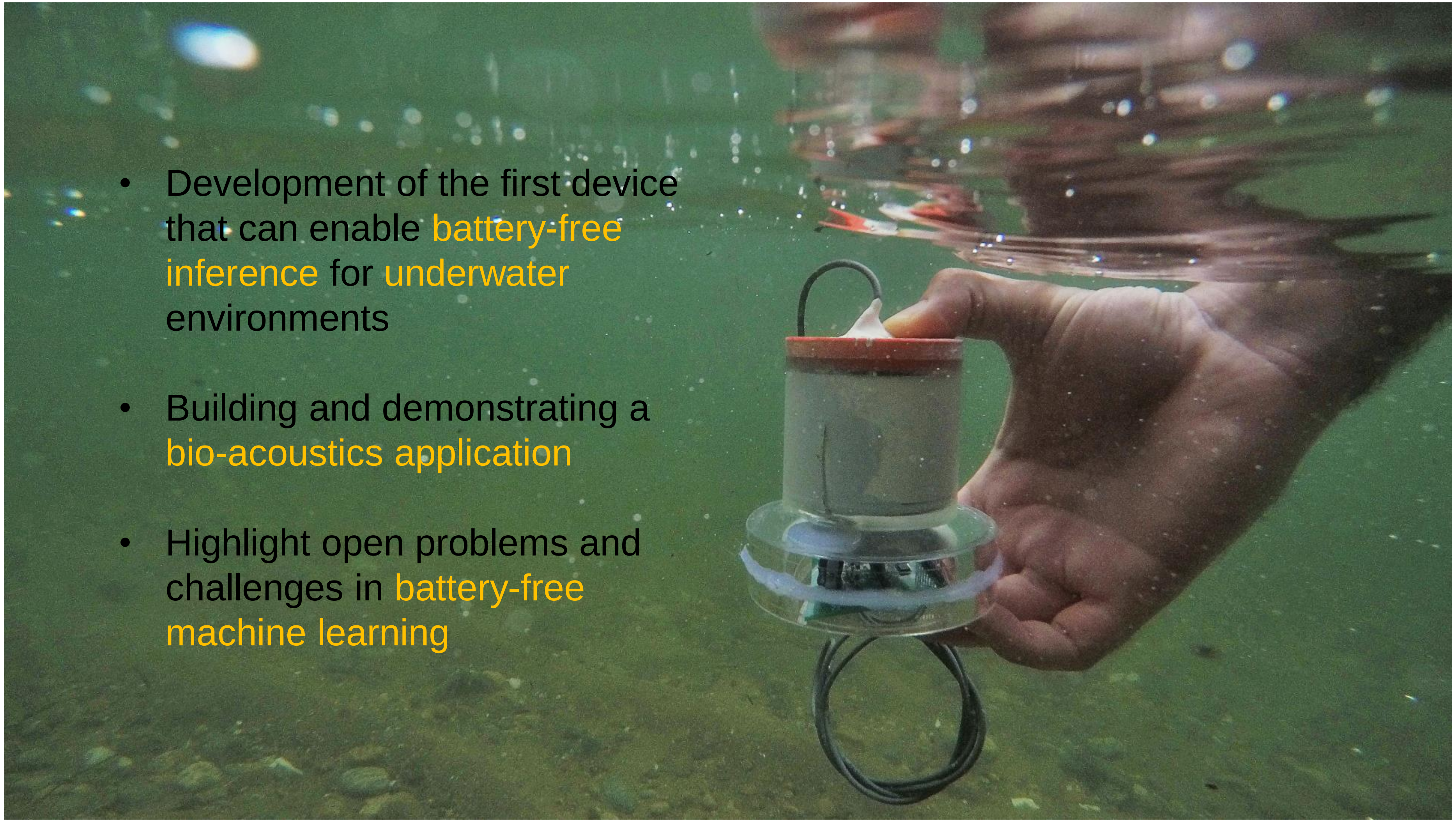
Underwater sensor



Hydrophone

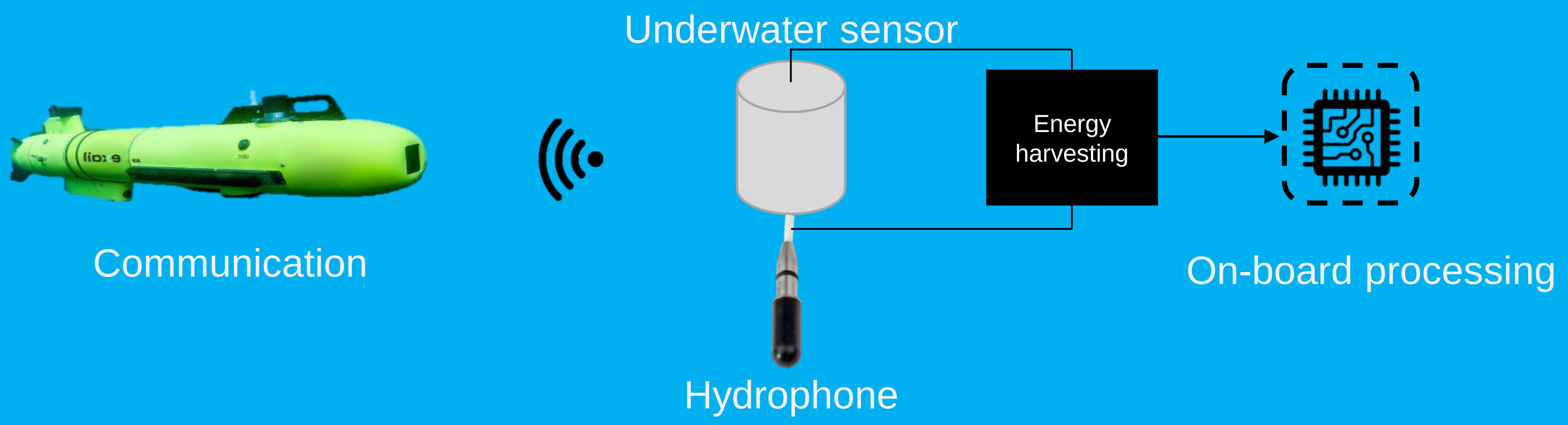
- How can we determine which sounds need to be stored and which ones can be discarded?
- Can we use these sounds to identify animals?
- Can we develop machine learning modes that adapt different underwater environments?

