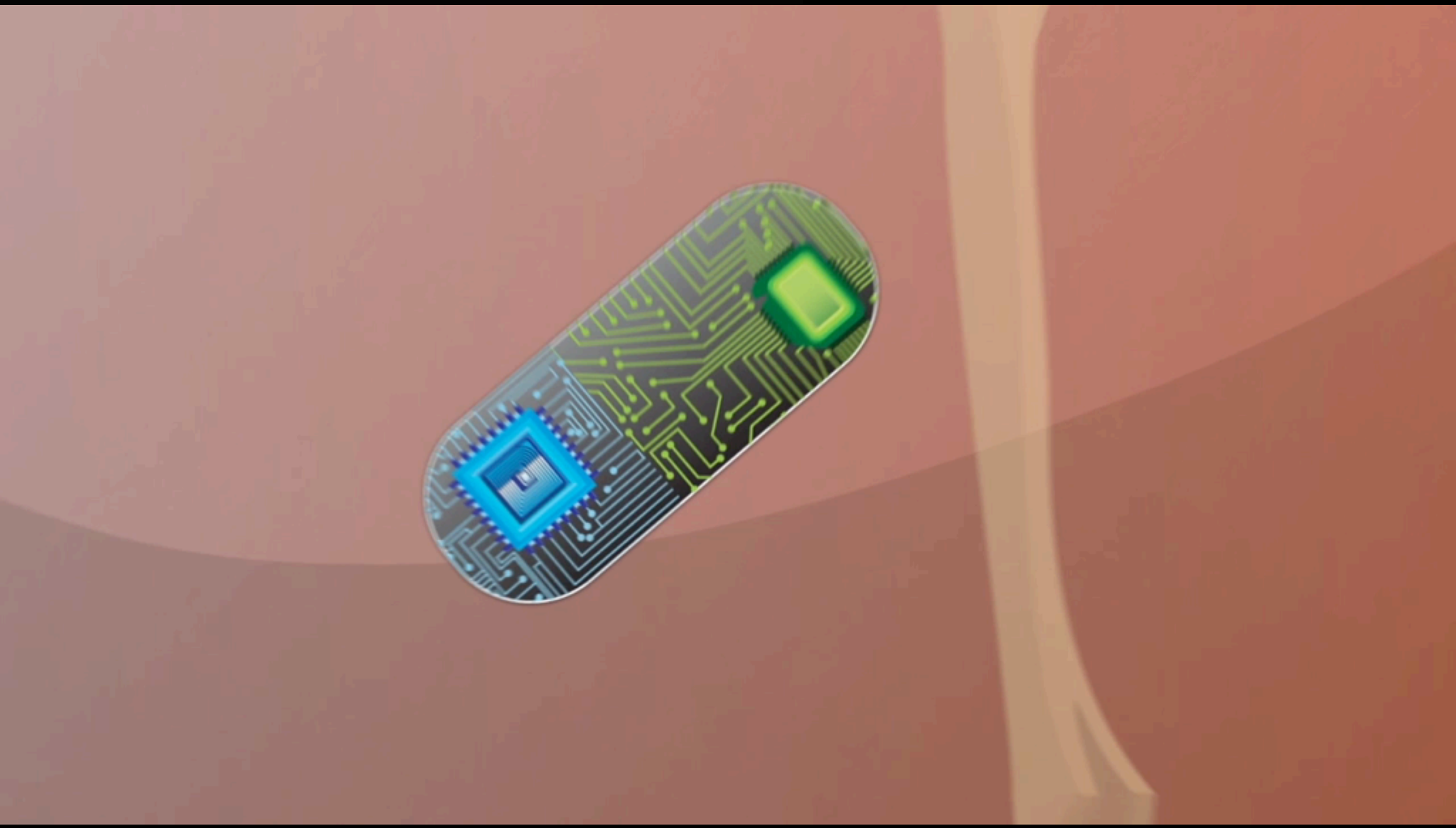
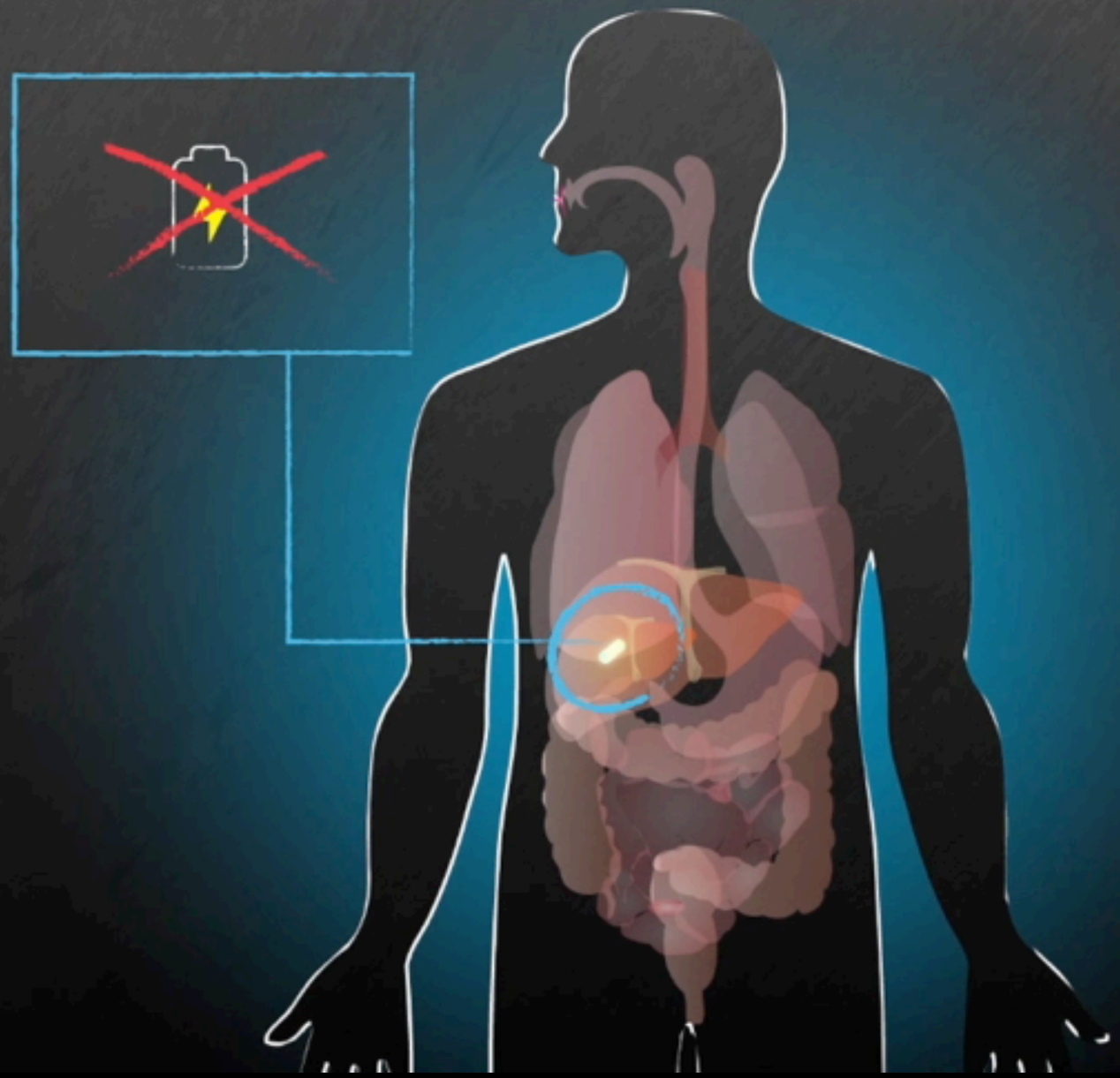
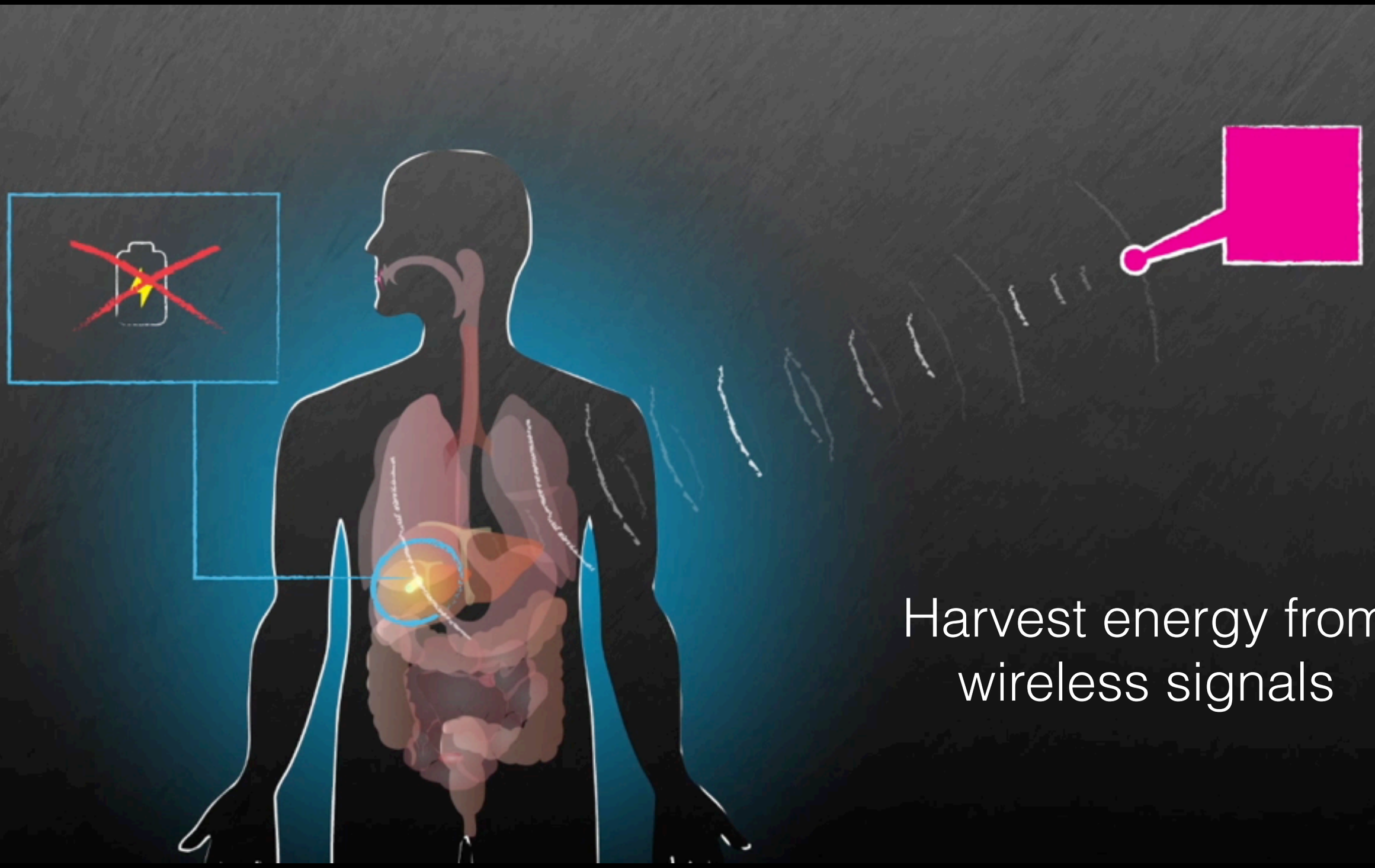
Enabling Deep-Tissue Networking for Miniature Medical Devices

