Minding the Billions:
Enabling Wide-Scale and In-vivo Networking in Low Power Internet of Things (IoT)

Yunfei Ma

MIT Media Lab

Internet Roadmap

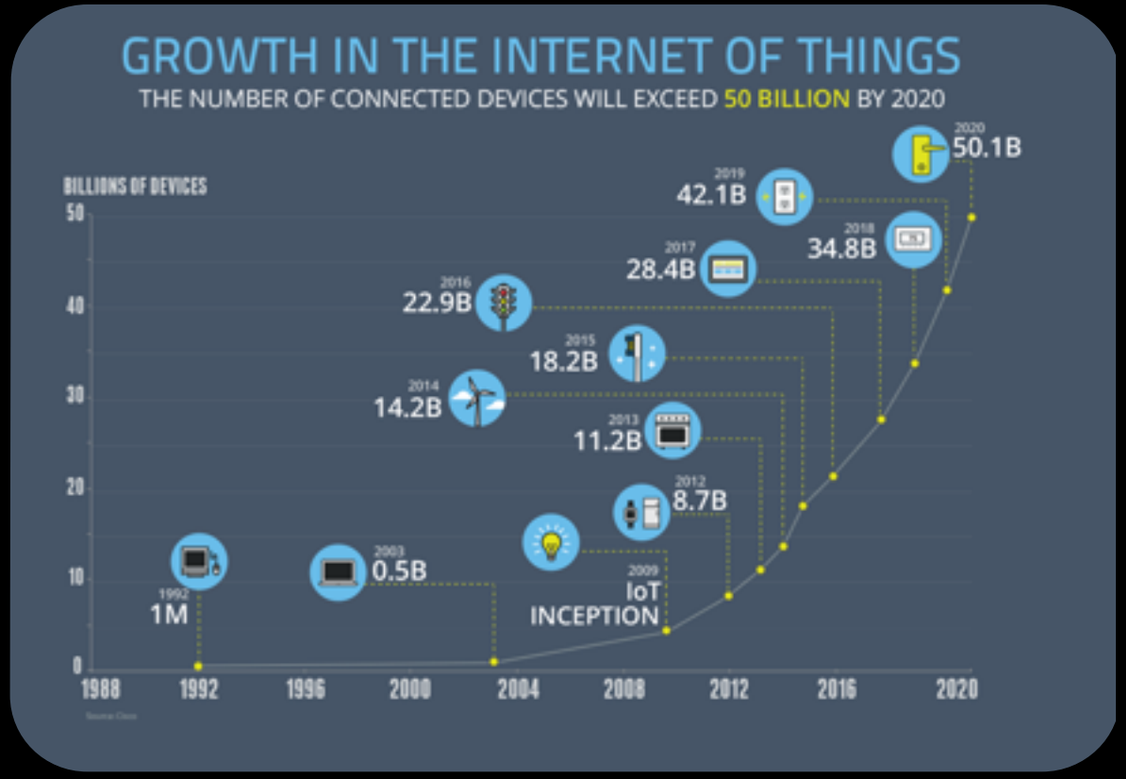
Internet of Documents

Internet of Commerce

Internet of Applications

Internet of People

Internet of Things



Over 50 billion devices by 2020

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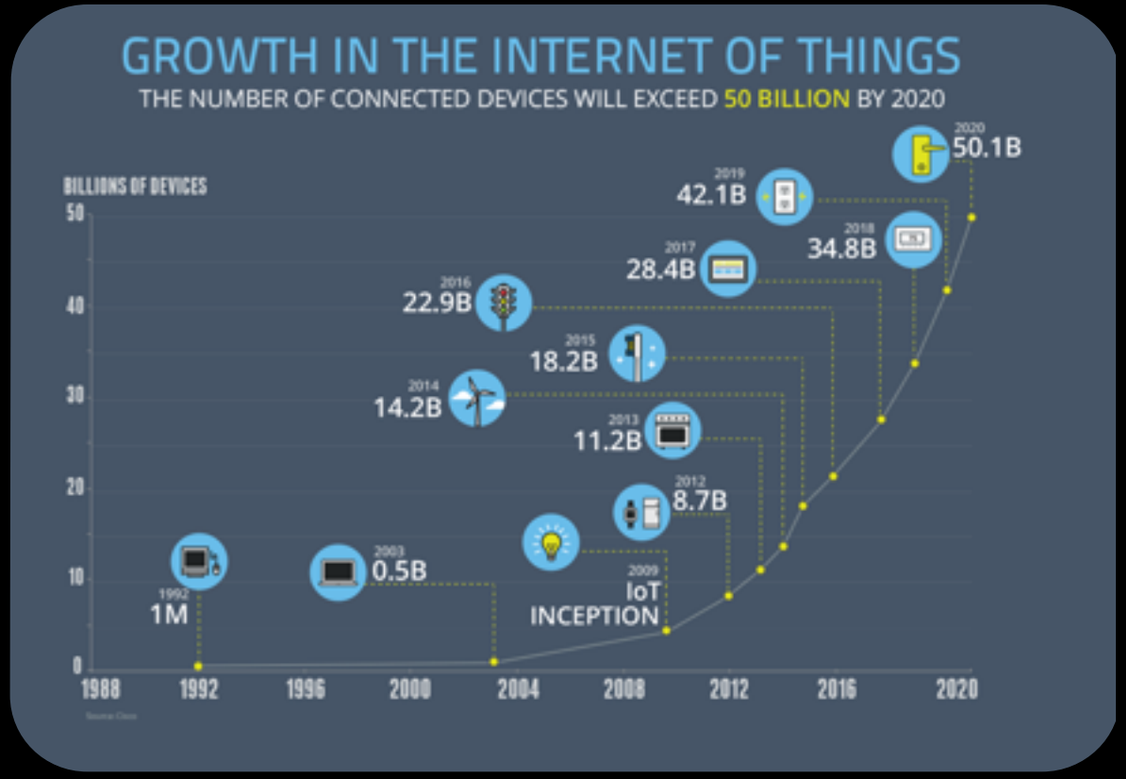


Over 50 billion devices by 2020

<u>Key Problem of IoT</u>:
How can we merge physical world and digital world?

Digital world

How to Close the Gap?

Physical world

Digital world

Physical world

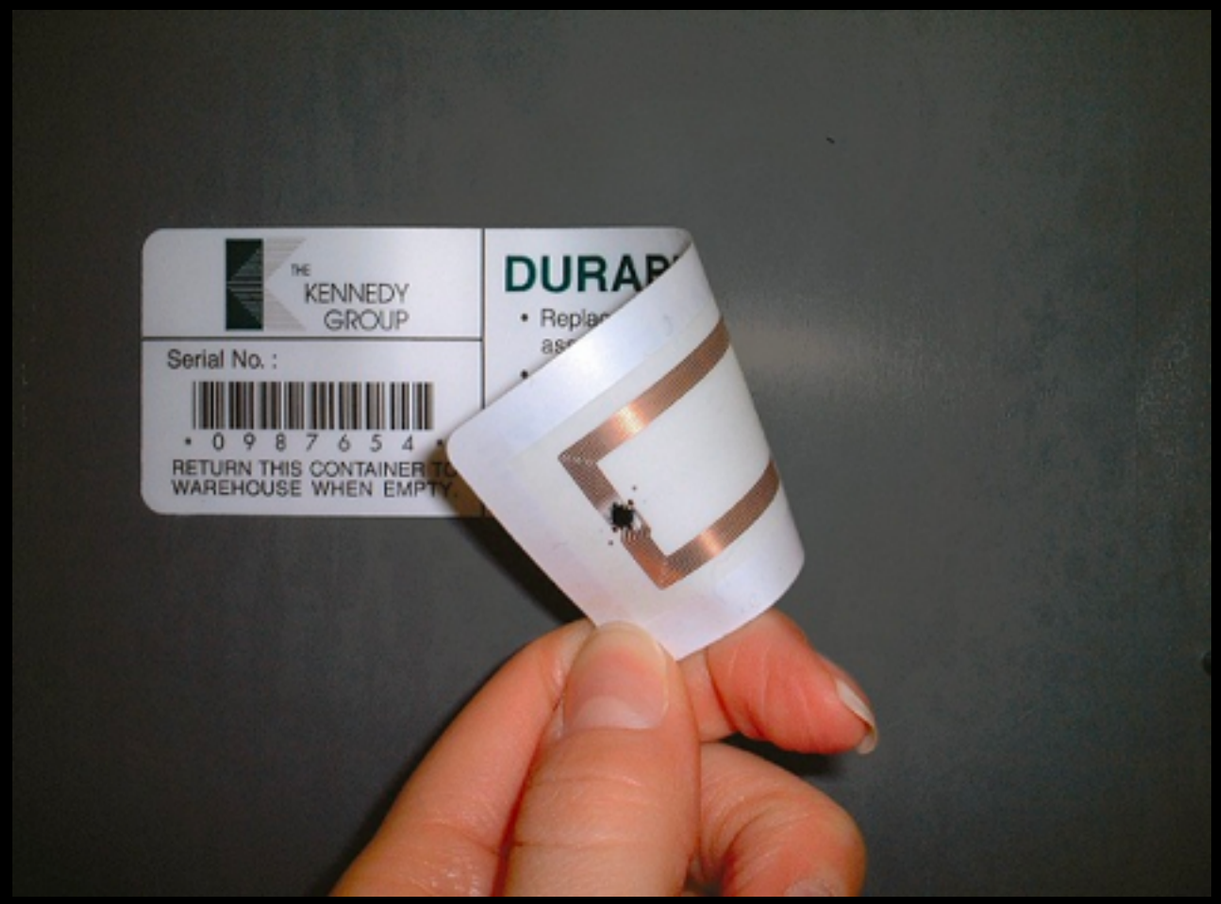
Digital world

Low power IoT devices

Physical world

Low Power Internet-of-Things: Billions of Devices

5-cent battery less stickers



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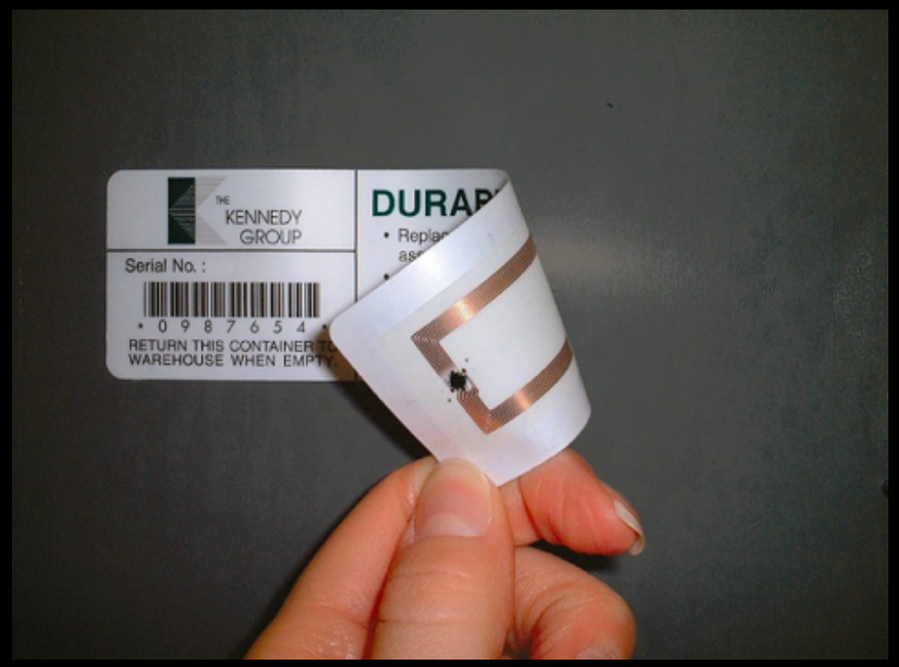

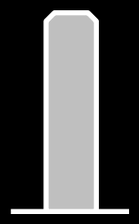

Reader

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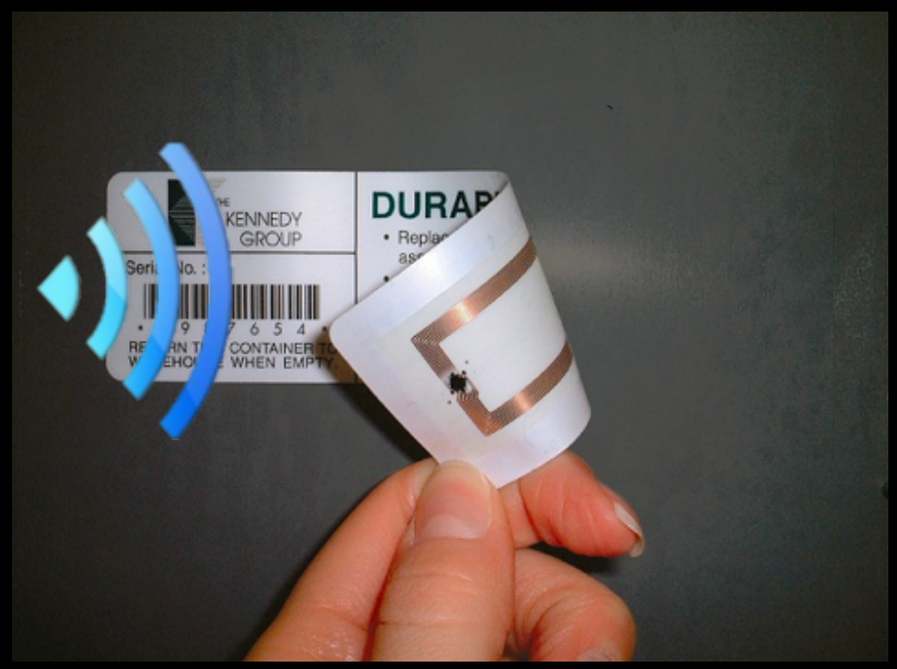

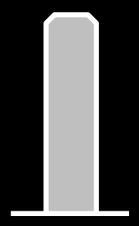

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Low Power Internet-of-Things: Billions of Devices

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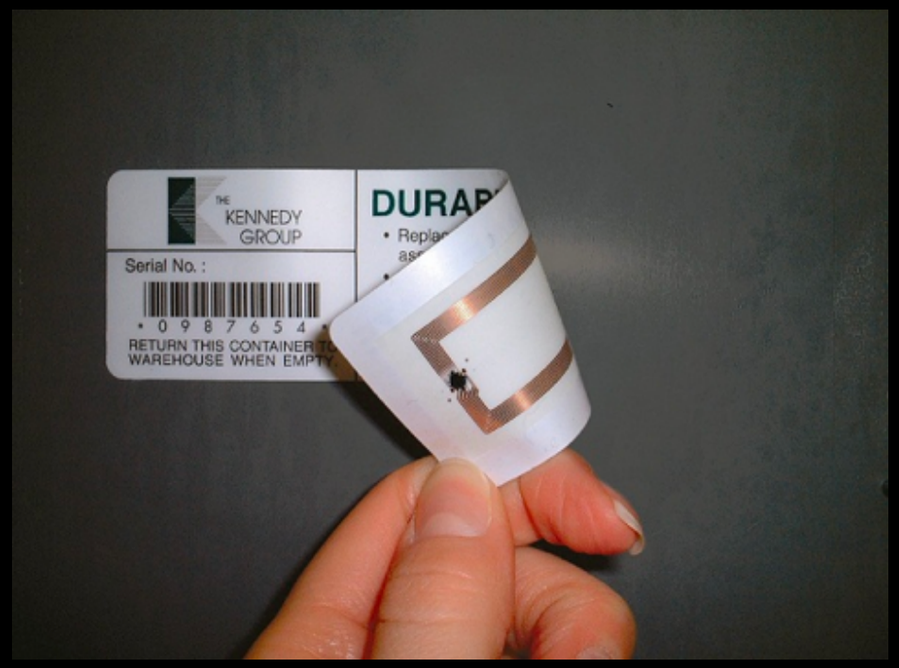
Reader

Reply to wireless reader with a unique identifier



Enable New Applications

Enable New Applications

Where are
my keys?

Enable New Applications

Where are
my keys?

The US army lost 13.6 billion
dollars due to misplaced items

Enable New Applications

Where are
my keys?

Enable New Applications

Where are my keys?

Robotic Manipulation

Enable New Applications

Where are my keys?

Robotic Manipulation

Drug Delivery

Challenges

Challenges

Scale is limited

Scope is limited

Challenges

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- low power nature
=> tens of centimeters to several meters
communication range

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- batter-free nature
=> networking of these battery-free devices today are only possible outside of our body

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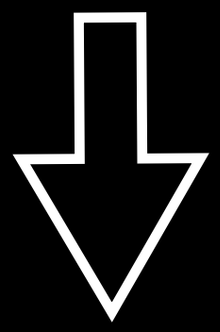

RFly: Drone-based relay
increased coverage by 100x
[SIGCOMM ’17]

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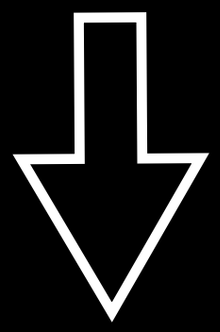

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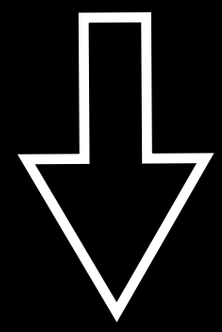

IVN: In-body Networking
[SIGCOMM’18]

Challenges

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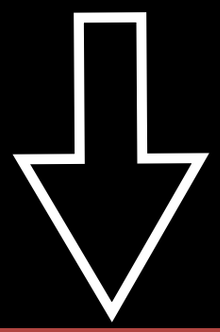

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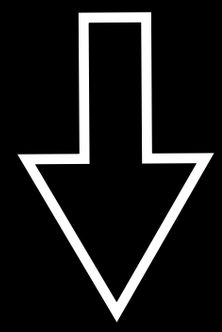

IVN: In-body Networking
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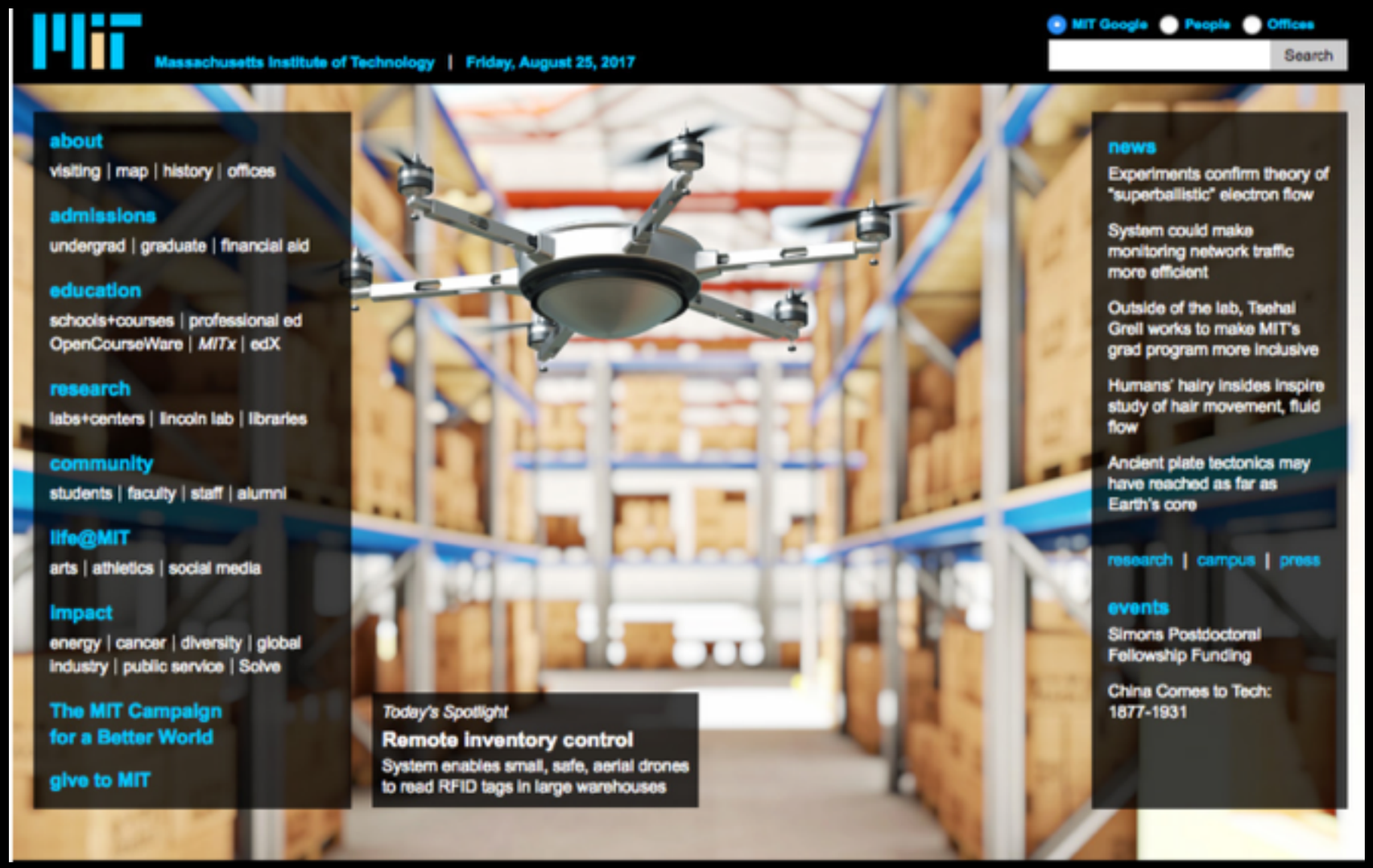
RFly: drone relays for battery-free network



MIT today's spotlight

Other media: BBC, The verge, IEEE Spectrum, Yahoo，新浪，搜狐, etc.

Warehouse Management

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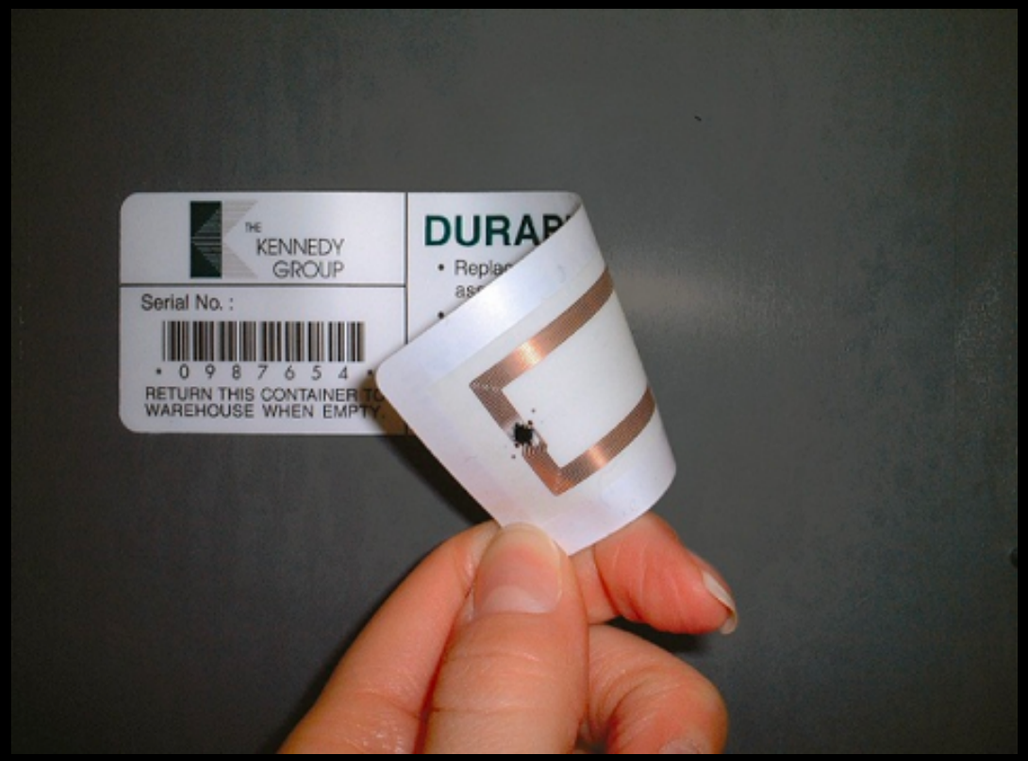
Battery-Free RFIDs for Inventory Control



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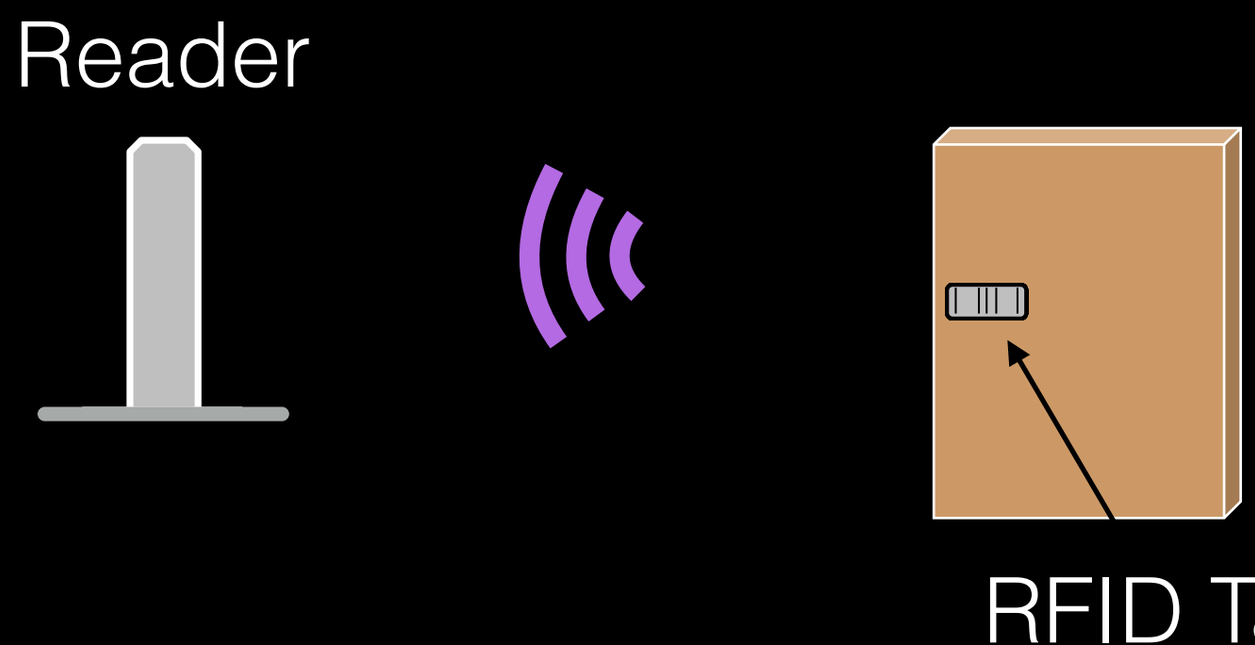

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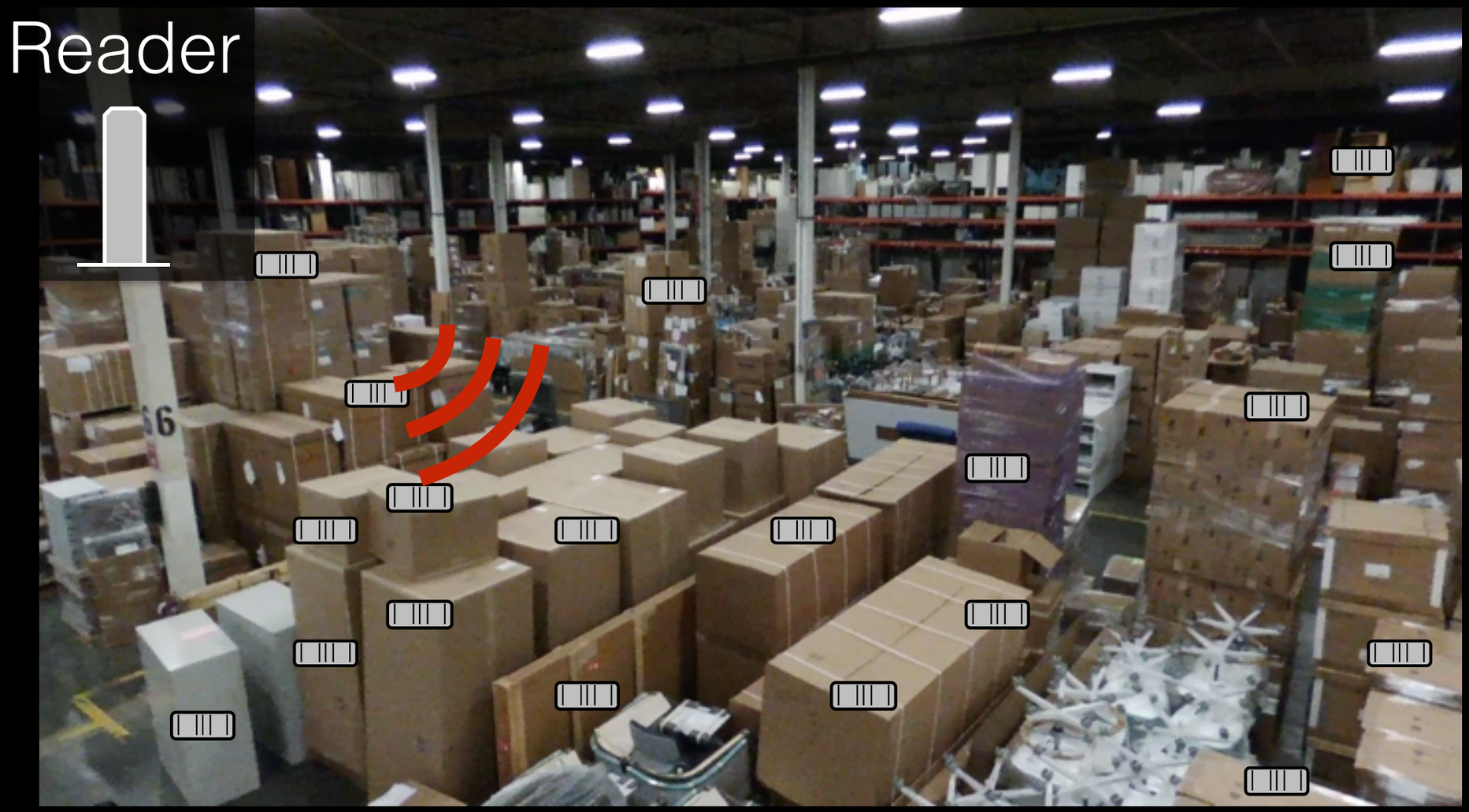
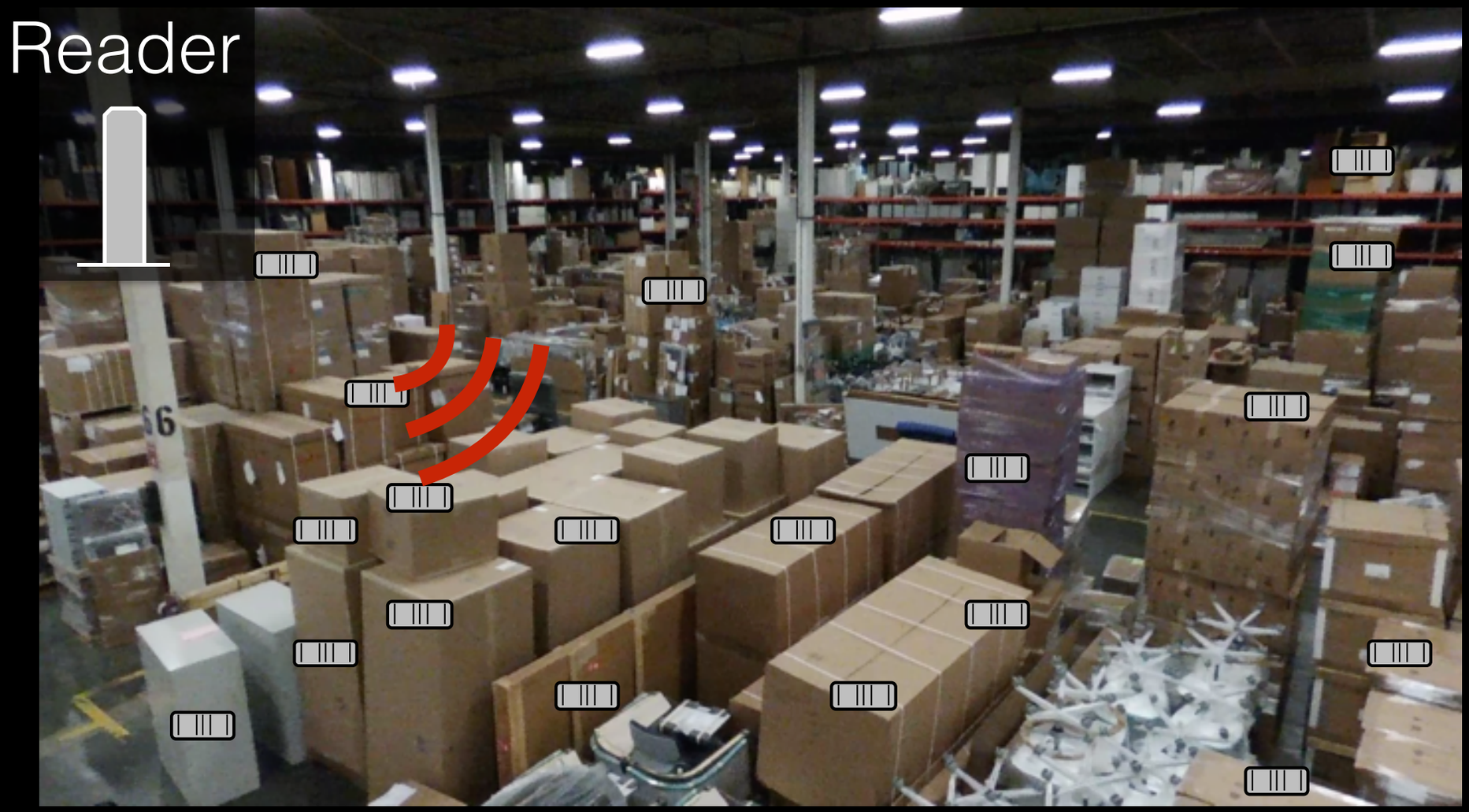


Battery-free RFIDs are fundamentally crippled by their limited communication range



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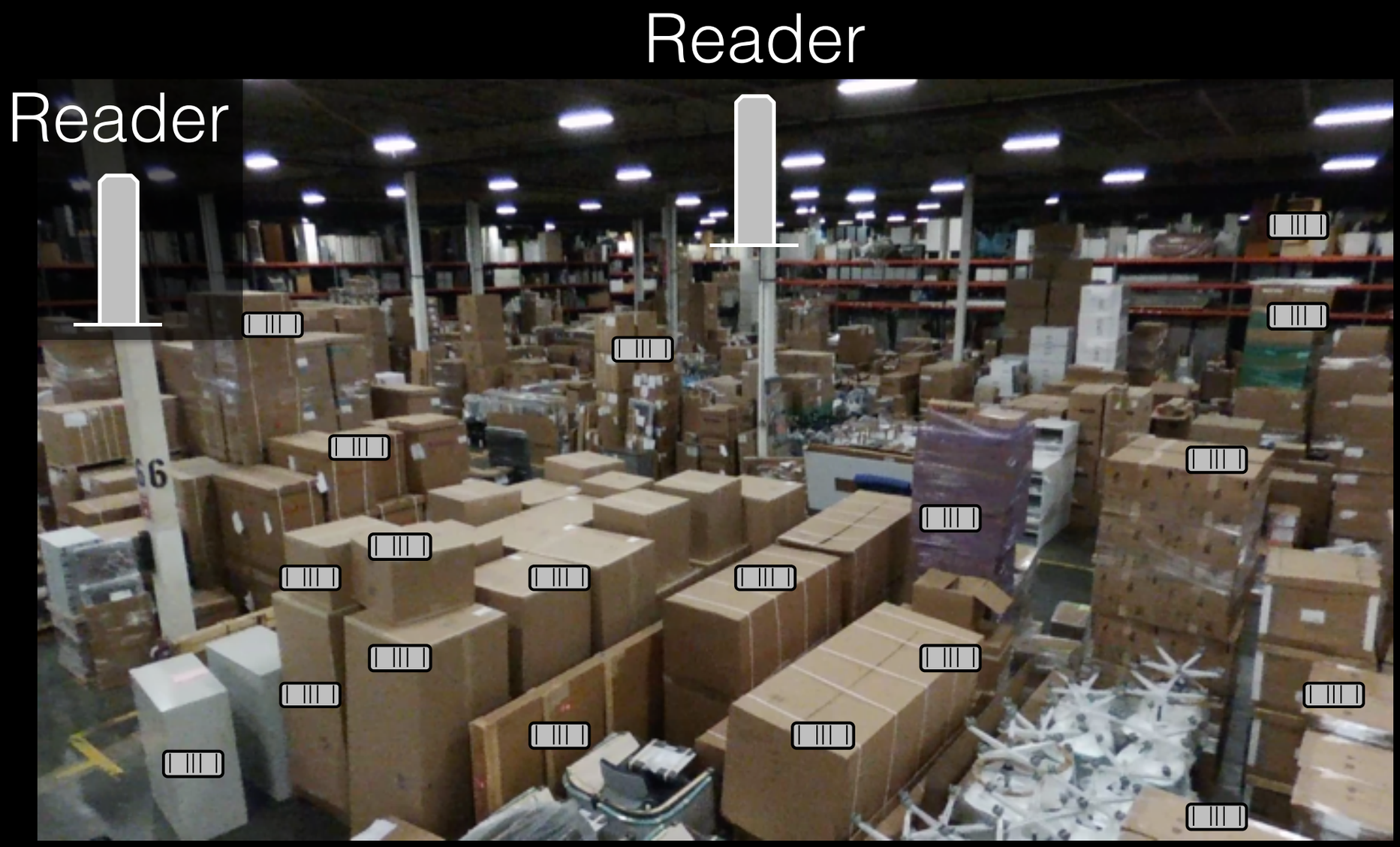

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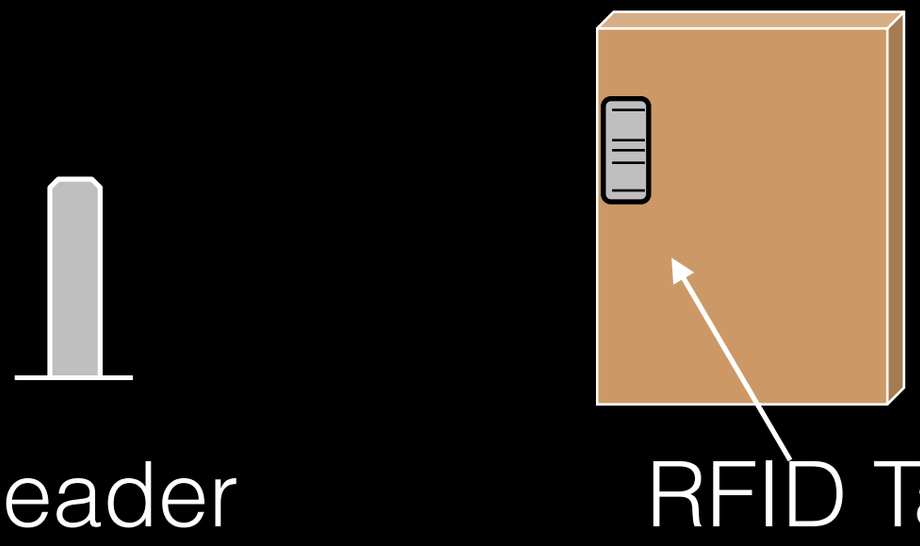
RFly: Enabling wide-area battery-free sensing using drone relays



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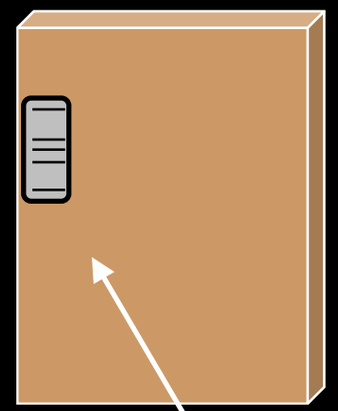
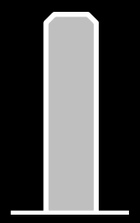


RFID Tag



Reader

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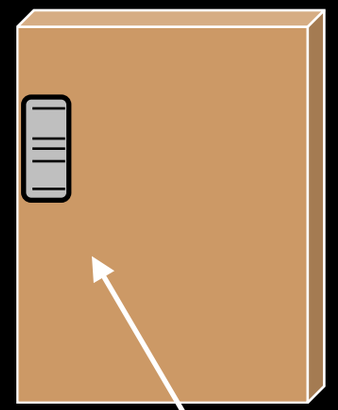
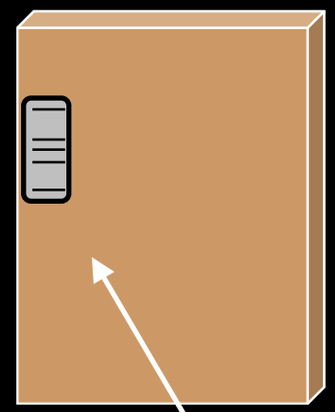


RFID Tag

RFly: Enabling wide-area battery-free sensing using drone relays

Signal too weak to power up tag



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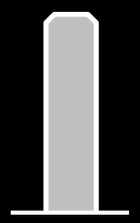

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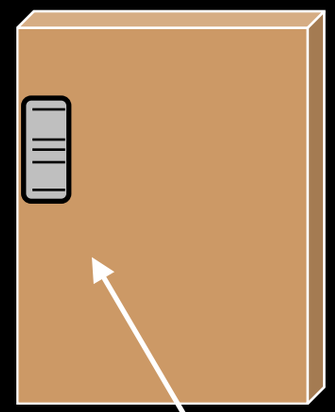

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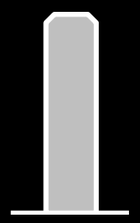

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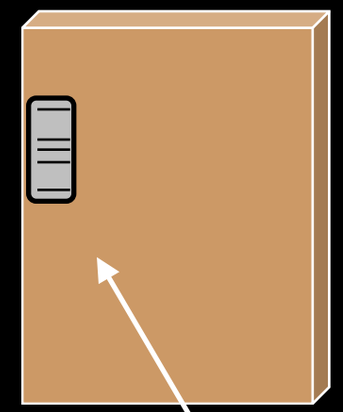

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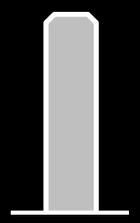