Underwater battery-free inference

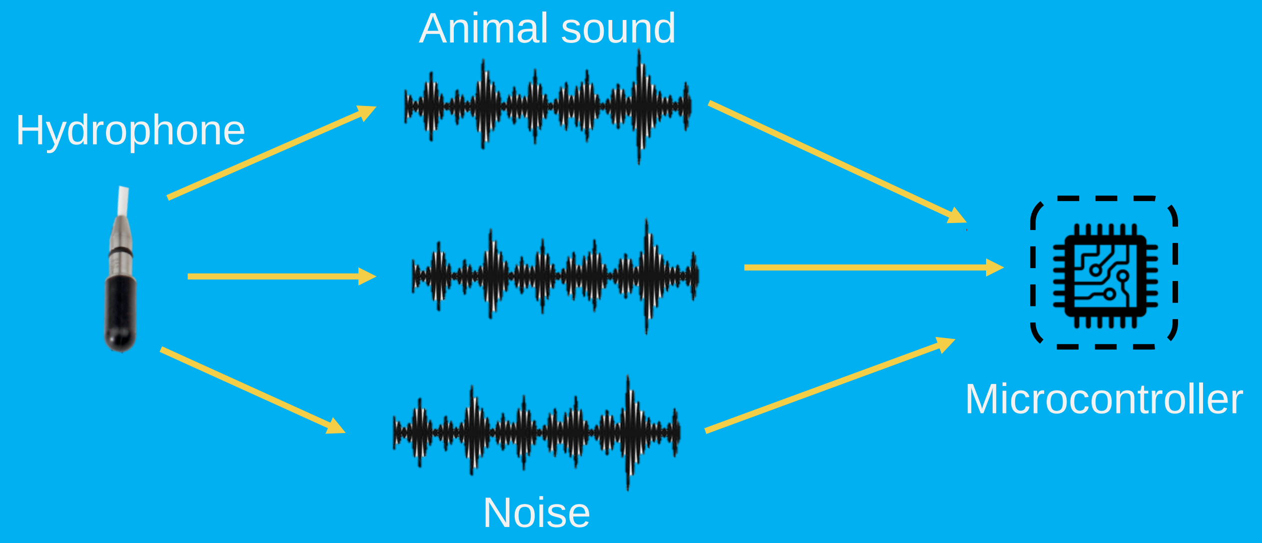


- Development of the first device that can enable battery-free inference for underwater environments
- Building and demonstrating a bio-acoustics application
- Highlight open problems and challenges in battery-free machine learning

Underwater battery-free inference system architecture



On-board processing: Differentiating noise from animal sounds



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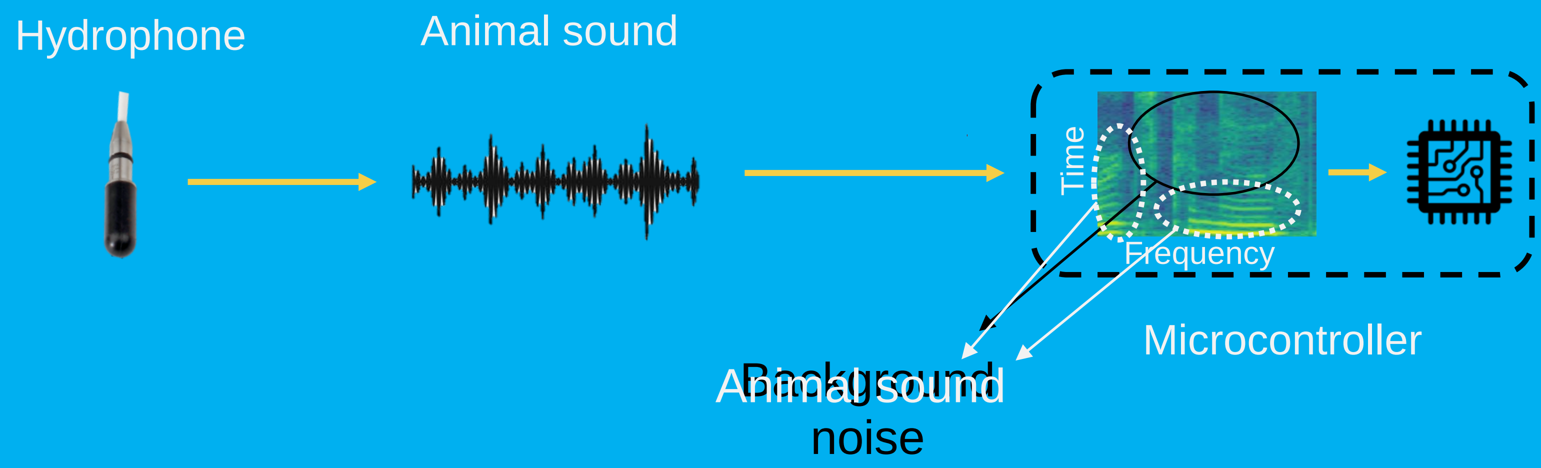