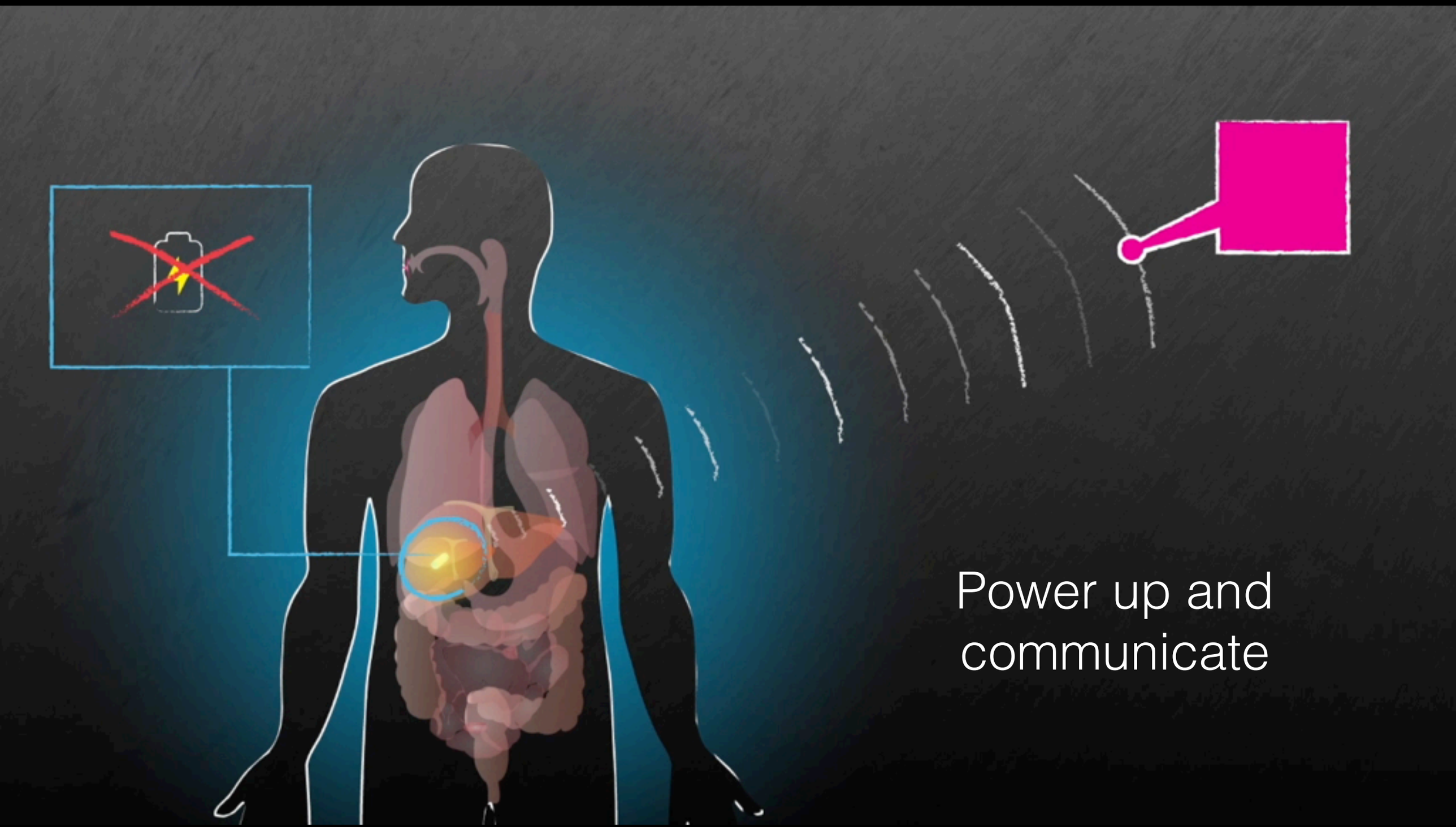
Yunfei Ma
Zhihong Luo, Christoph Steiger, Giovanni Traverso
and Fadel Adib