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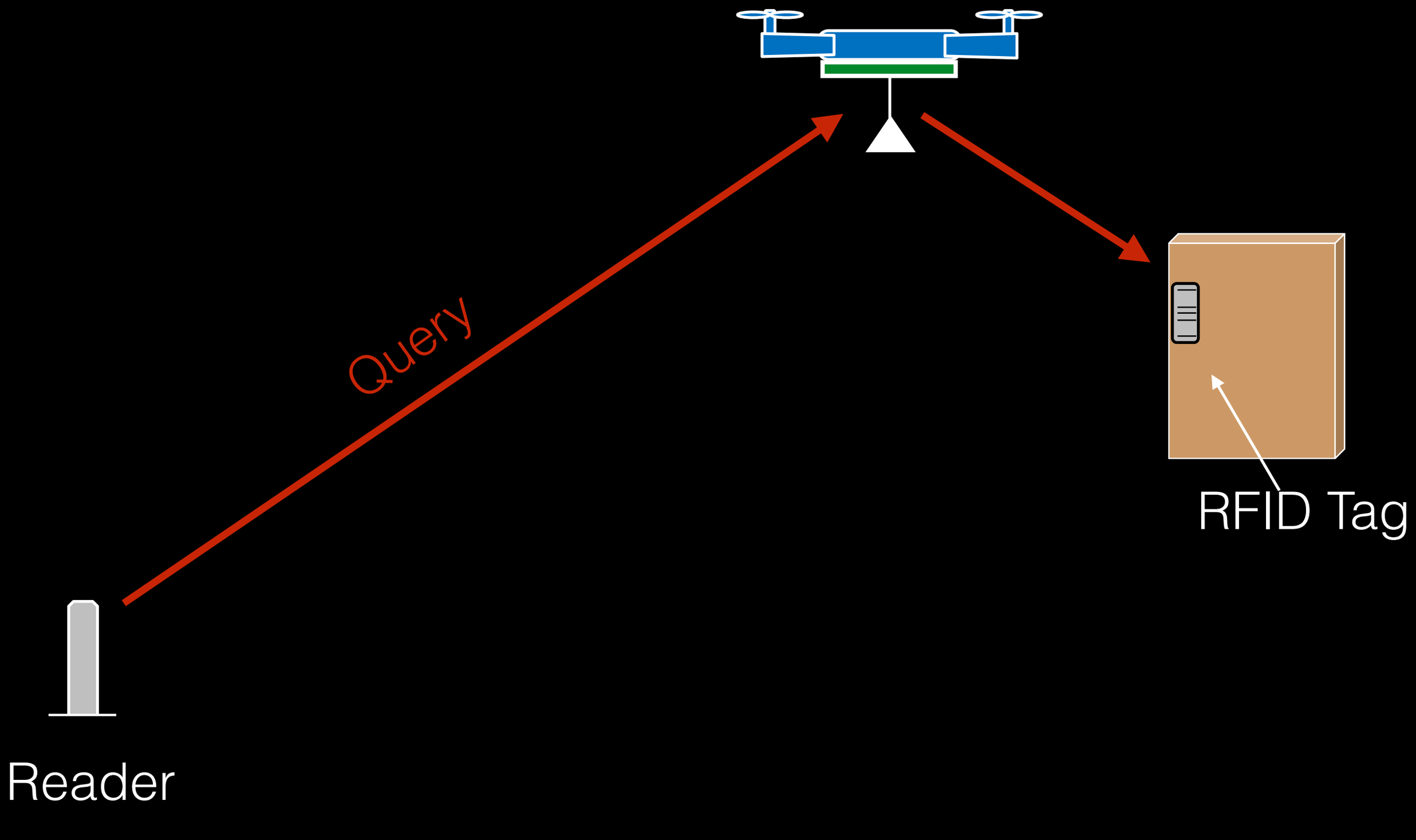

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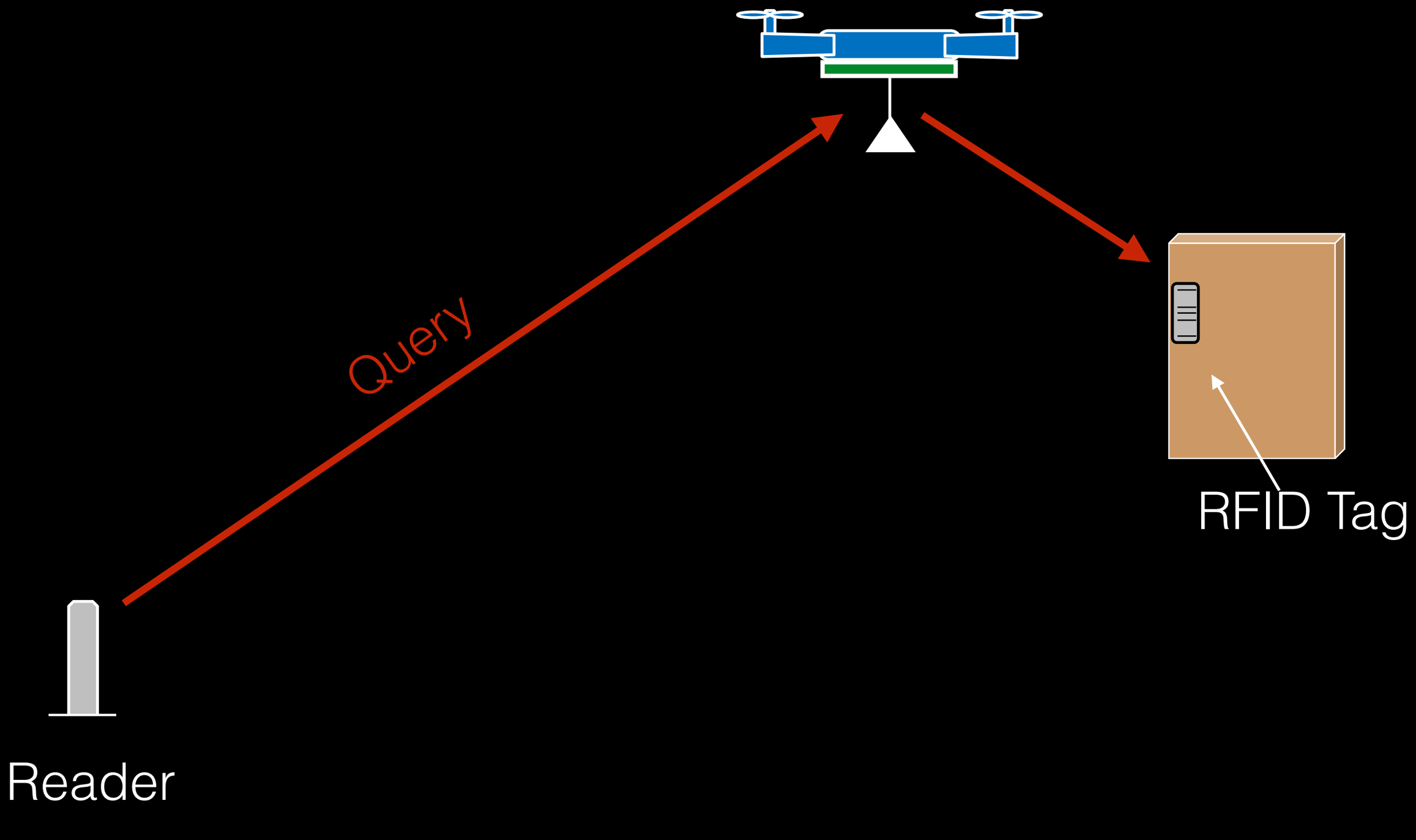

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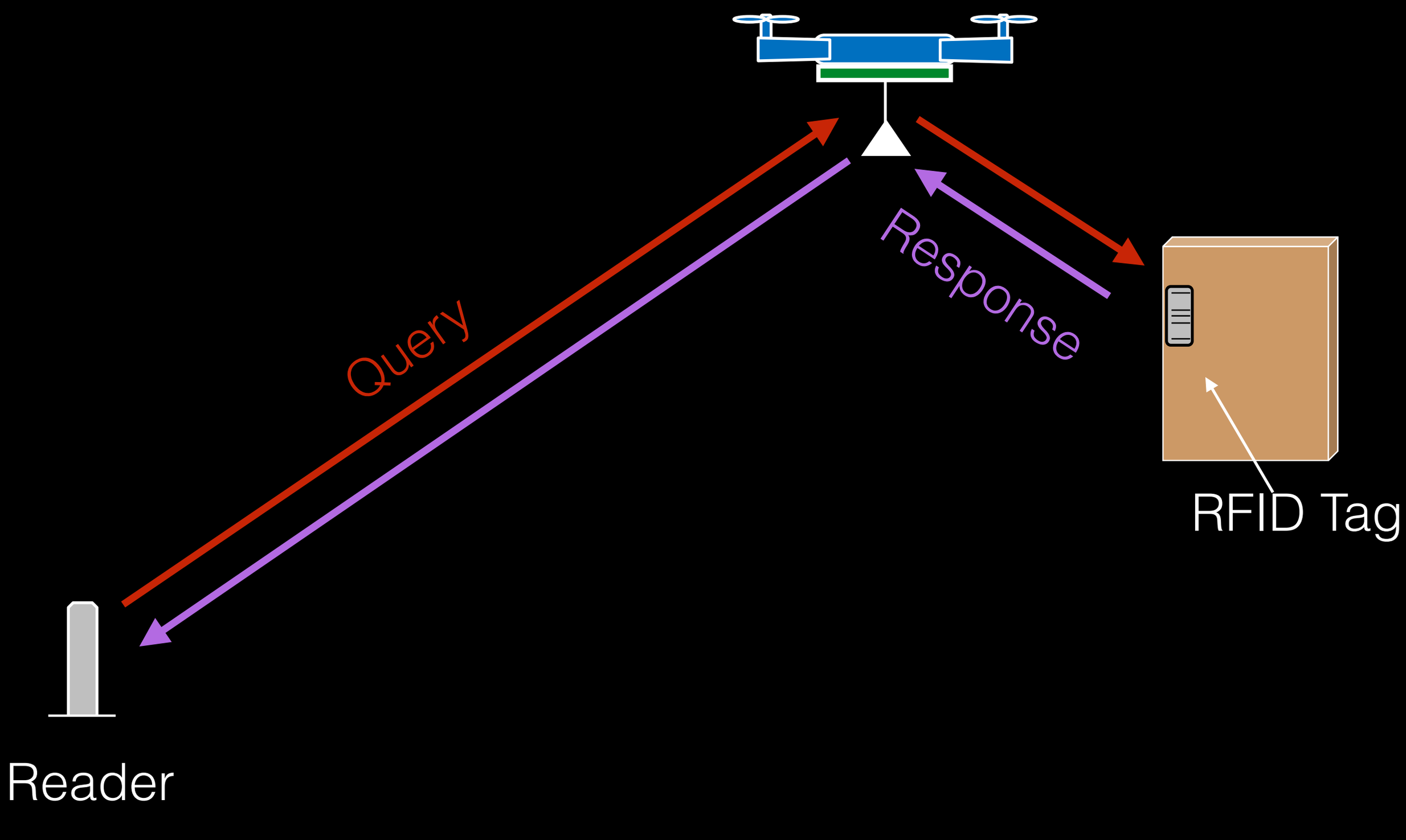

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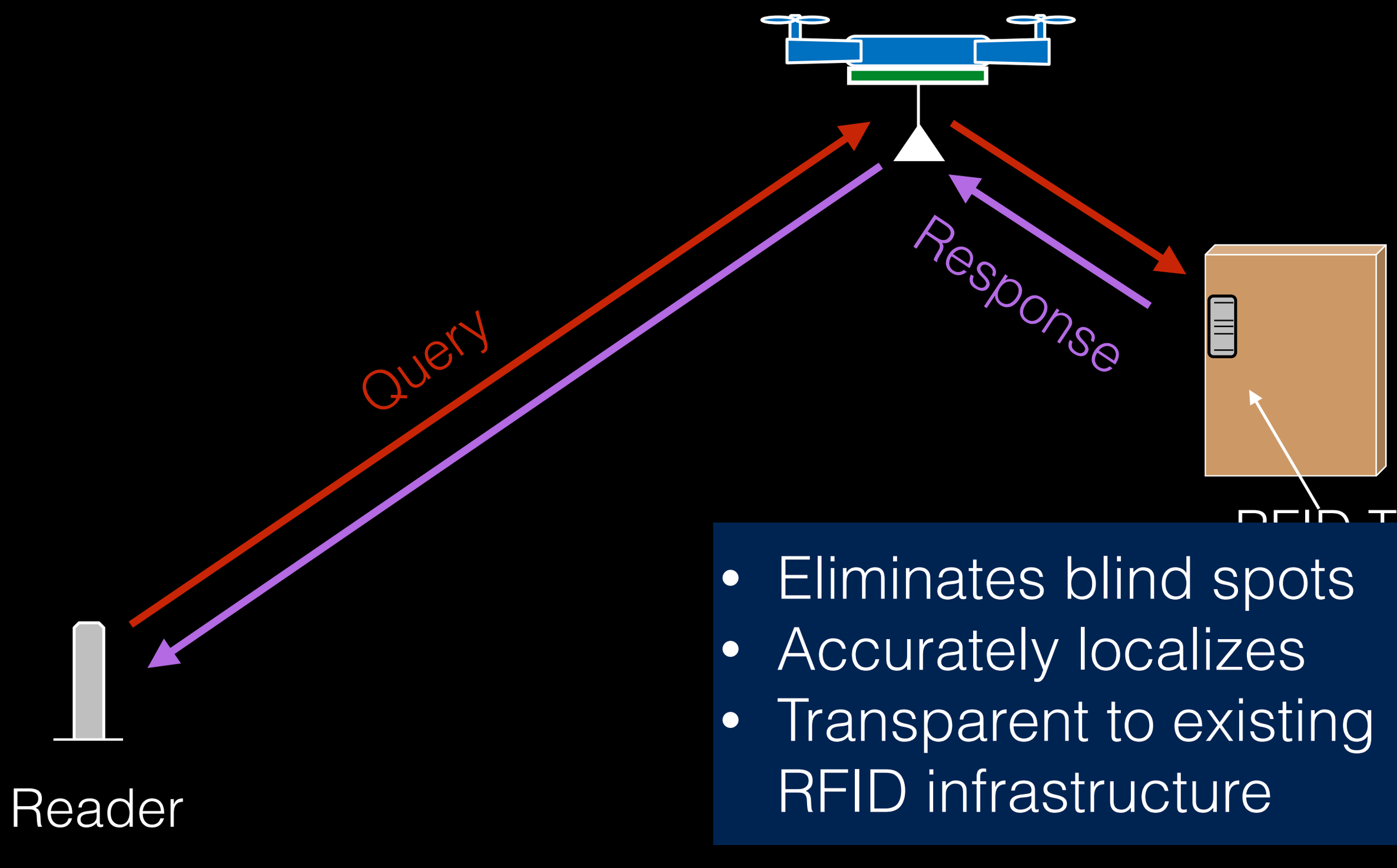
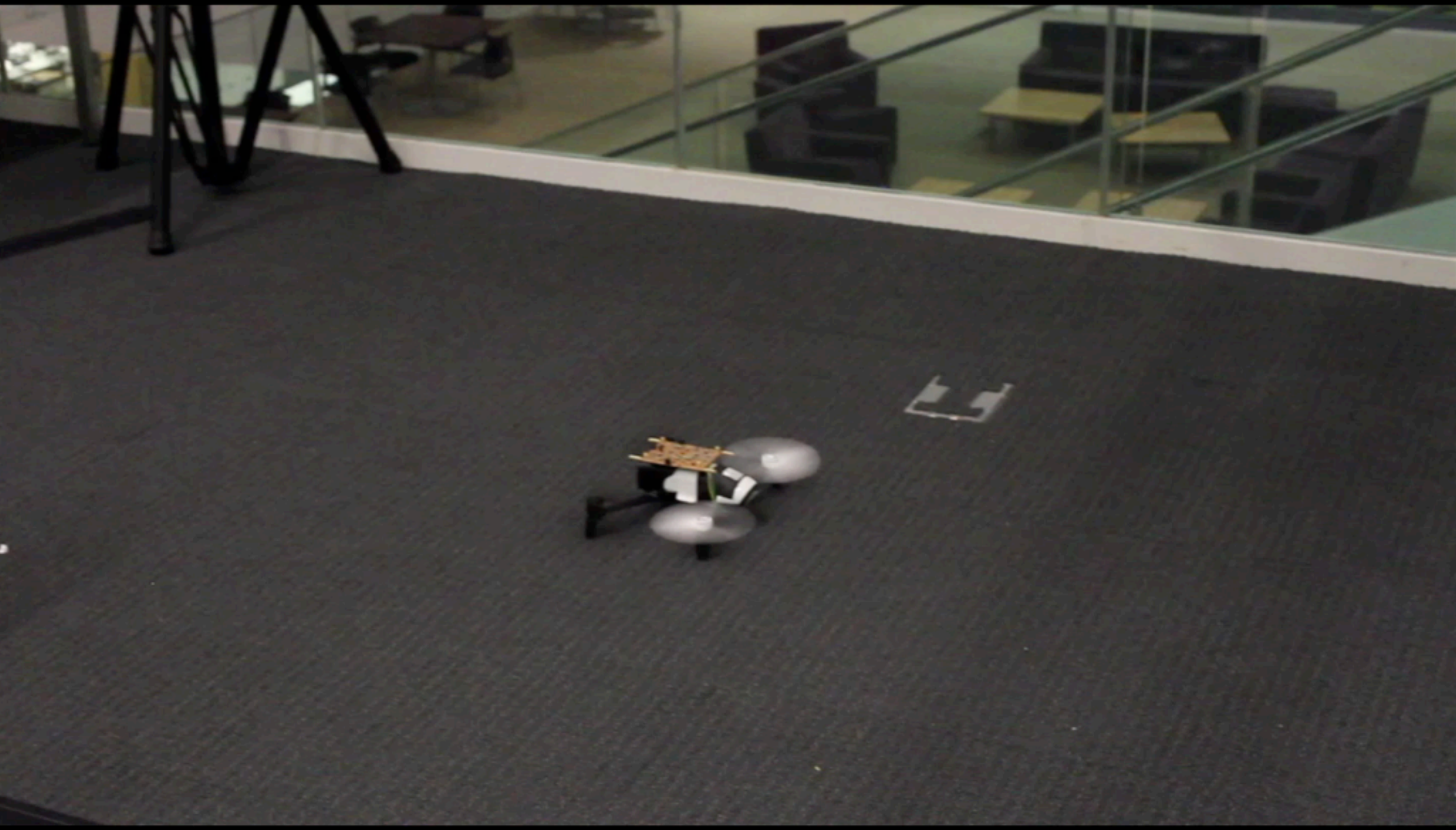
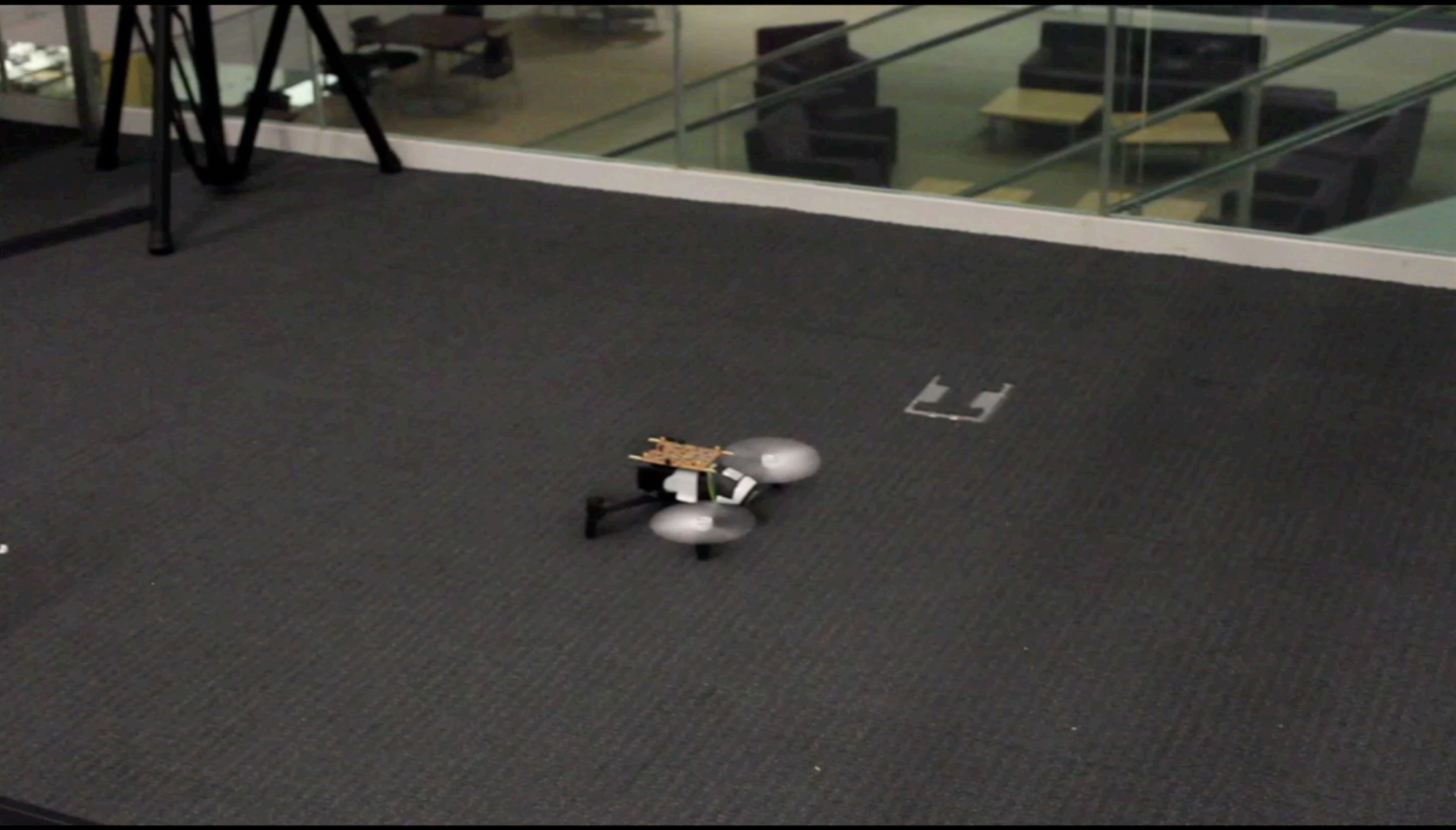
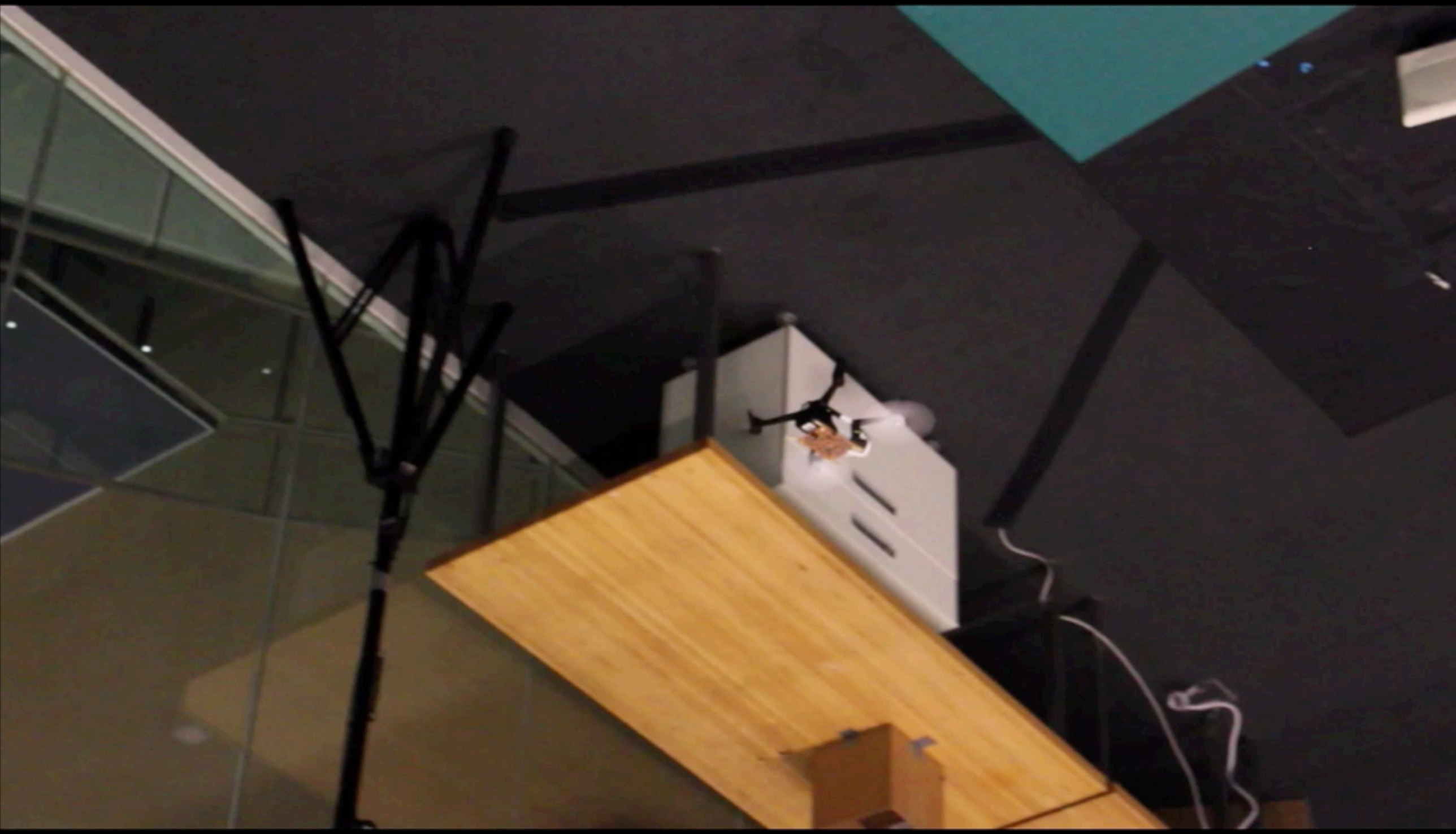
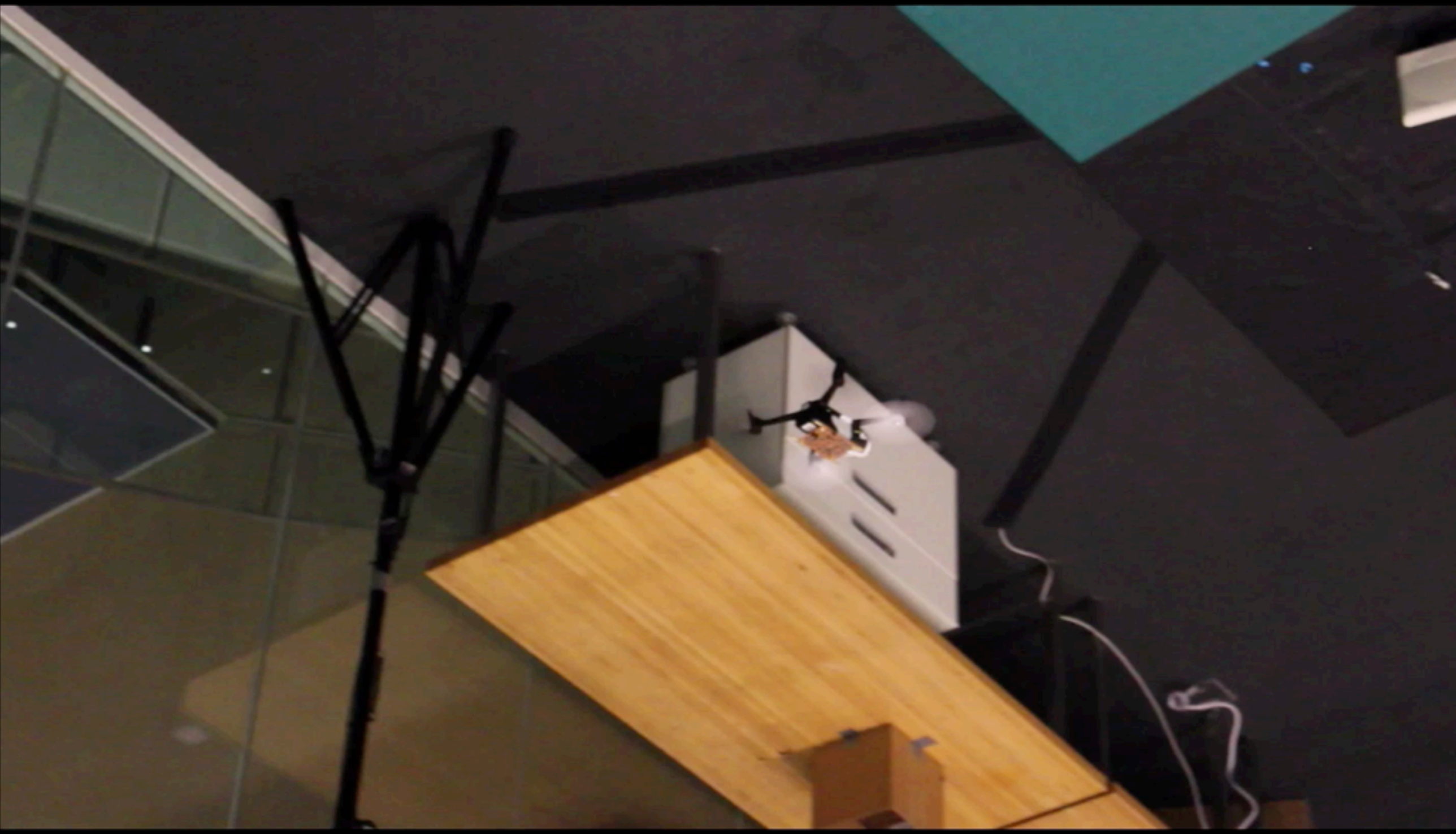


- Eliminates blind spots
- Accurately localizes
- Transparent to existing RFID infrastructure

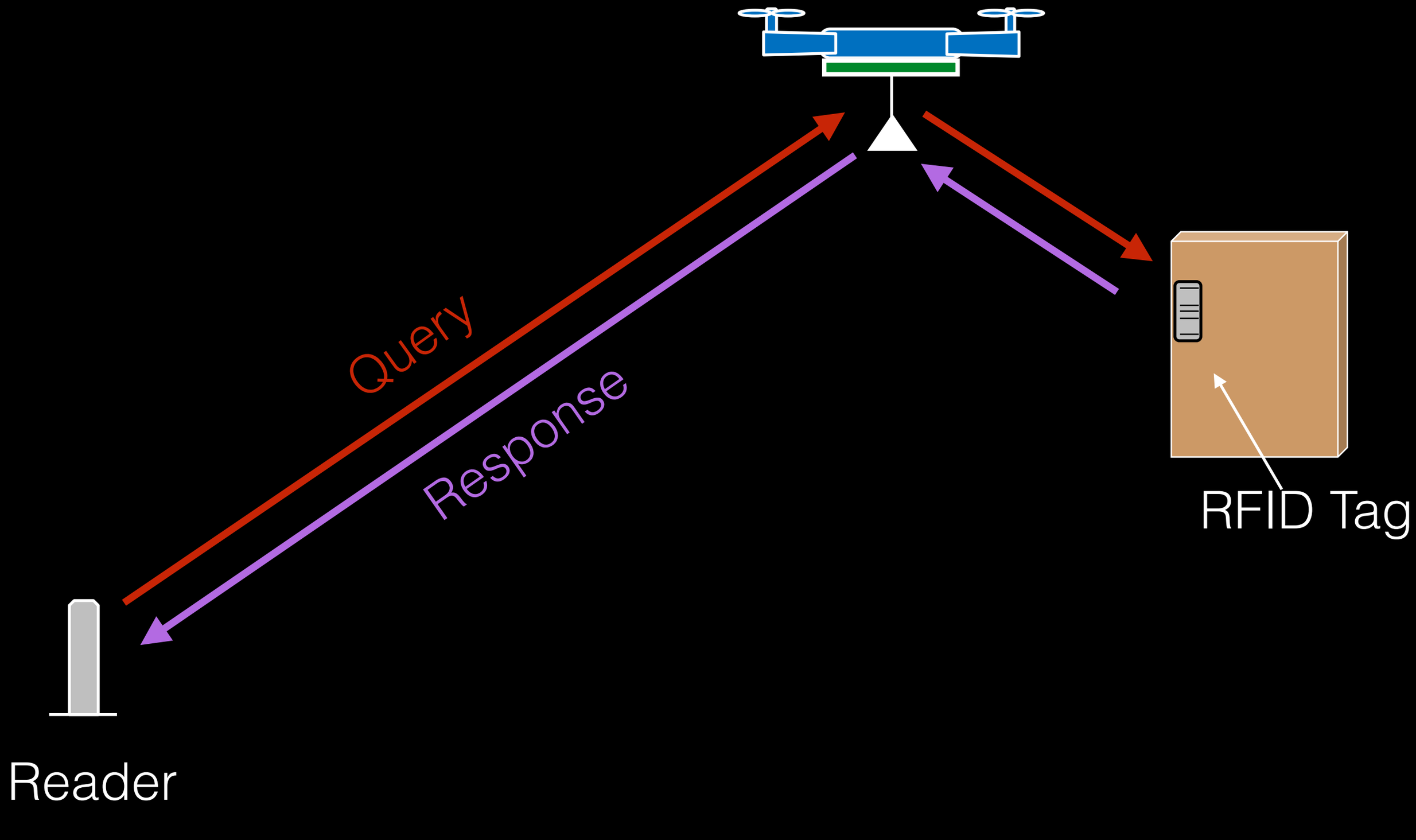








How can we preserve the phase through a relay while extending the range?



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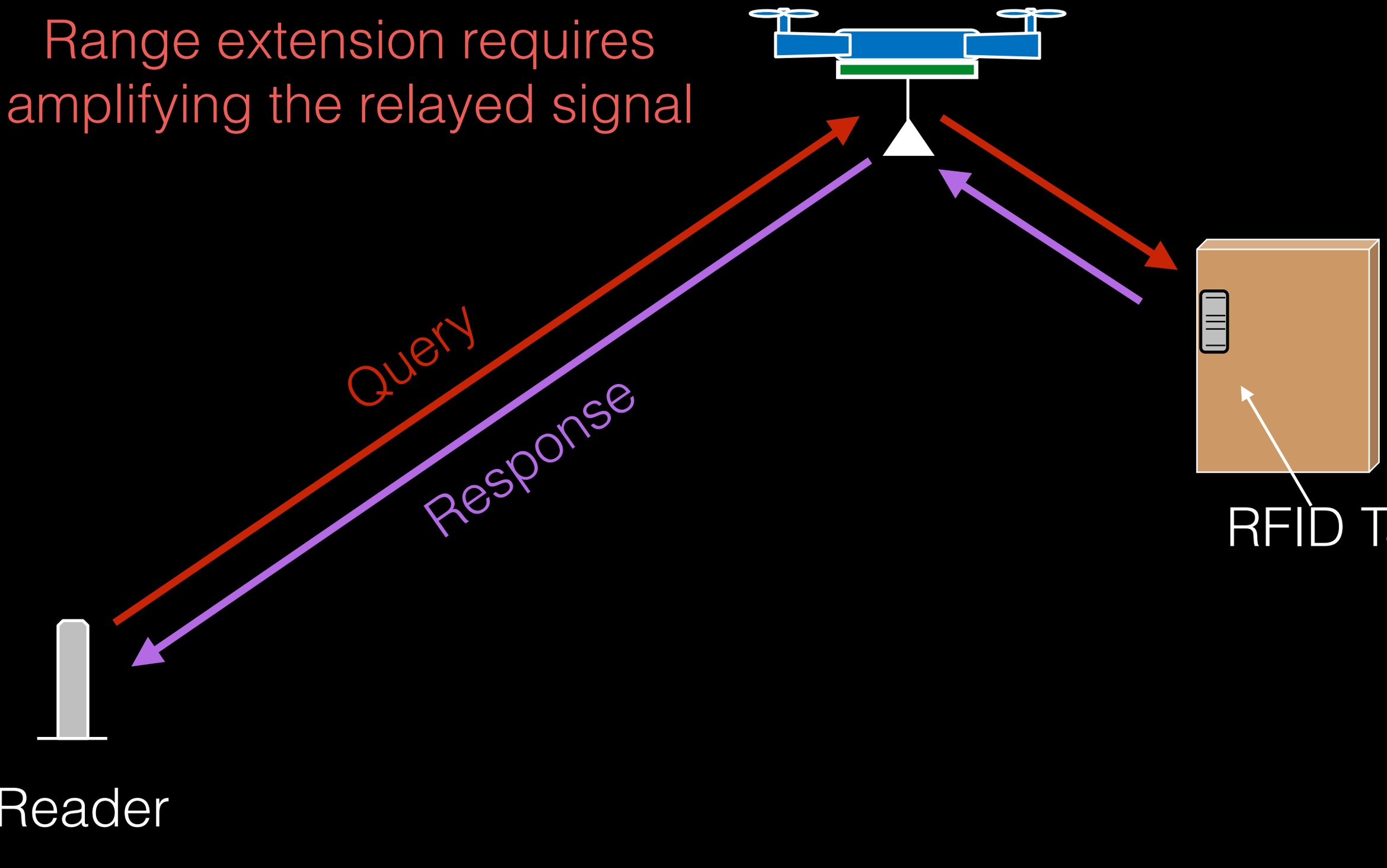
Range extension requires amplifying the relayed signal



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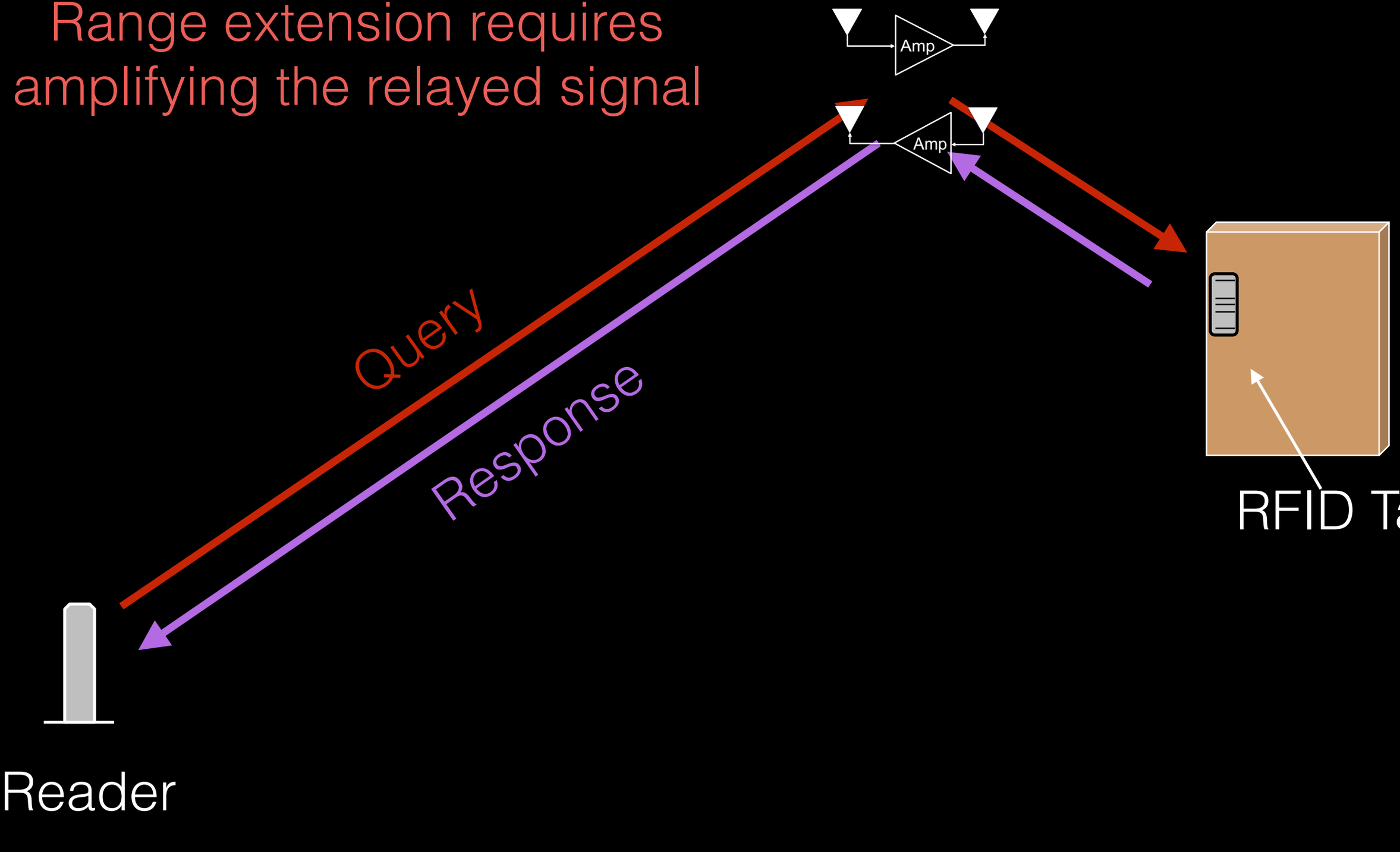
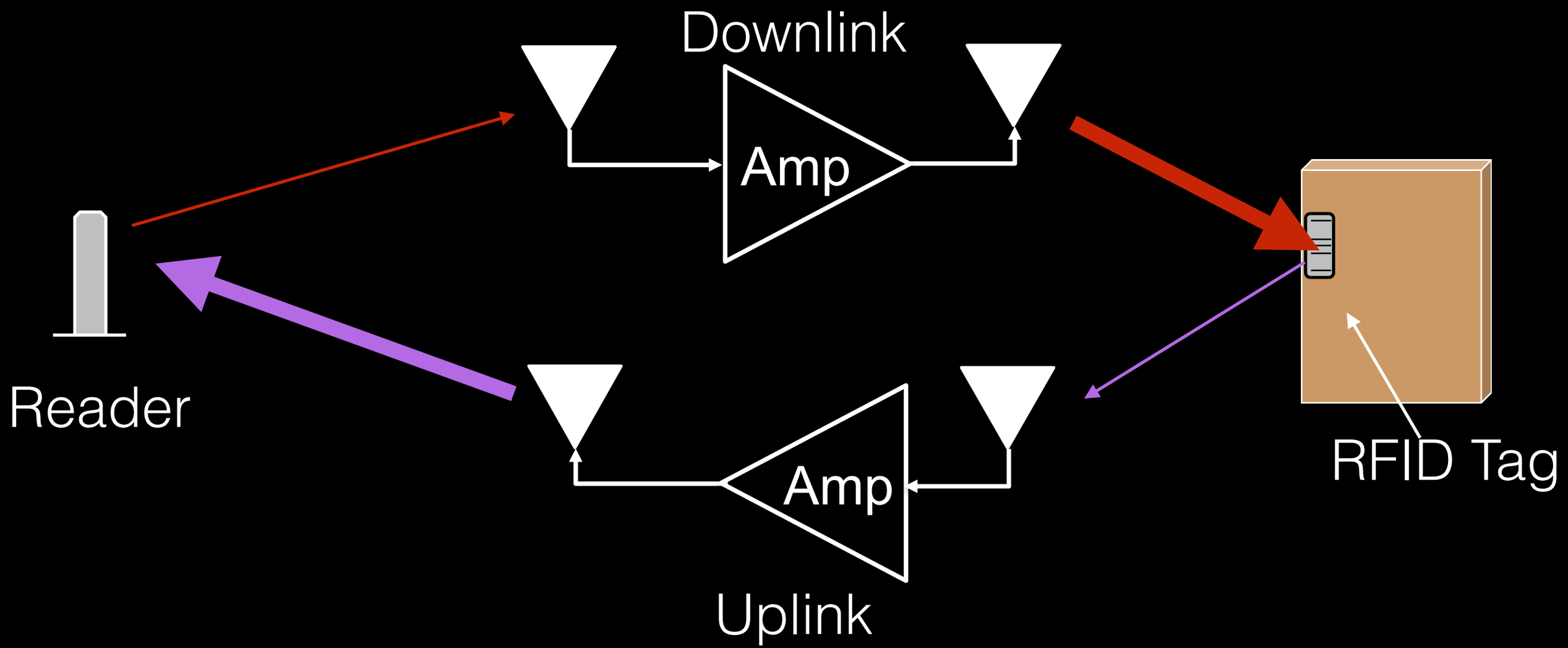