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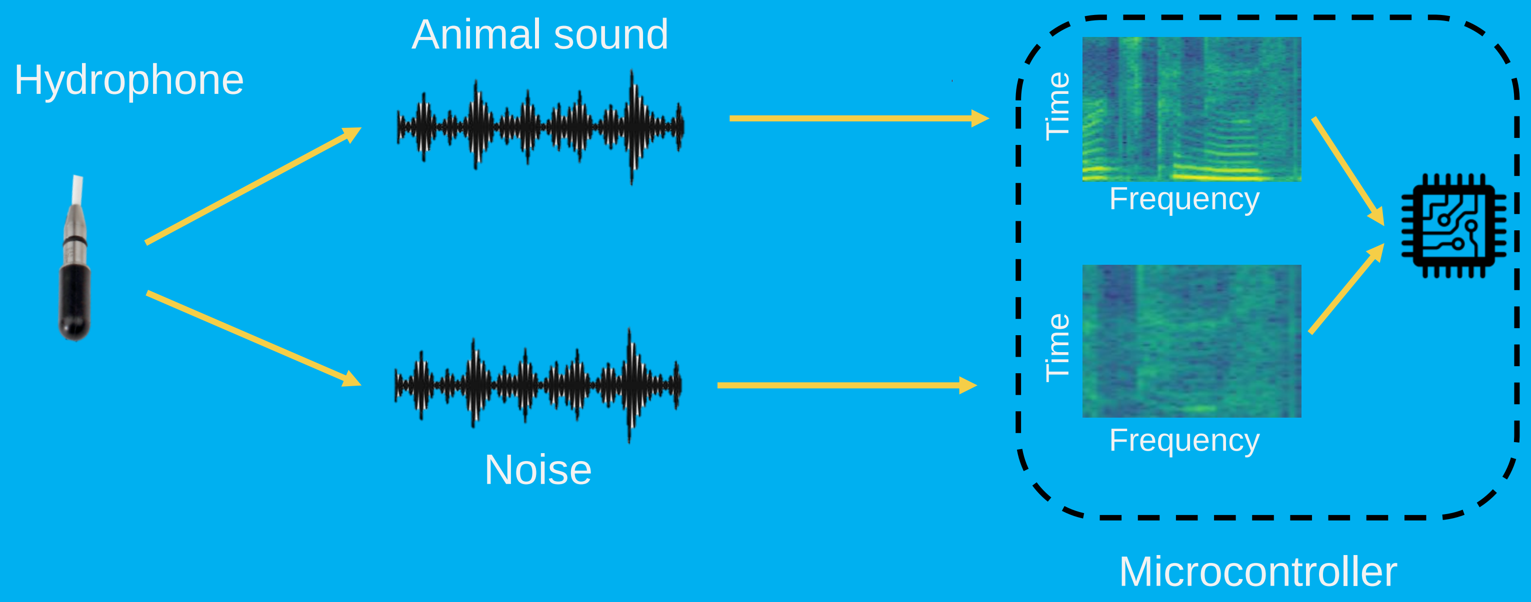
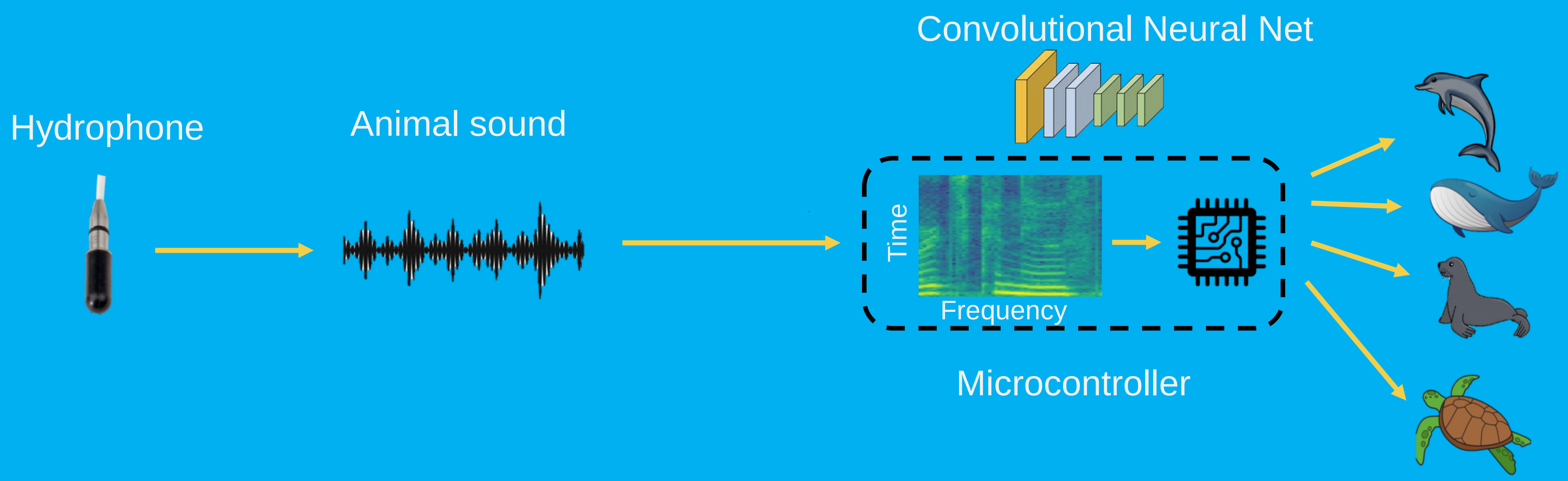