Harvest energy from
wireless signals


Power up and
communicate

Key Challenge:

Wireless signals die exponentially in the human body

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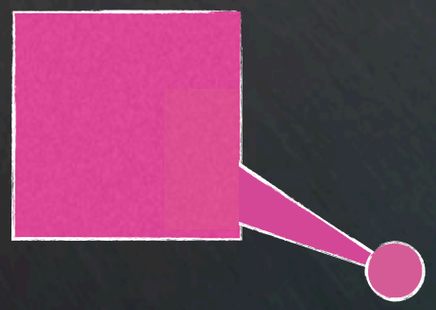
Wireless signals die exponentially in the human body

Signals decay more than 1000x faster inside the body than in air



Cannot power up battery-less sensor in deep tissues

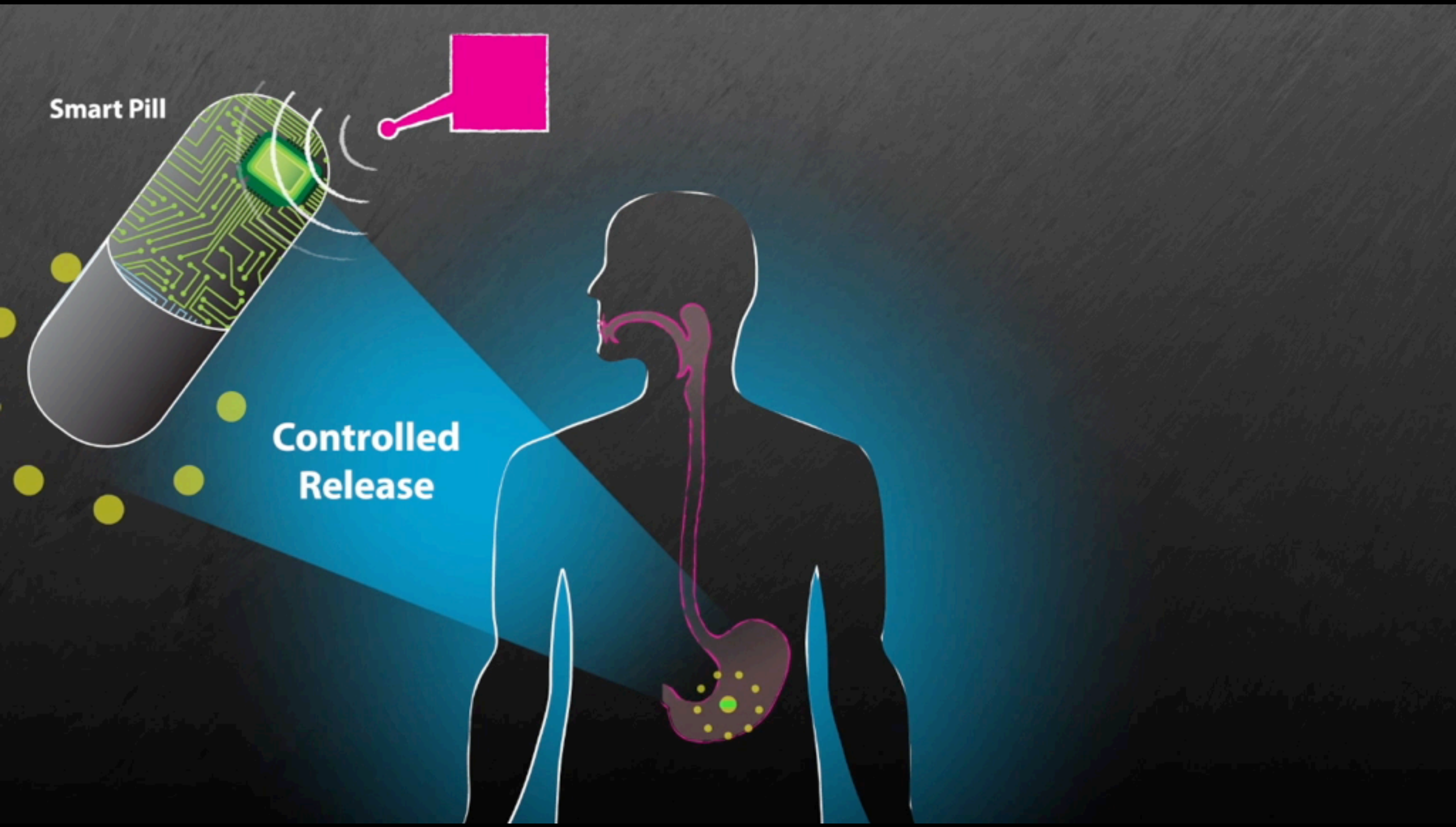
In-Vivo Networking (IVN)

- System that enables networking with deep-tissue battery-free medical sensors from a distance.