Problem: More amplification results in more self-interference



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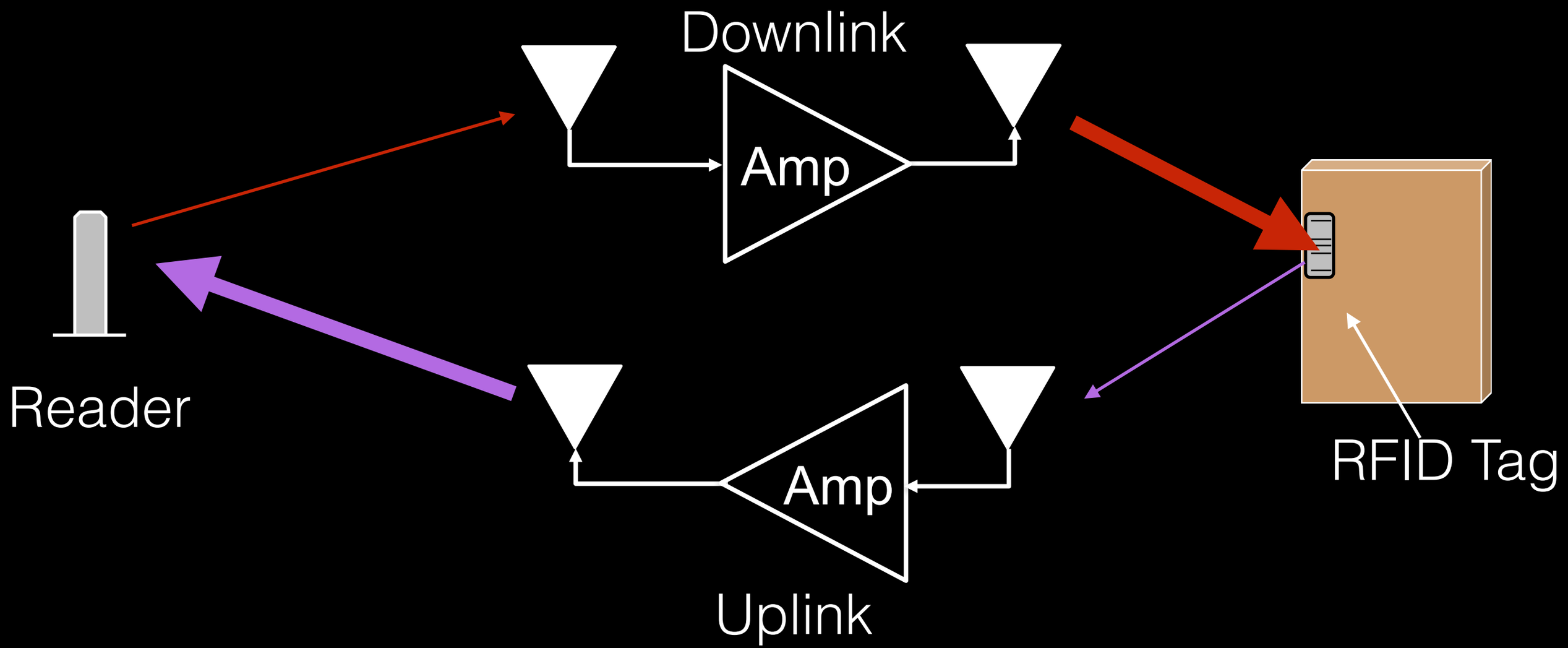
Four sources of self-interference



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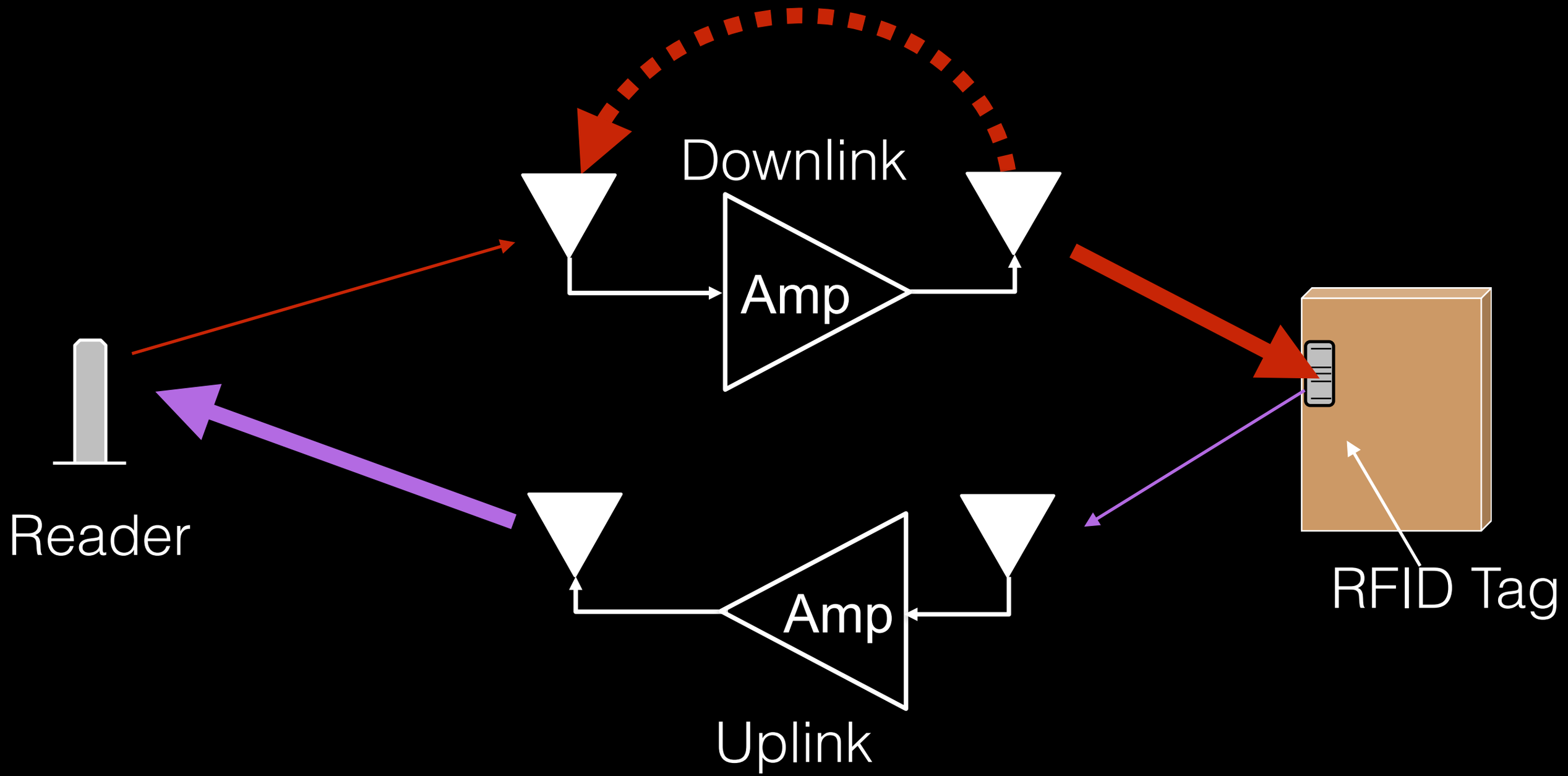

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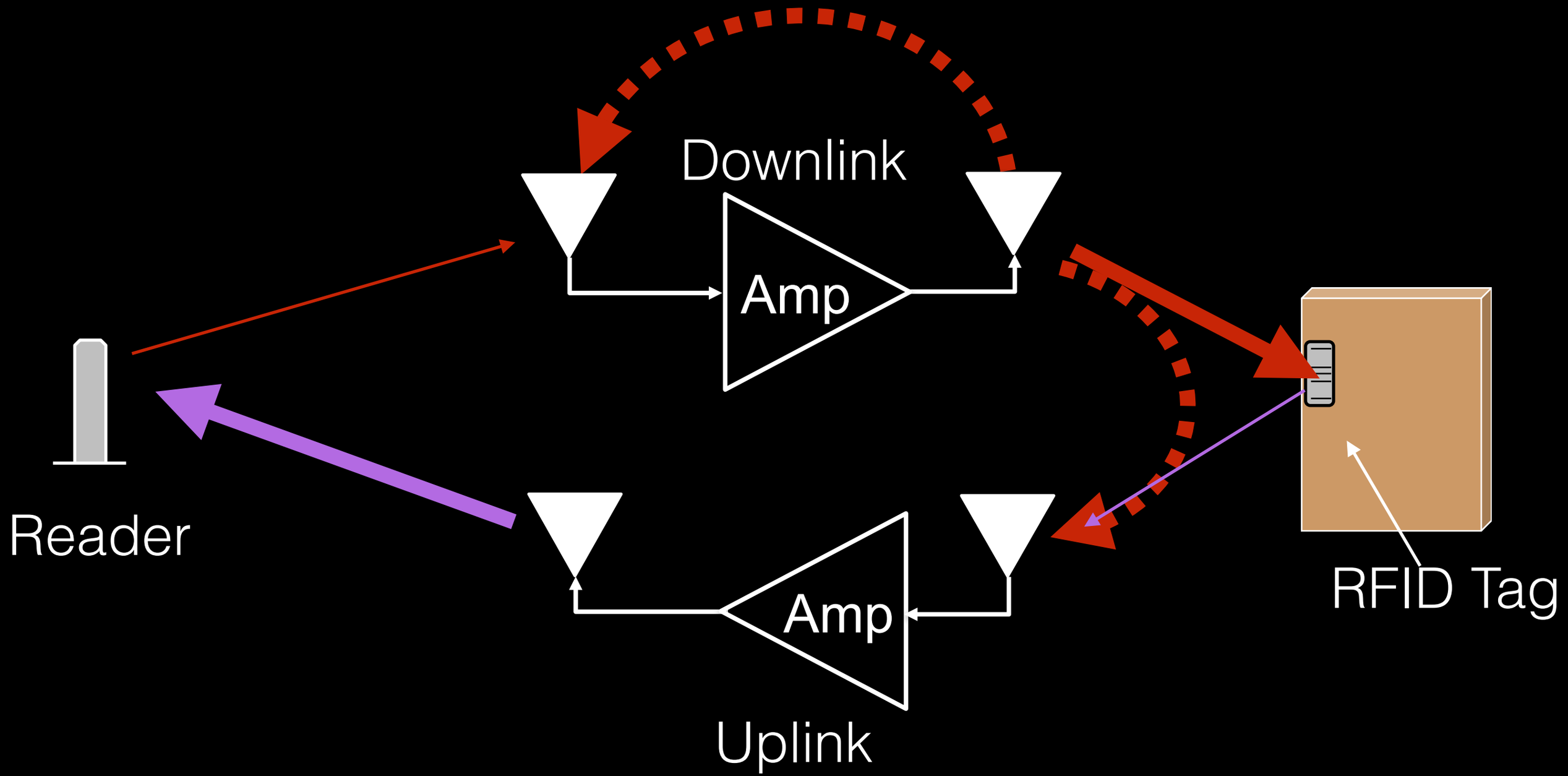

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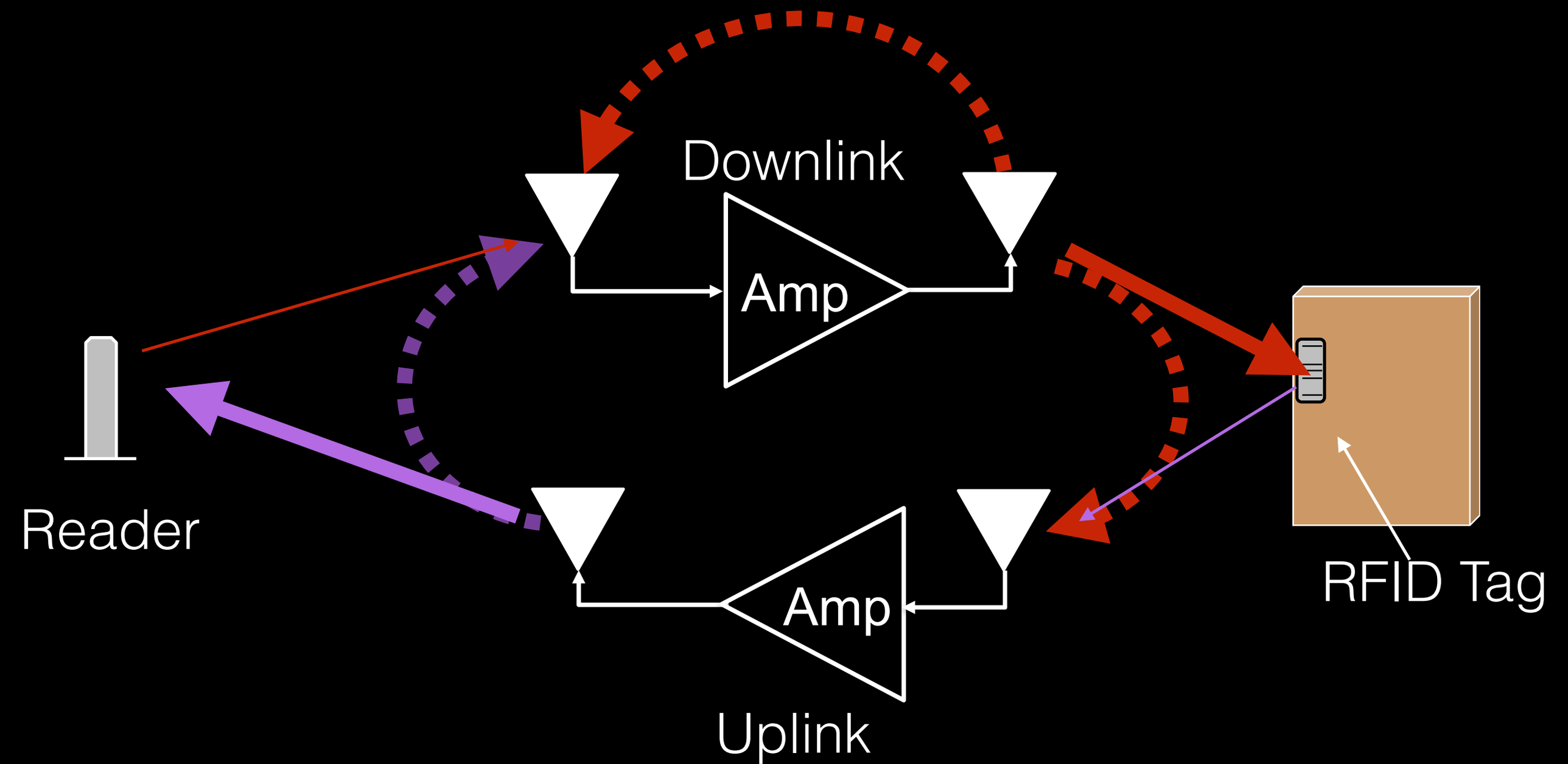

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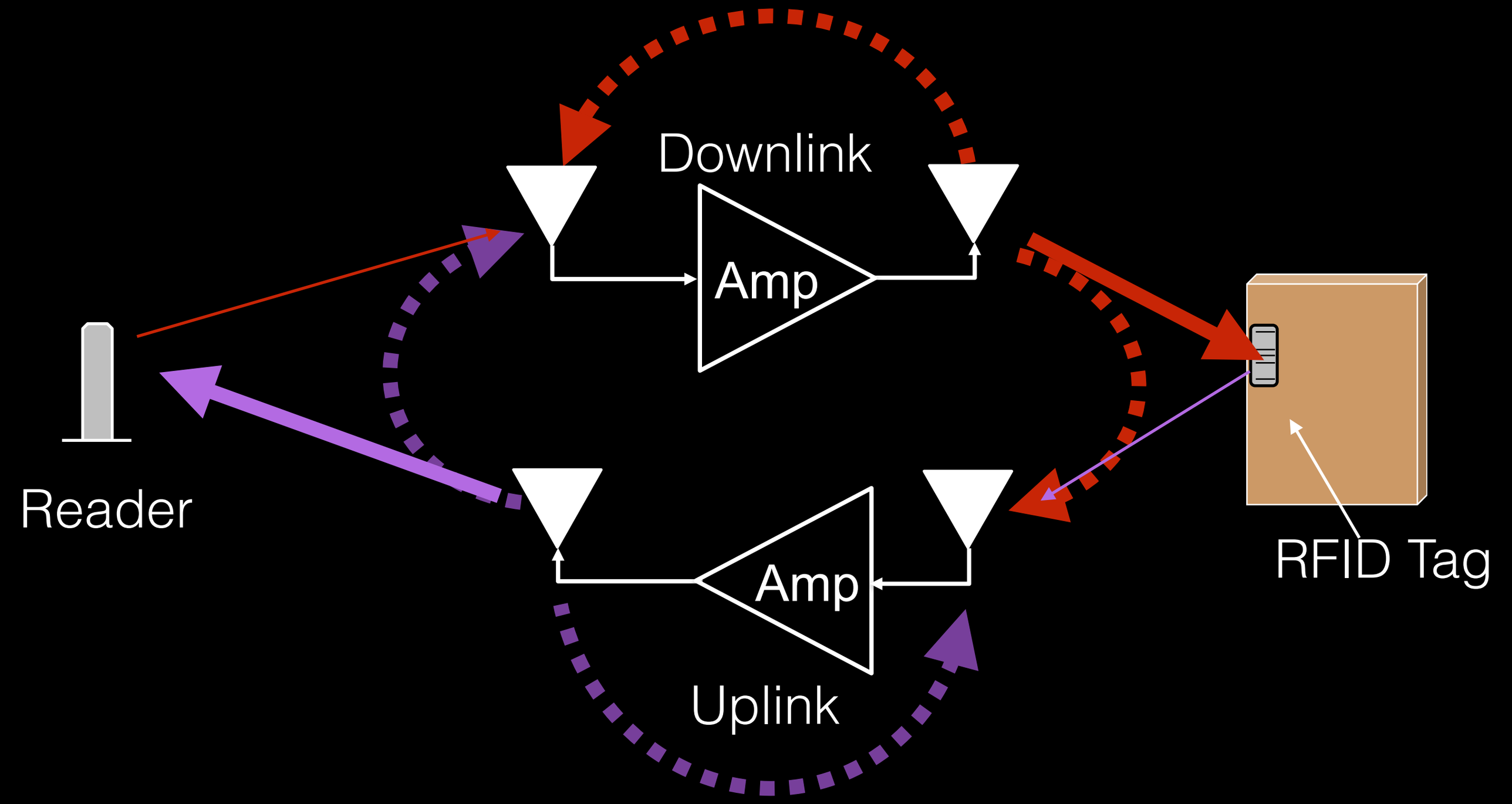

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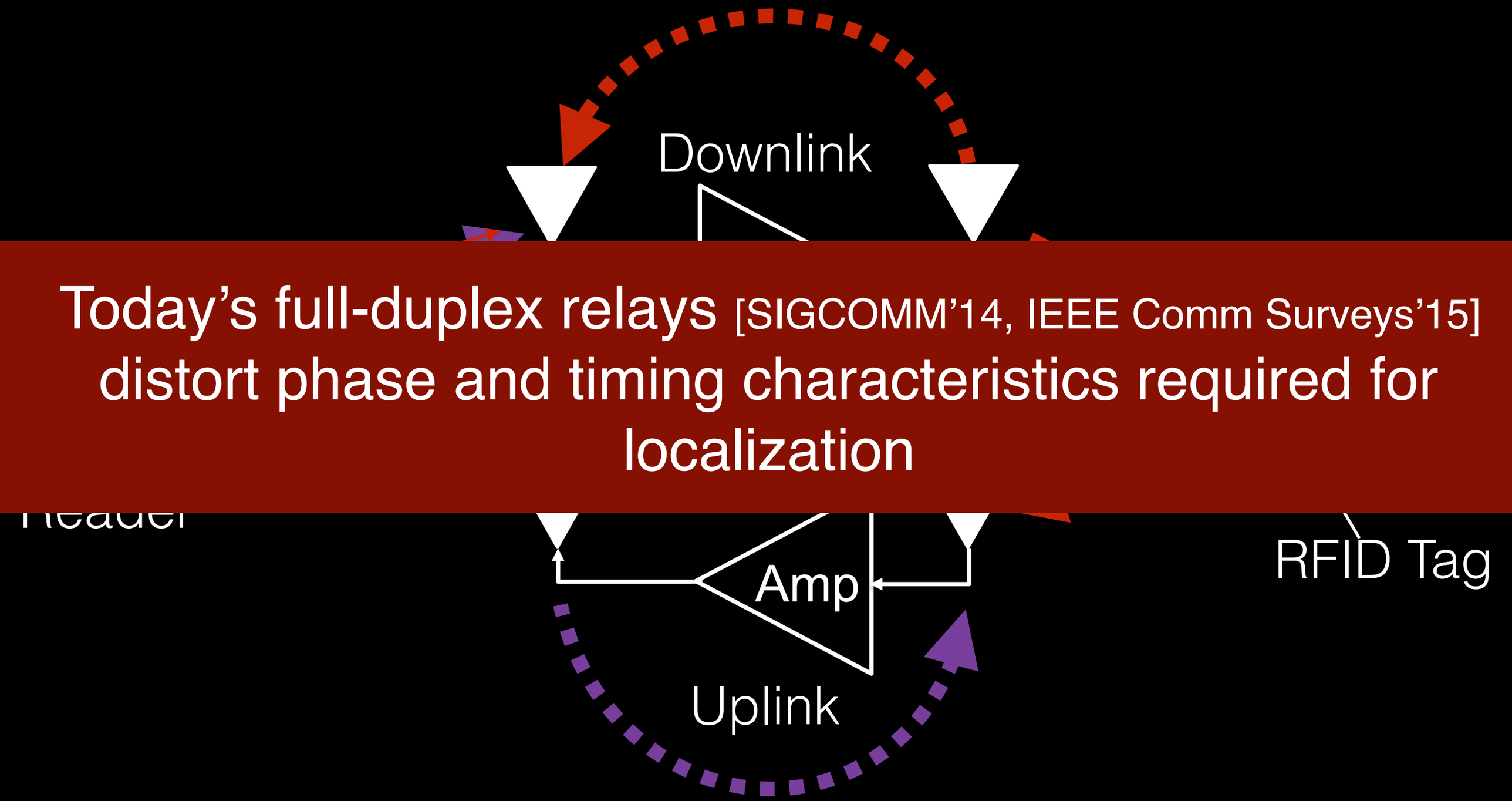
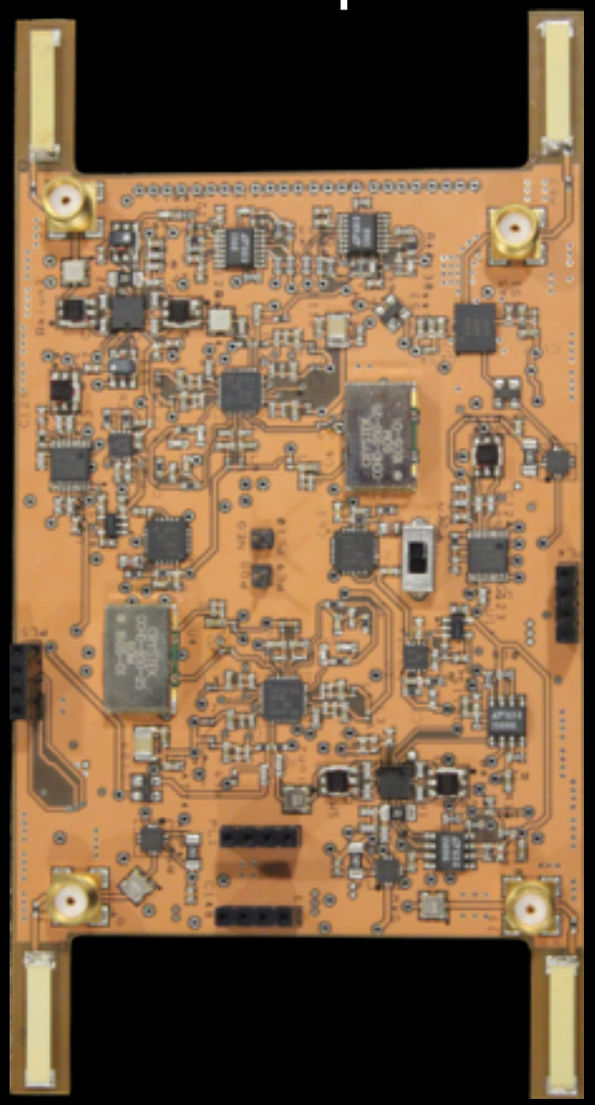


Today's full-duplex relays [SIGCOMM'14, IEEE Comm Surveys'15] distort phase and timing characteristics required for localization

Solution: Bi-directional full-duplex relay with phase & timing preservation



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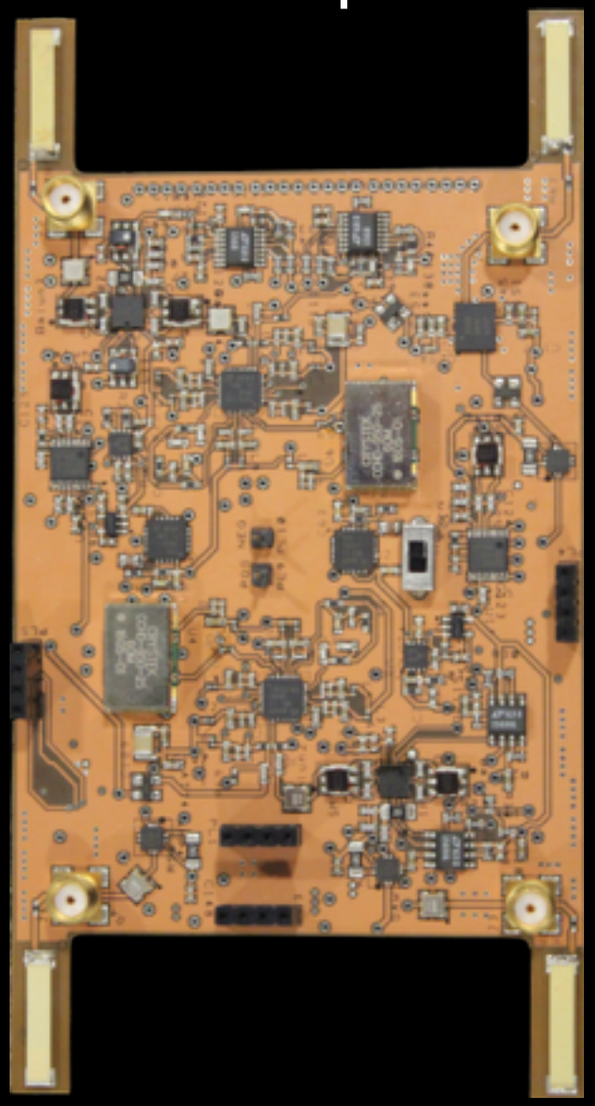

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- >70dB isolation in all directions
- <1 degree phase preserving error

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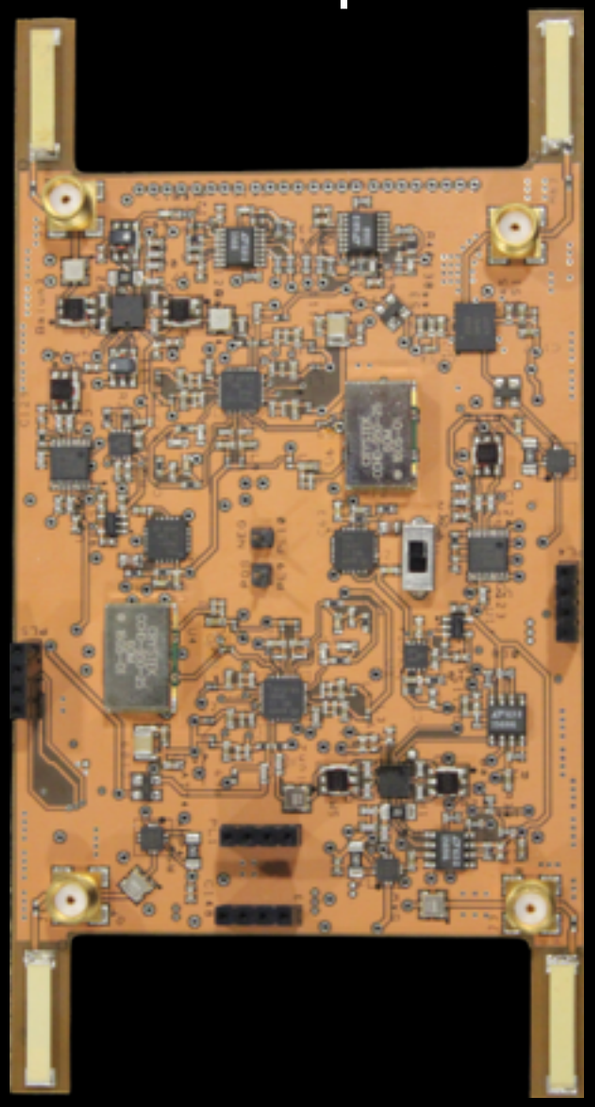

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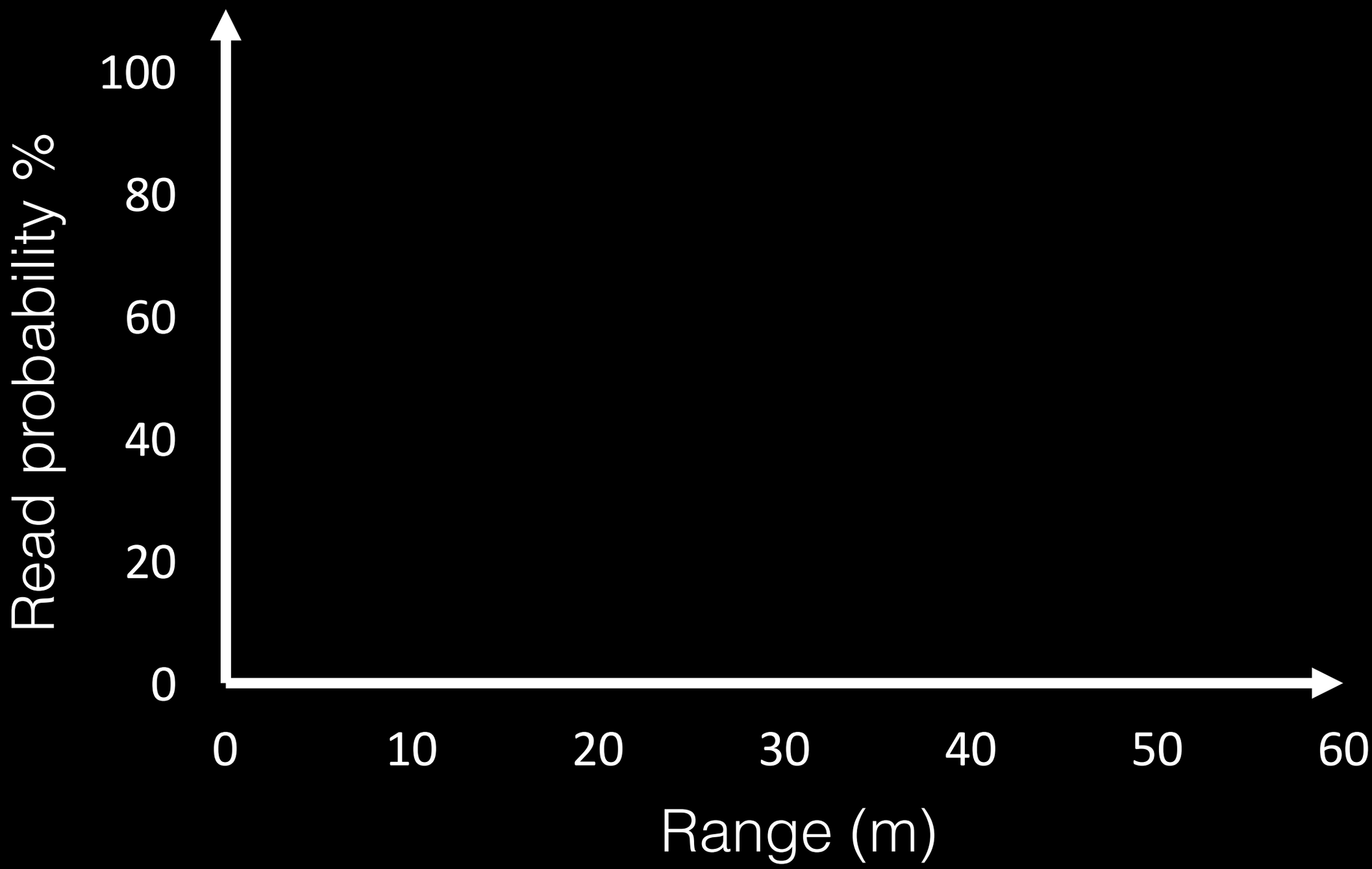
- >70dB isolation in all directions
- <1 degree phase preserving error

- Size: 10 x 7.5 cm
- Weight: 35 g
- Low power: <3% drone battery

How much can RFly extend reading range?



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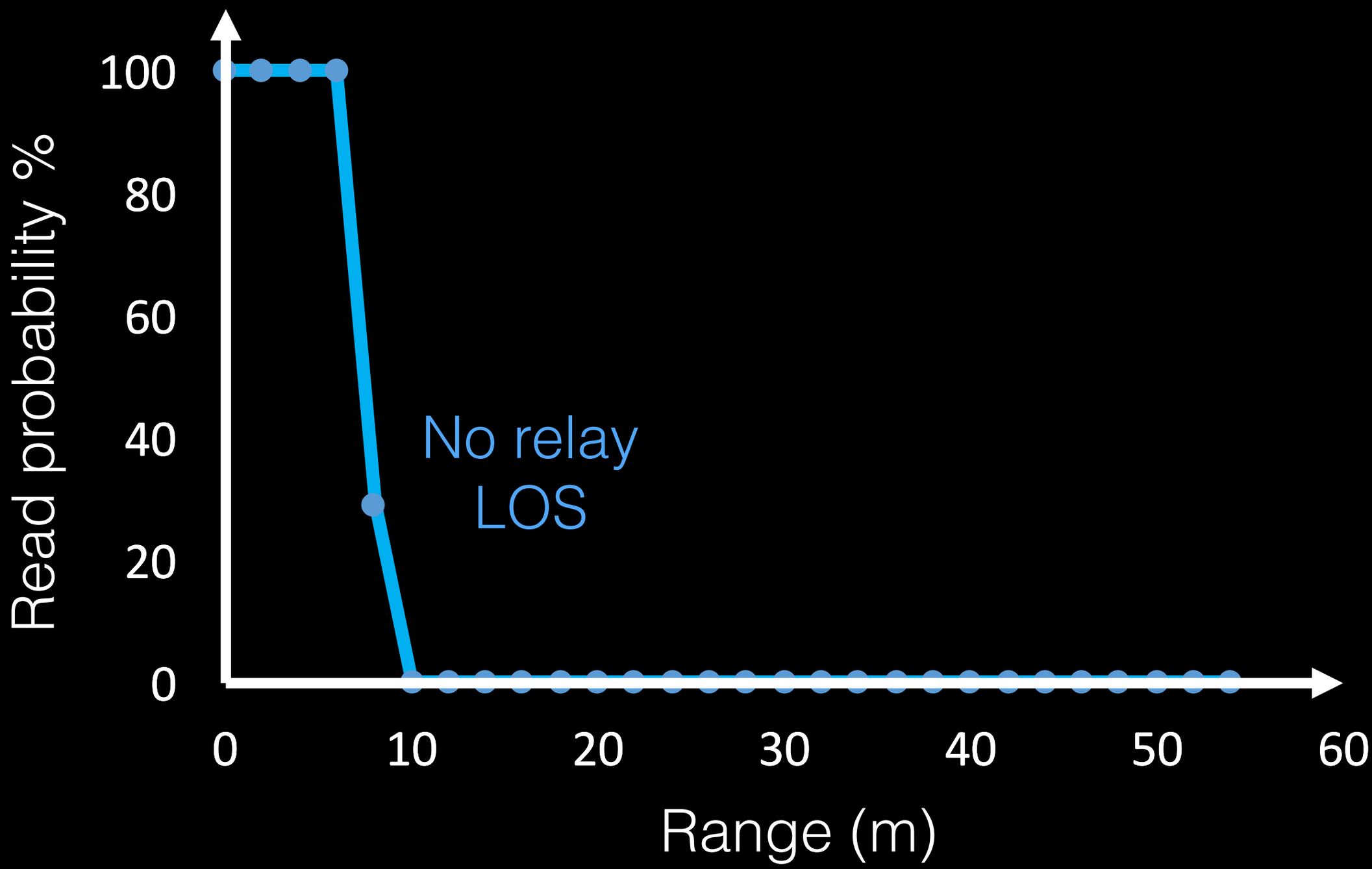

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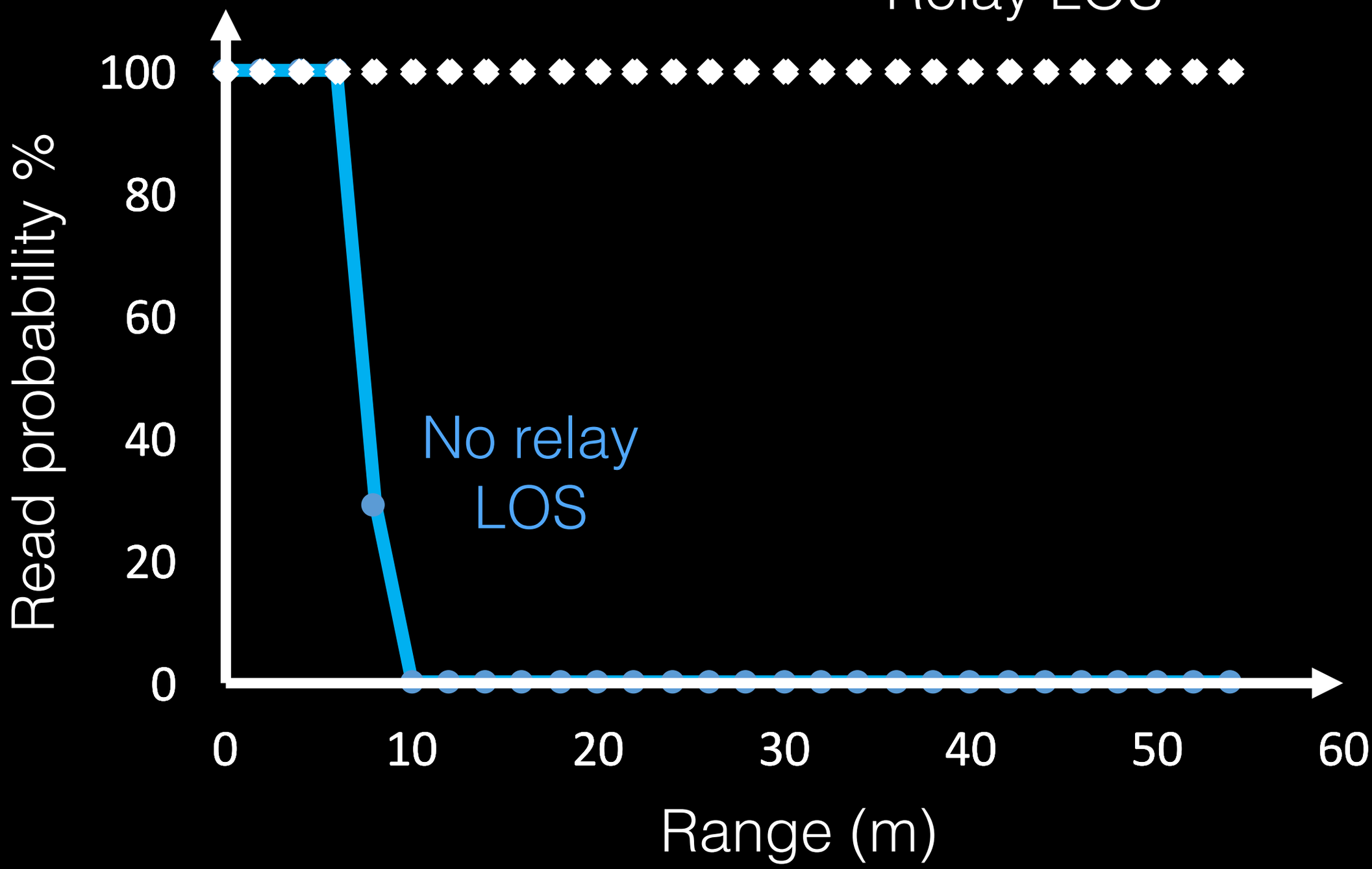

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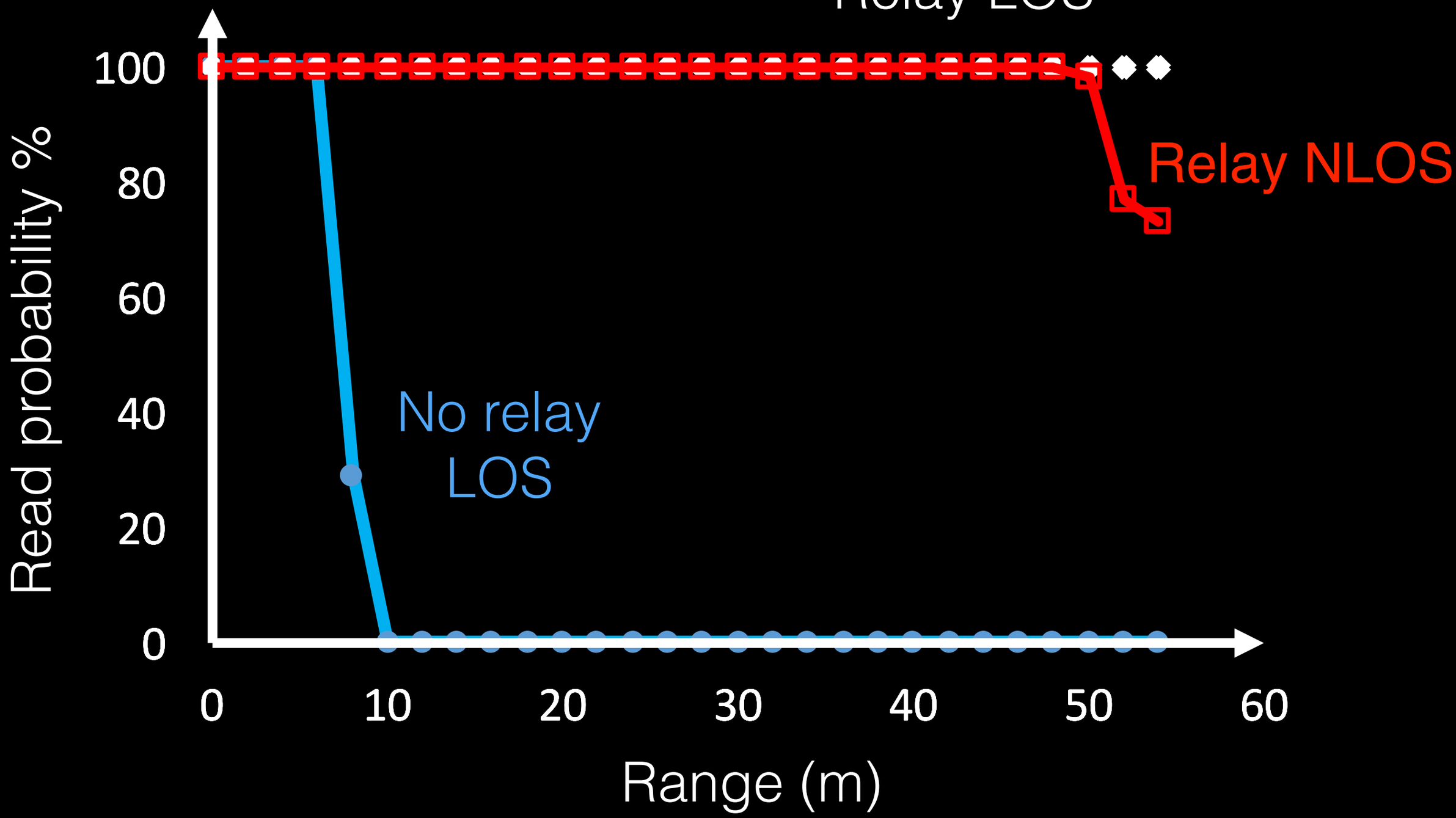