On-board processing: classify different marine animals



State-of-the art machine learning models require a lot of memory (~2MB), which cannot fit on a memory constrained device (256~kB)

Enabling inference on memory-constrained underwater environments

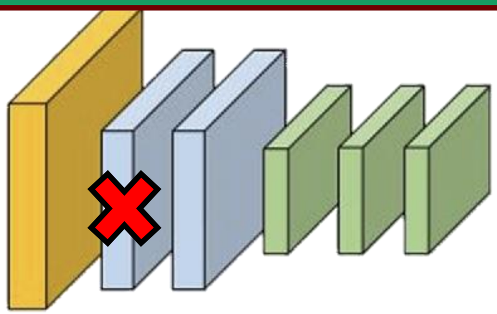
Resampling the input and trimming the CNN models reduced the memory consumption by ~200x so that the CNN model fits the memory

Original signal

- Memory: ~272kB

Resampled signal

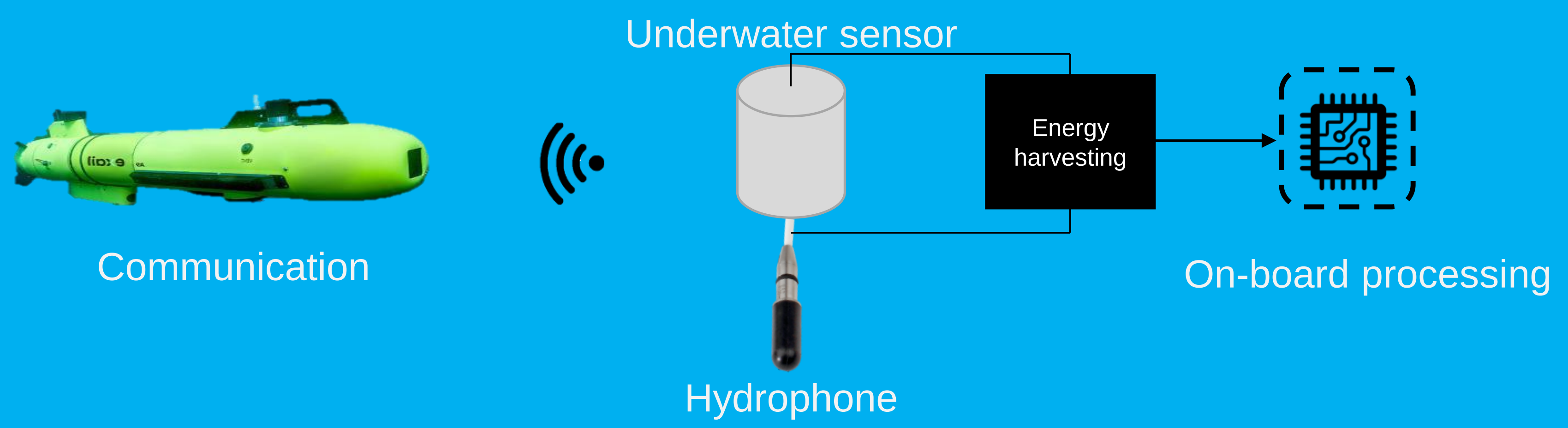
- Memory: ~2kB



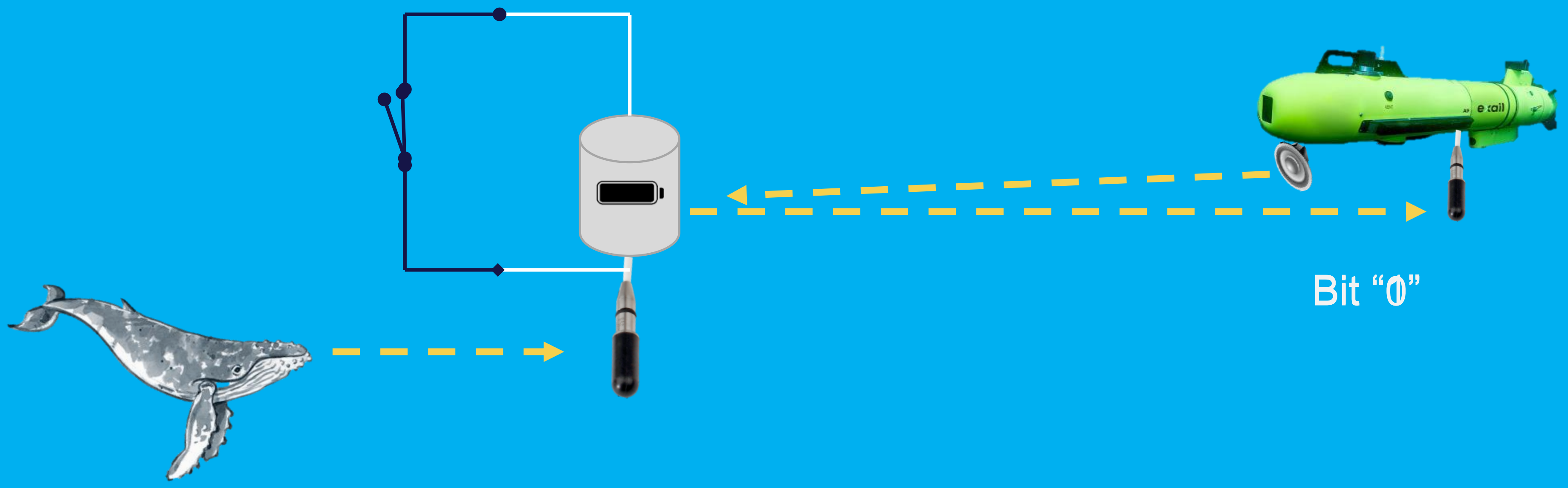
Storing the inference result and discarding the resampled signal gives us further improvement in memory by a factor of 1000x