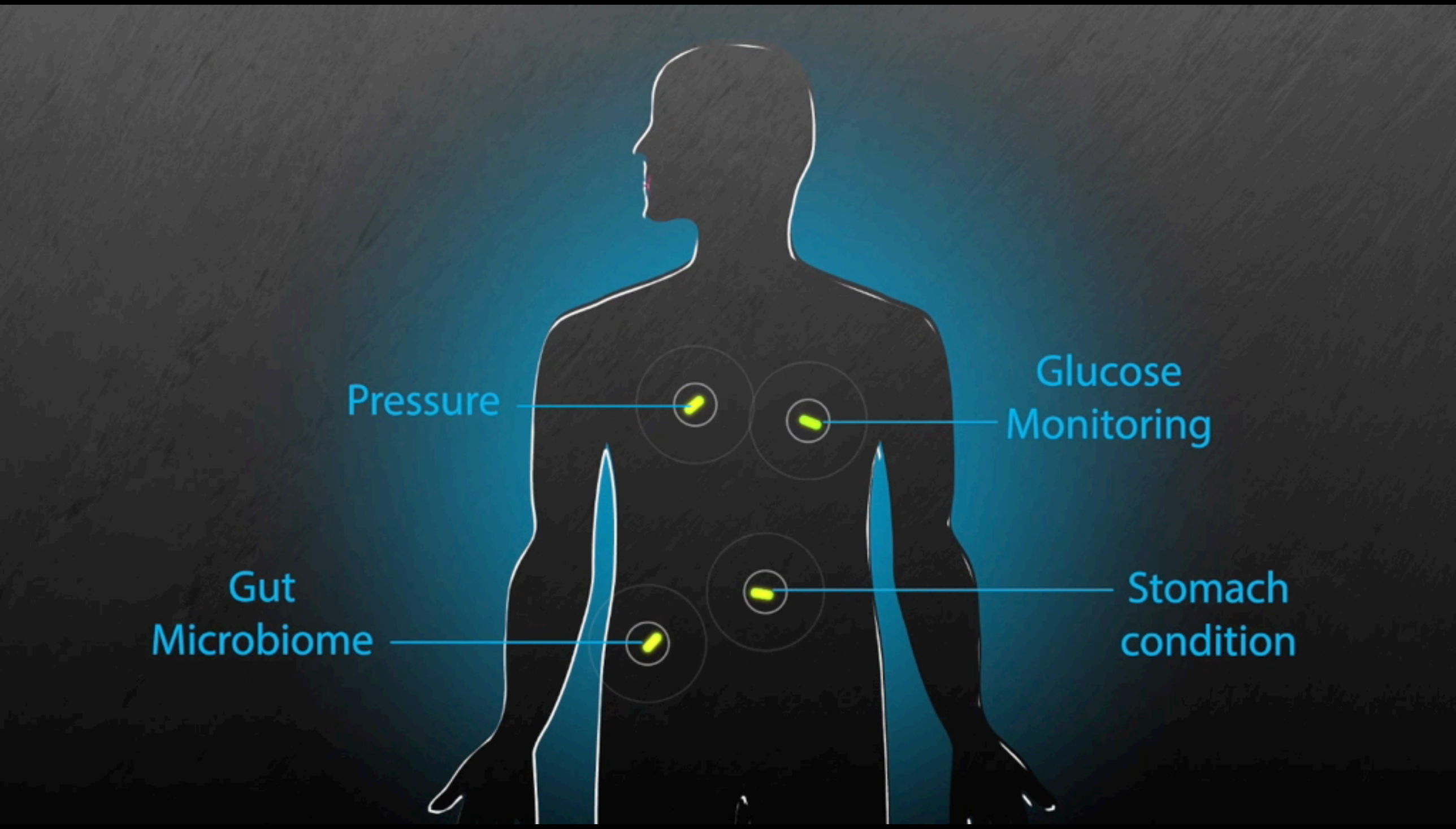
- Introduce a new technology that can power and communicate in deep tissues and deal with anatomical constraints like tissue losses.

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

Continuous and Long-Term Drug Delivery



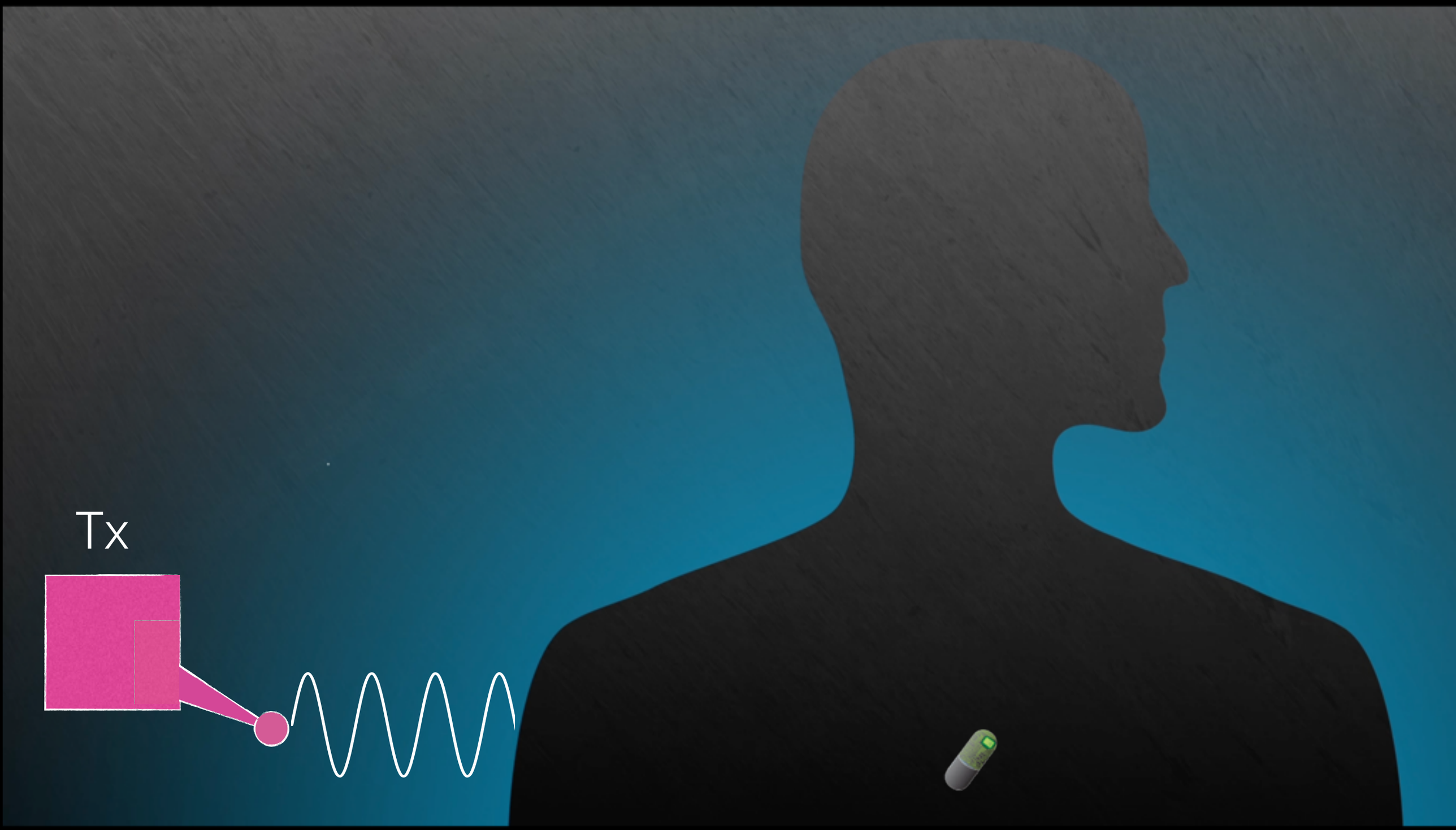
In-body Sensing and Diagnosis



Deep brain sensing and stimulation

Key Challenge:

Wireless signals die exponentially in the human body



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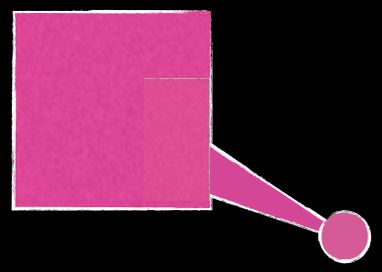

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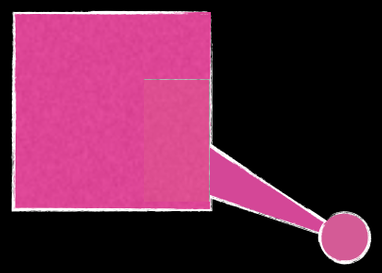
Because of non-linear electronics (e.g., diodes, transistors), a battery-free sensor needs a minimum energy to power up



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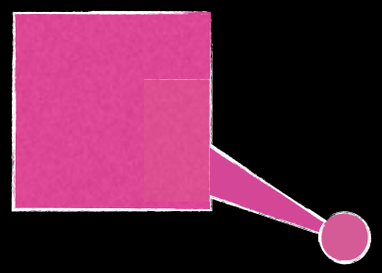

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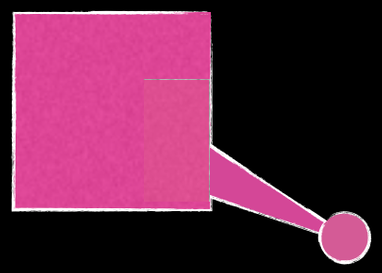

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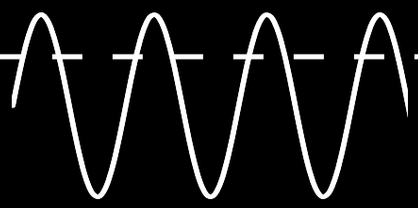

In air

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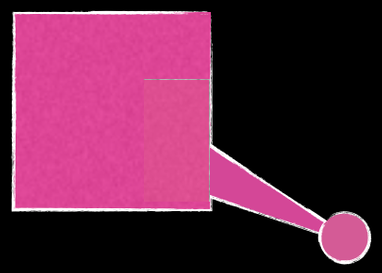

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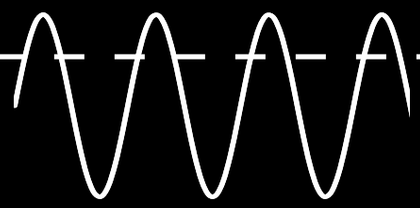

In air

instantaneous energy above threshold => powers up

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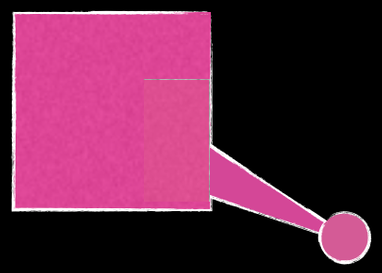

Energy threshold

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In the body

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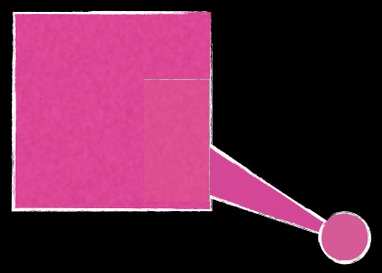

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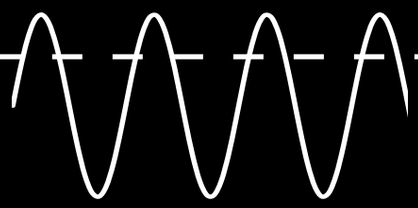


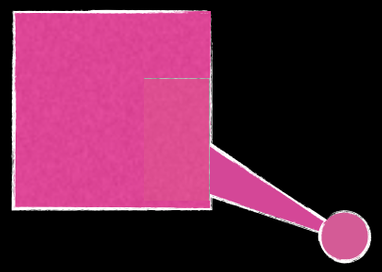
In air

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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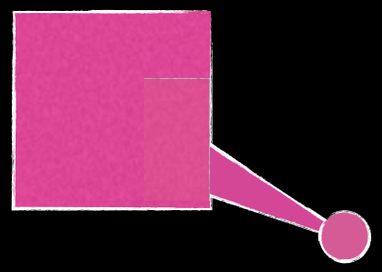

TX power is limited by FCC regulations and device properties

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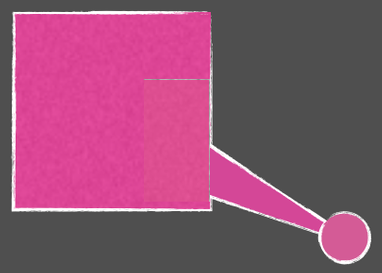

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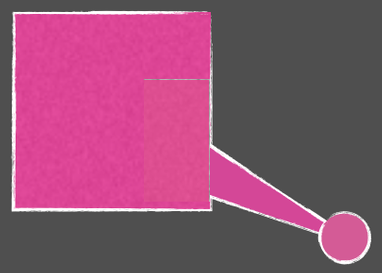
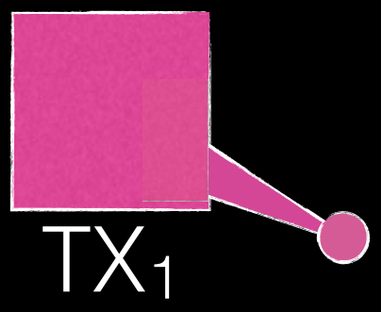


TX power is limited by FCC regulations and device properties

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

Standard Solution: Use Multiple Antennas (MIMO)