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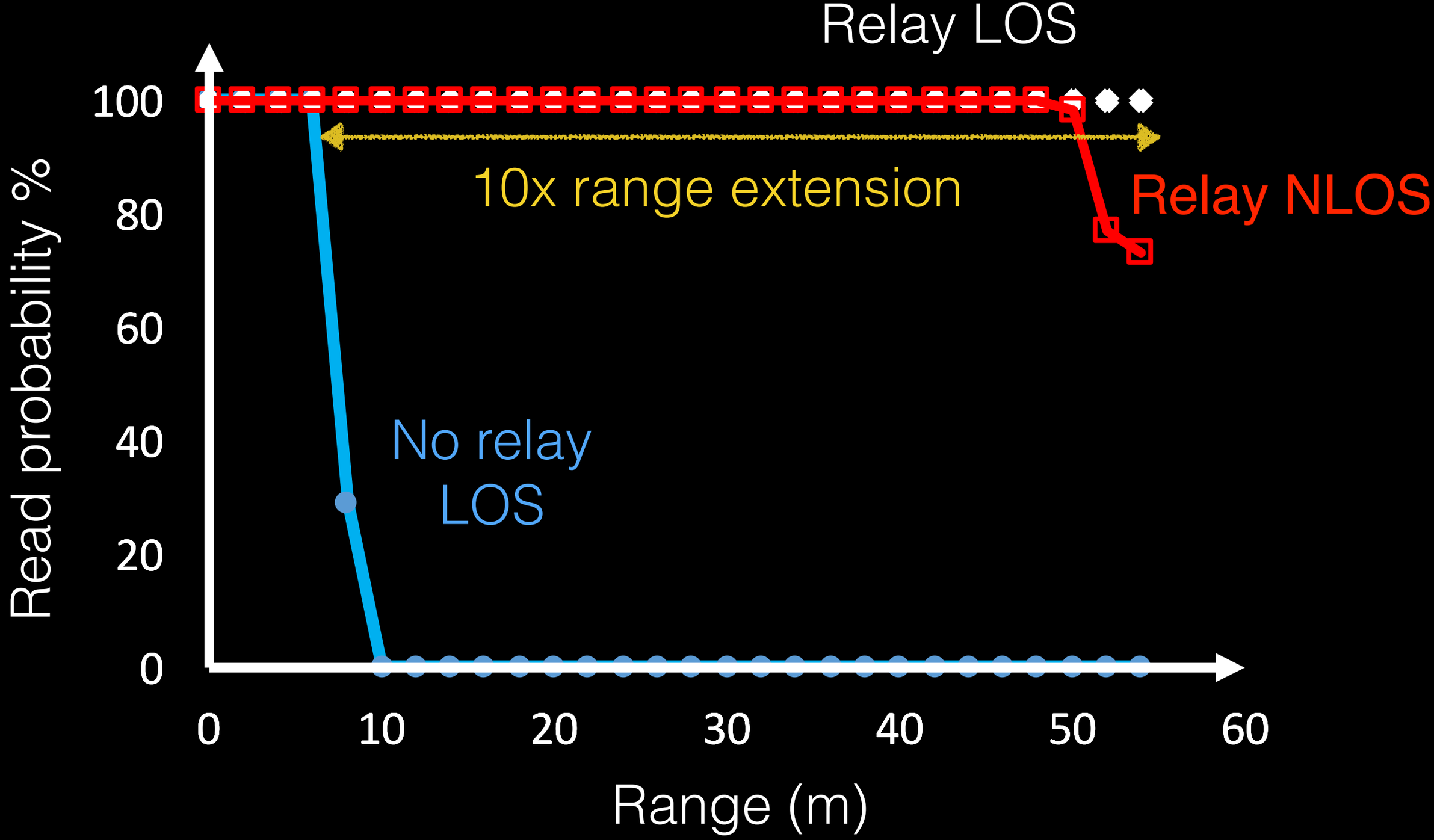

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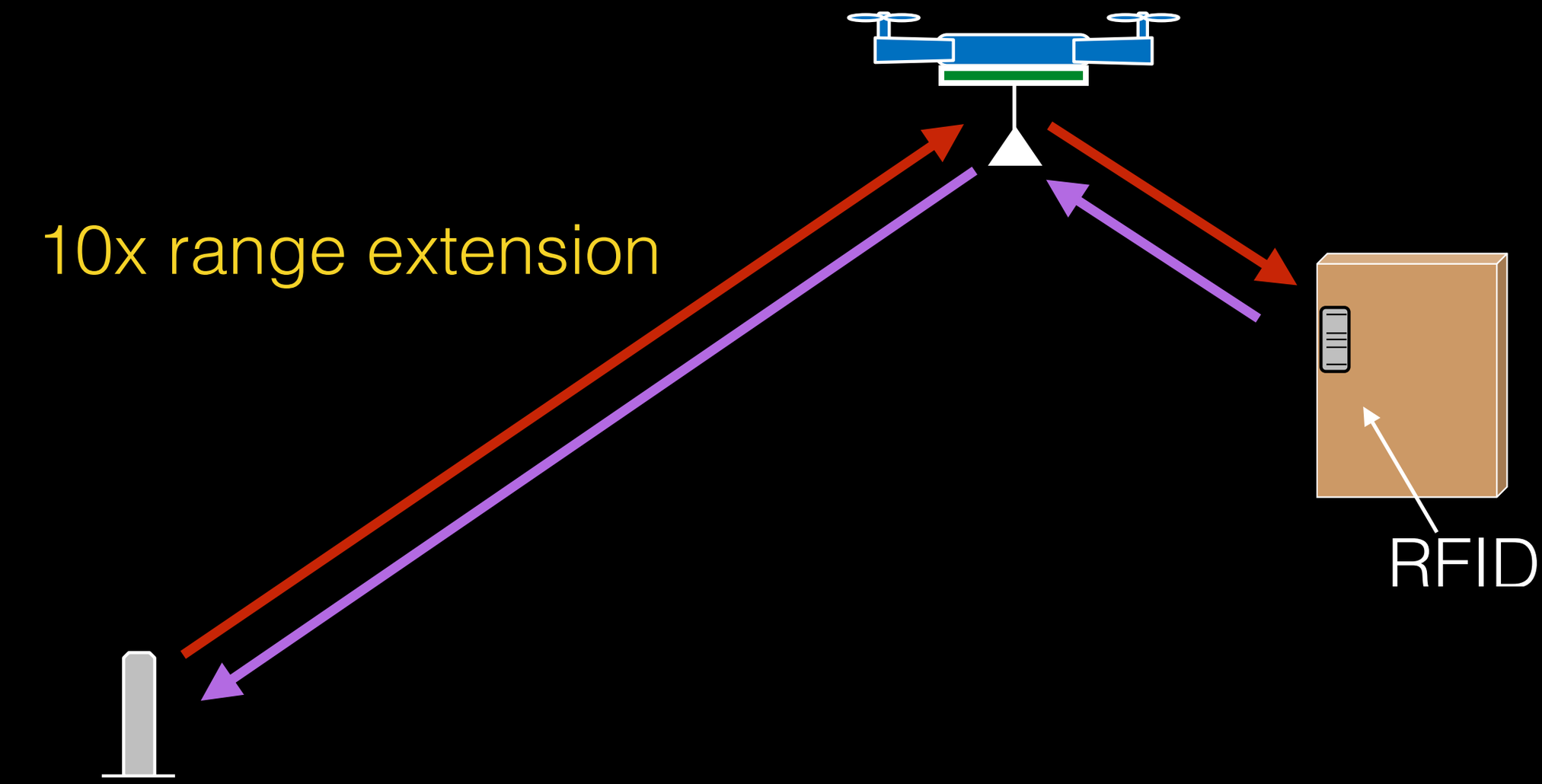
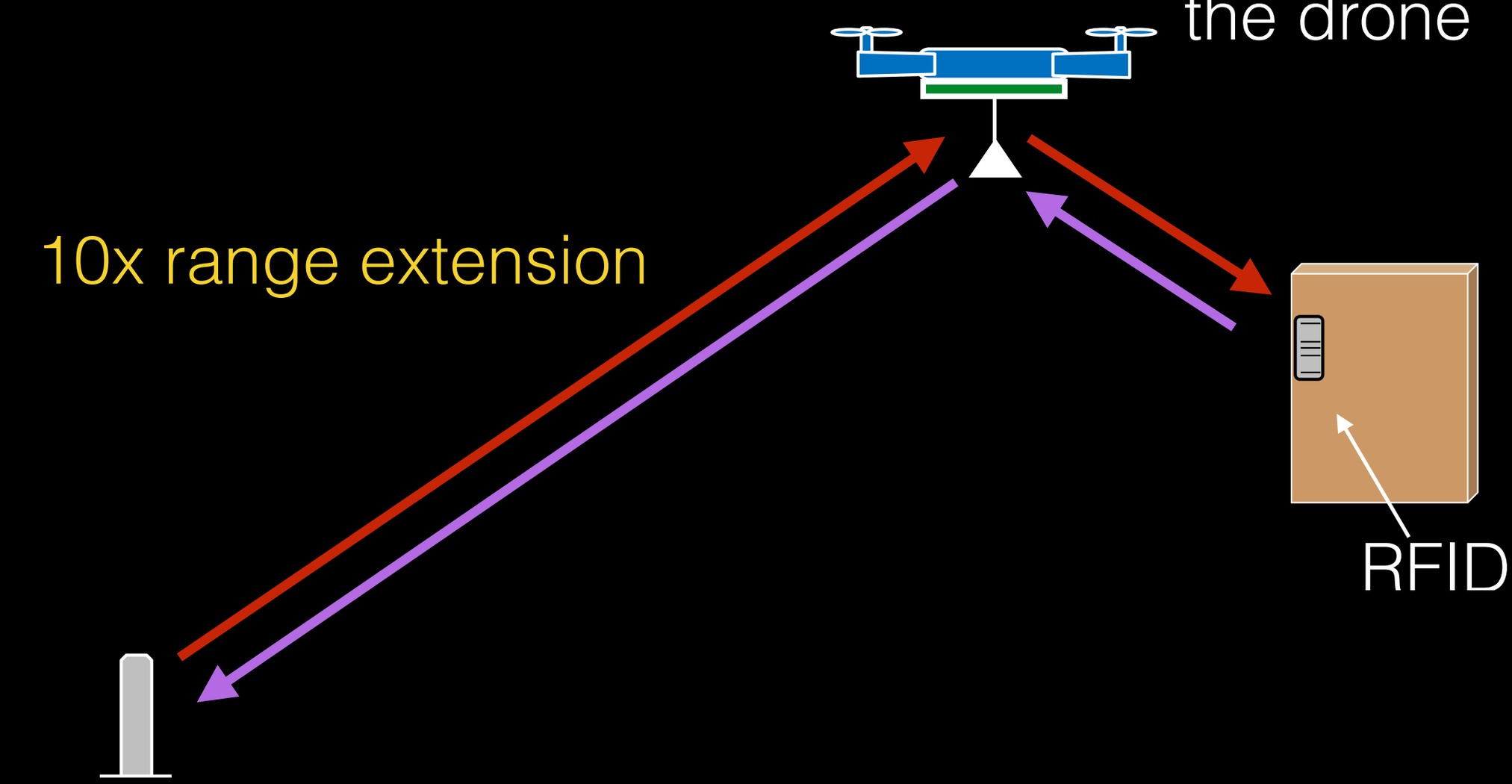


How much can RFly extend reading range?

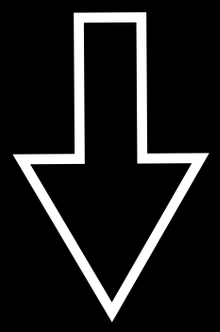
Relay is powered up by the drone



Challenges

Scale is limited

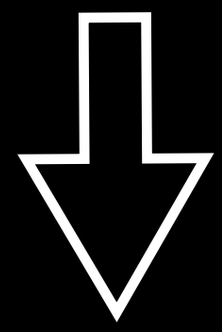
- low power nature
=> tens of centimeters to several meters
communication range



RFly: Drone-based relay
increased coverage by 100x
[SIGCOMM ’17]

Scope is limited

- batter-free nature
=> networking of these battery-free devices today are only possible outside of our body



IVN: In-body Networking
[SIGCOMM’18]

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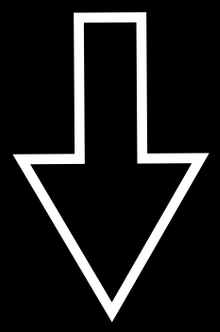

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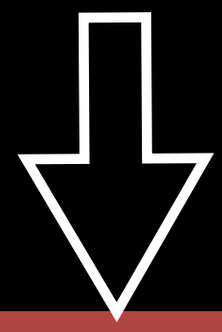

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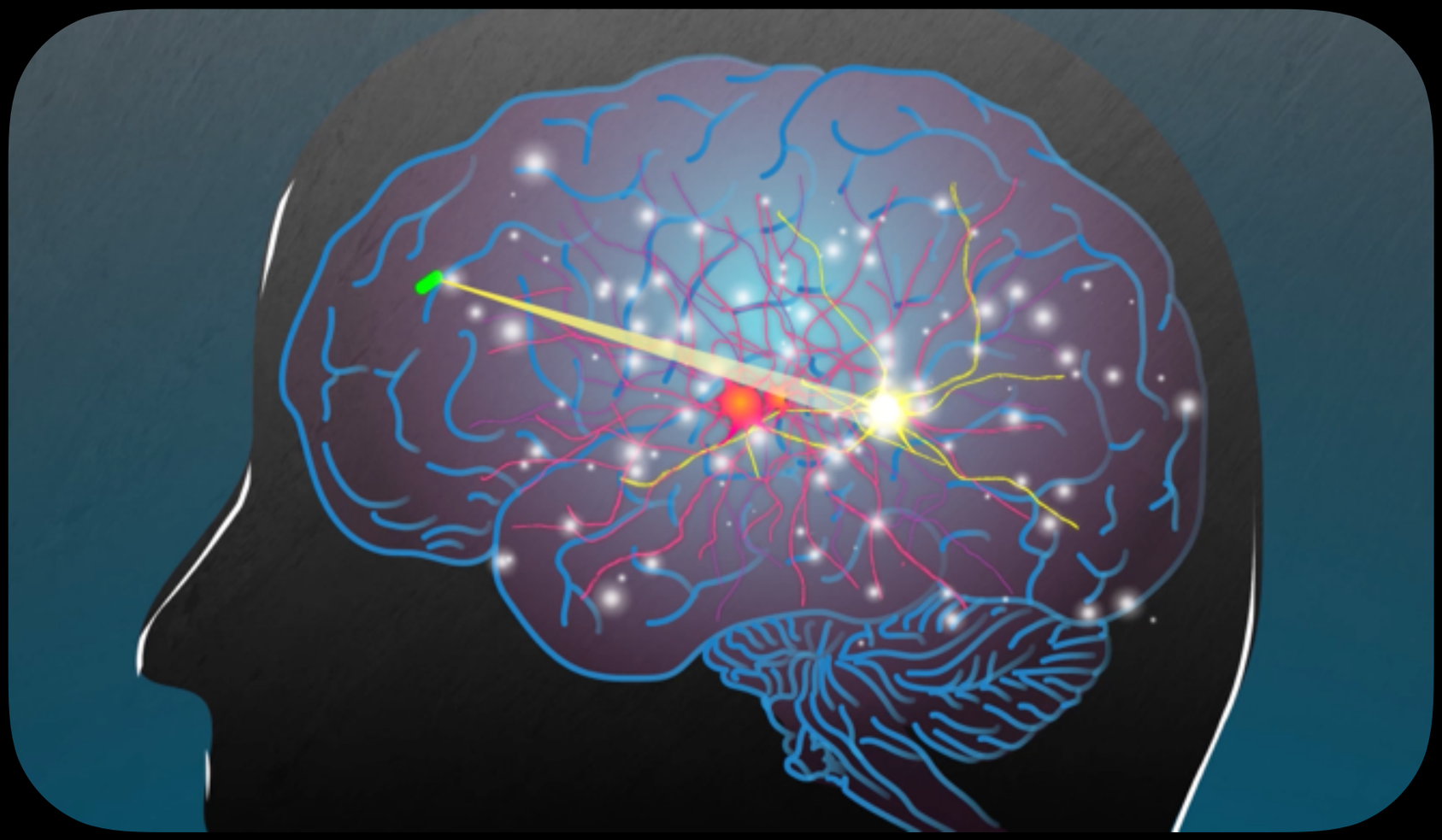
In-Vivo Networking (IVN)



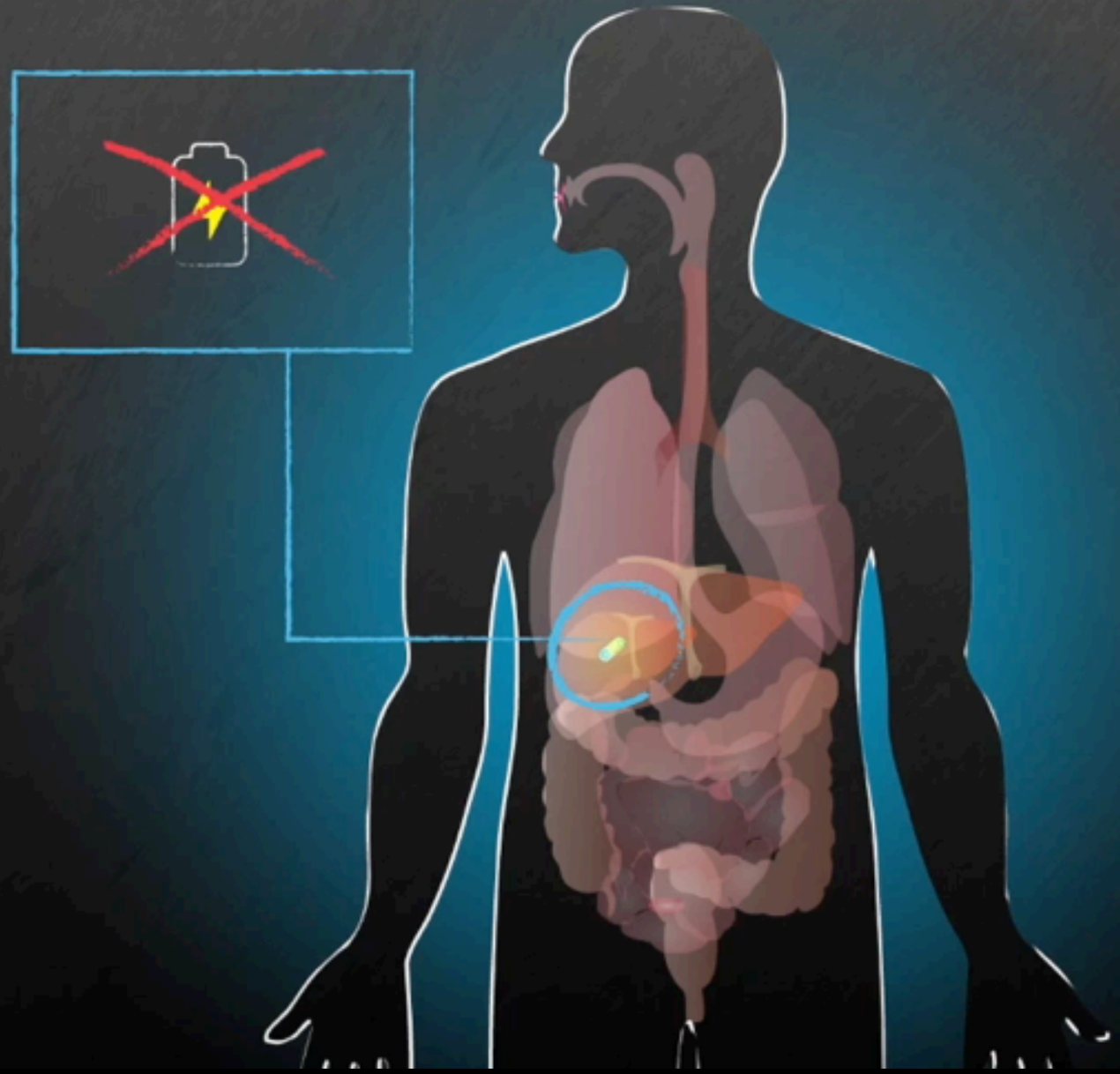
SIGCOMM'18
Research Highlights

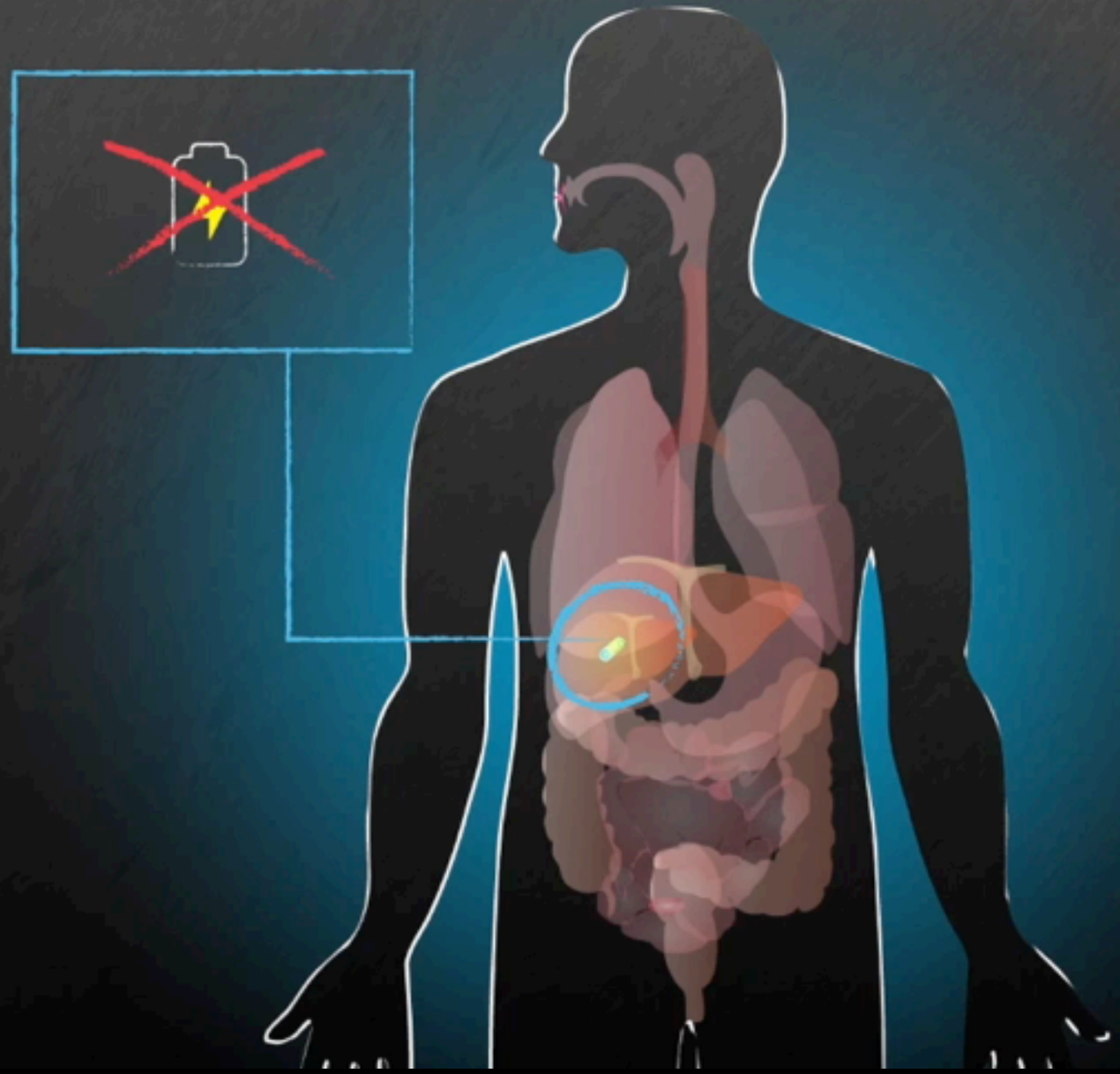
Other media: Technology Review, Yahoo News, Boston Herald，新华社，etc

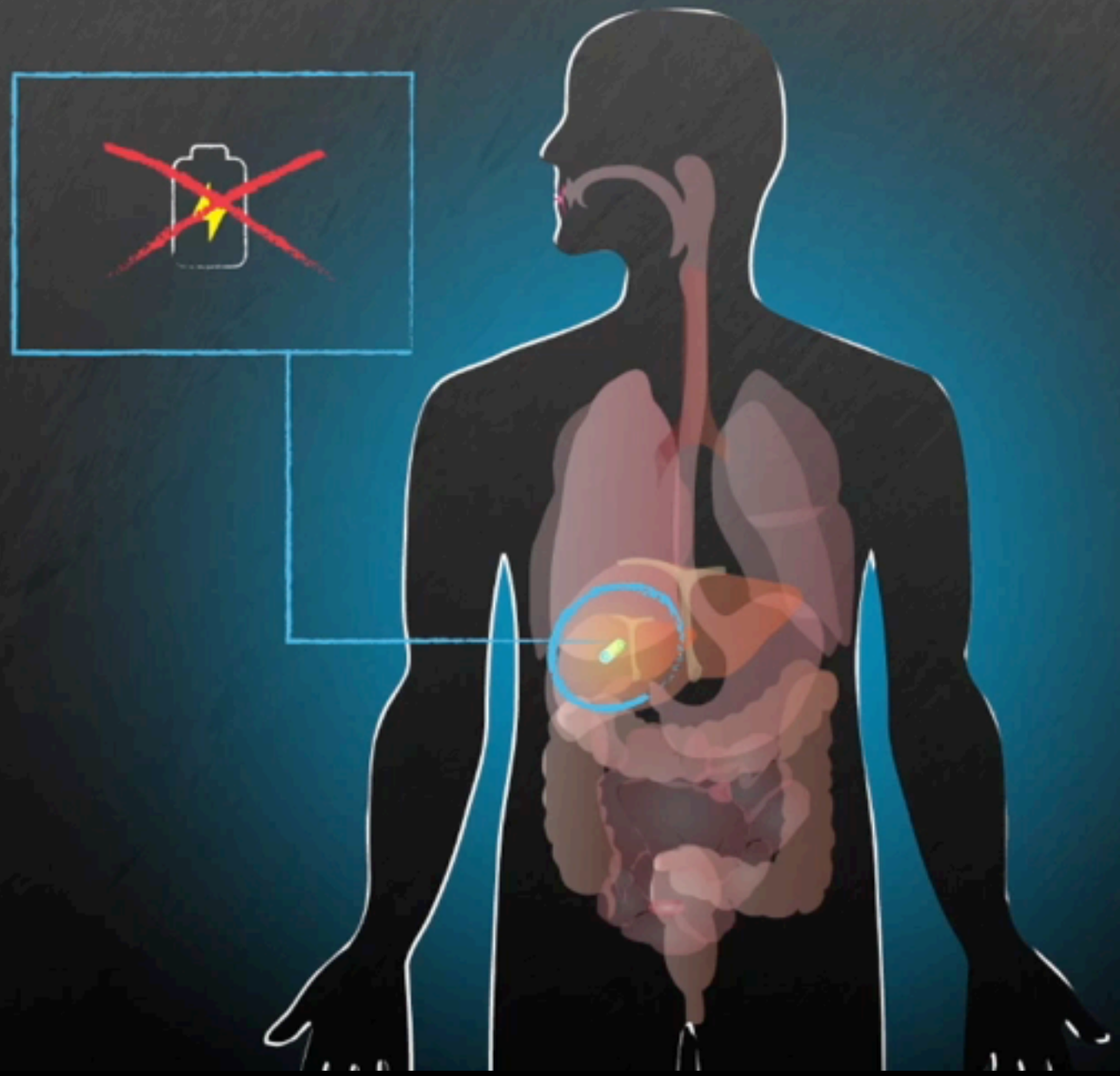
MIT

HARVARD MEDICAL SCHOOL

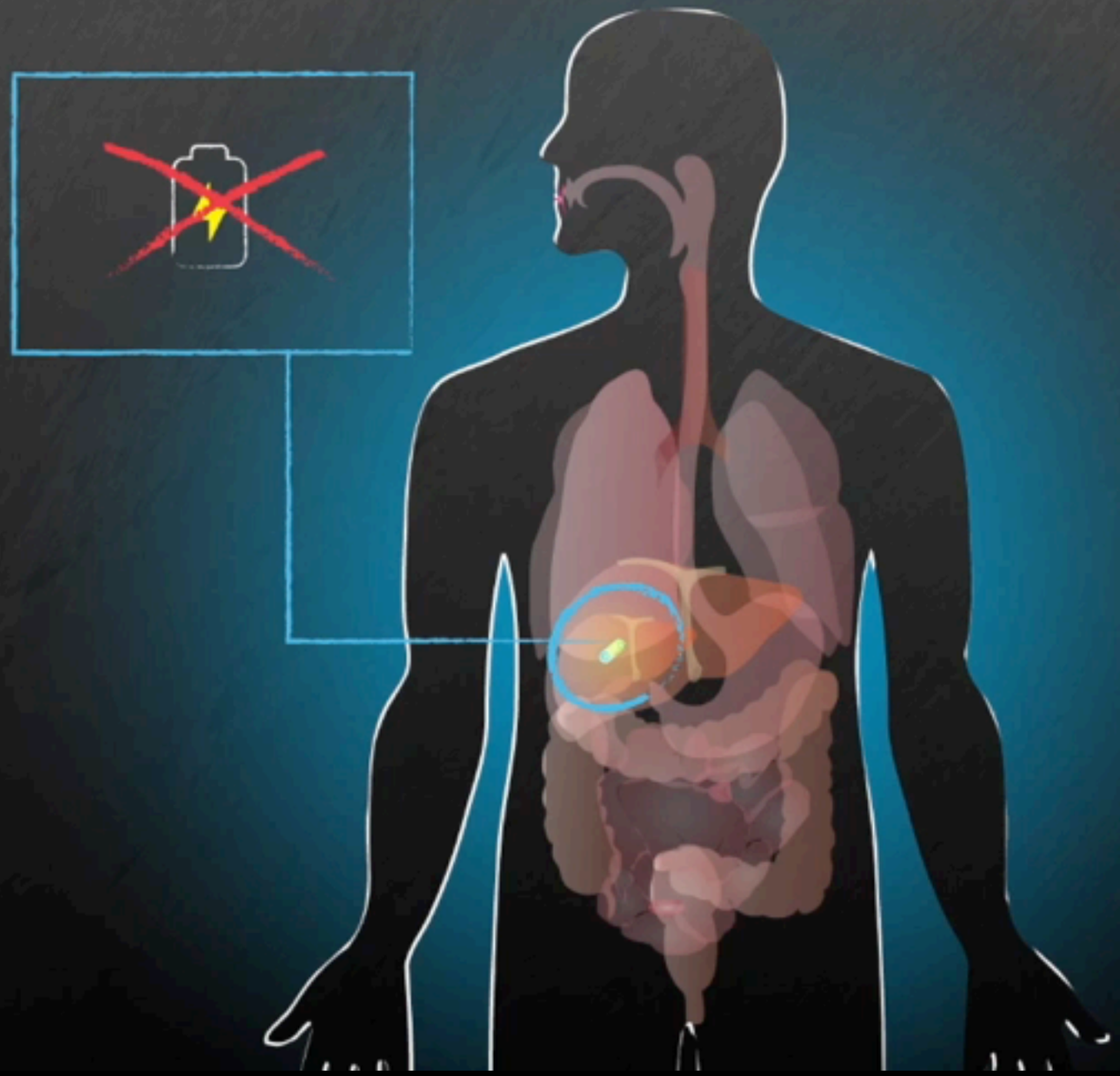
BWH BRIGHAM AND WOMEN'S HOSPITAL







Harvest energy from
wireless signals



Power up and
communicate

Key Challenge:

Wireless signals die exponentially in the human body

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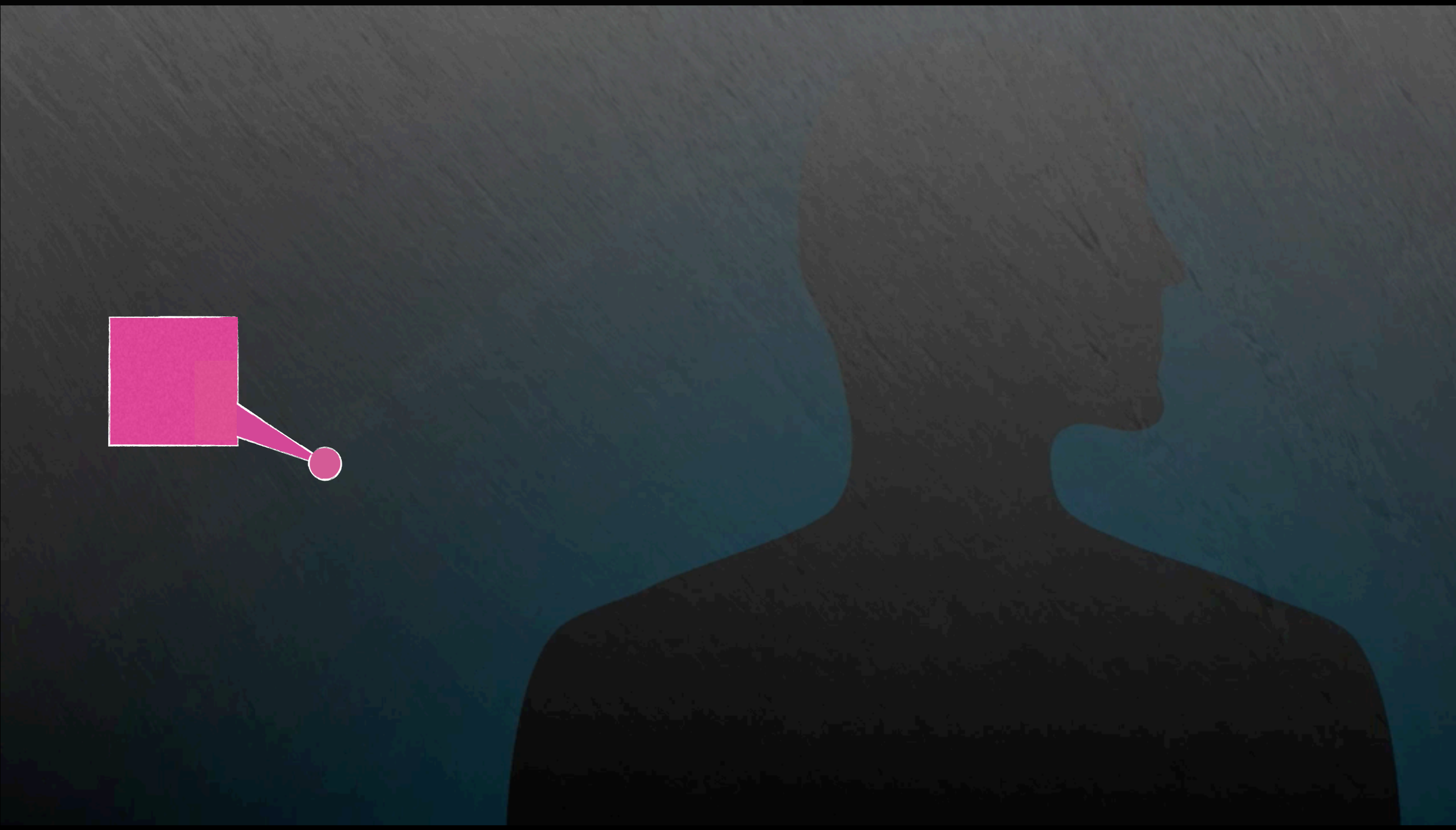

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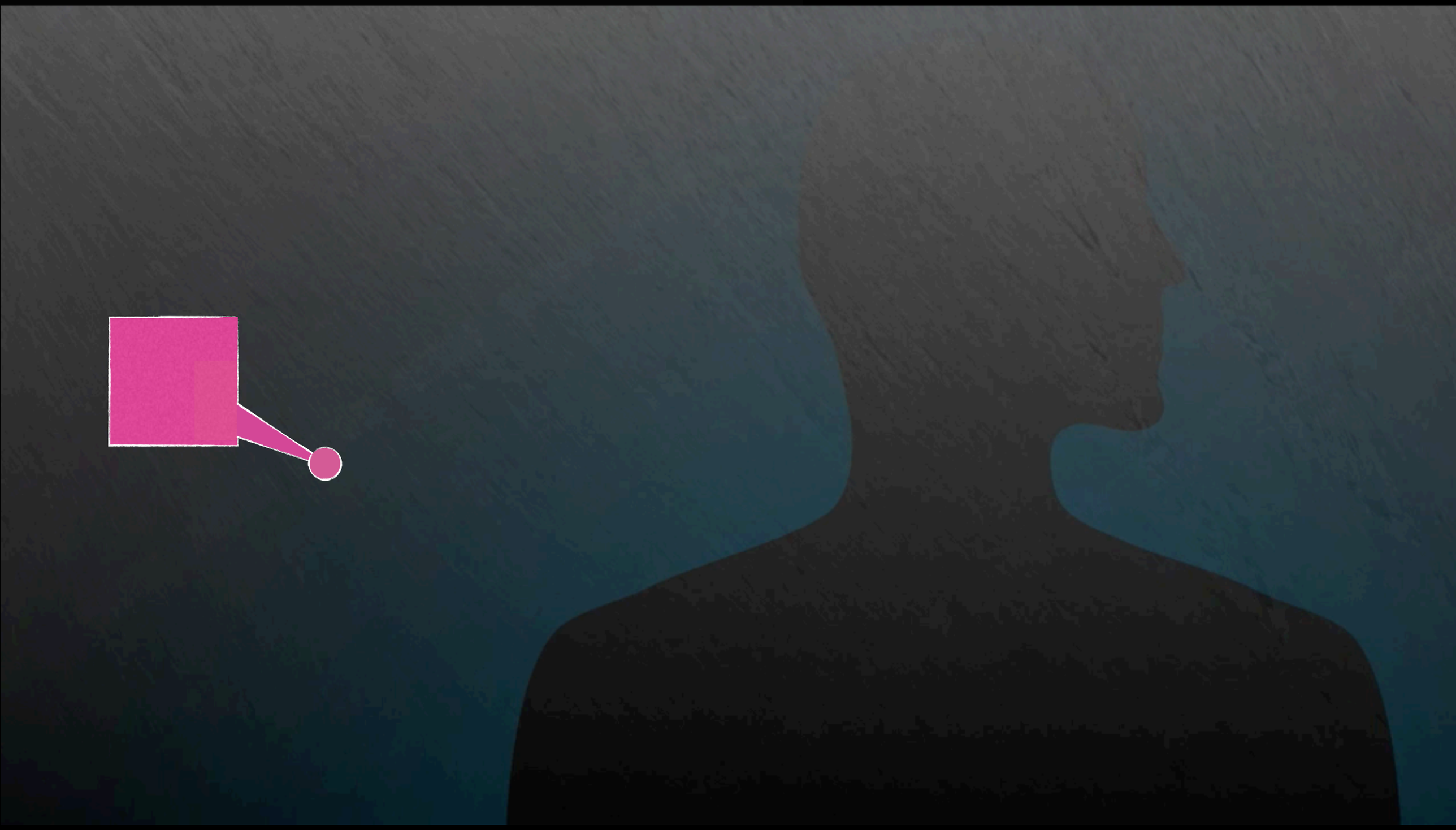

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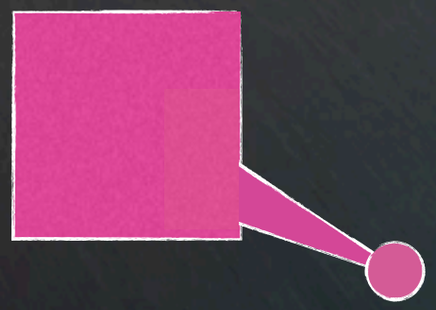

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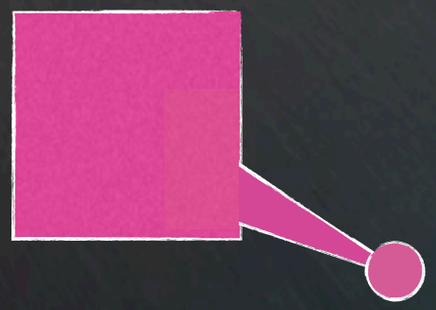

Cannot power up battery-less sensor in deep tissues

In-Vivo Networking (IVN)

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- Implemented and evaluated with different tissues and in real living animals.