Memory: ~60kB

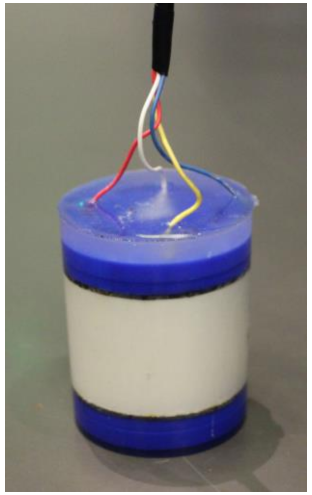
Underwater battery-free inference system architecture



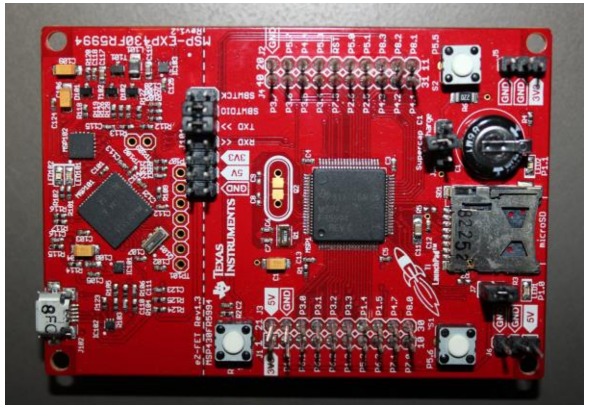
Underwater battery-free inference system architecture



Implementation

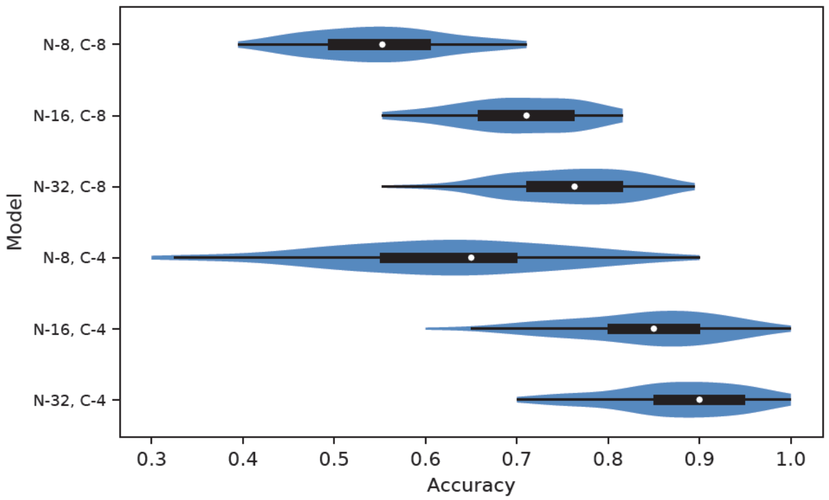


Potted transducer



MSP430 launchpad

Evaluation



- The implemented prototype consumes ultra-low-power of 3.13mW
- Resampling and trimming the CNN can reduce the memory consumption by 200x
- Performing inference gives us a further 1000x improvement in memory consumption