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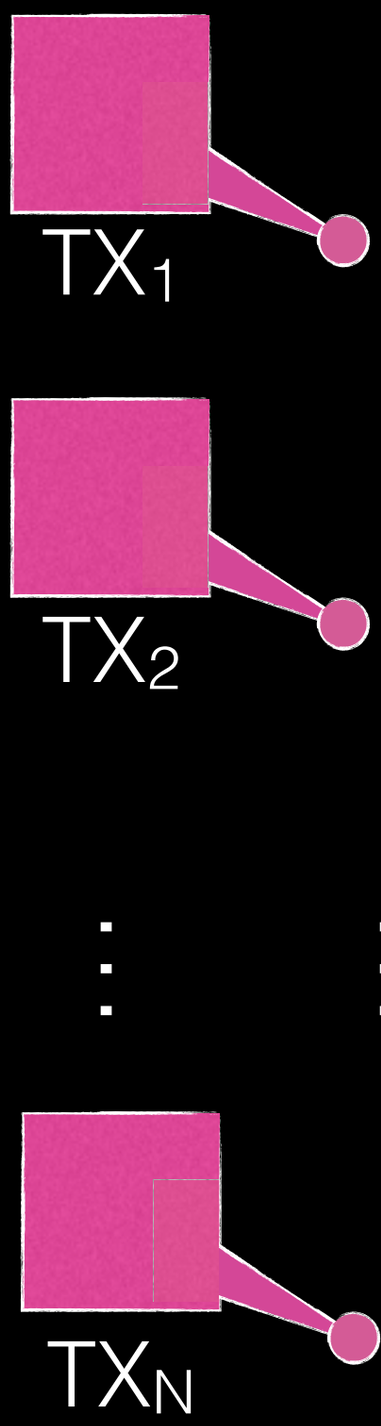

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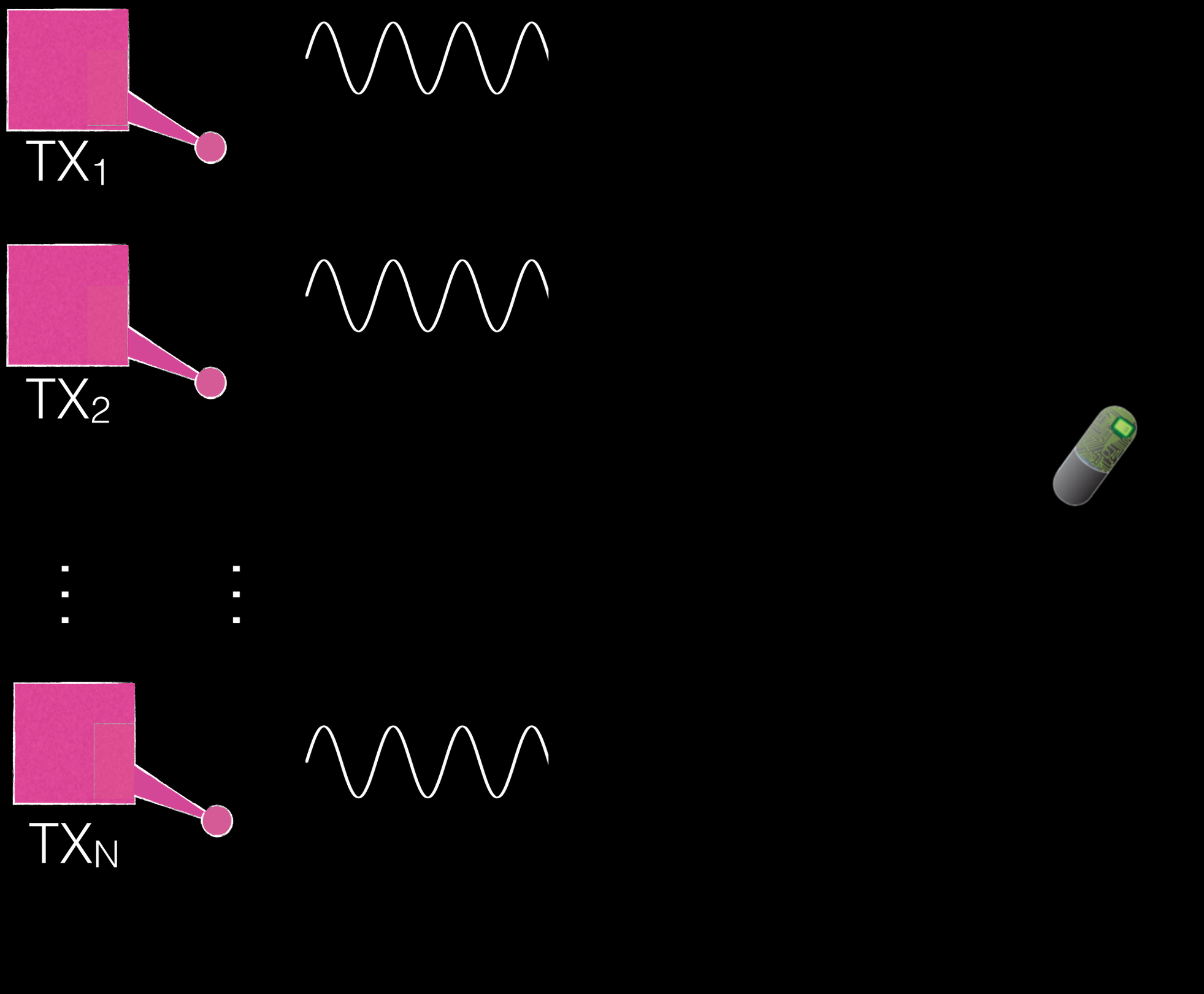