Continuous and Long-Term Drug Delivery

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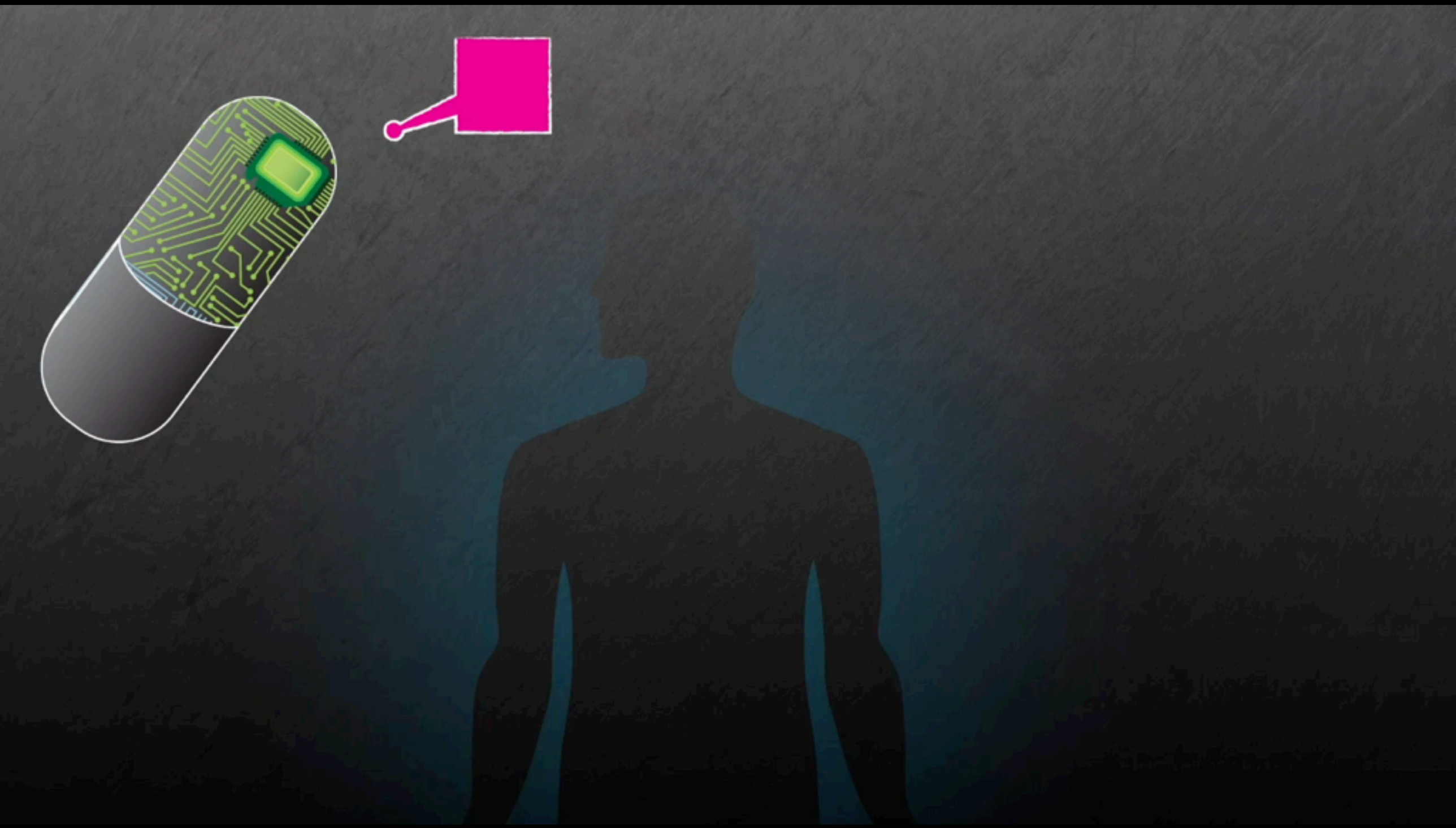

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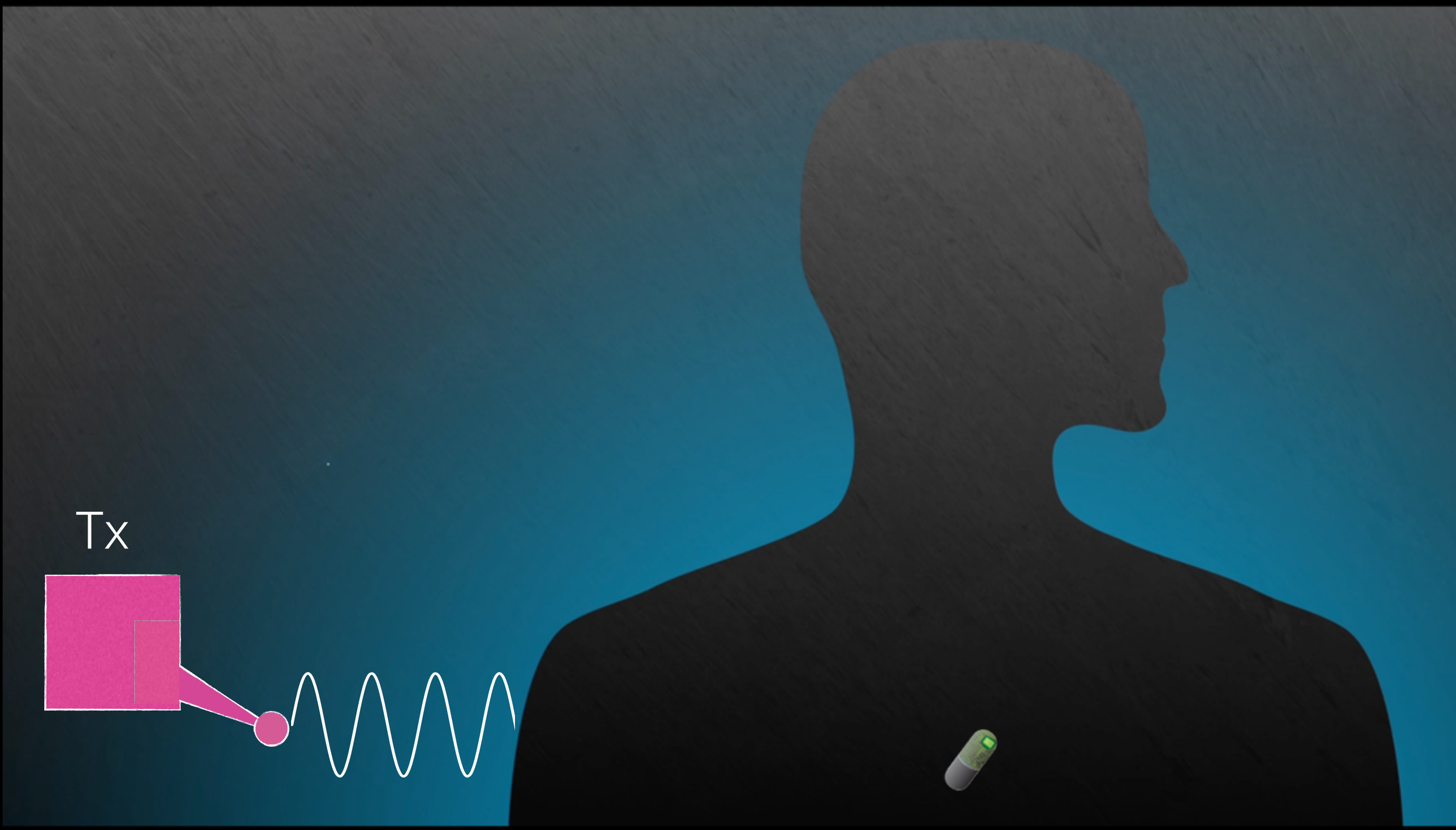

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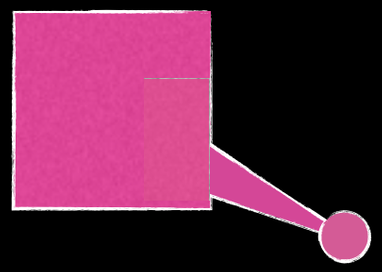

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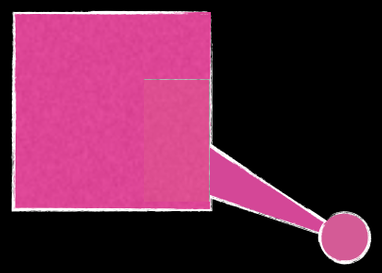
Because of non-linear electronics (e.g., diodes, transistors), a battery-free sensor needs a minimum energy to power up



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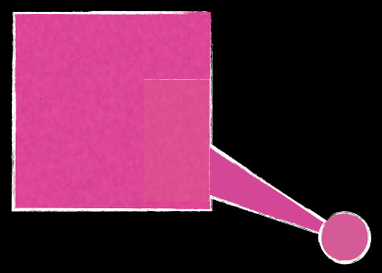

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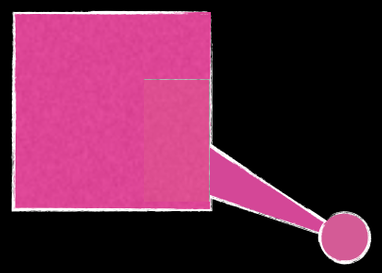

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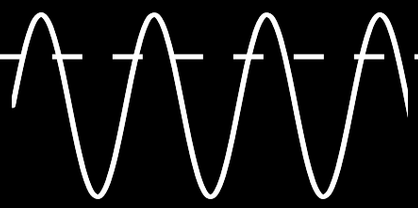

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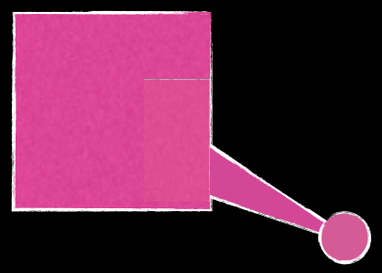

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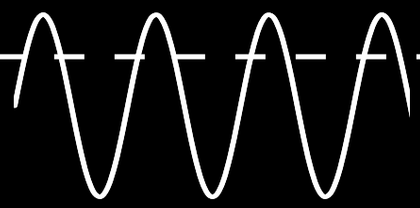

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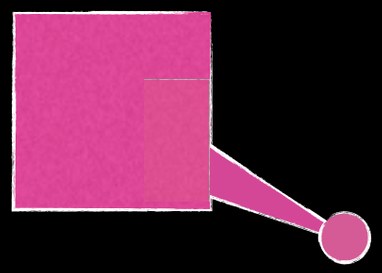

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In the body

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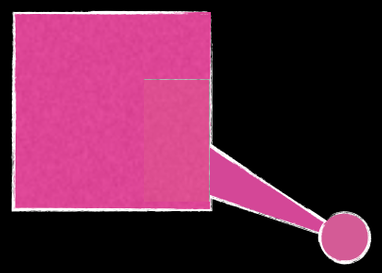

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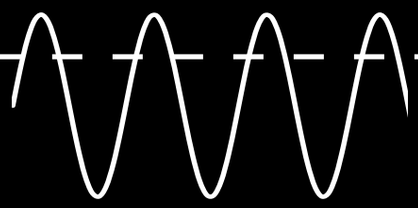


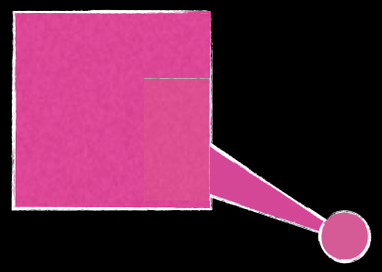
In air

instantaneous energy above threshold => powers up

In the body

instantaneous energy below threshold => can't power up

Why not transmit more power from a signal antenna?



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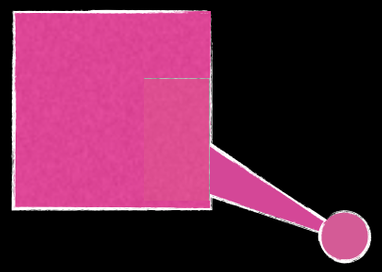

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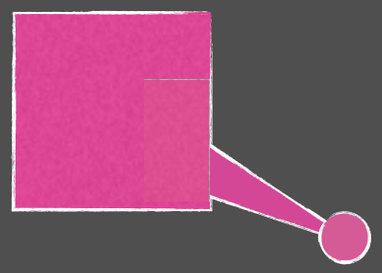

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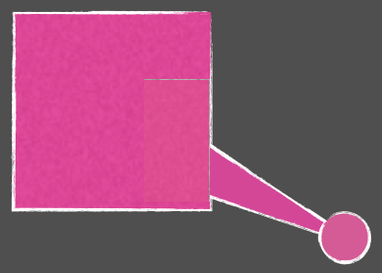

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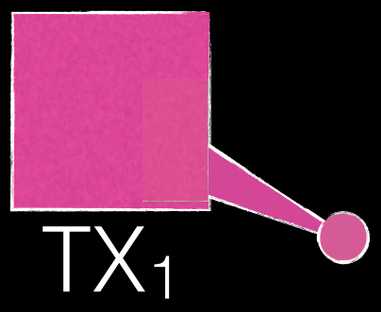
With single antenna, power is transmitted in all directions
=> Inefficient

Standard Solution: Use Multiple Antennas (MIMO)



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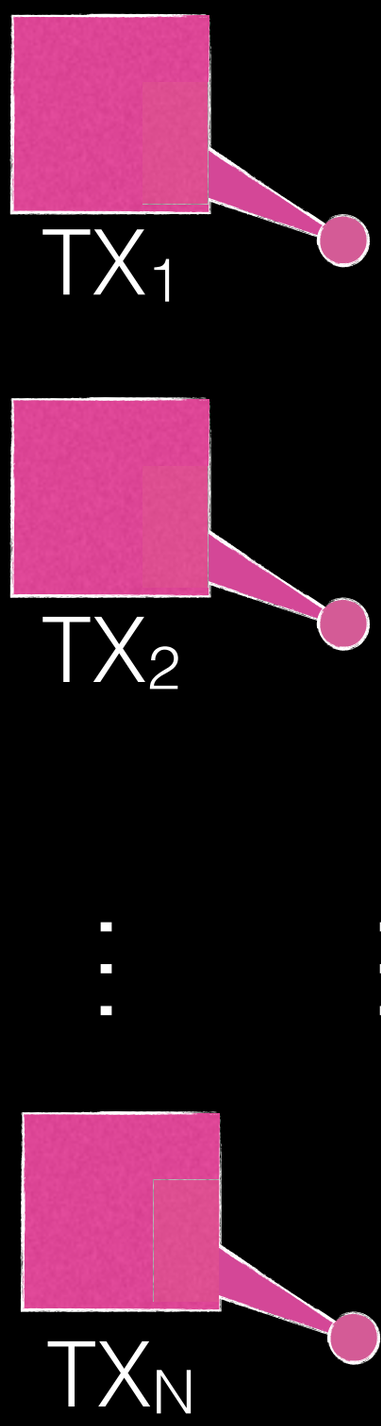

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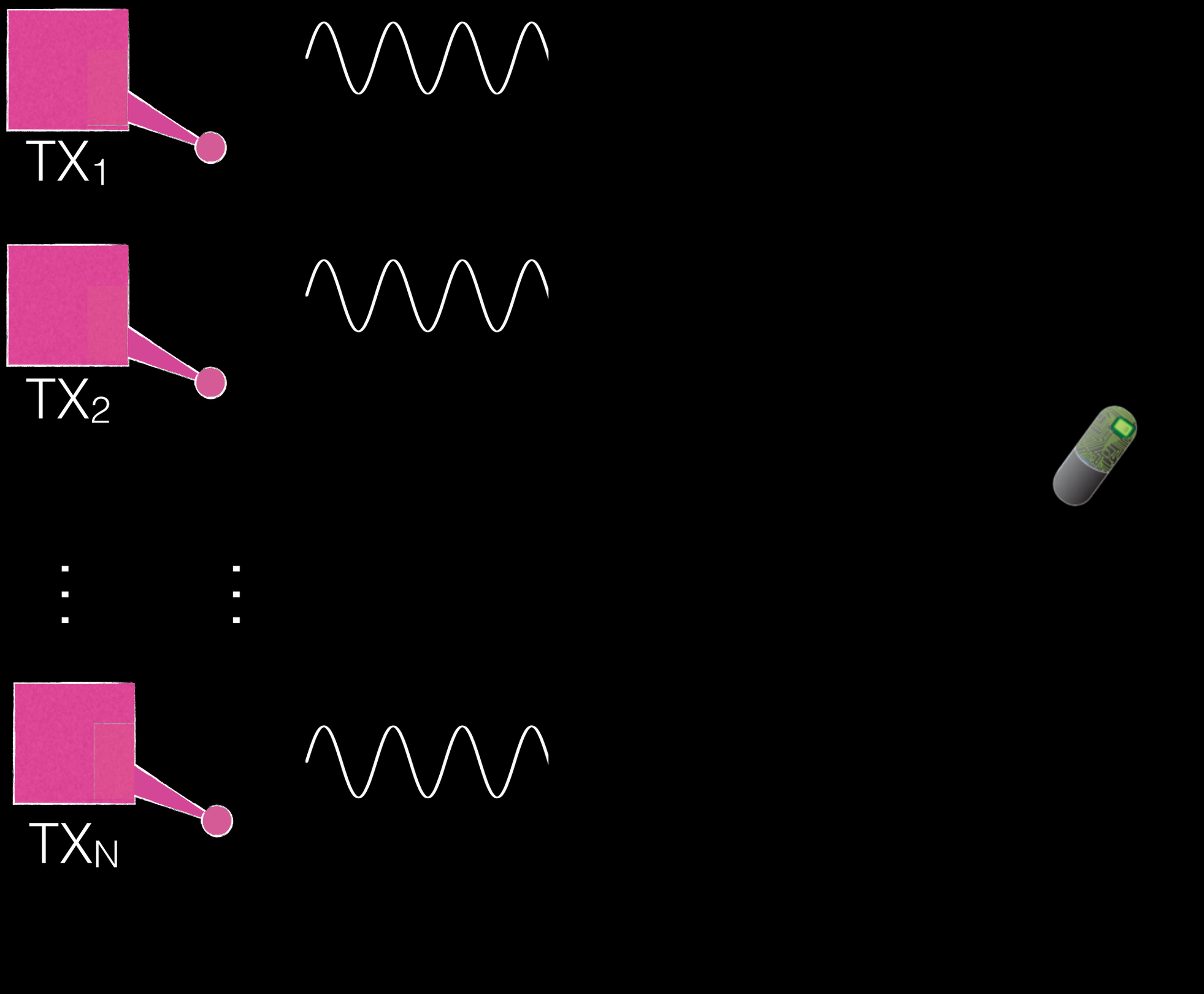

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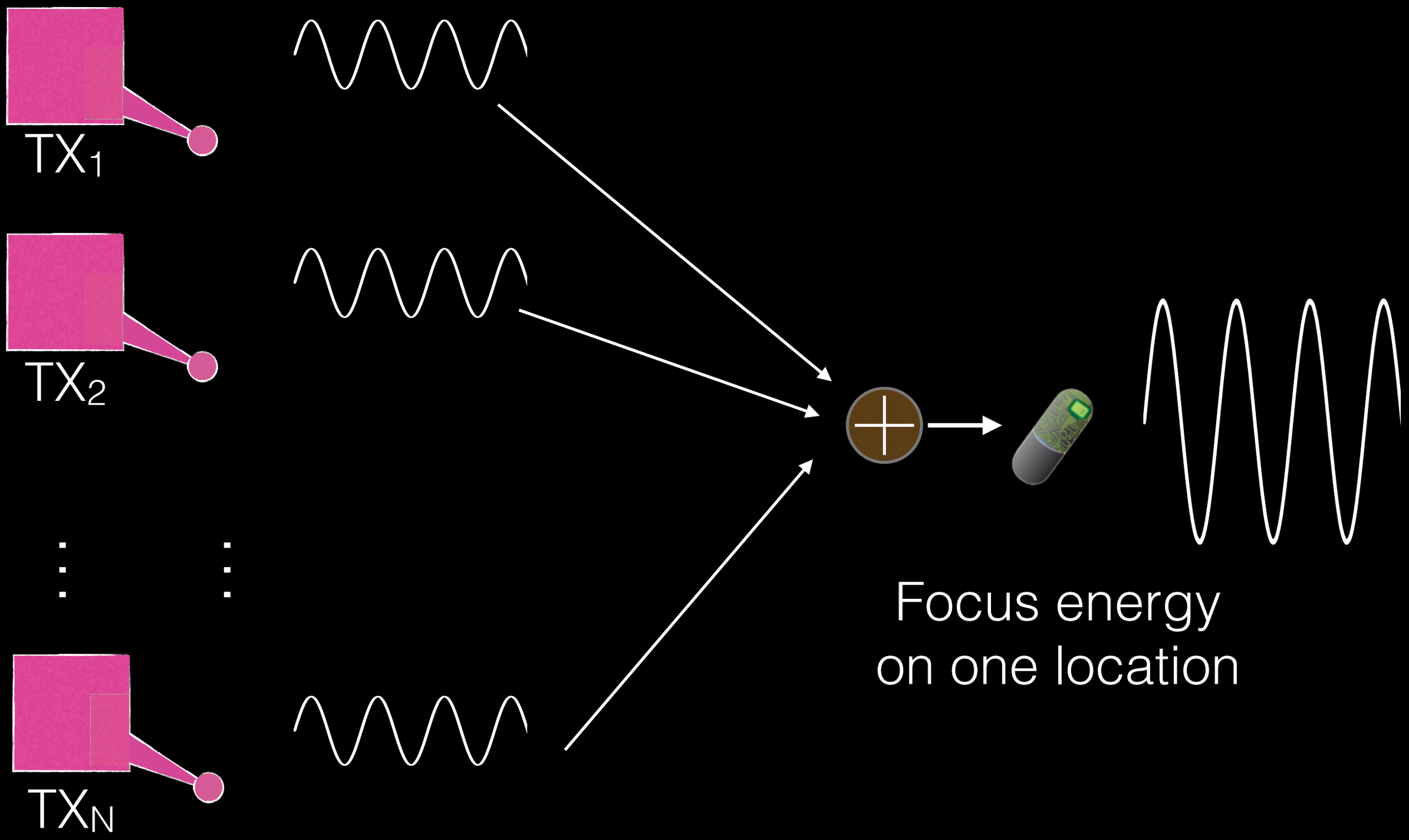

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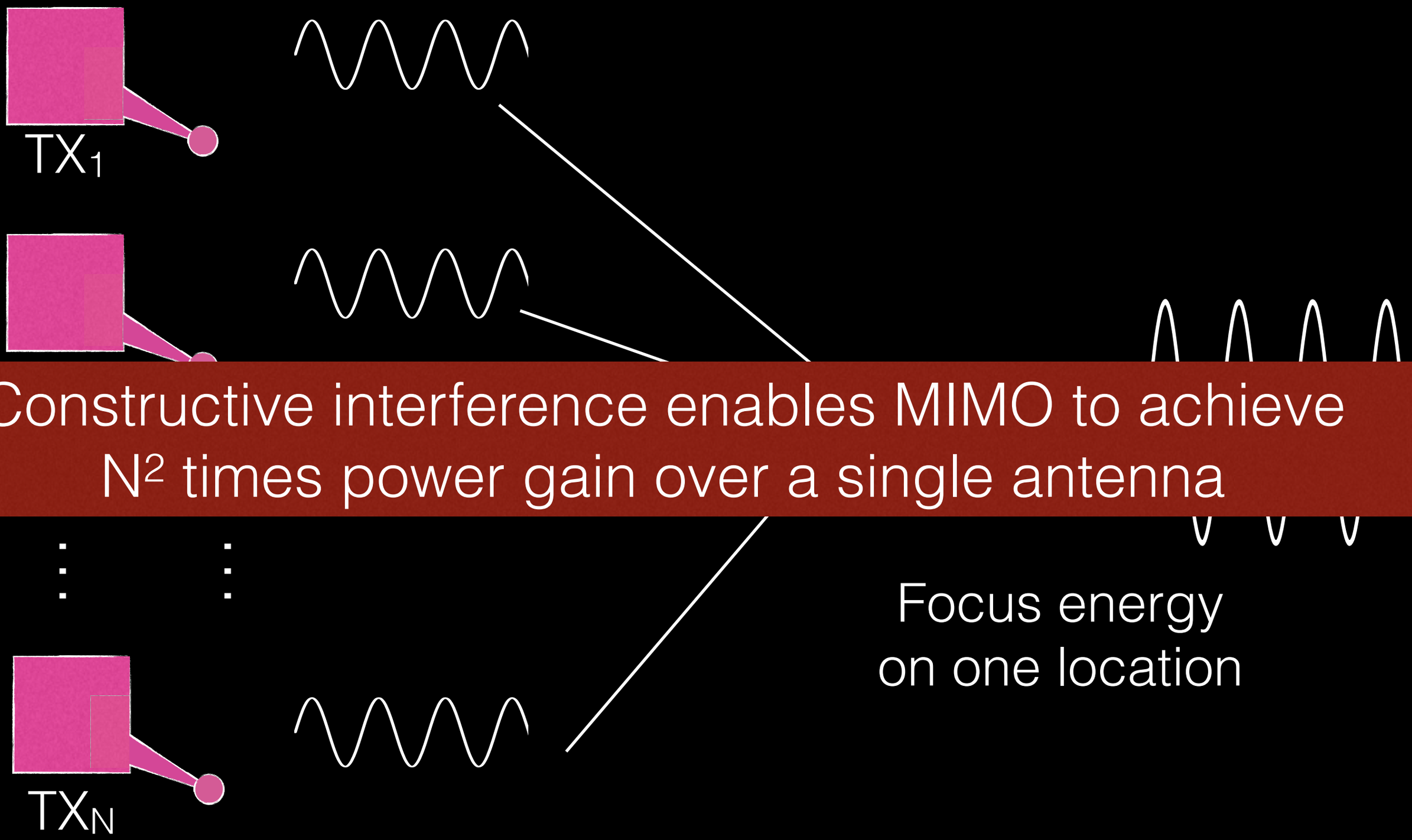

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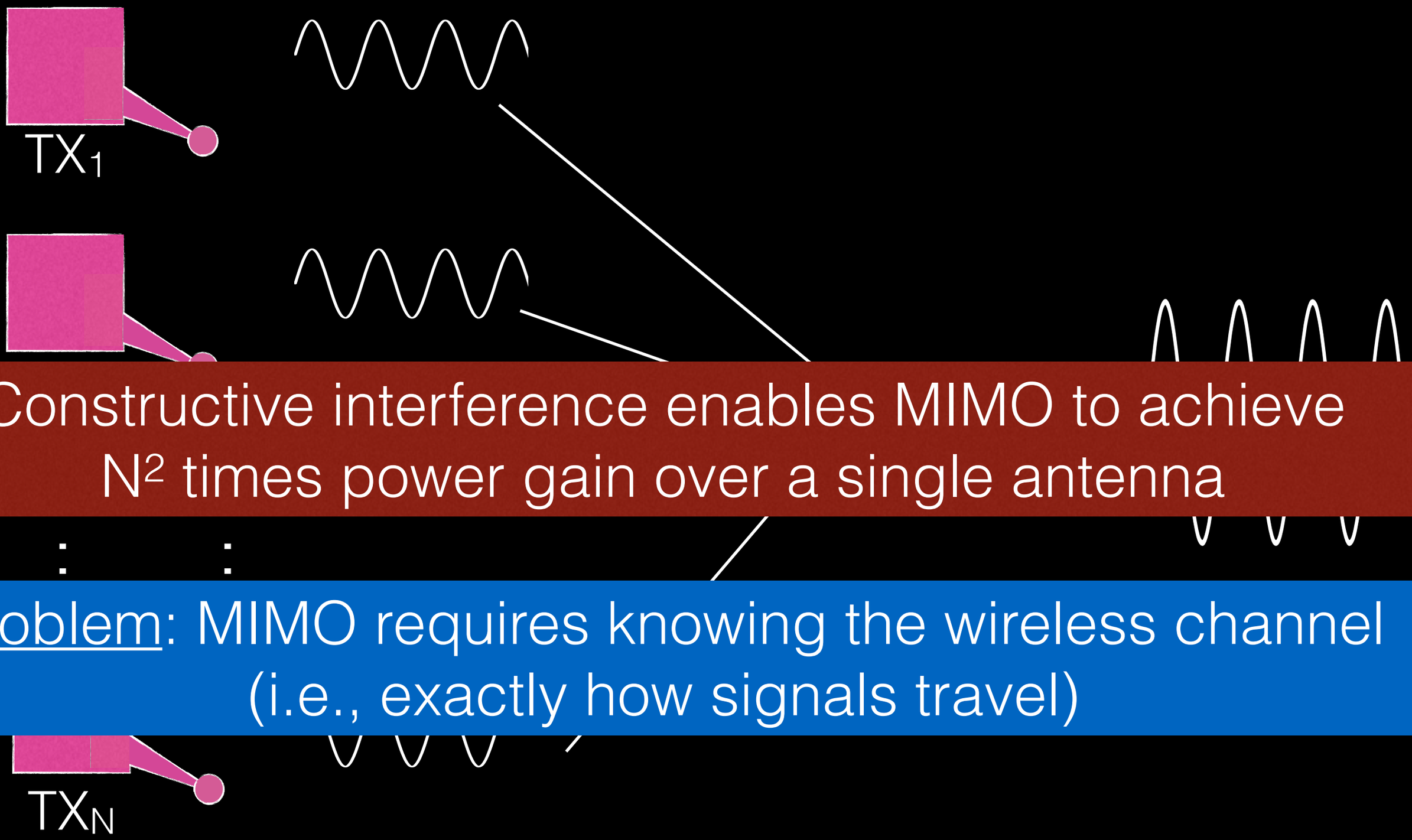

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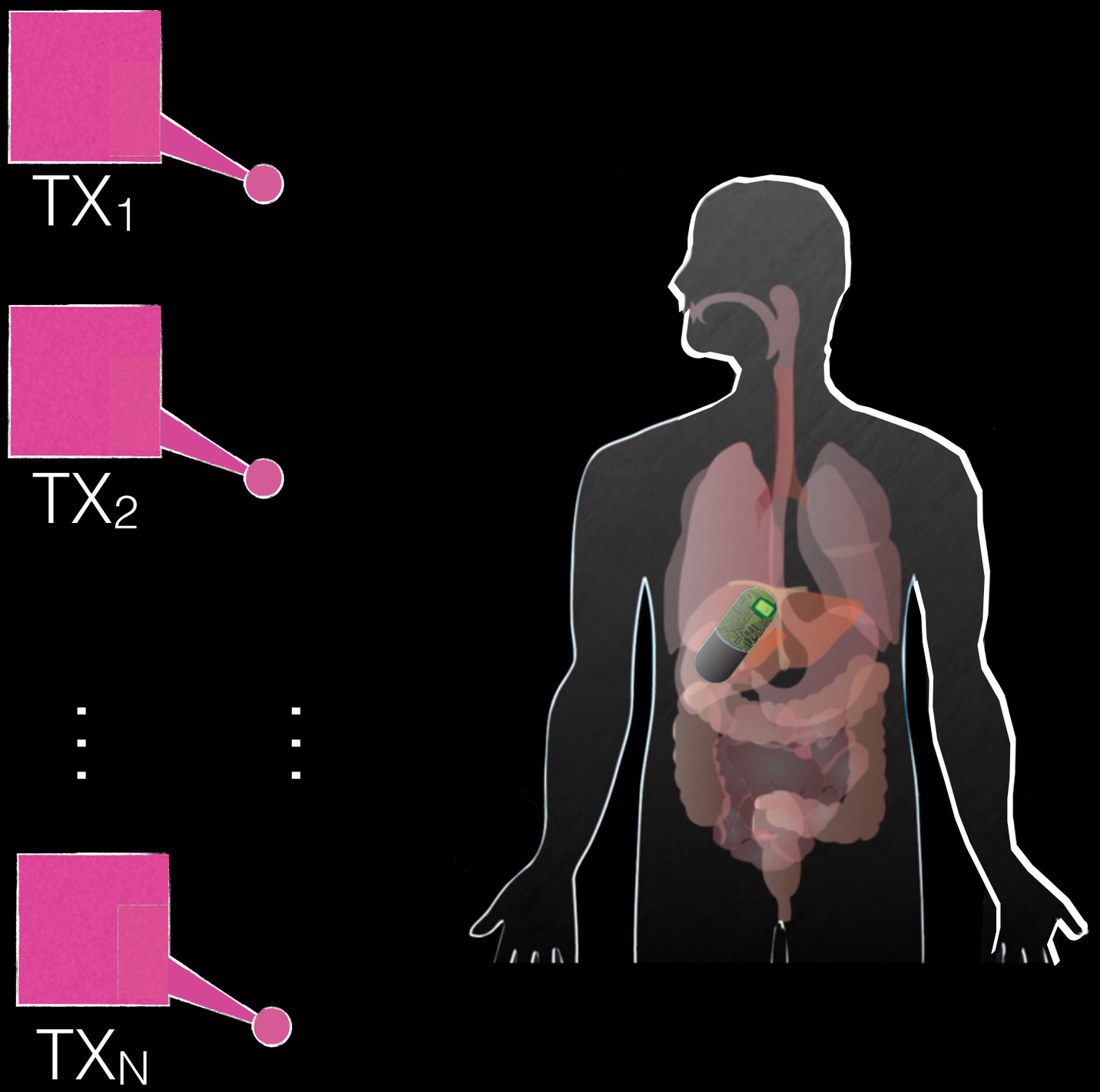
Problem: MIMO requires knowing the wireless channel (i.e., exactly how signals travel)

Wireless channel is intractable inside human body



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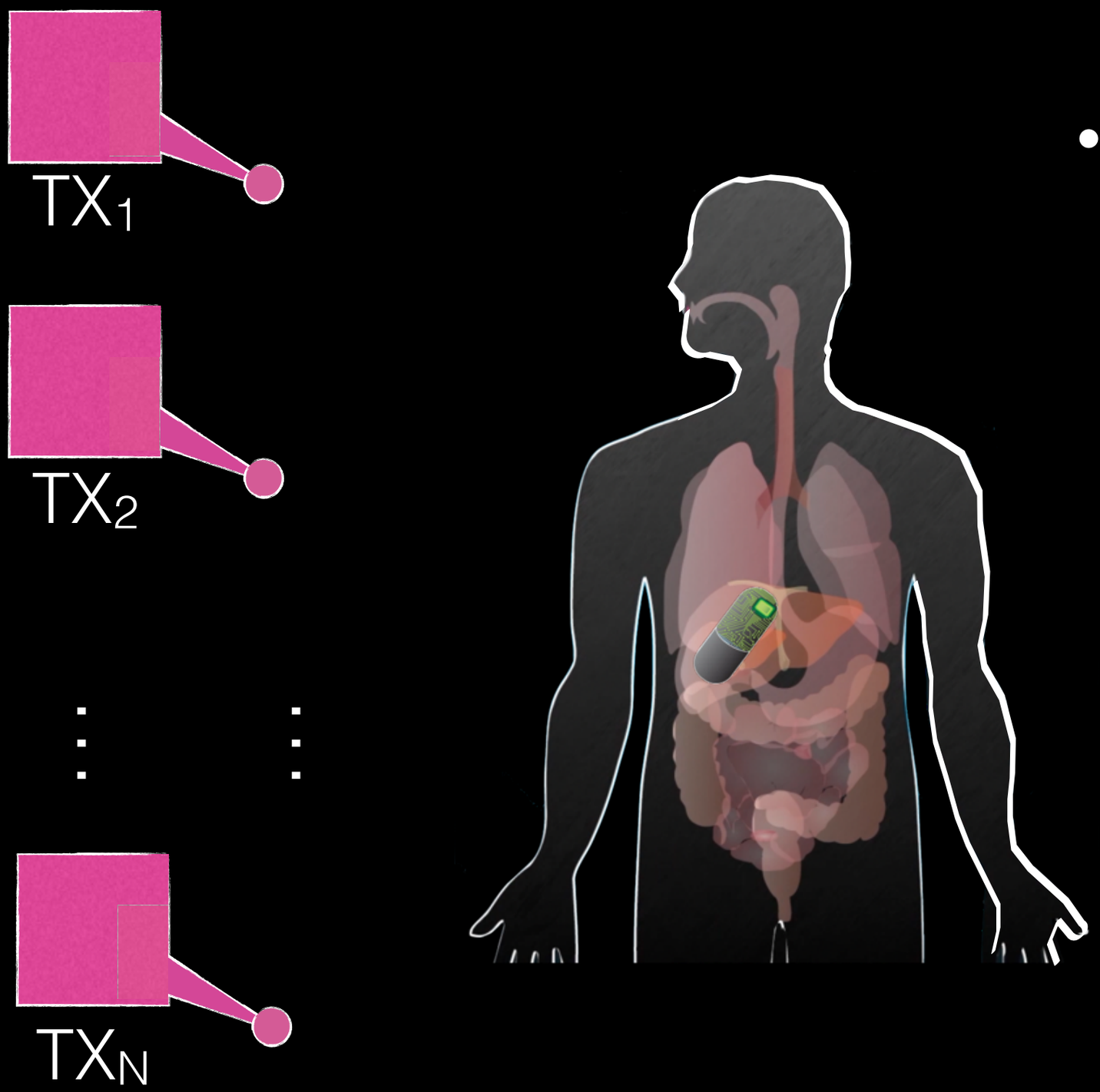

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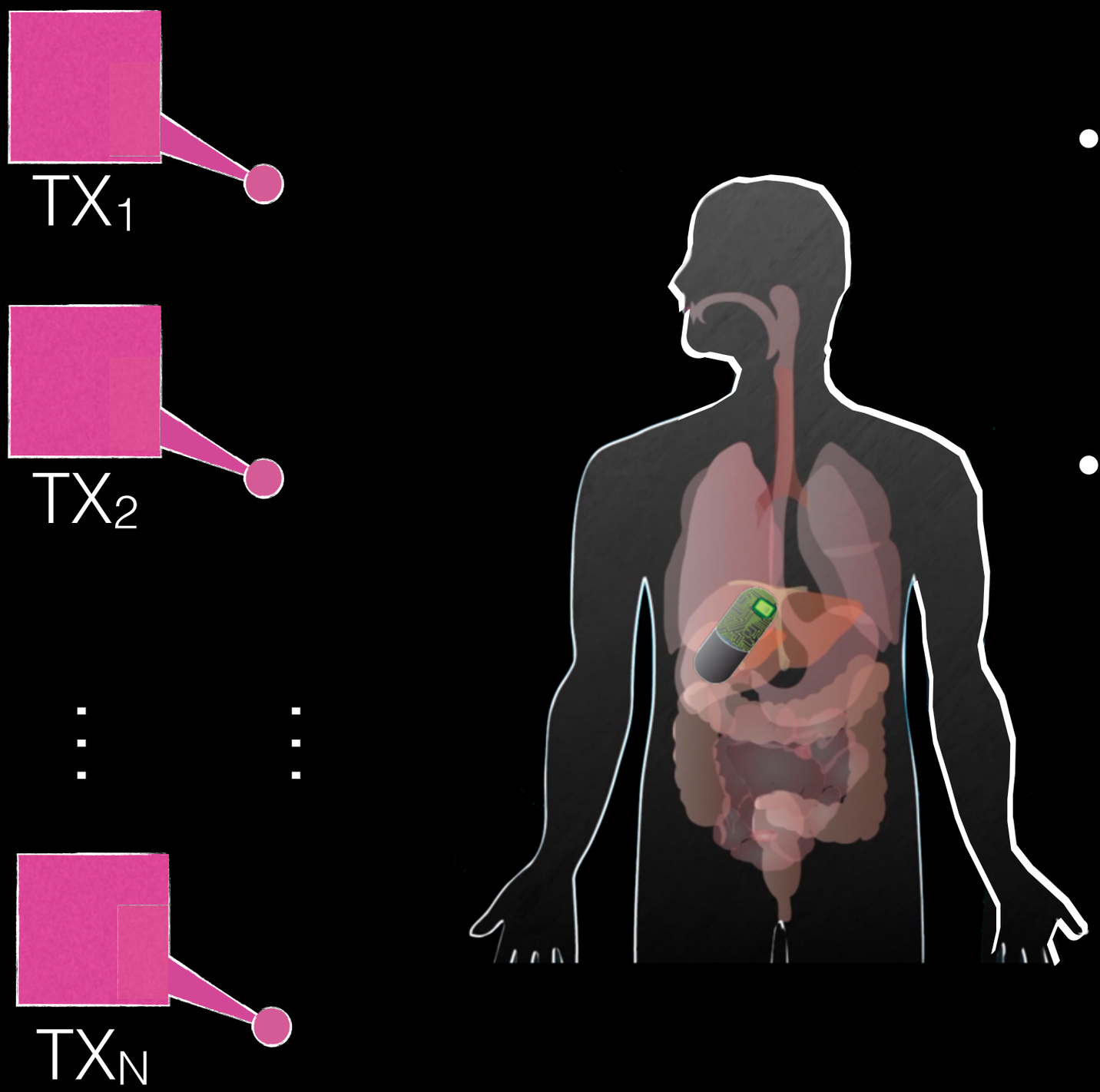

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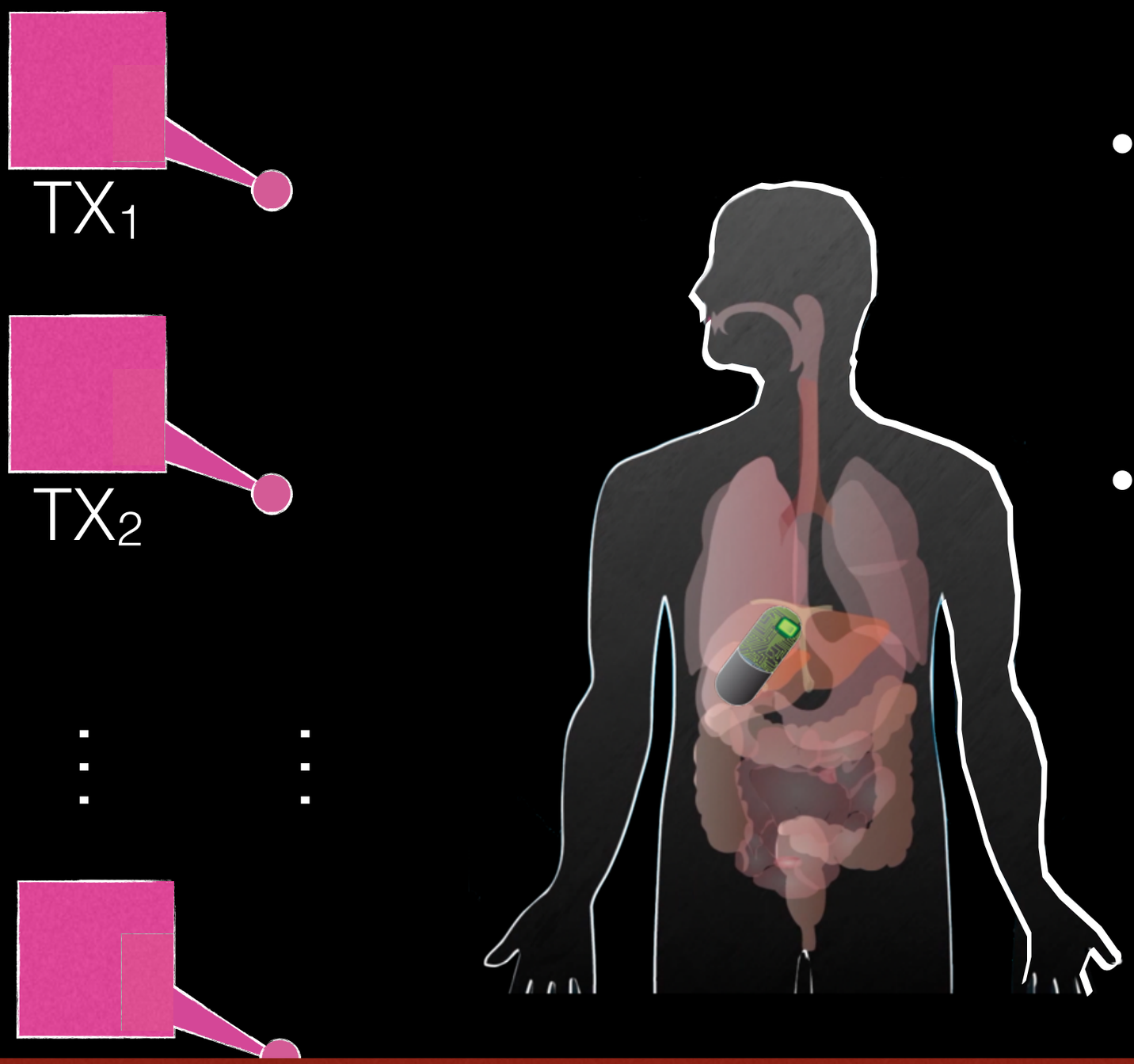

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Cannot estimate the channel because need to power up deep-tissue sensor in the first place

How can we power and communicate with sensors in deep tissues despite unpredictable channels?