Open research questions

1. Adapting to different environments

2. Enabling underwater inference for other applications

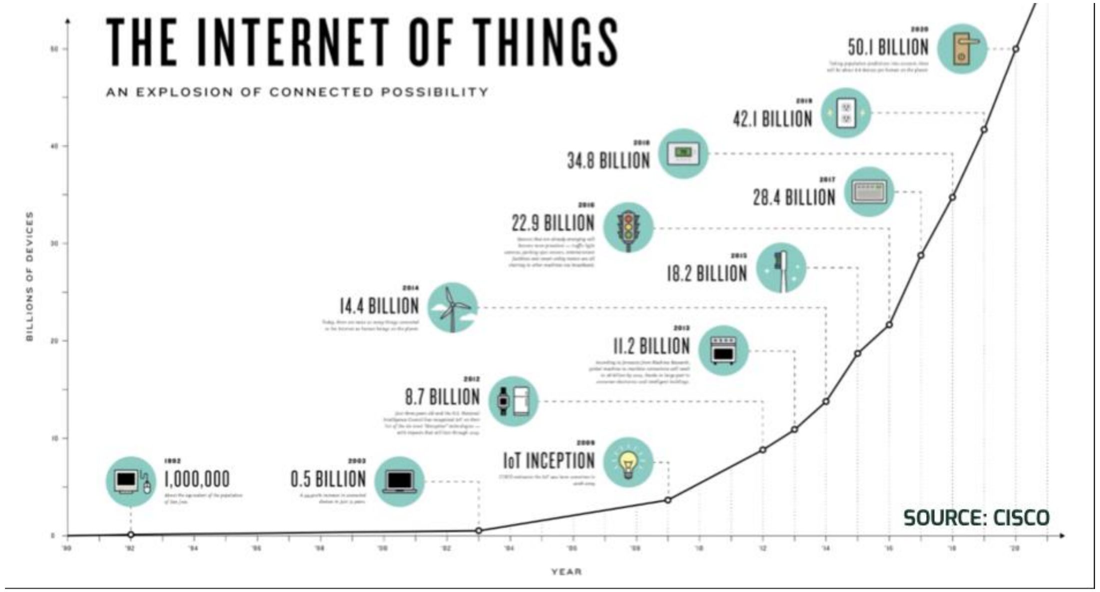
3. Battery-free distributed ML training

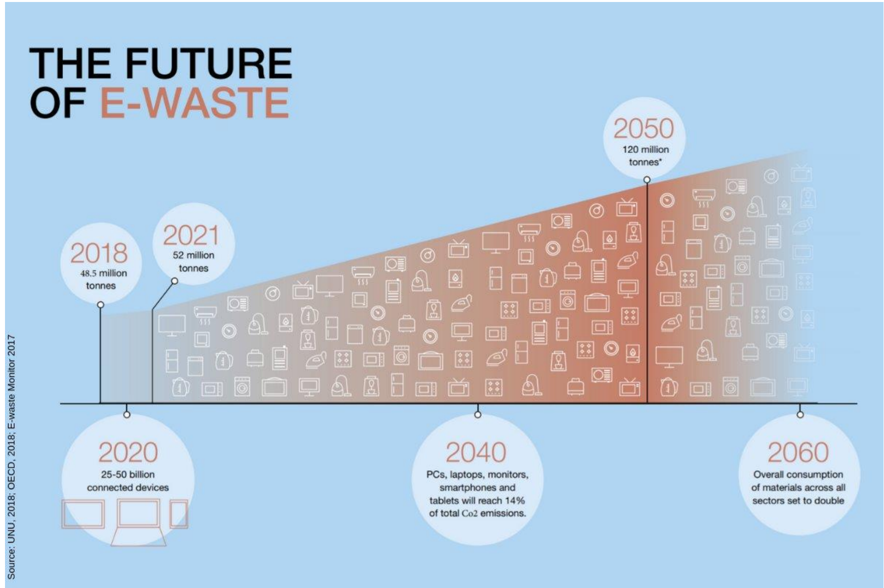
Arora, N., Iyer, V., Oh, H., Abowd, G. D., & Hester, J. D. (2023). ***Circularity in Energy Harvesting Computational 'Things***'. 931–933. Presented at the Proceedings of the 20th ACM Conference on Embedded Networked Sensor Systems, Boston, Massachusetts.

Viewpoint:

Researchers has focused a lot on low-power battery-free operation of IoT but that is not enough for environmental sustainability.

Explosion of IoT devices and global E-waste





50 billion devices in 2021

52 million tonnes E-waste in 2021

Viewpoint:

Researchers has focused a lot on low-power battery-free operation of IoT but that is not enough for environmental sustainability.

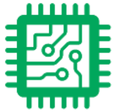
There is a need to include circularity as a system design parameter.

How do you develop computational “things” with a fully circular life cycle?

Rethinking the computing stack

Rethinking the computing stack

Energy Neutral System



Low/unreliable energy/operation

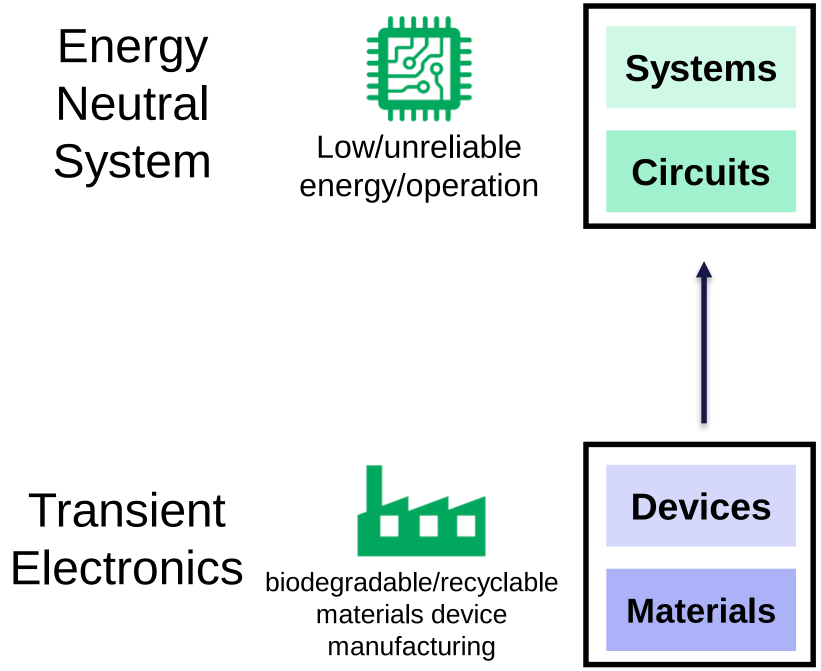
Systems
Circuits

Of the shelf components

Active elements: Silicon, germanium
Heavy metals: Cu, Au
Substrate: Ceramics, epoxy, plastic