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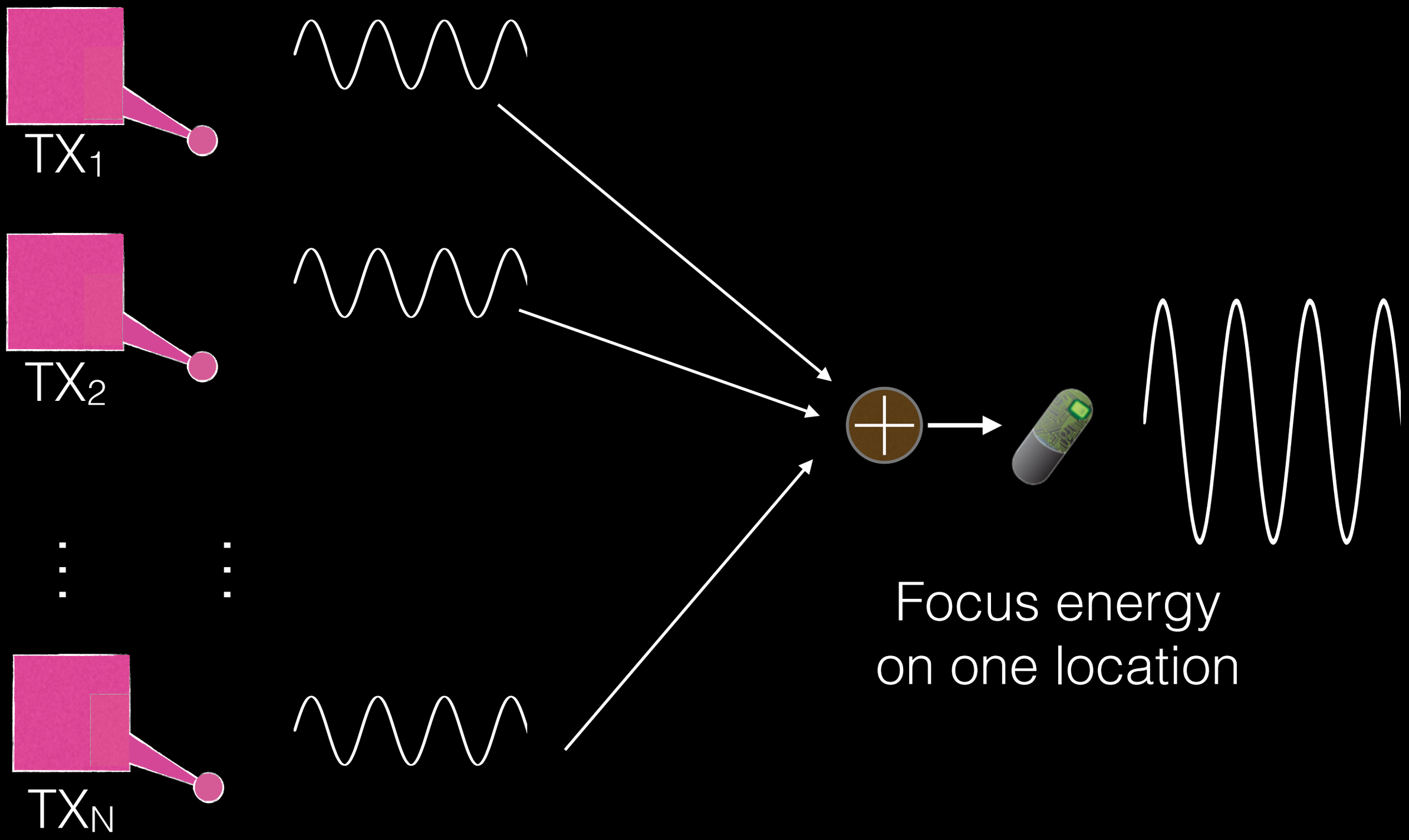

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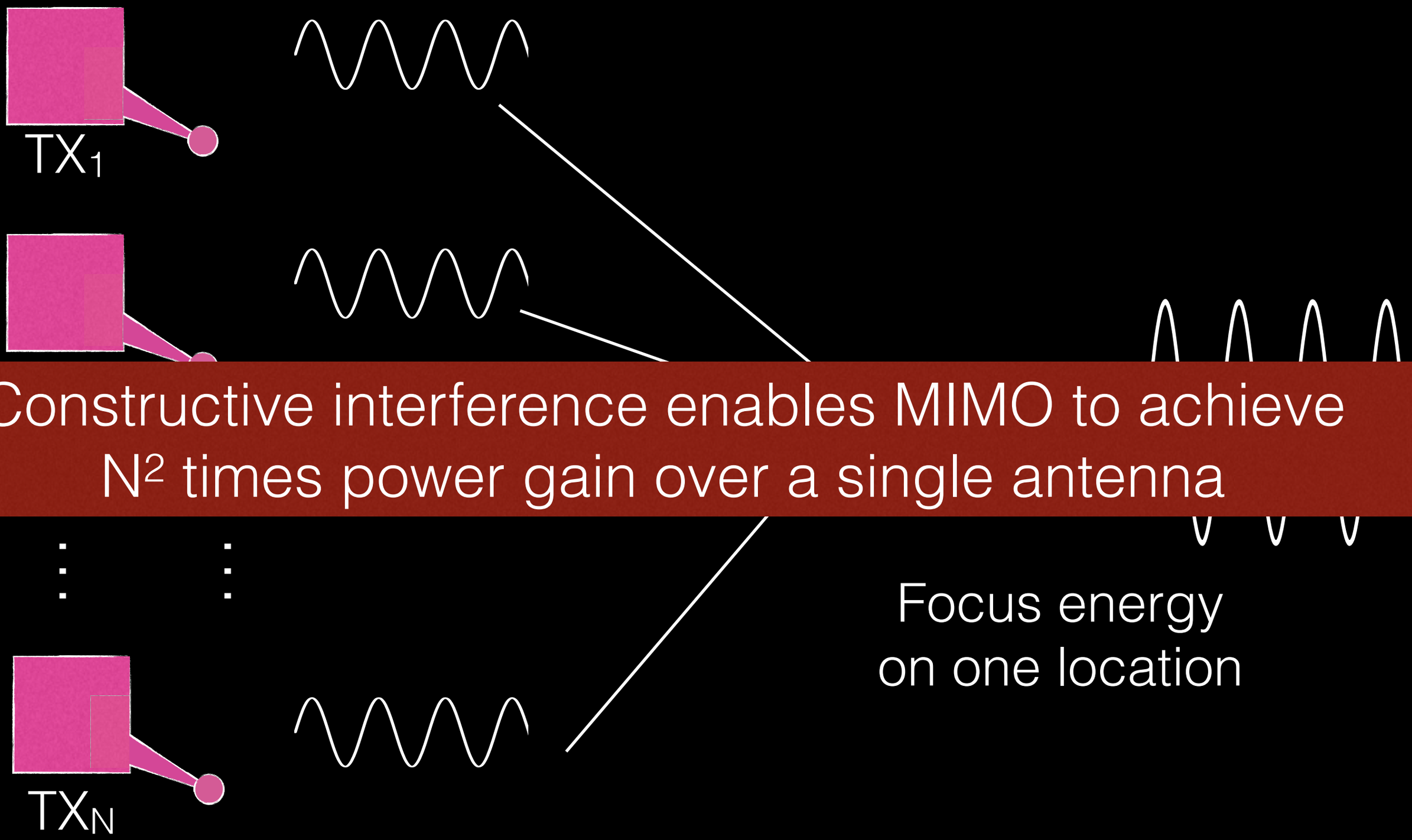

Constructive interference enables MIMO to achieve N^2 times power gain over a single antenna