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Wireless Communication

Time-invariant Channel

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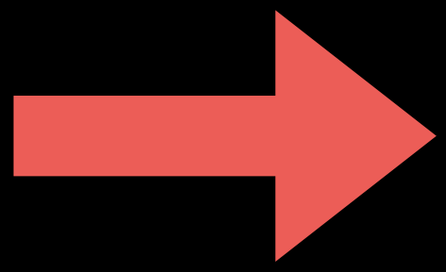
Wireless Communication

Time-invariant Channel

Time-varying hardware

Time-varying protocol



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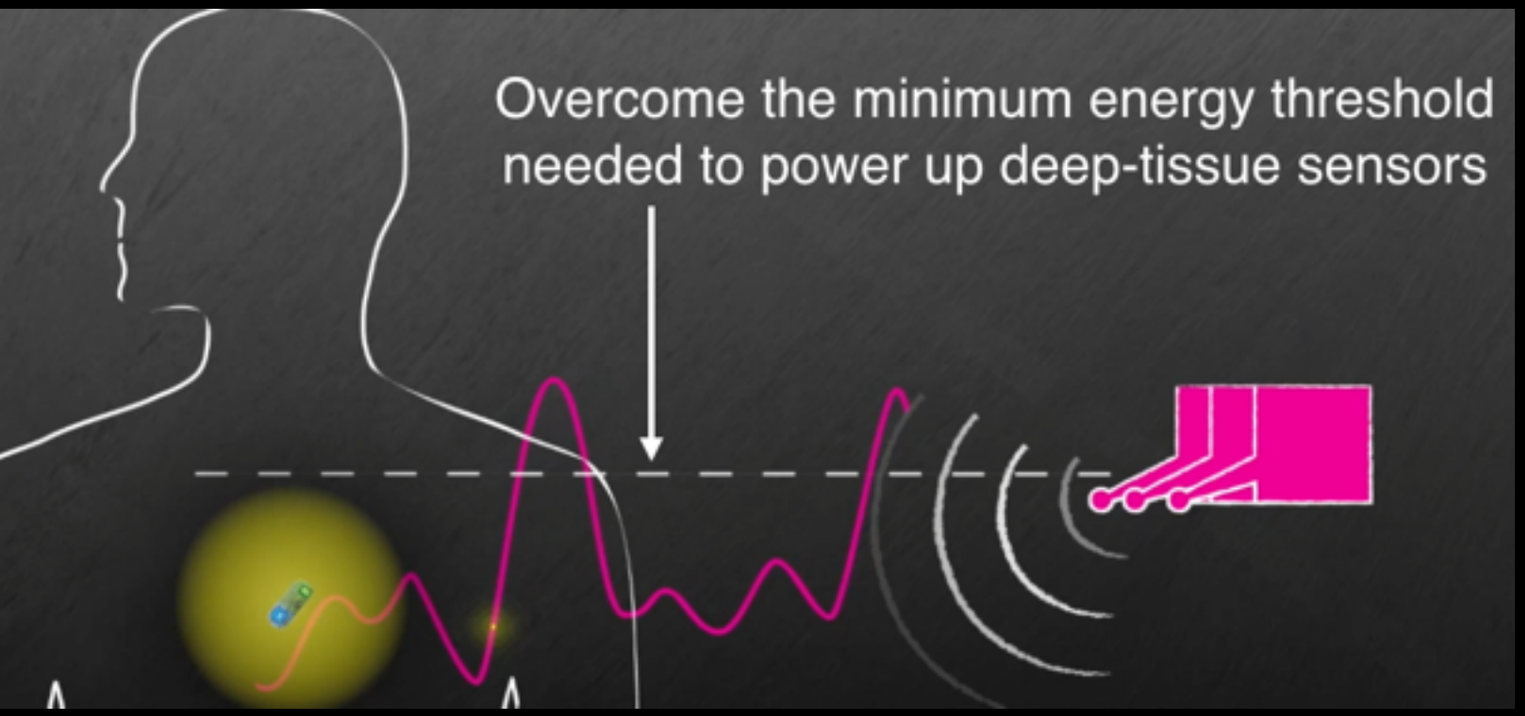

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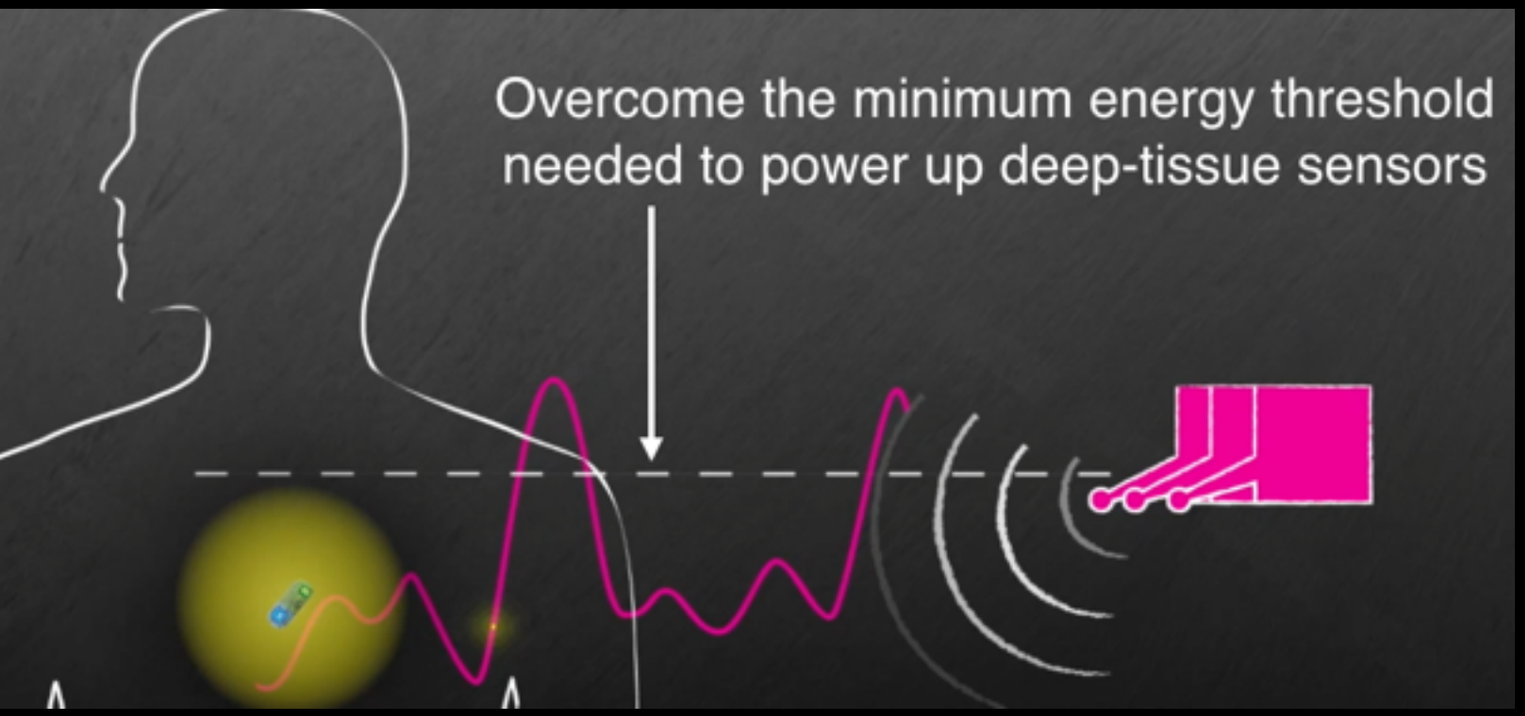
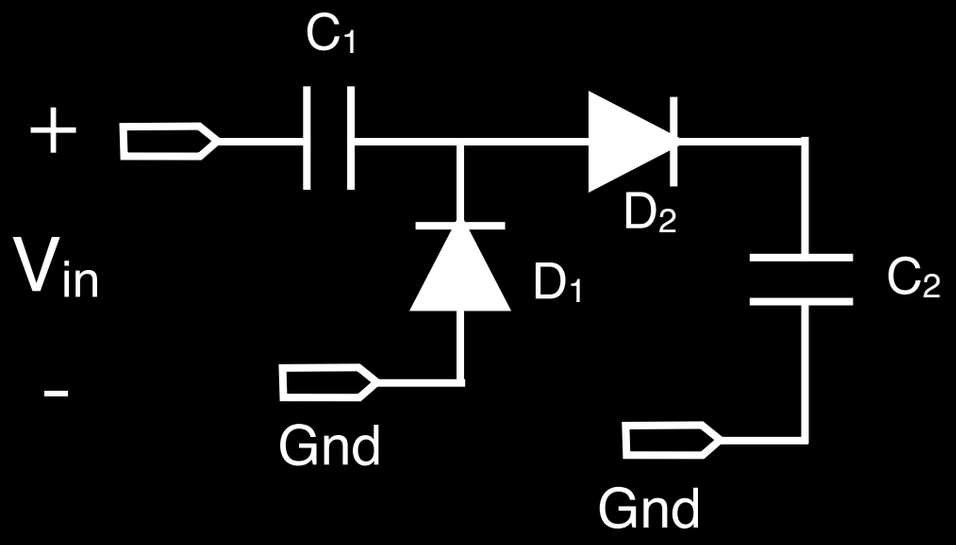


Overcome Threshold



Mathematically, IVN introduces a time-varying channel

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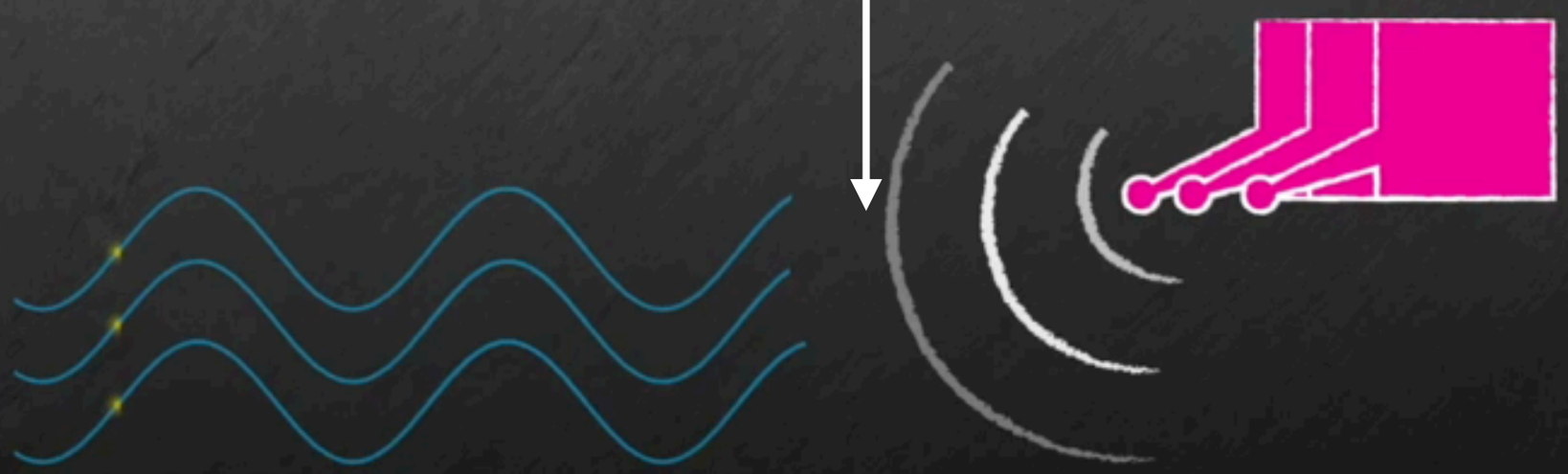
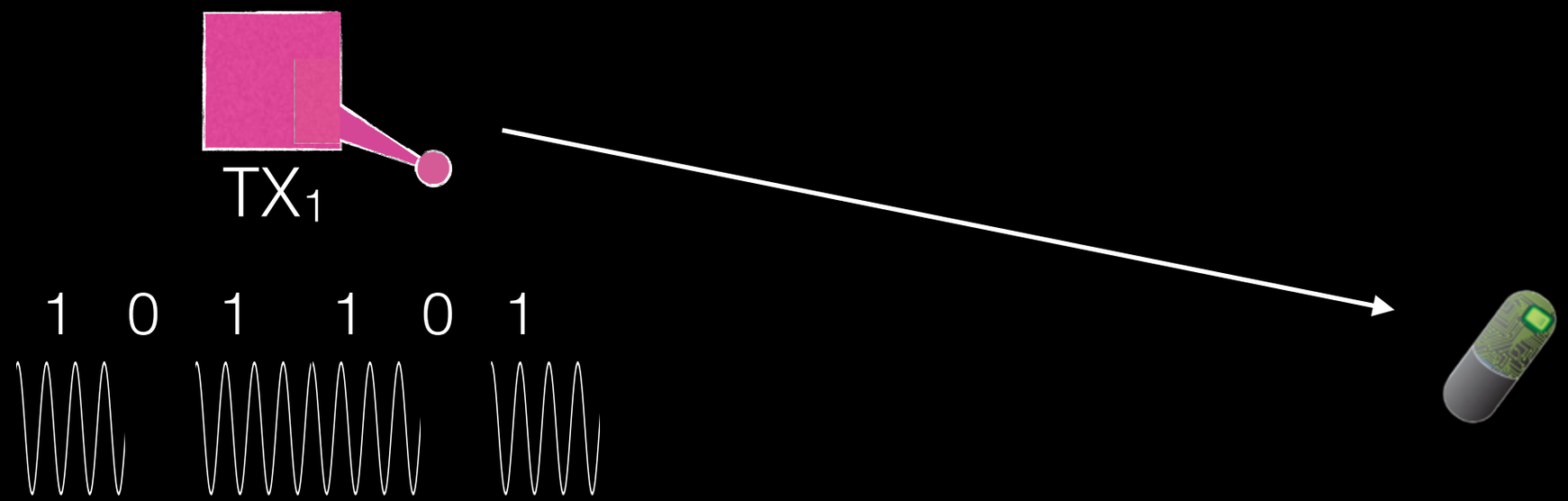
Overcome the minimum energy threshold needed to power up deep-tissue sensors



Deep-Tissue Communication

IVN leverages backscatter, the most energy-efficient communication technology



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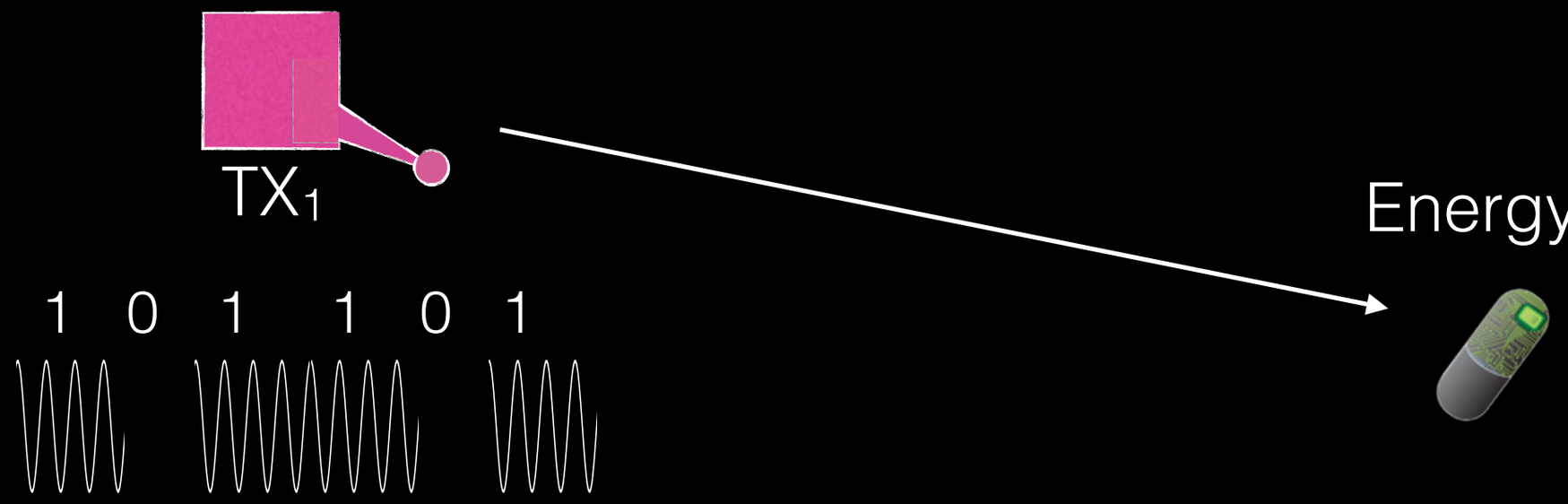

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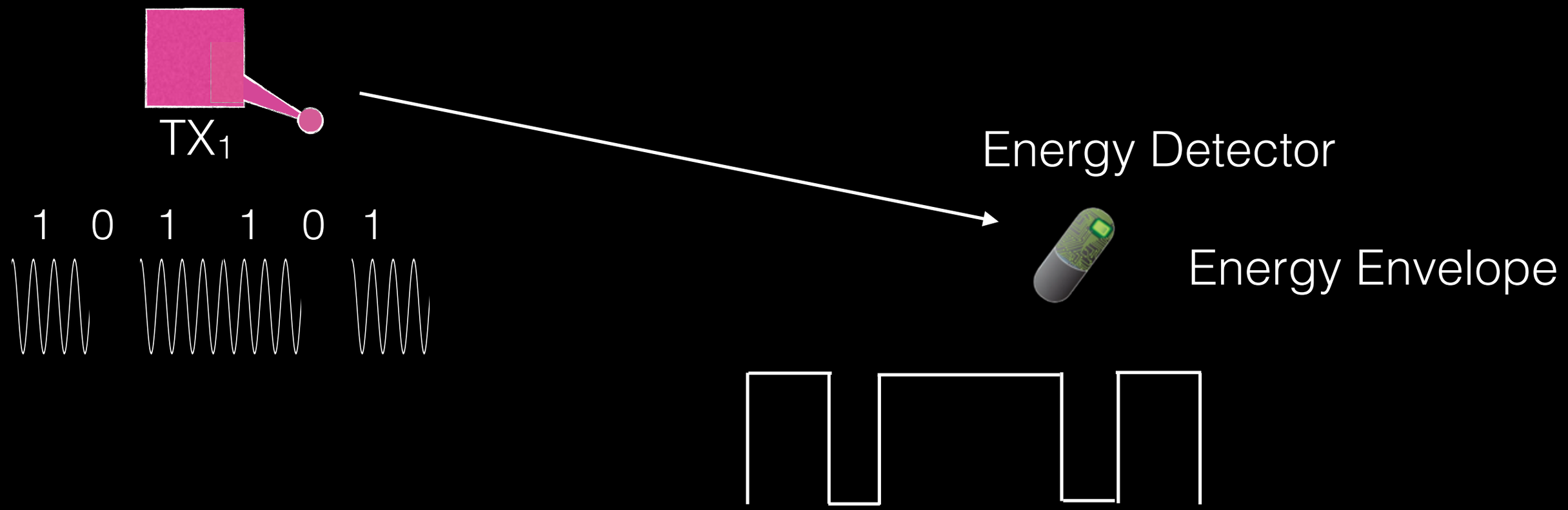

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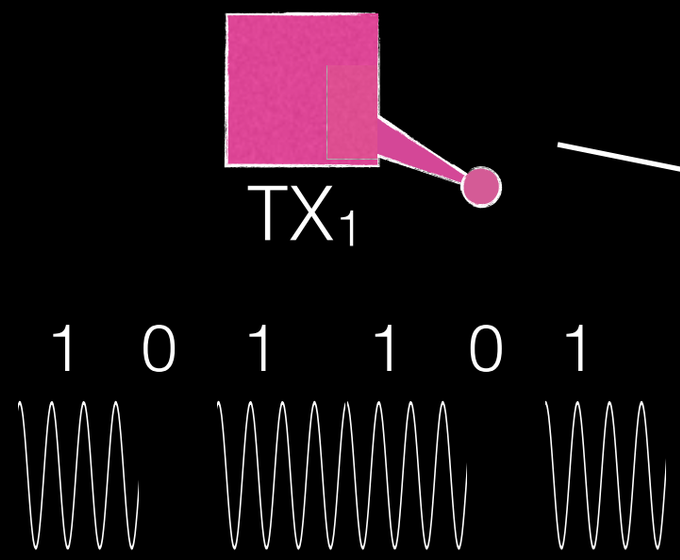

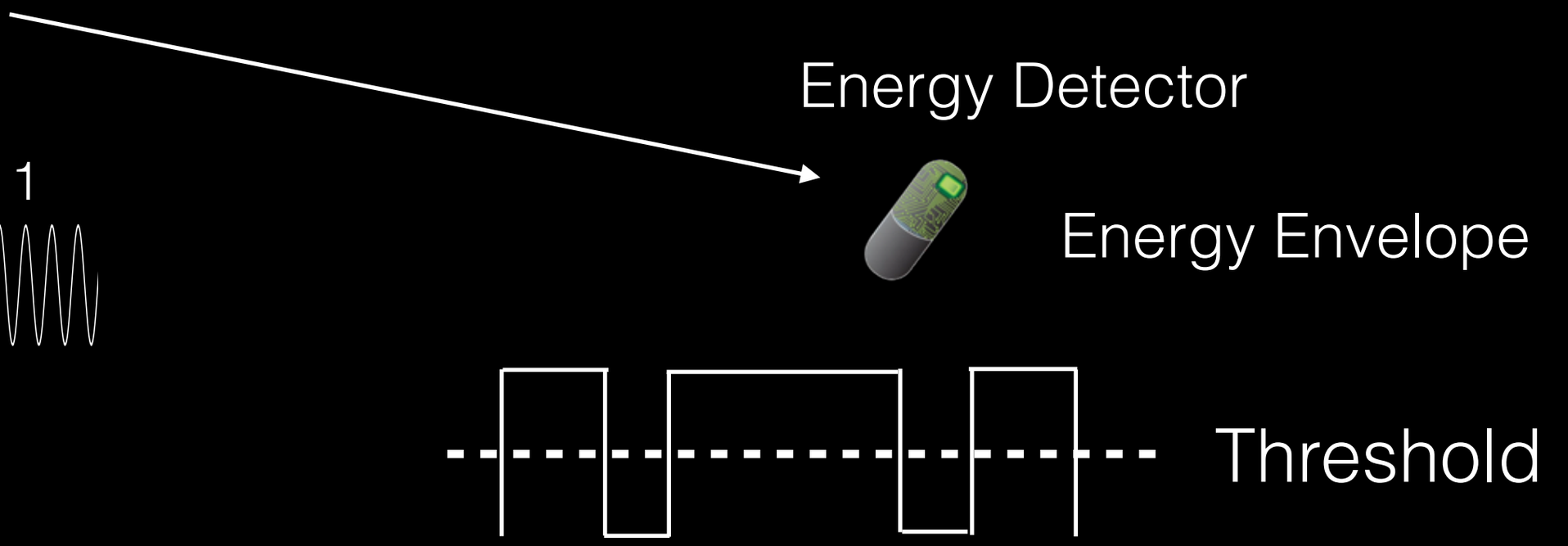

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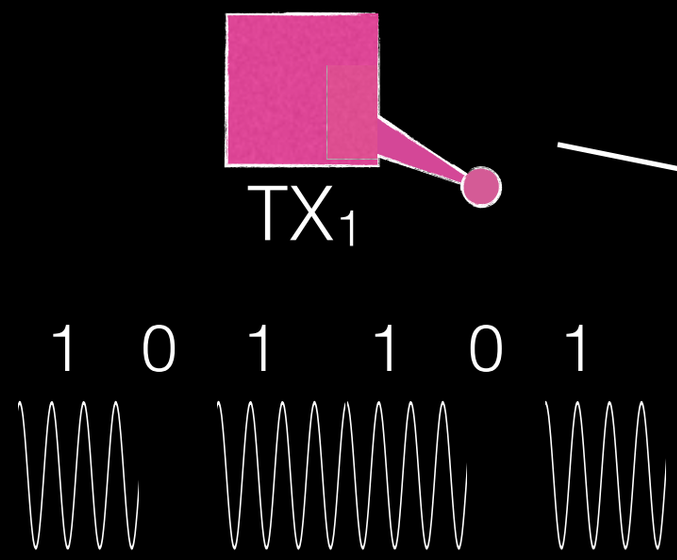
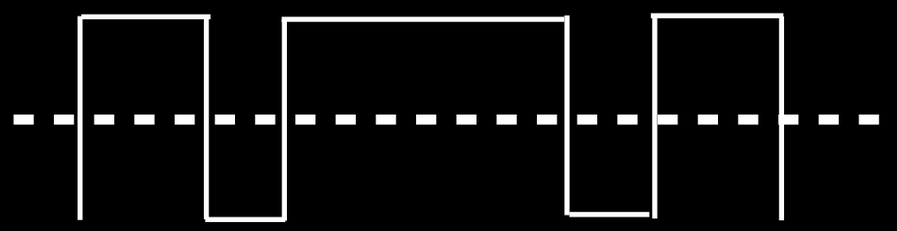


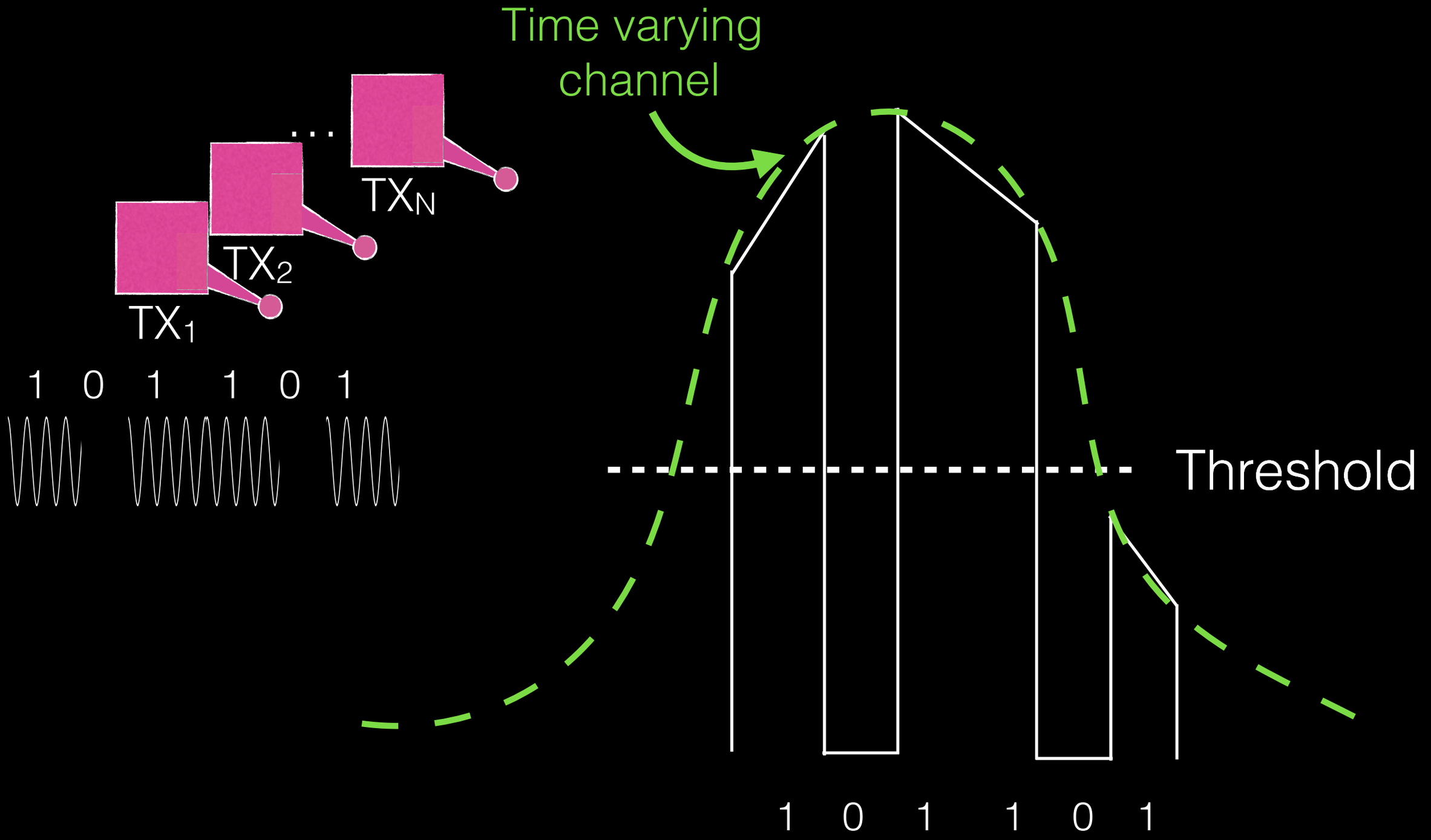
Energy Envelope



Threshold

1 0 1 1 0 1

Energy Thresholding with IVN's Beamformer



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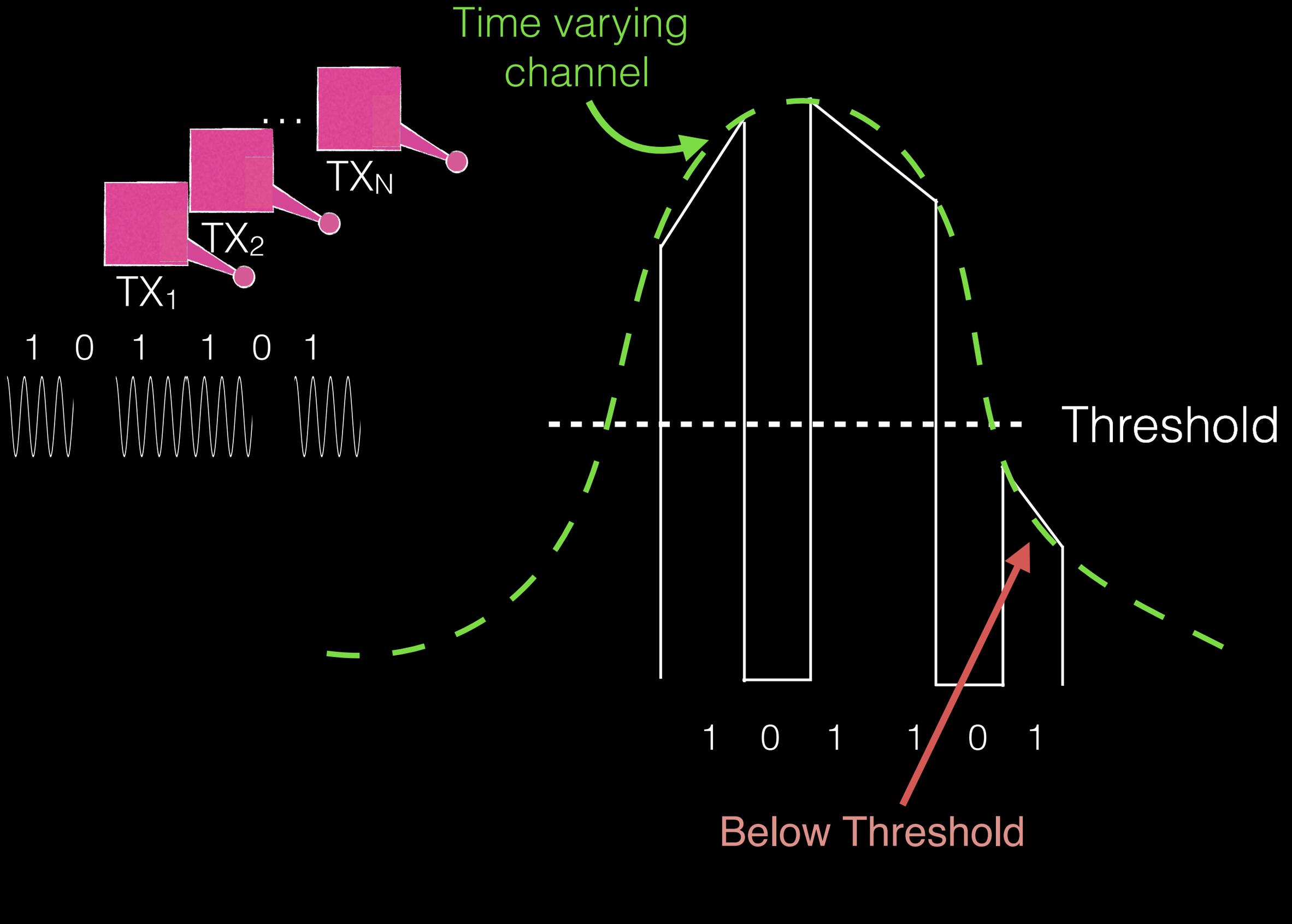

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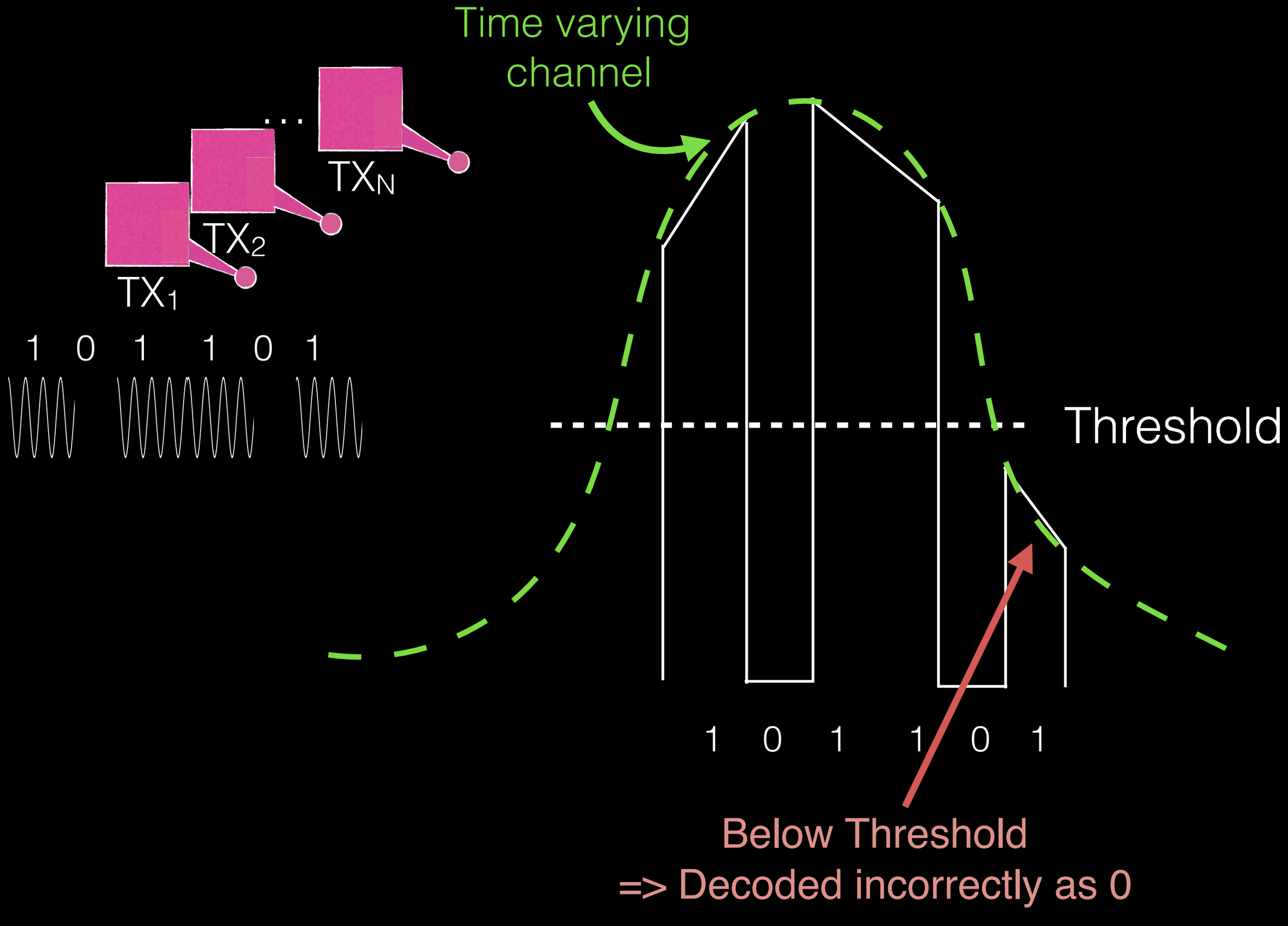

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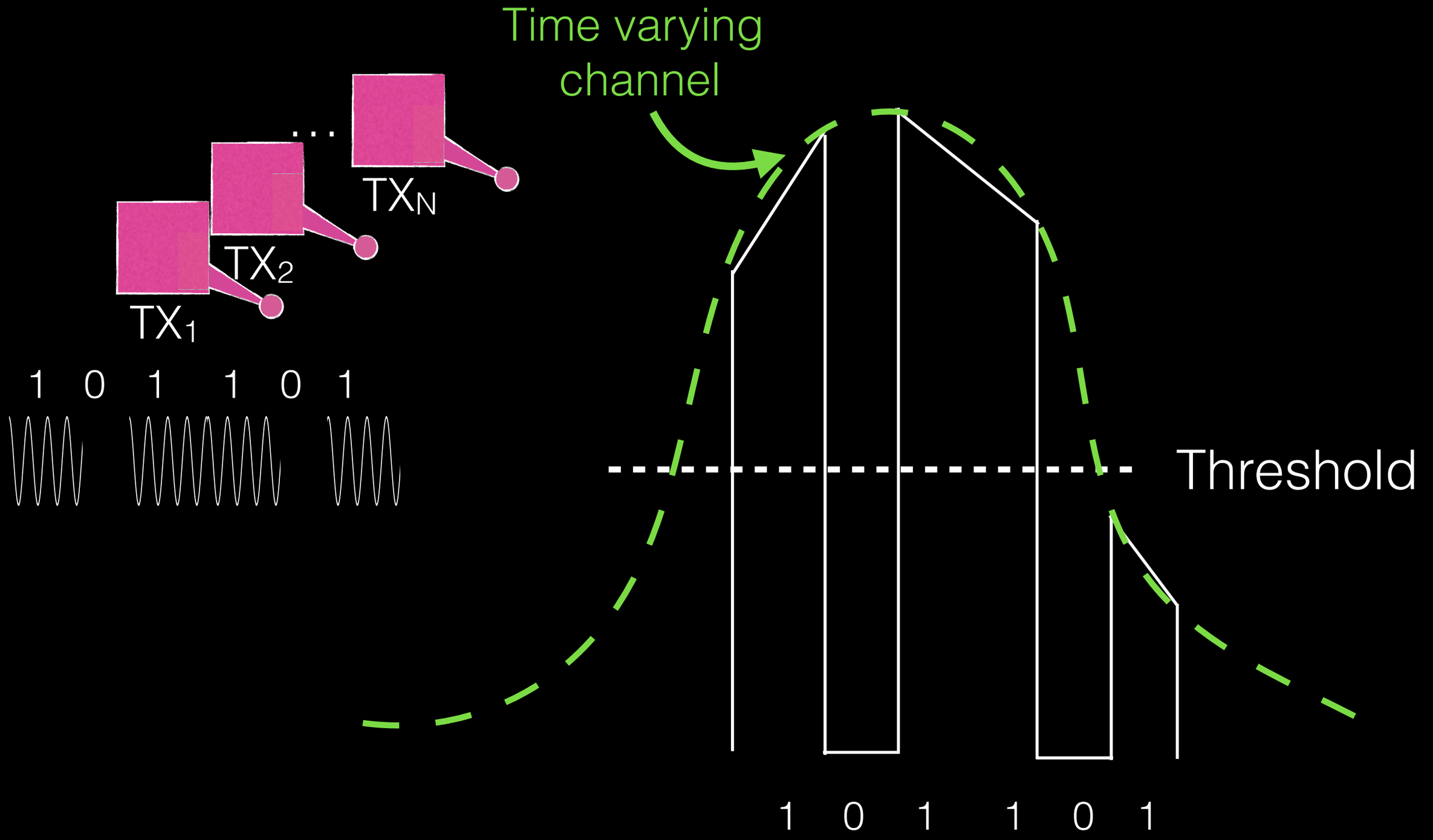

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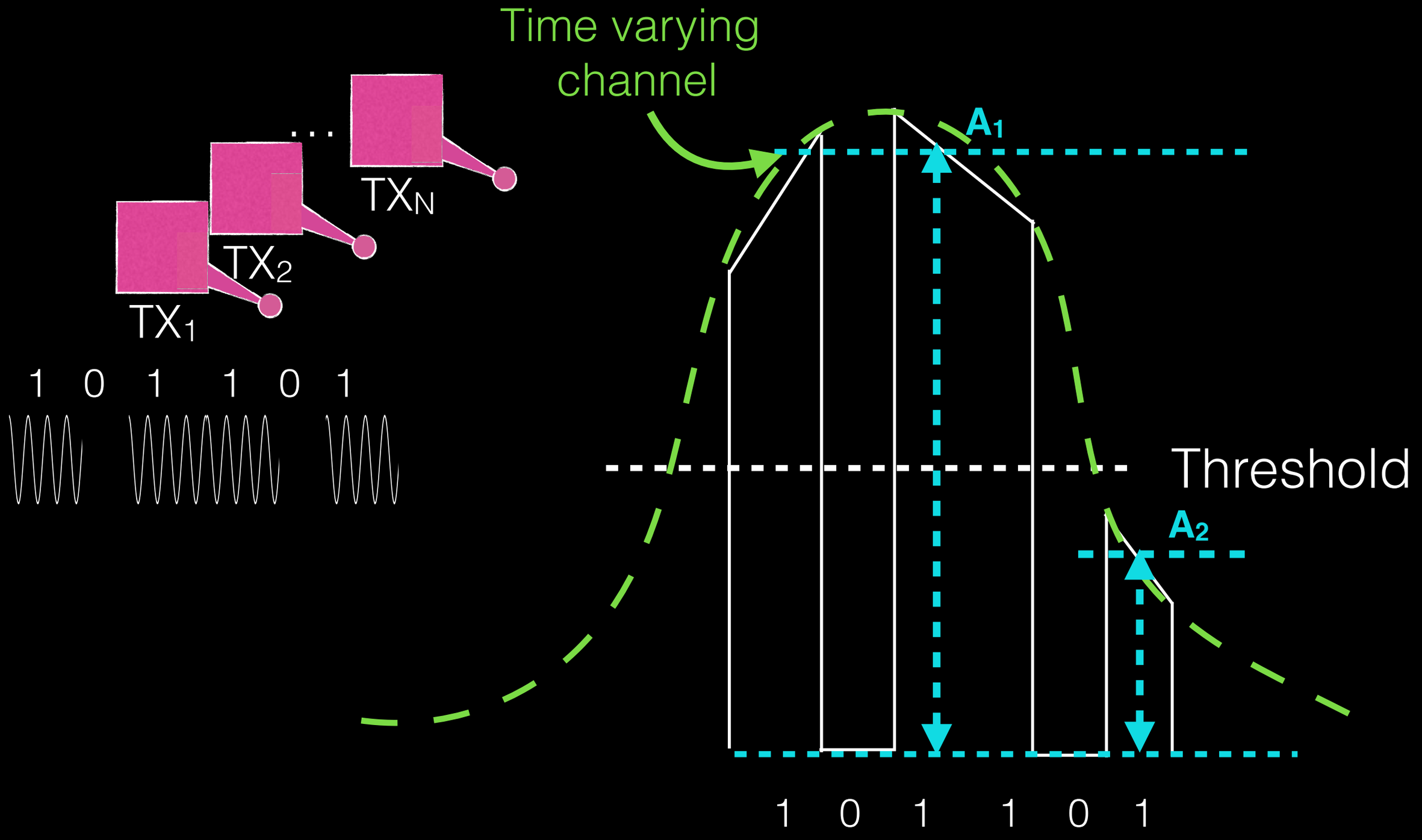