Use bio-degradable or re-usable material for functional device design

Transient electronics

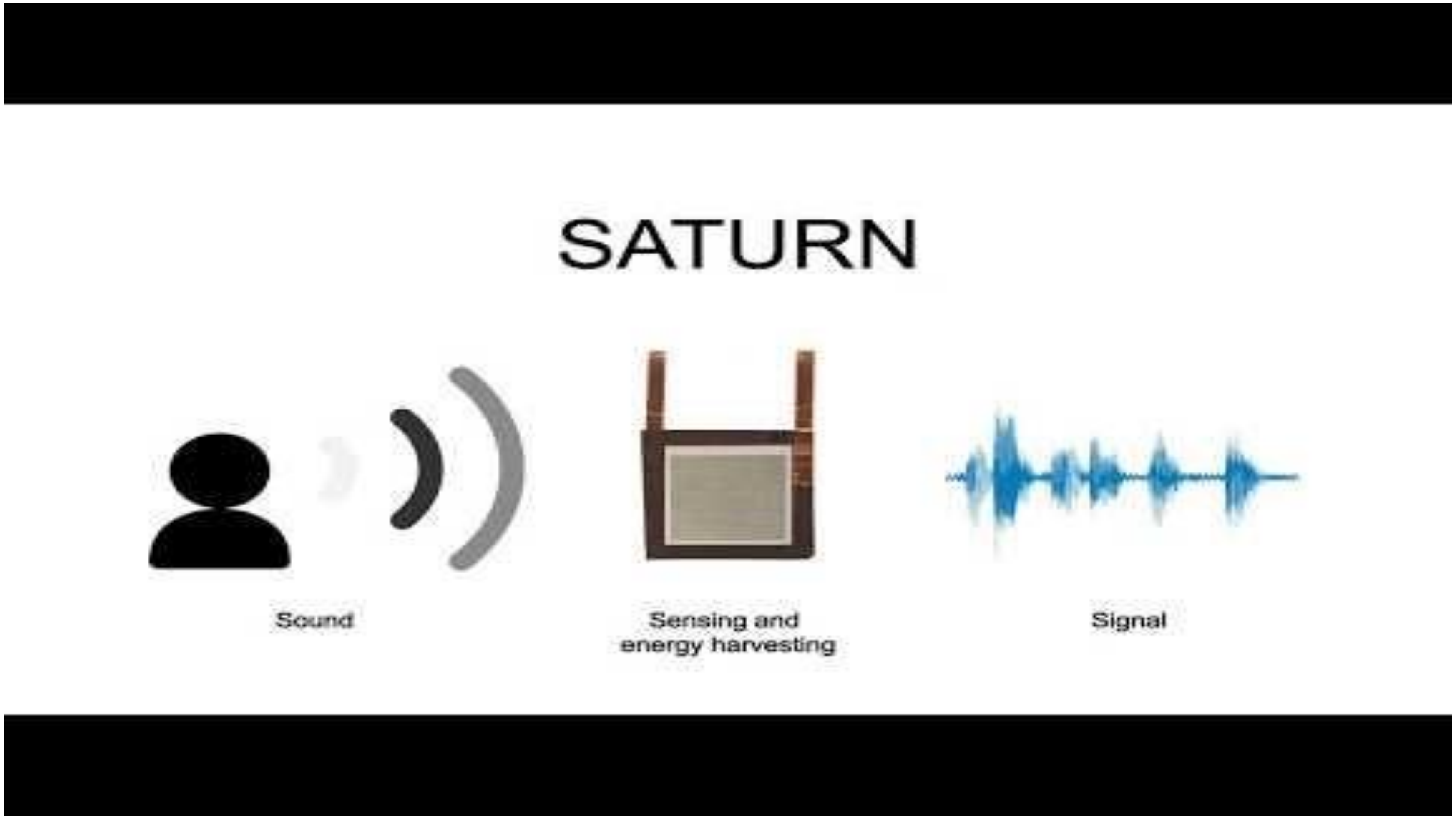


BUILD MATERIAL DEVICES with:

Plant, animal or artificial Proteins Polymers

Benign metals or conductive organic polymers

Bio-degradable flexible self-powered microphone



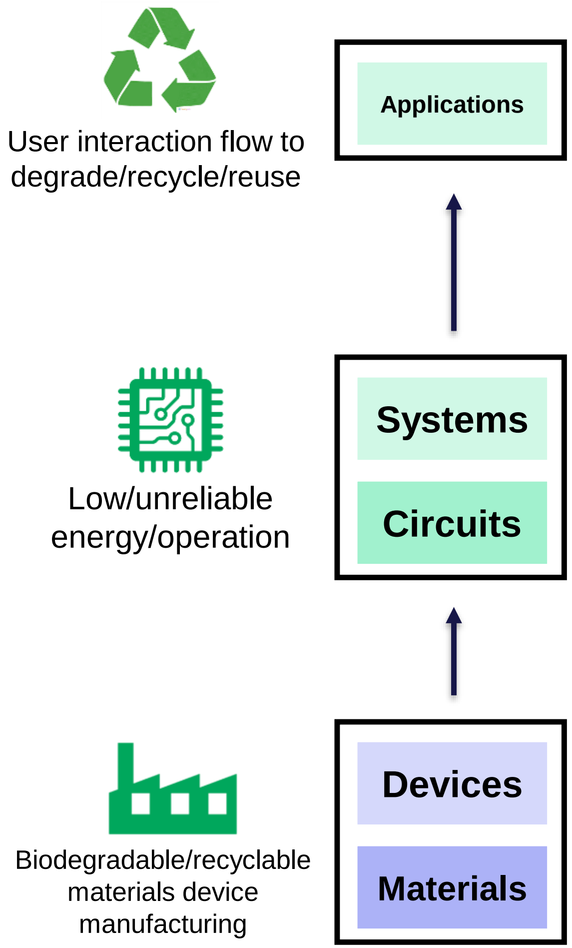
Nivedita Arora, Thad Starner, and Gregory D. Abowd. 2020. SATURN: an introduction to the internet of materials. Commun. ACM 63, 12 (December 2020)

Sustainable interaction design

Sustainable Interaction Design

Energy Neutral System

Transient Electronics



Product features that ease assembly/disassembly
e.g. Modularity

Interaction that includes behavioral change
towards adopting circularity

Open research questions

Power and performance of transient devices is not at par with traditional SI electronics.

Materials and device issues:

Transient Electronics

Devices

Materials

1. How can we build transient electronics that **perform equivalent with the state of the art?**
2. How can **tune transiency** – device lifecycles for

   1 week, 1 year to 5 years?

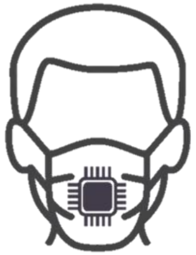
Open research questions

Power and performance of transient devices is not in par with traditional SI electronics.

Circuits and systems:

1. What types of **energy neutral circuits are possible with transient devices?**
2. How can we do things **at programmable system level** to overcome them?

Example: **Timer made from biodegradable transistor in face-mask**



1. Biodegradable timer has limited frequency.
2. Adapting the FFT window with degradation of timer.

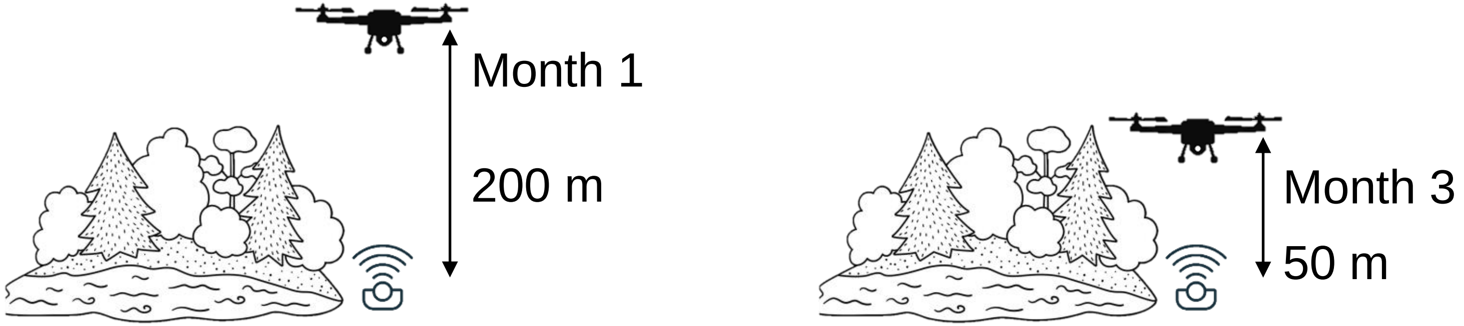
Open research questions

Power and performance of transient devices is not in par with traditional SI electronics.

Circuits and systems:

1. What types of **energy neutral circuits are possible with transient devices?**
2. How can we do things **at programmable system level** to overcome them?

Example: **degradable bio-inspired sensors interrogated by a drone**

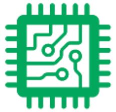


Intra-disciplinary research for circular computational things

Sustainable Interaction Design

User interaction flow to degrade/recycle/reuse

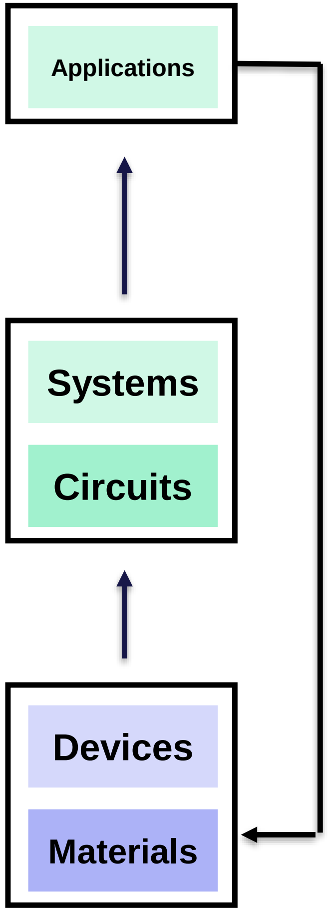
Energy Neutral System



Low/unreliable energy/operation

Transient Electronics

Biodegradable/recyclable materials device manufacturing



Come and join us to do research!