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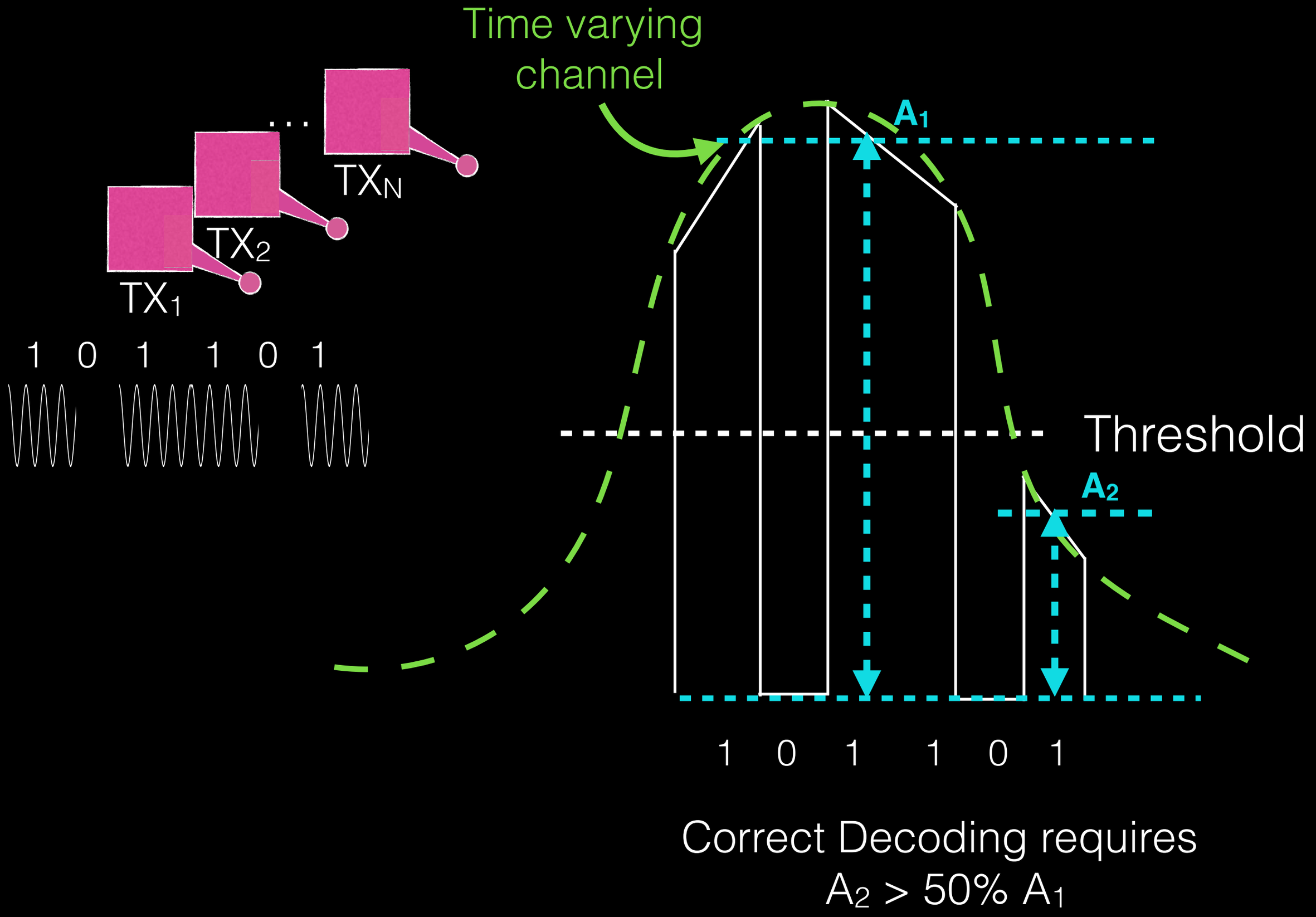

Correct Decoding requires
$A_2 > 50\% A_1$

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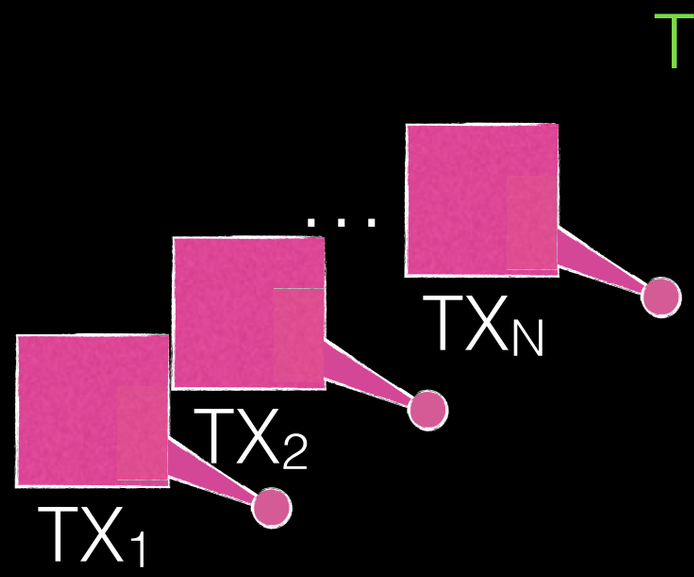

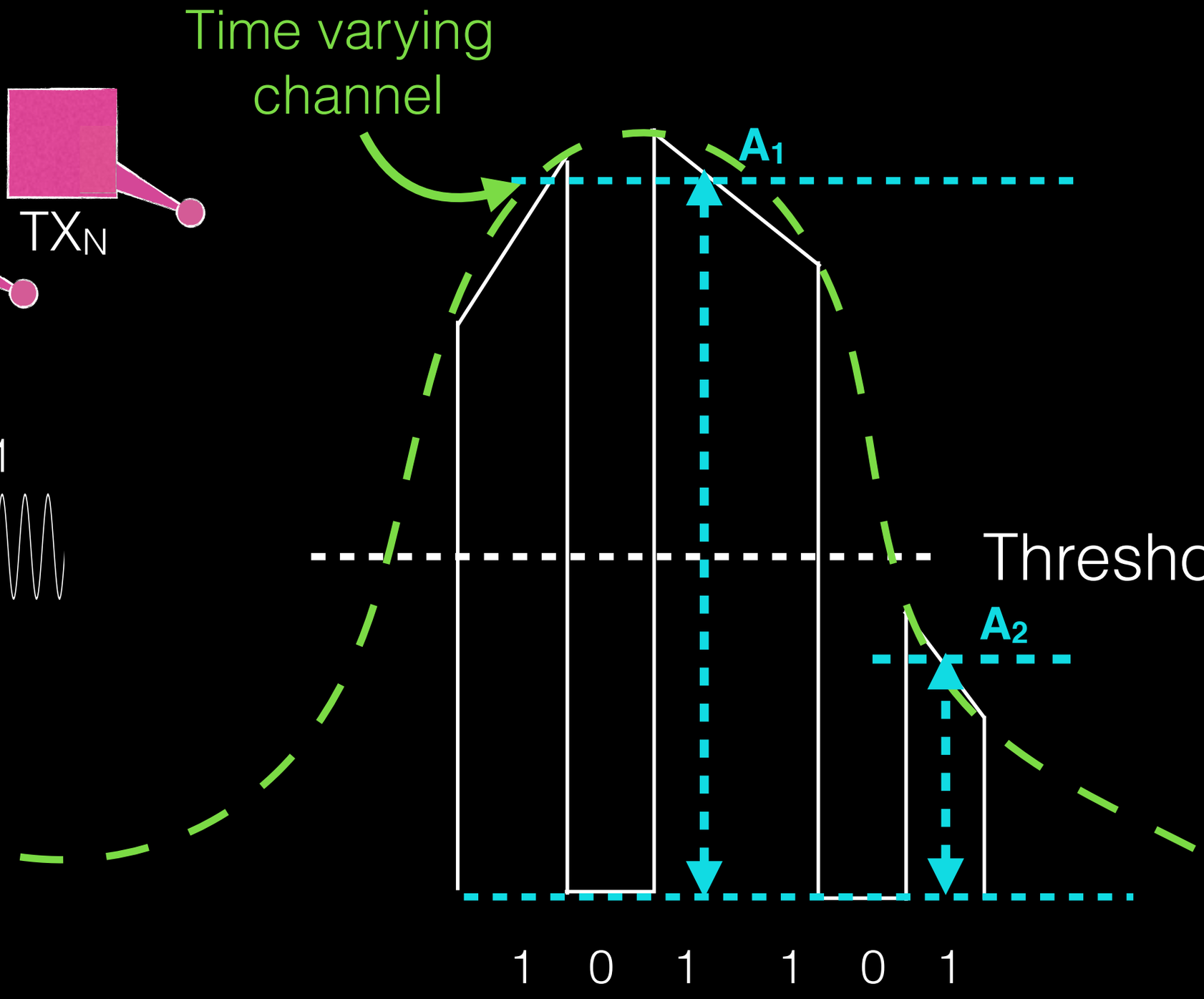

$$\frac{1}{N}\sum_{i=2}^{N}\Delta f_i{}^2 < \frac{1}{4\pi^2\,(T_{cmd})^2}$$

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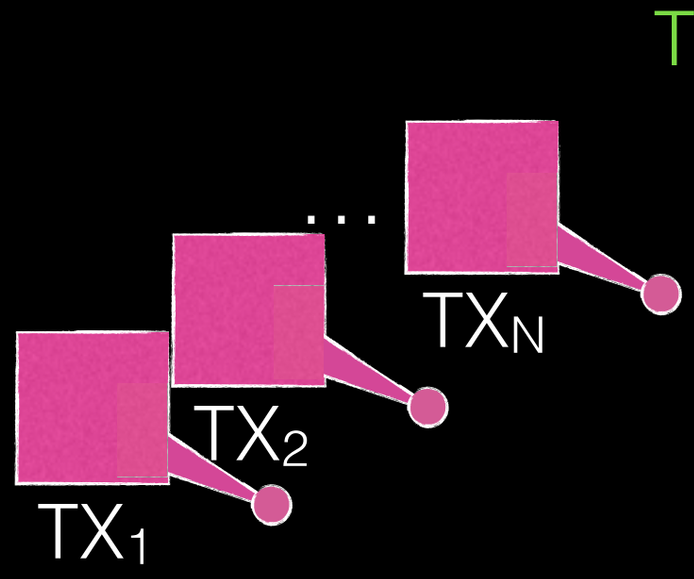
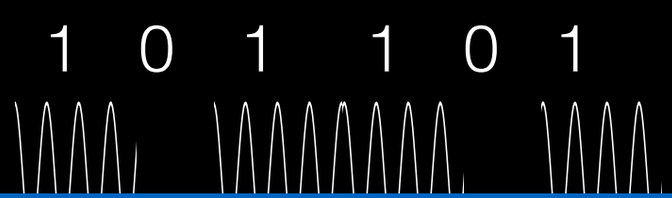
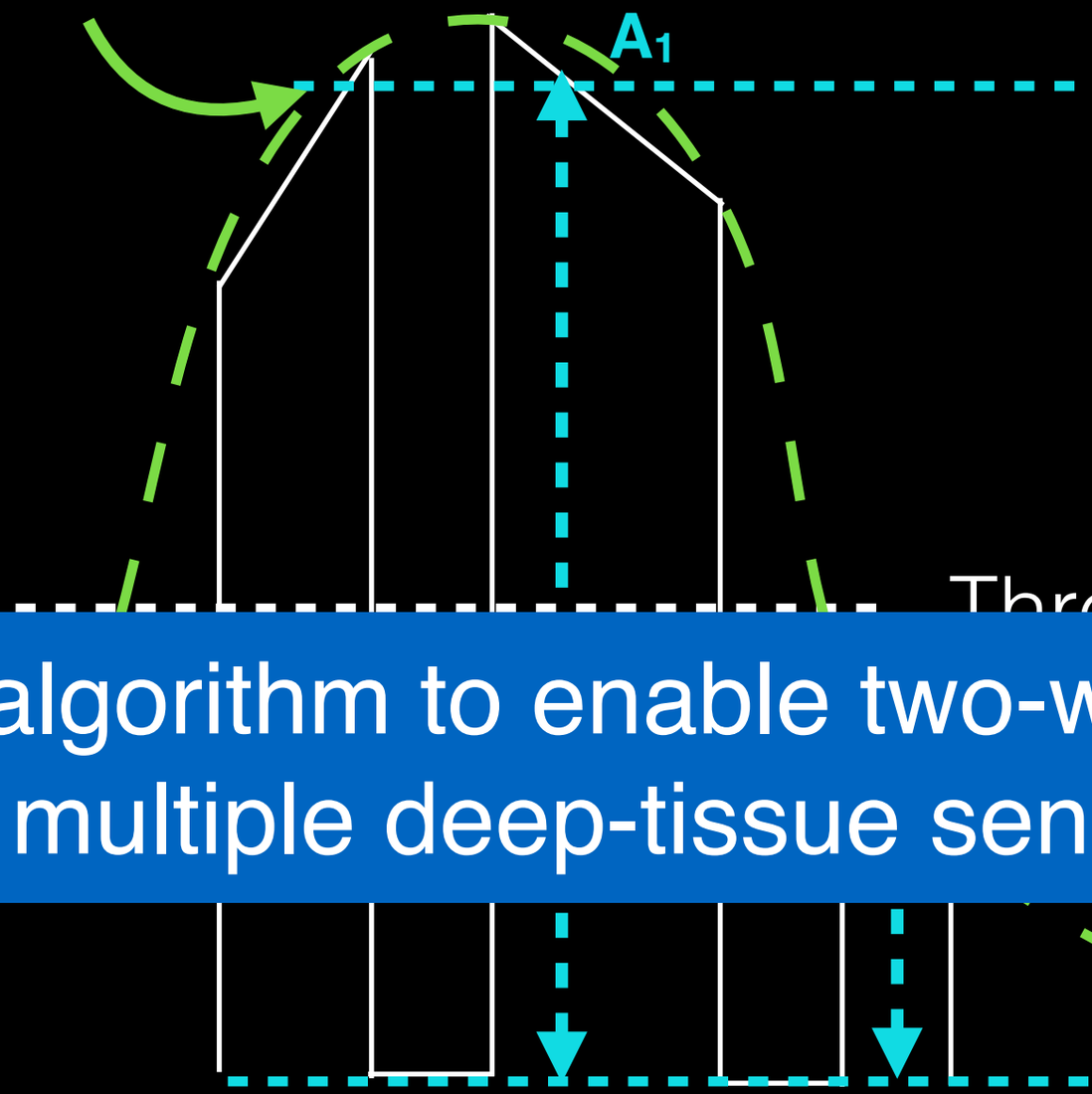




Time varying channel



IVN builds special algorithm to enable two-way communication with multiple deep-tissue sensors

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IVN's Multi-antenna beamformer

- USRP N210 software defined radios with SBX daughterboard
- 6-dBi patch antennas
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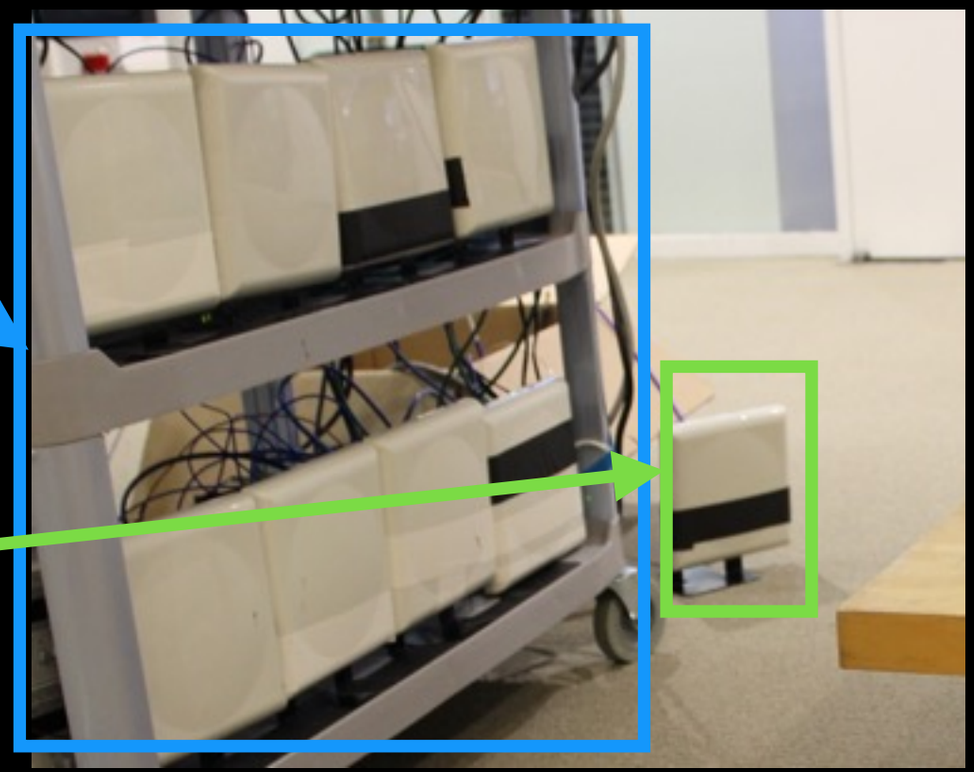
Out-of-band reader

- Deals with self-interference on uplink



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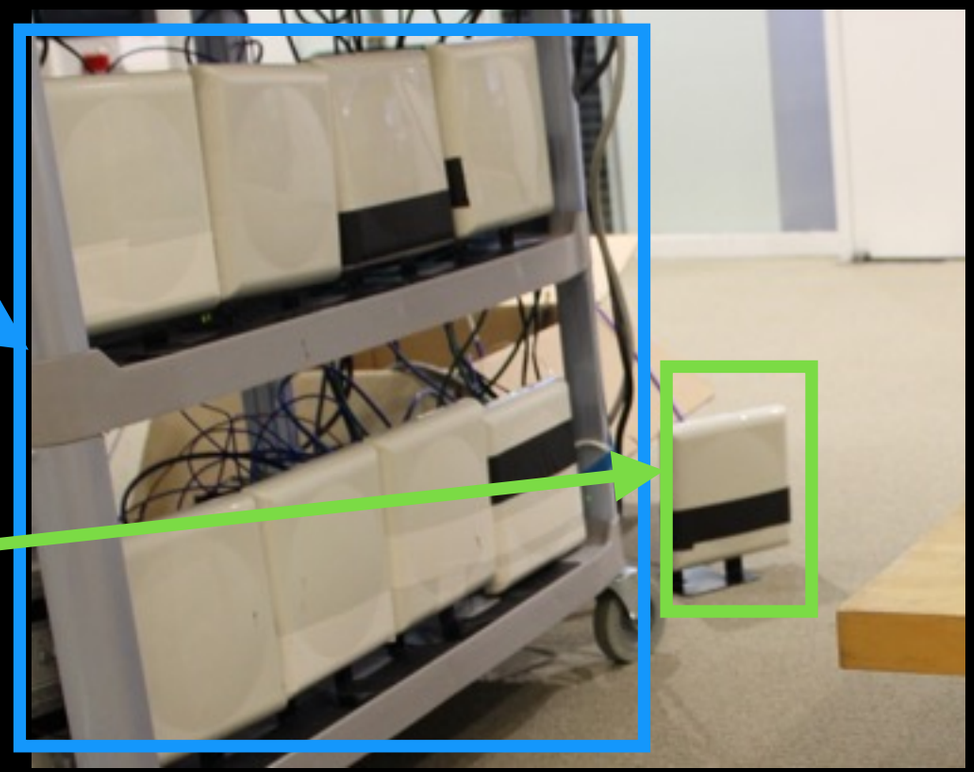

Beamforming and communication algorithms written in the USRP driver

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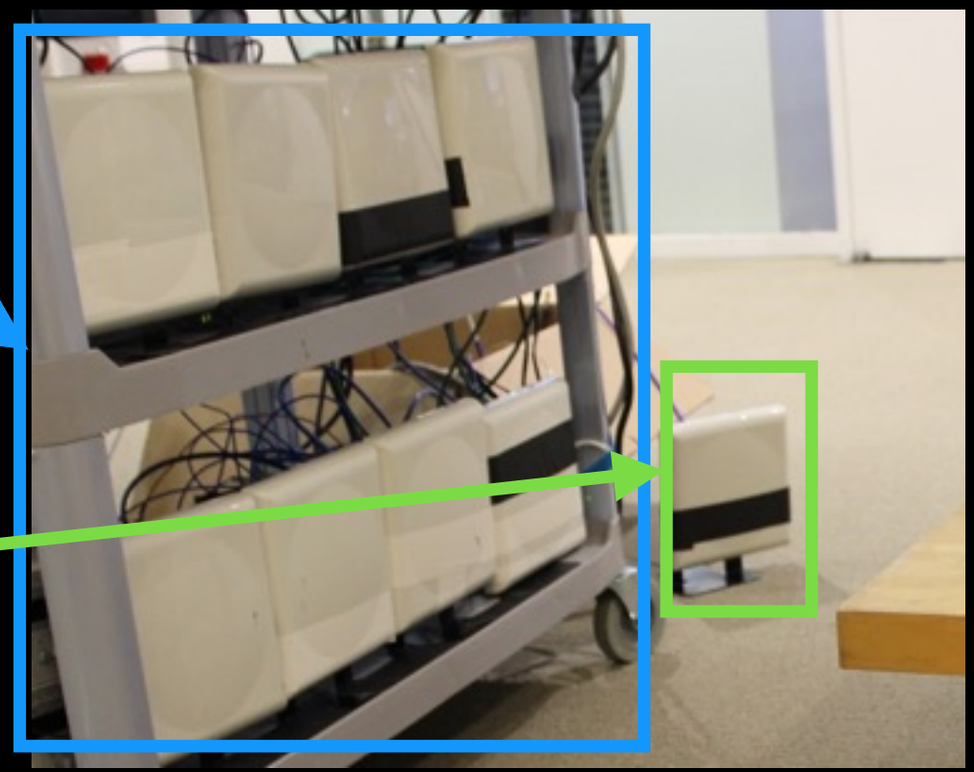

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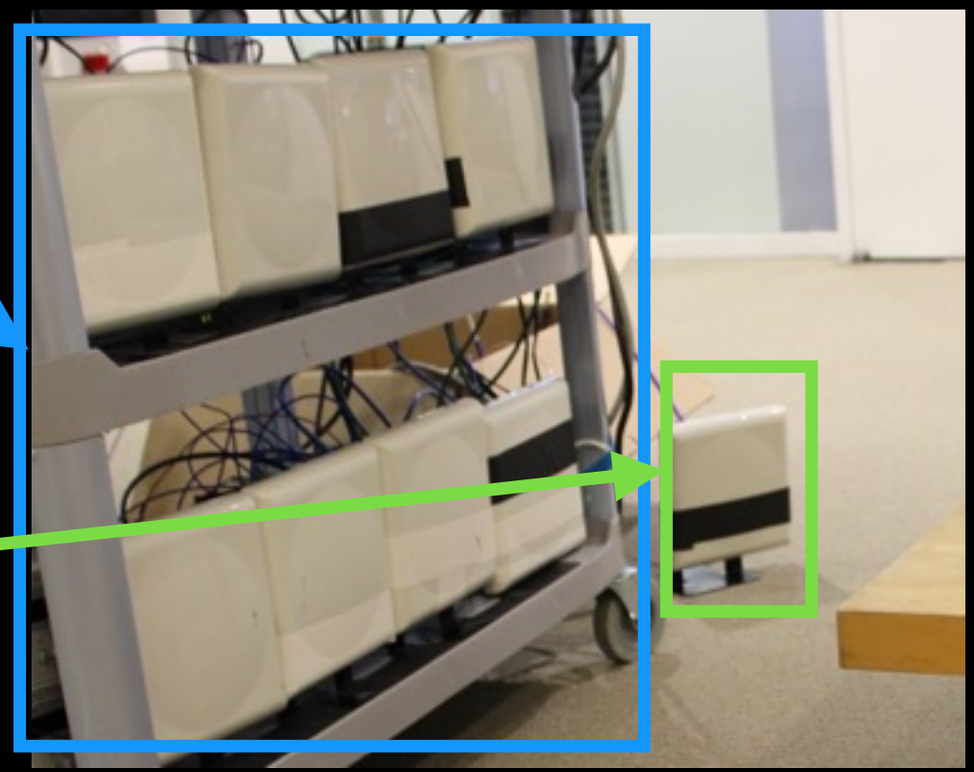

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Avery Dennison
AD-238u8 RFID

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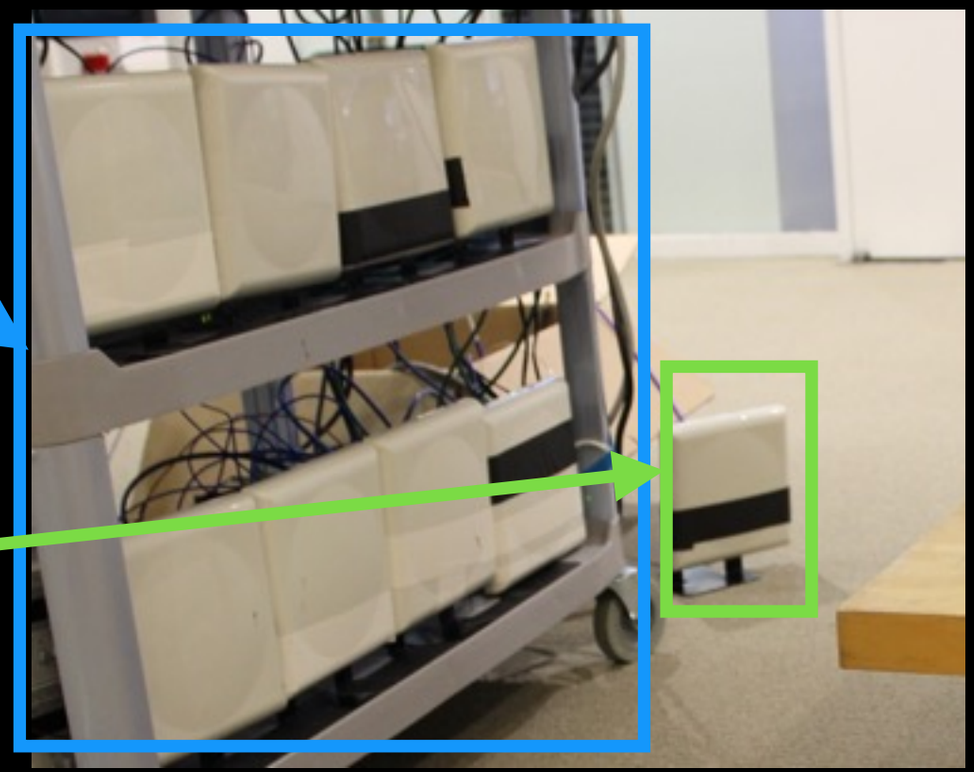

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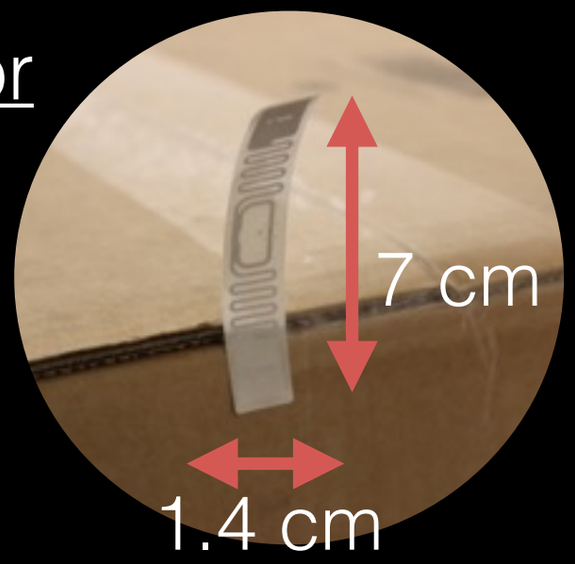

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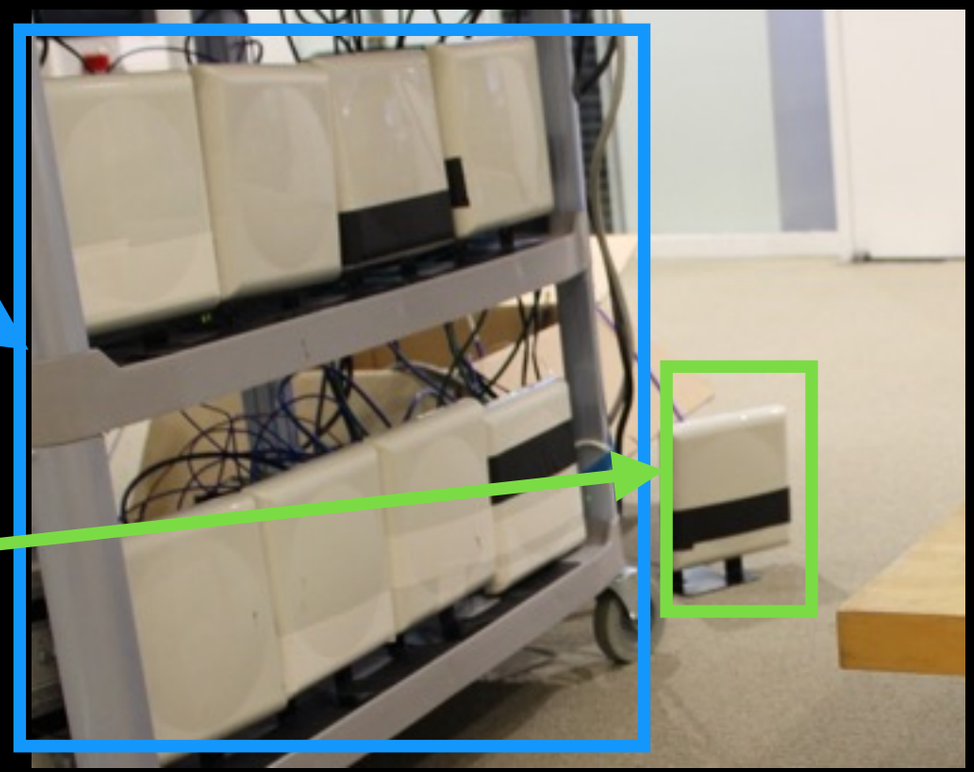

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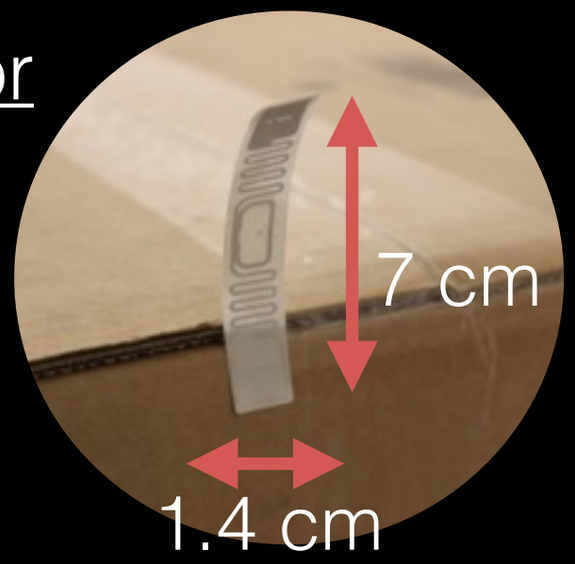

Miniature sensor

Xerafy Dash-On
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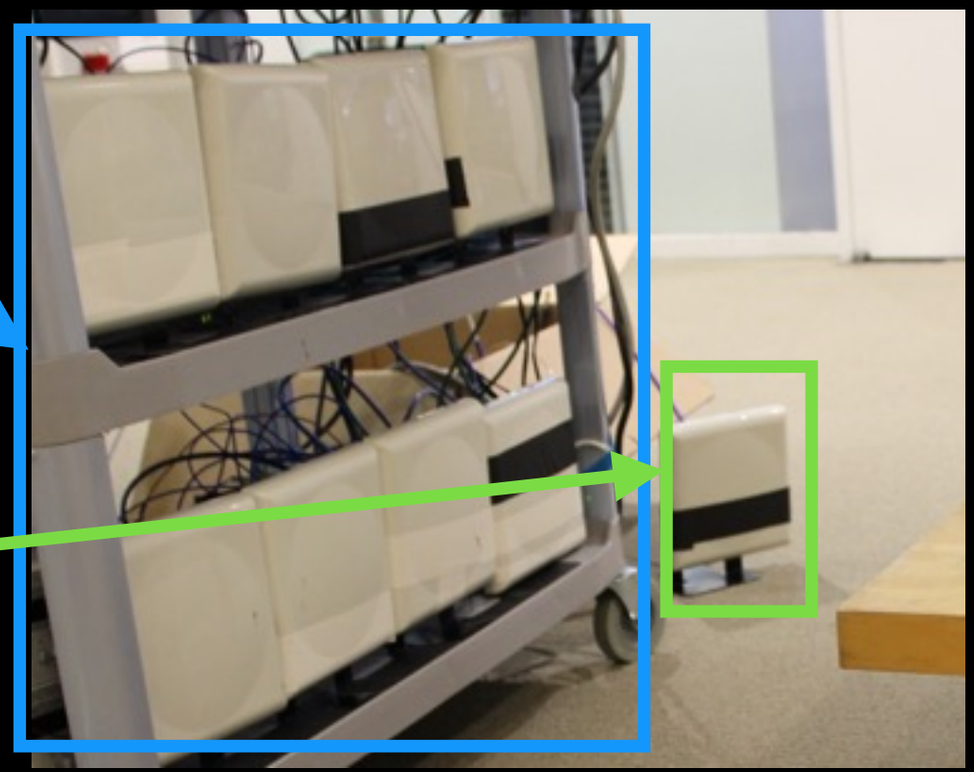

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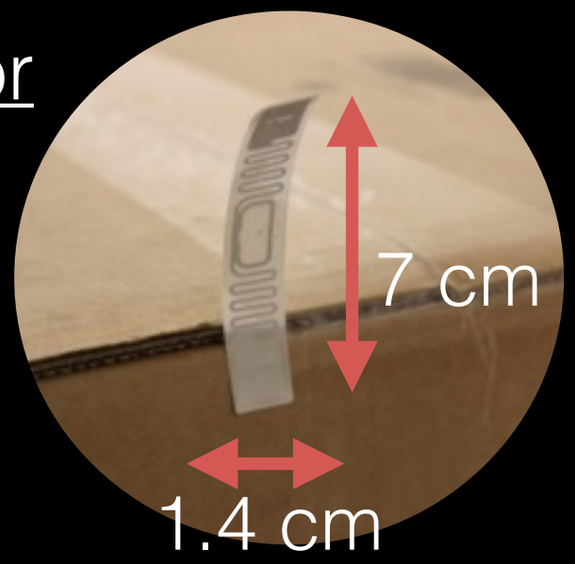

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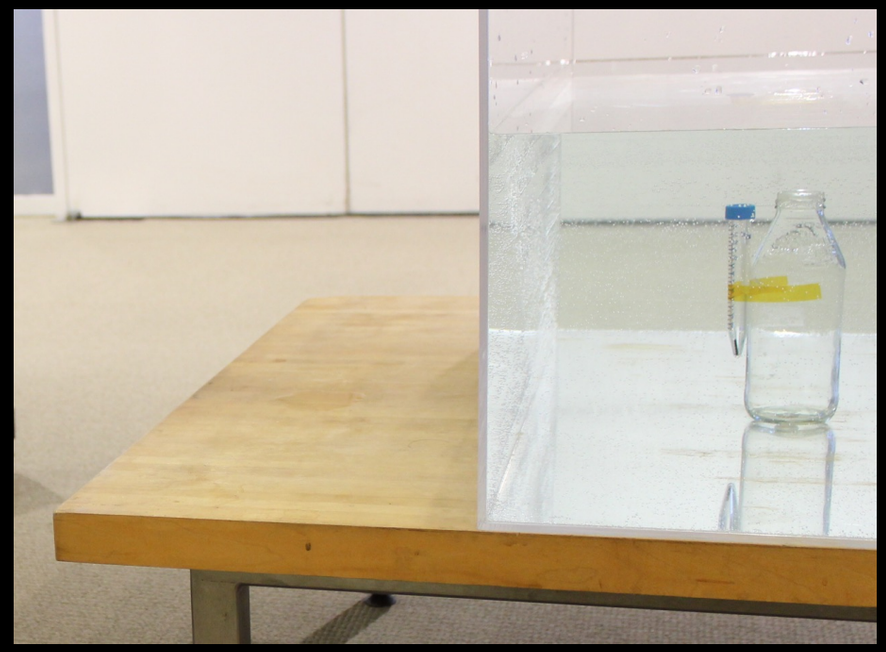

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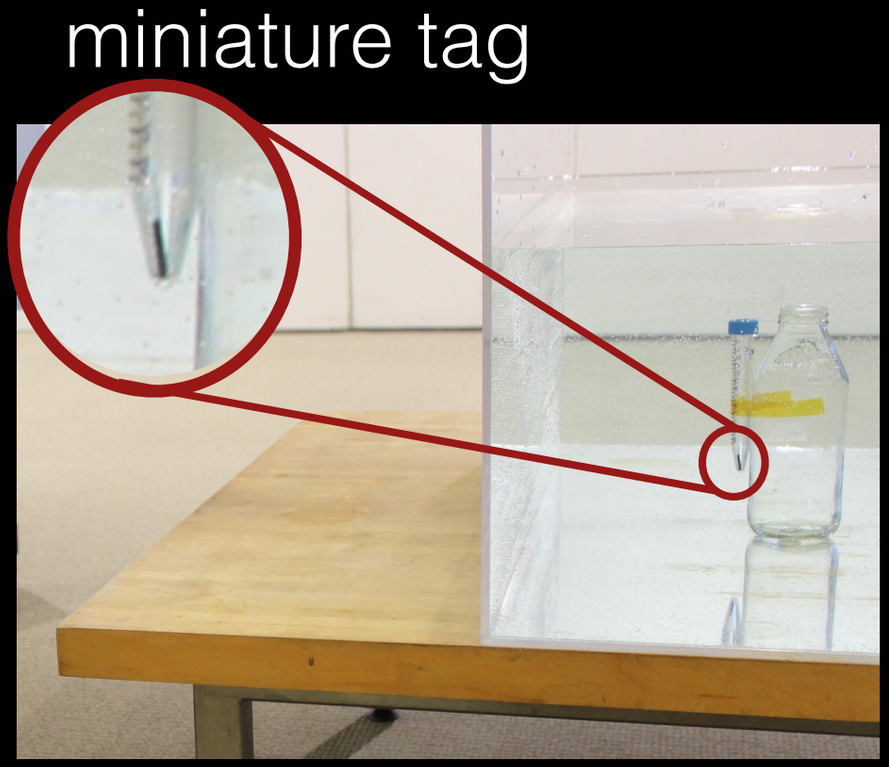

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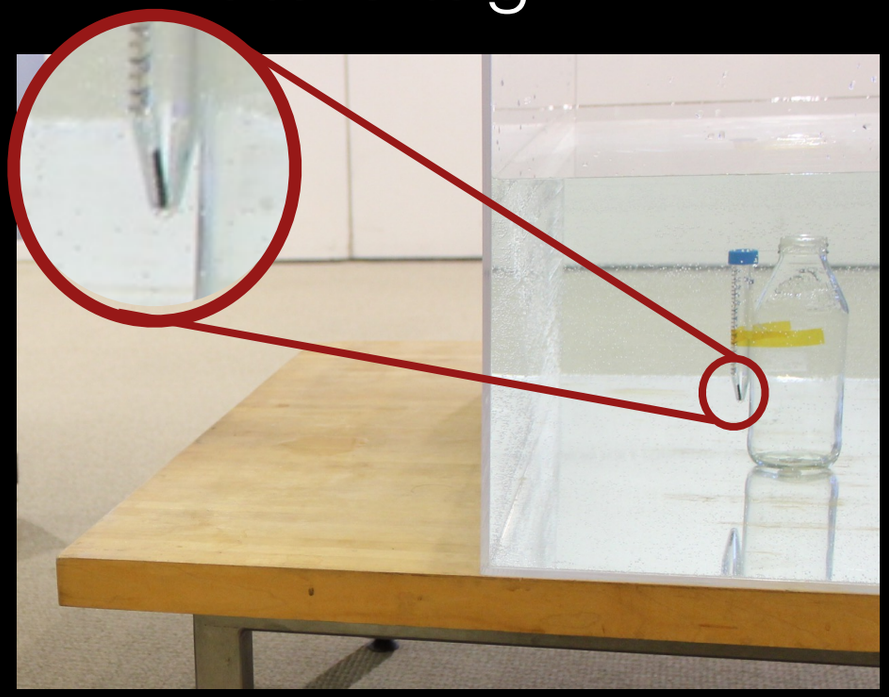
  - Water, gastric fluid, intestinal fluid



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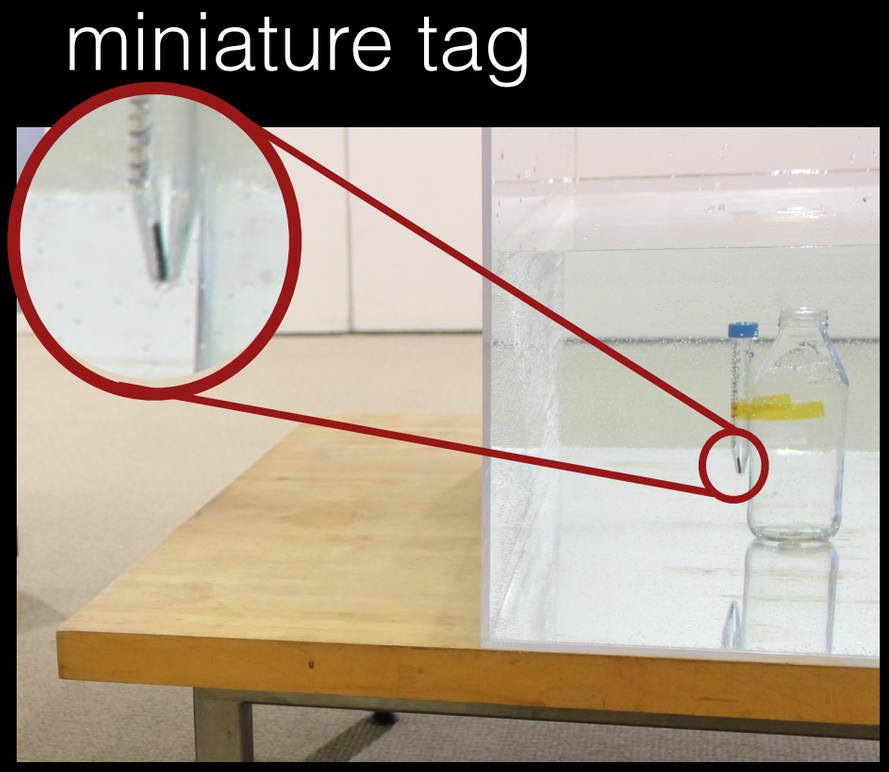

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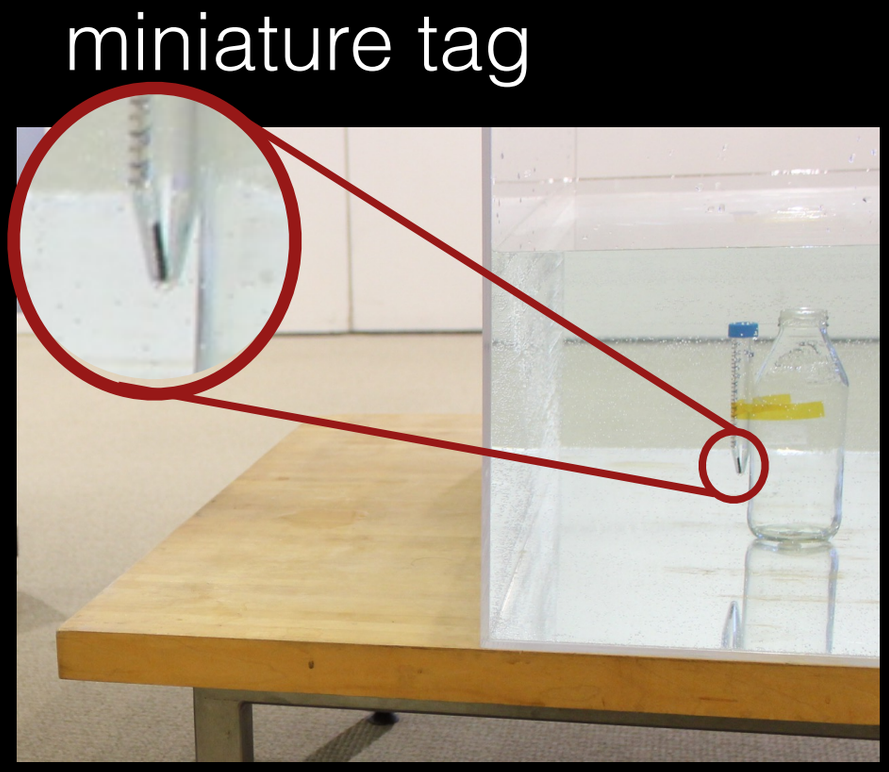

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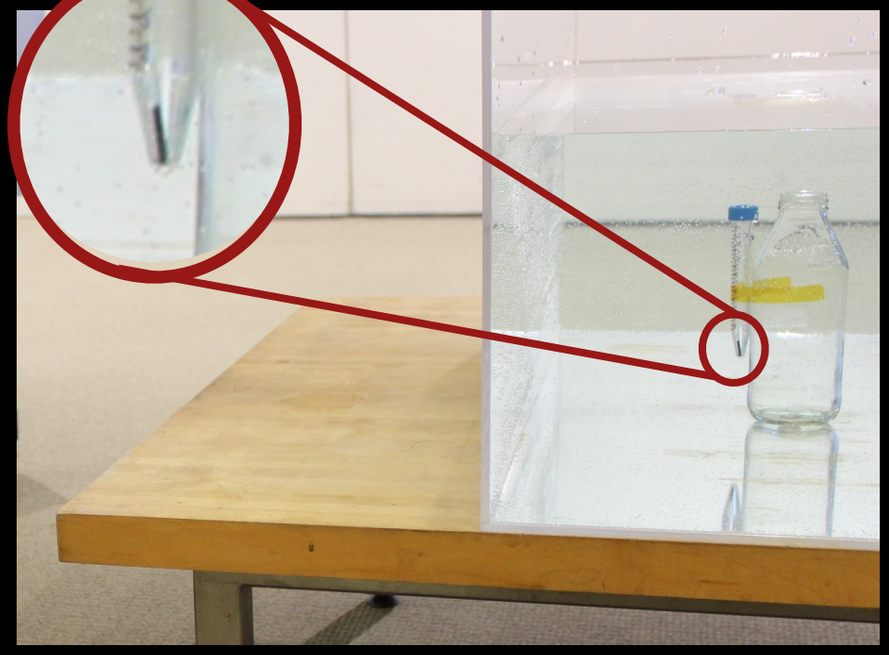
miniature tag



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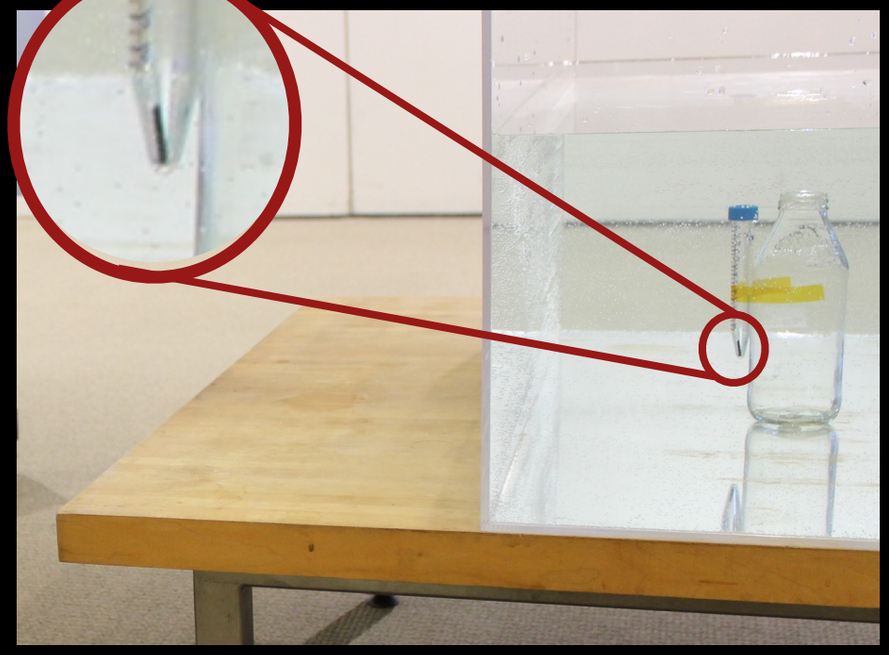
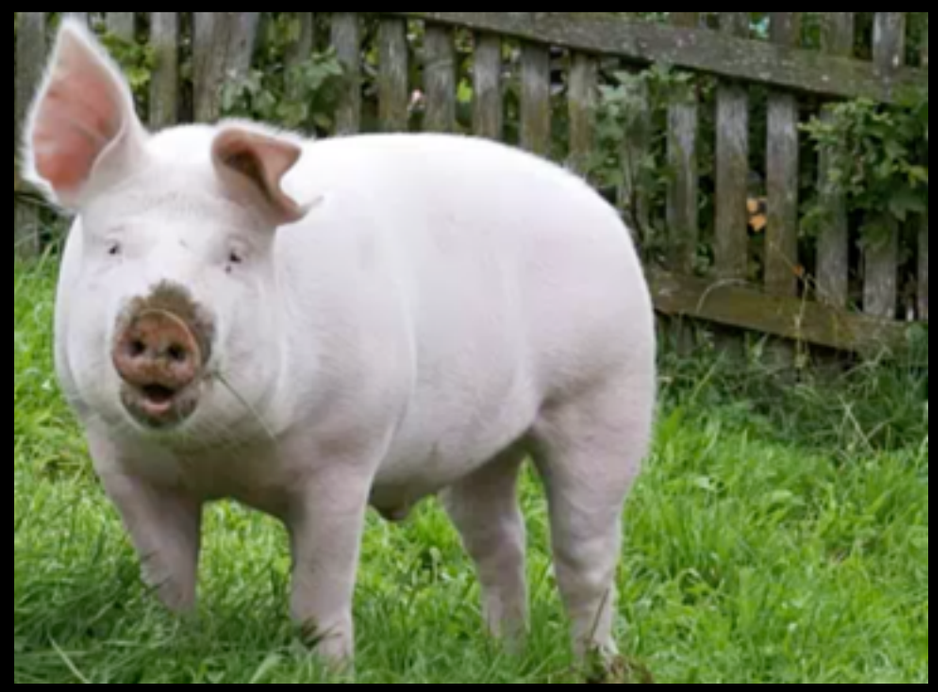
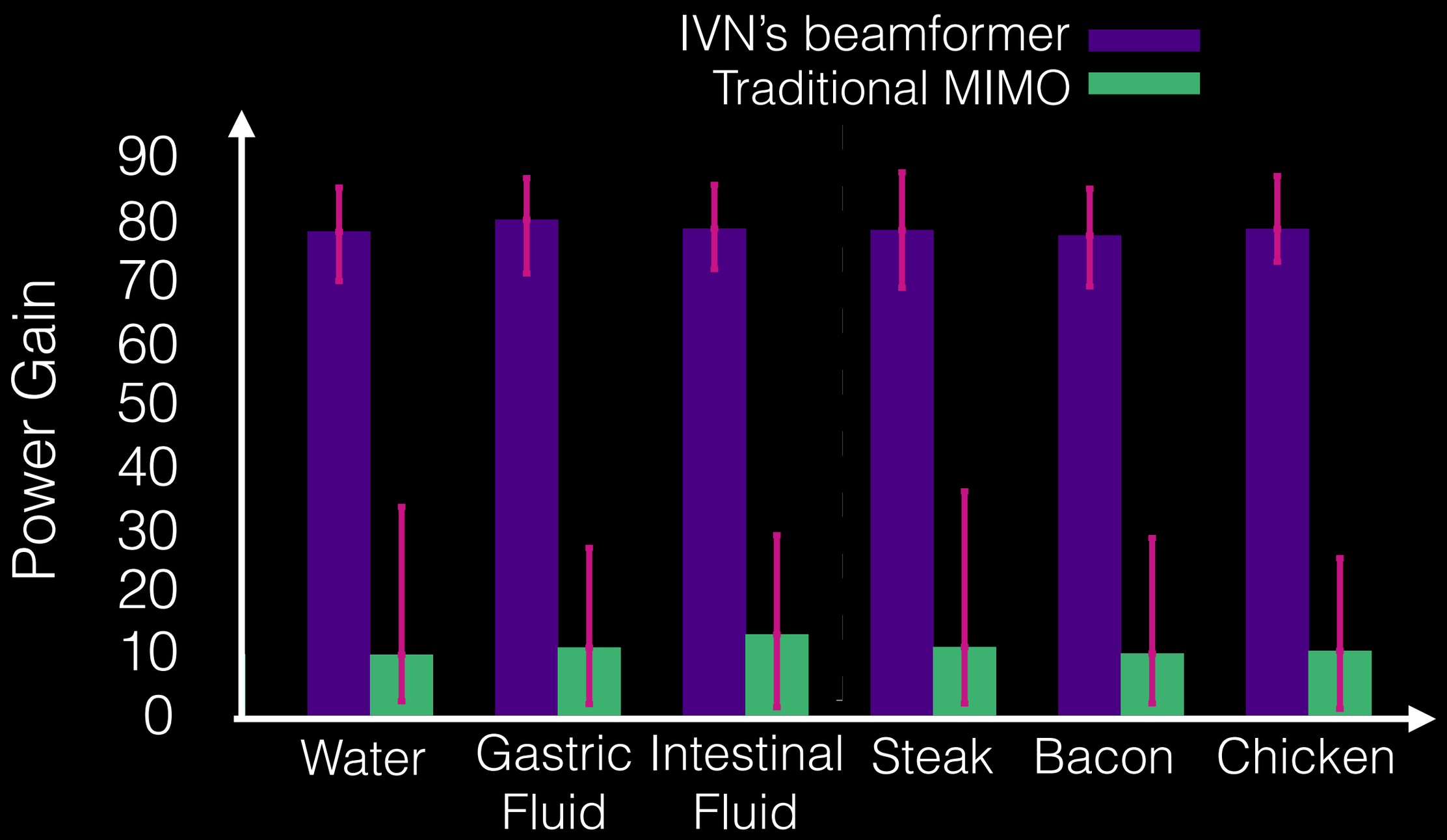




Can IVN deliver the multi-antenna power gain?

Experiment: Test 10-antenna beamformer in different tissues



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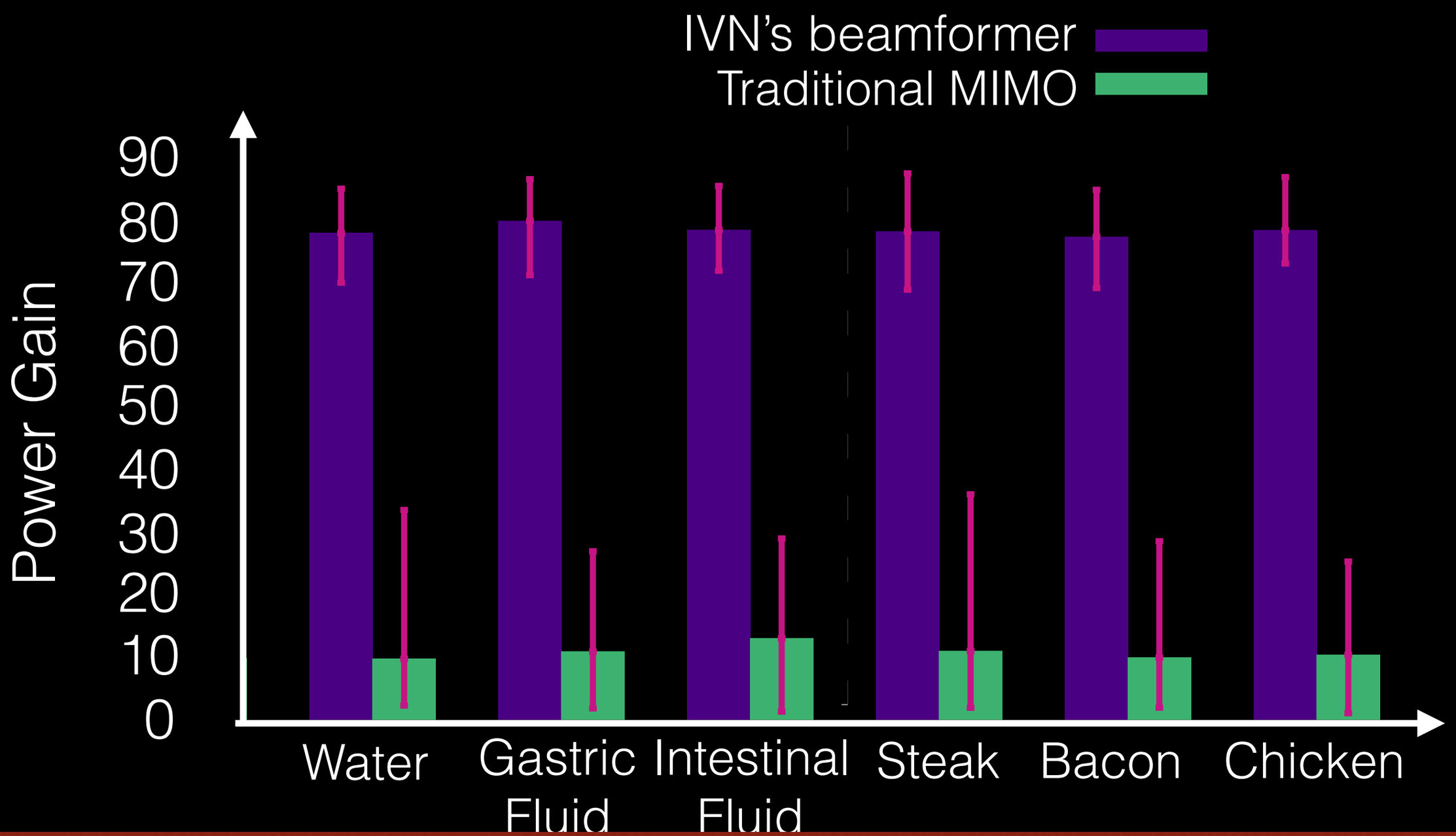

IVN can deliver MIMO gains under blind channel conditions to deep tissue battery-free sensors

In-Vivo Evaluation with Living Animal

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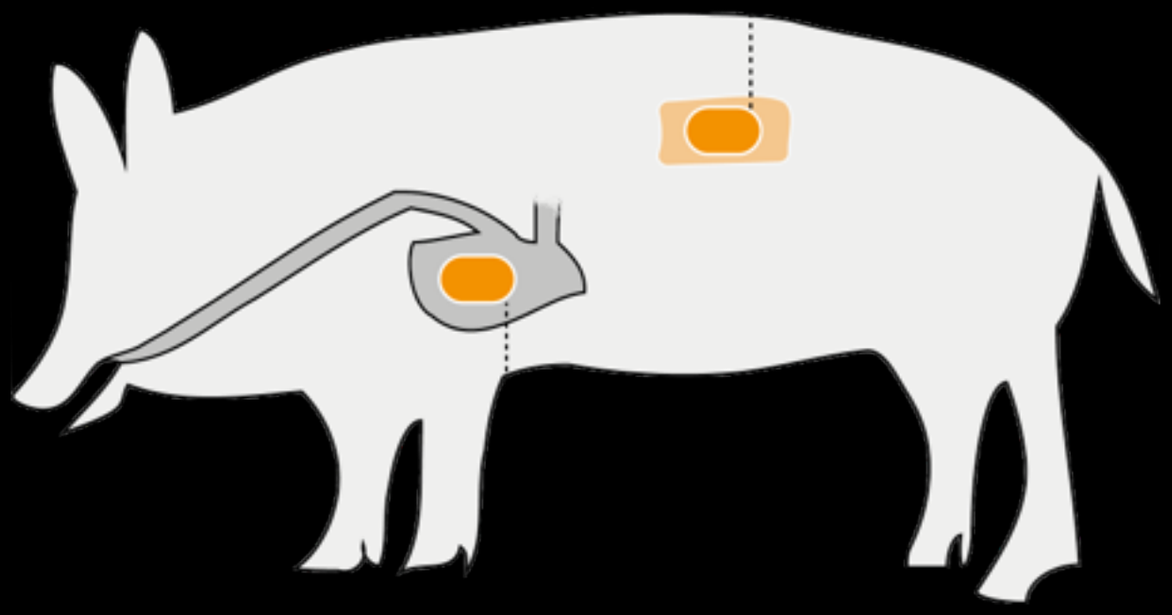

Female Yorkshire pig weighing 85Kg

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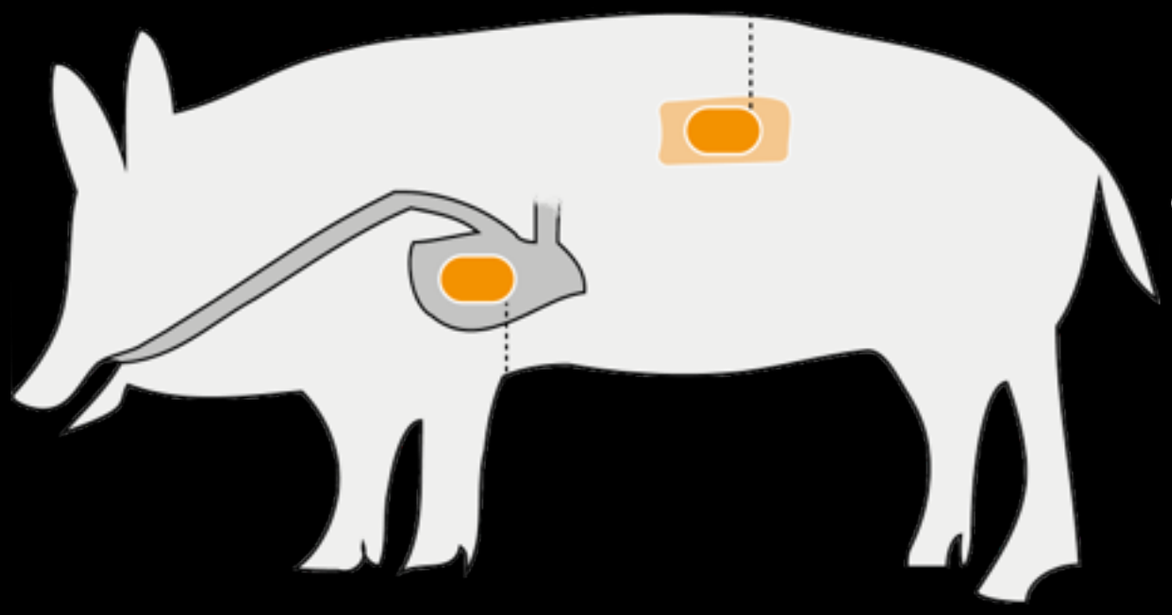

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- Sedation was performed by intramuscular injection of Telazol, xylazine, and atrophine

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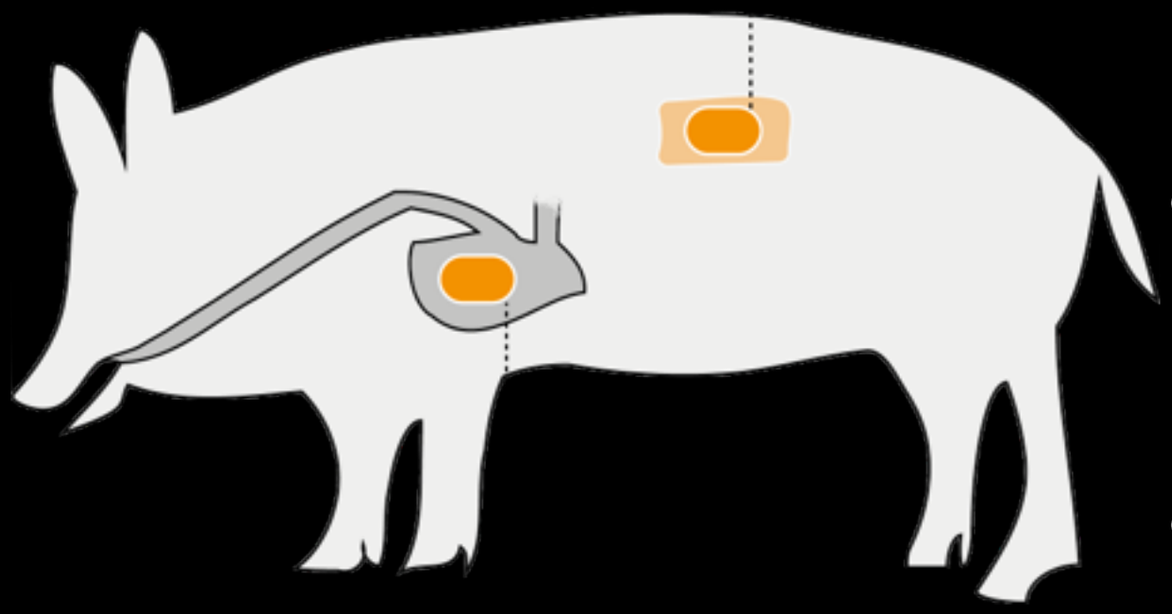

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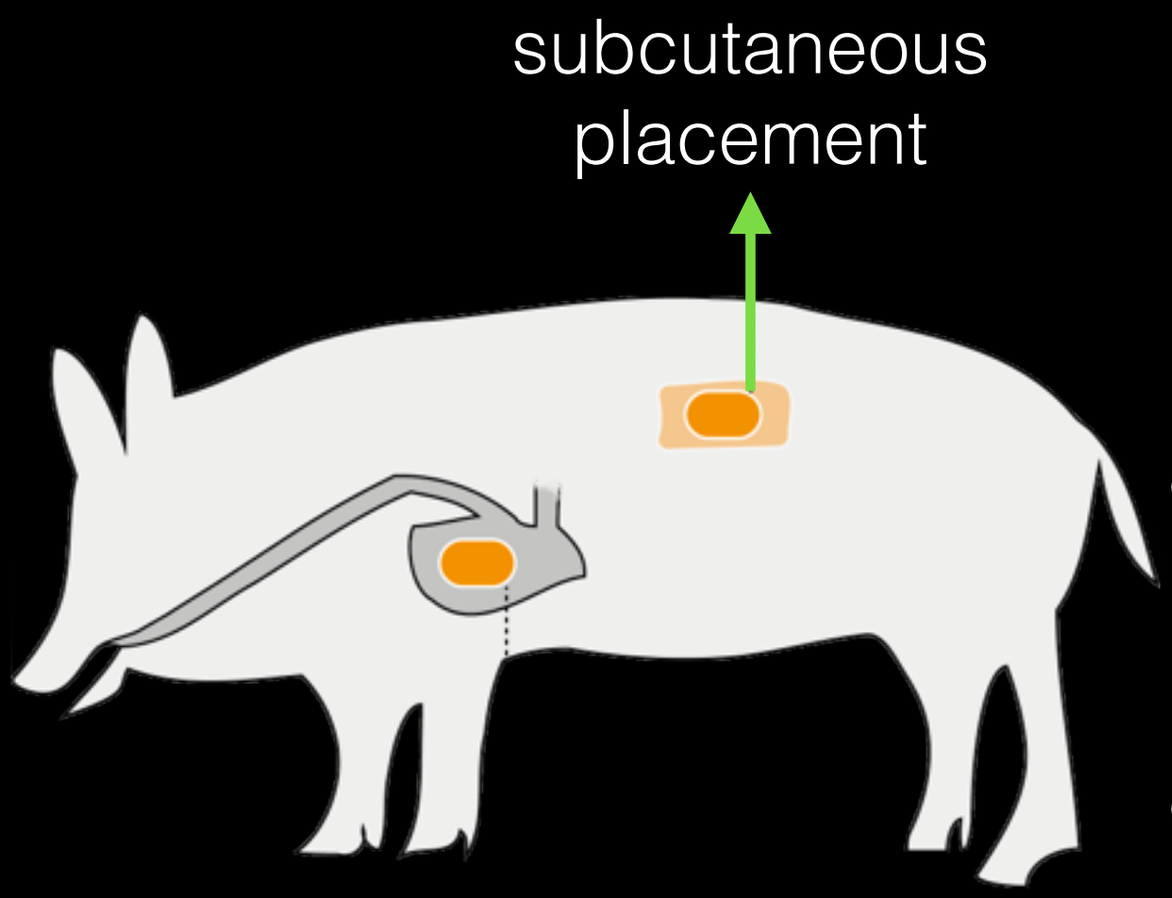

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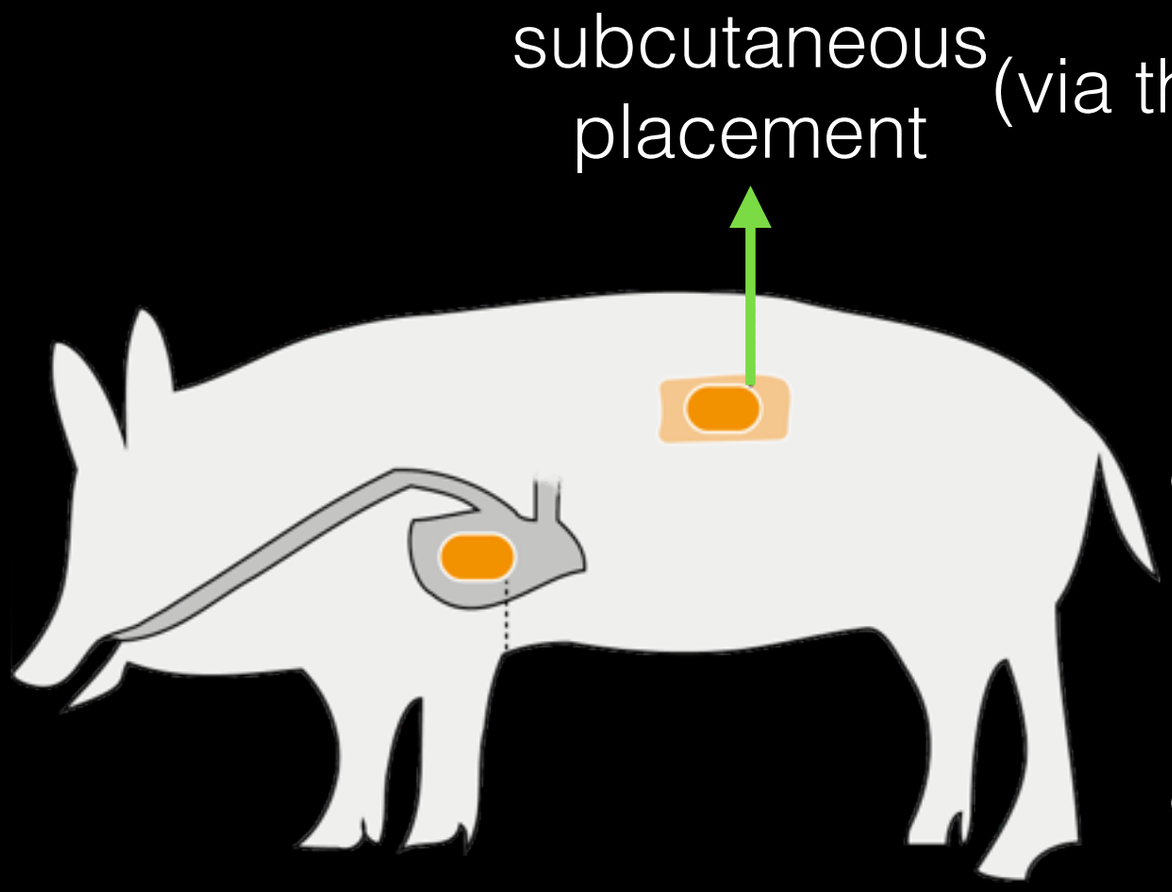

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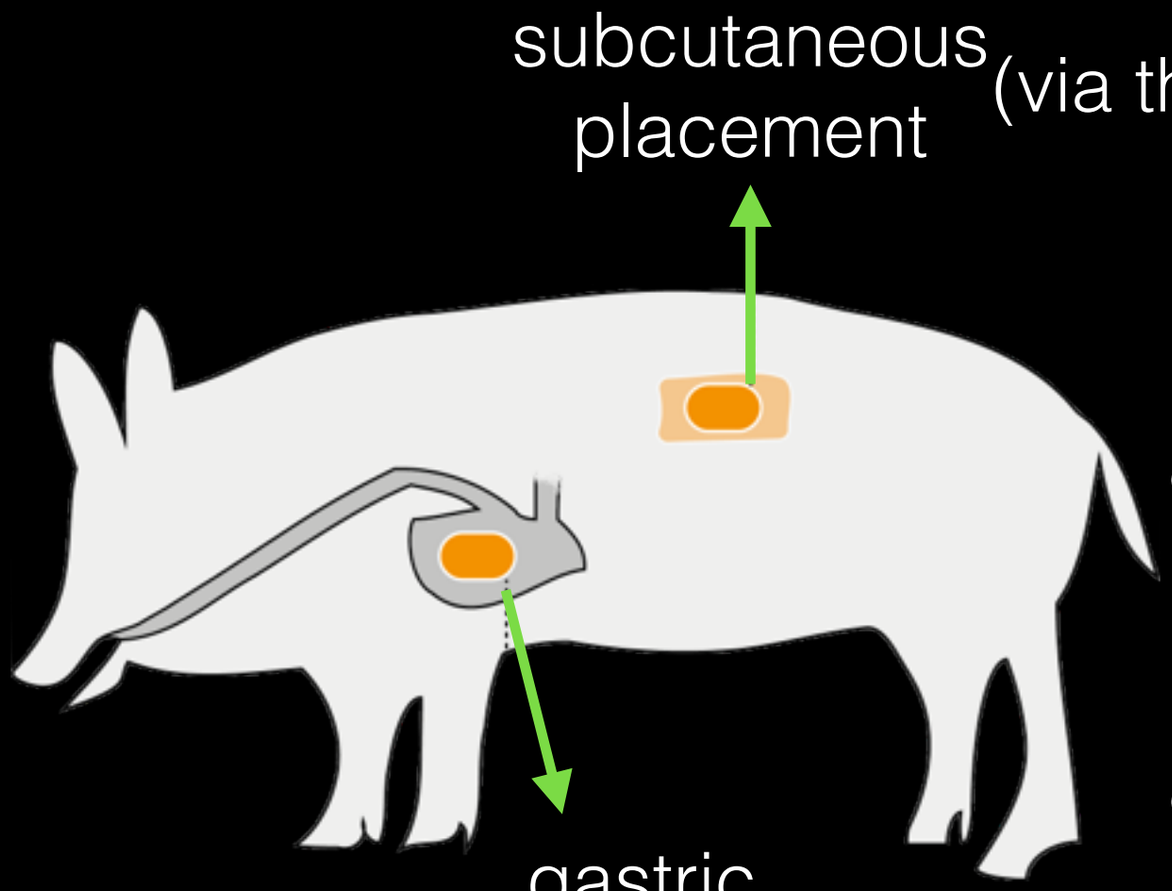

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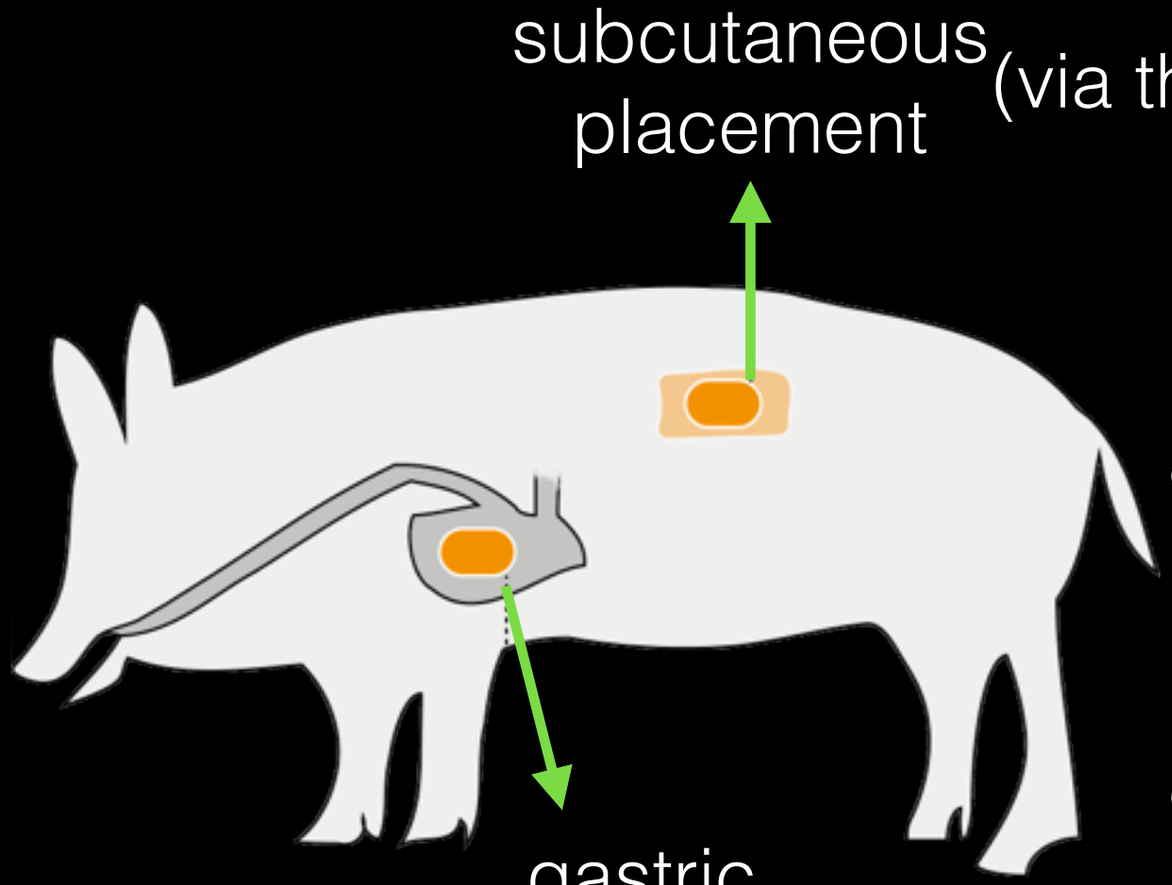
In-Vivo Evaluation with Living Animal

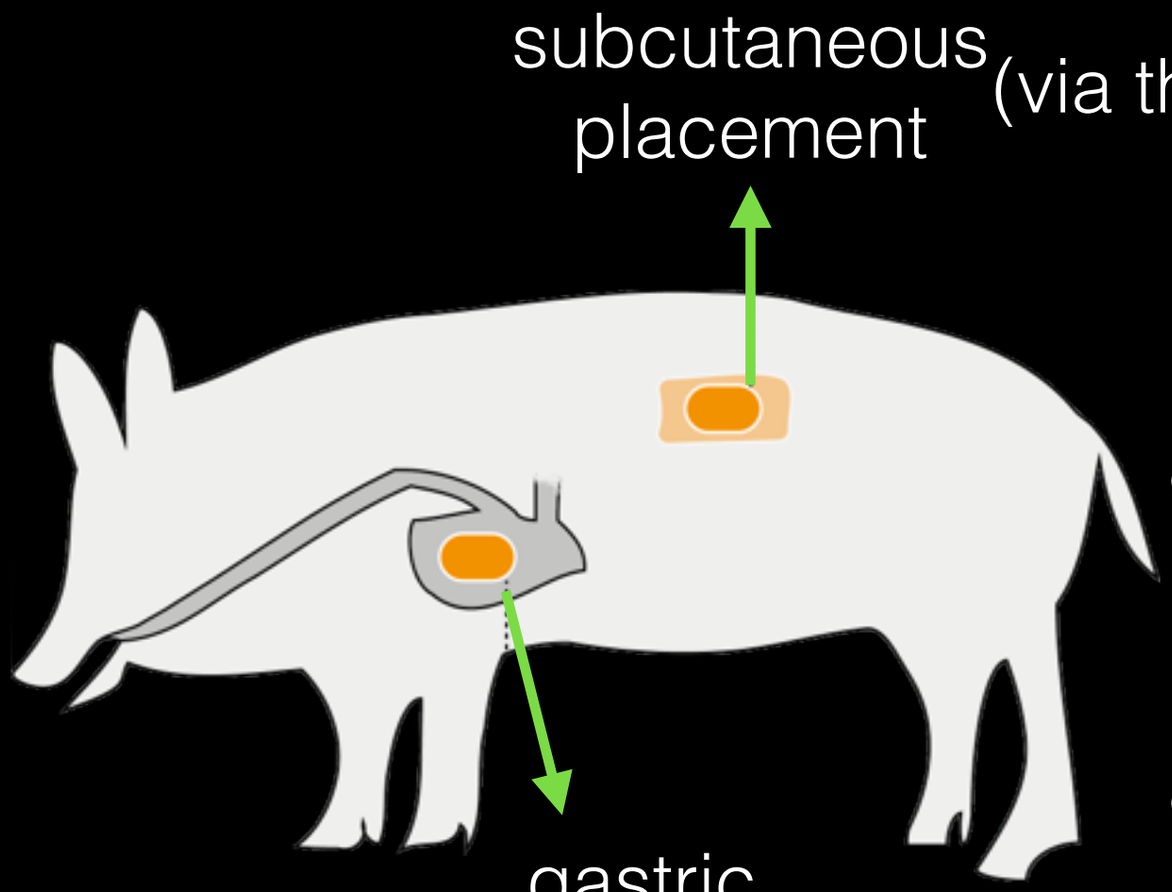


Female Yorkshire pig weighing 85Kg

- Sedation was performed by intramuscular injection of Telazol, xylazine, and atrophine
- Sensors tested in two placements

- Antennas placed laterally between 30 to 80cm from the animal's left side

In-Vivo Evaluation with Living Animal



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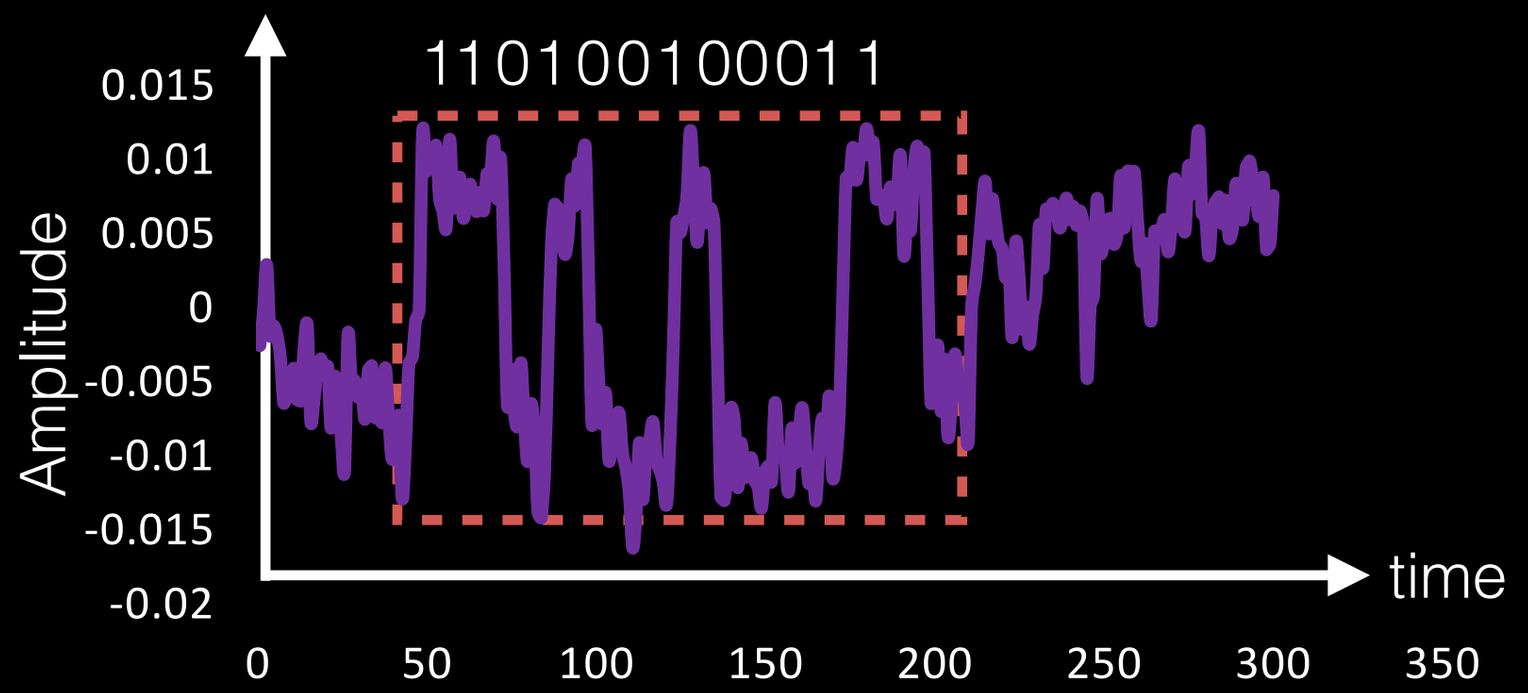
- Experiment carried at MIT's animal facility and approved by MIT's committee on animal care

In-Vivo Evaluation with Living Animal

<u>Experiment:</u> Send command to a deep-tissue sensor and measure its response to IVN

sensor placed in stomach



Results demonstrate IVN ability to wirelessly power and communicate with battery-free sensors in deep tissues inside living animals

Conclusion

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- We introduce IVN to allow in-body networking of miniature medical devices.
- Our results show promising applications in quality control, robotic automation, drug delivery, bio-sensing & bio-stimulation.