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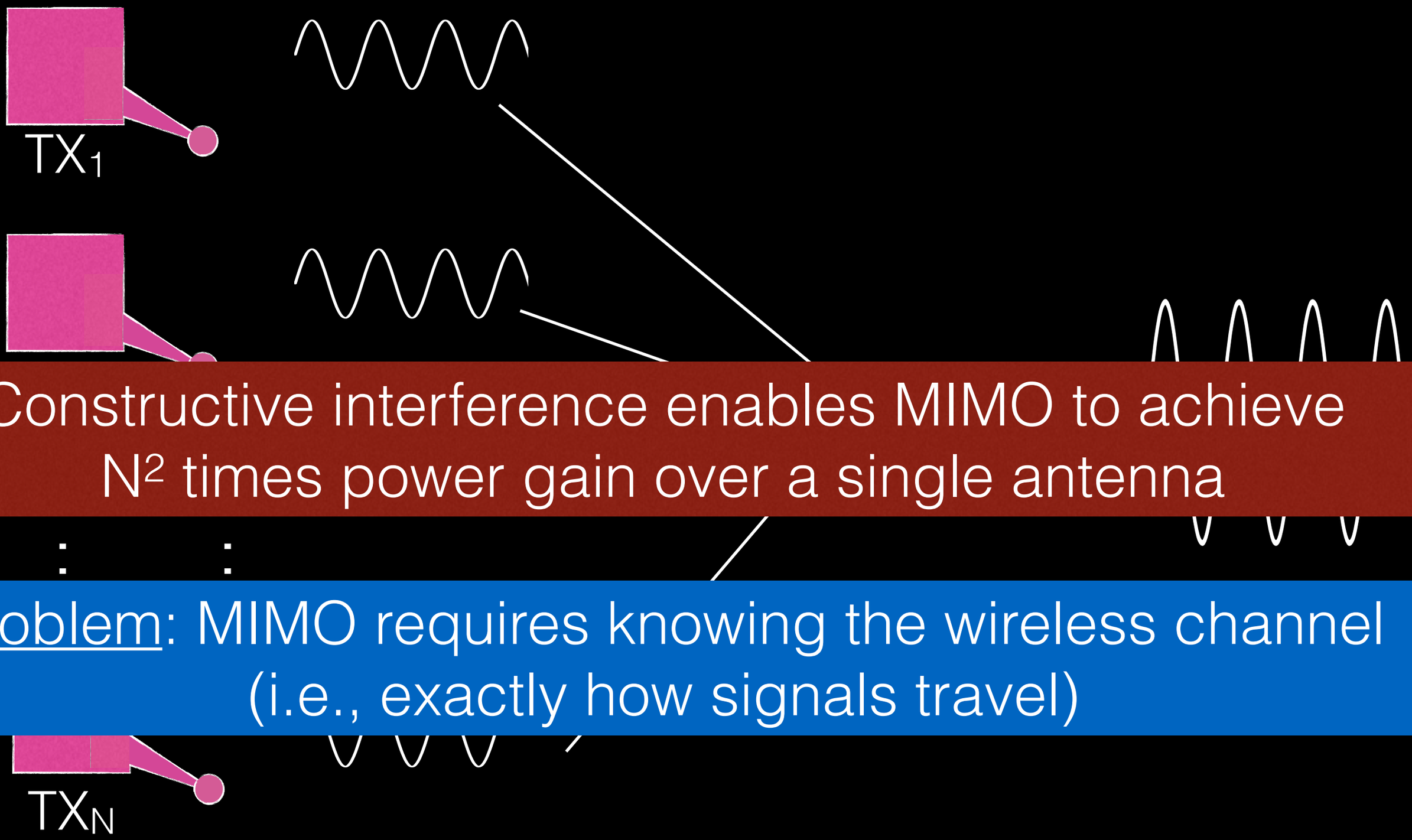
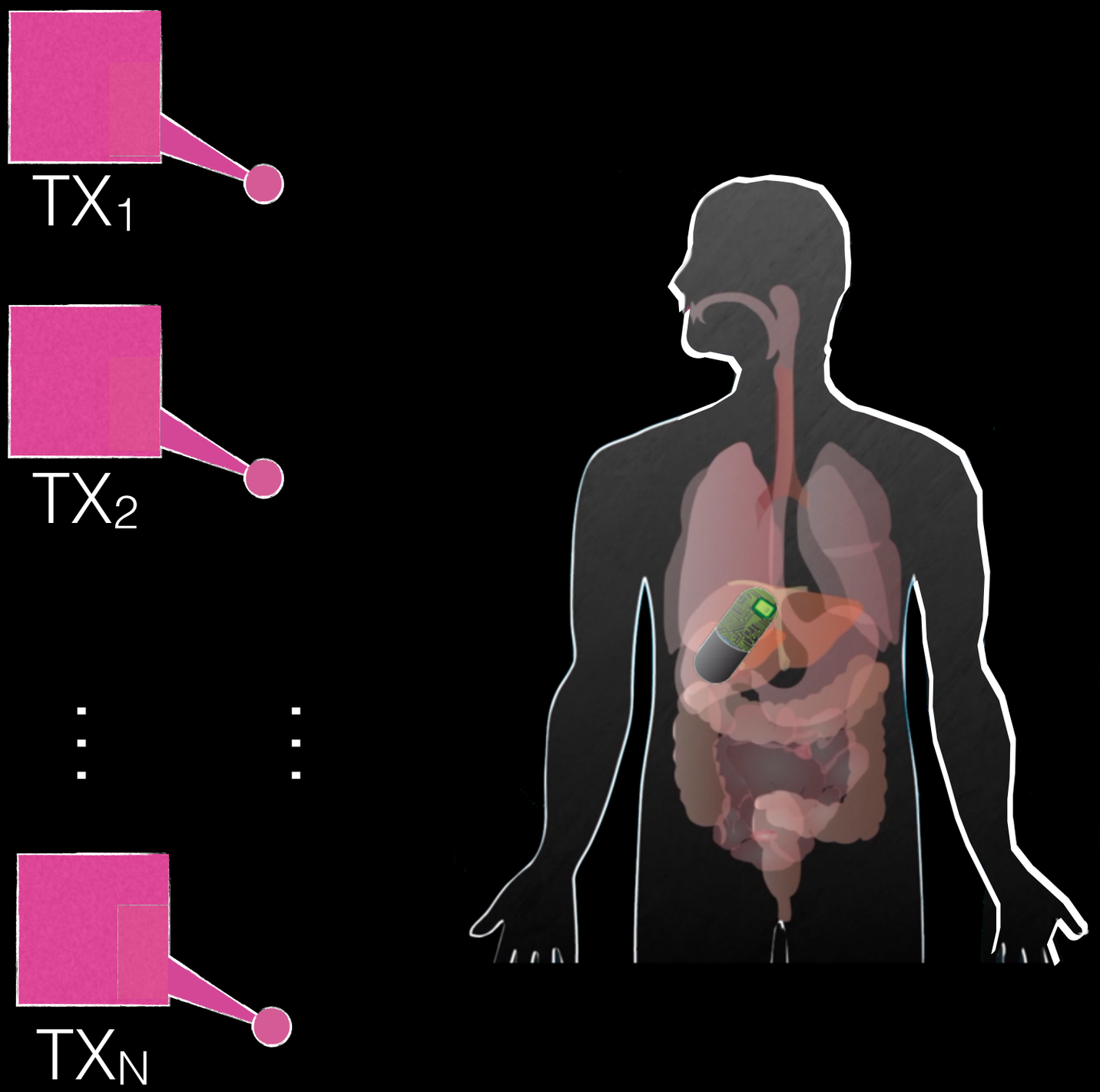


Constructive interference enables MIMO to achieve N^2 times power gain over a single antenna

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

Wireless channel is intractable inside human body



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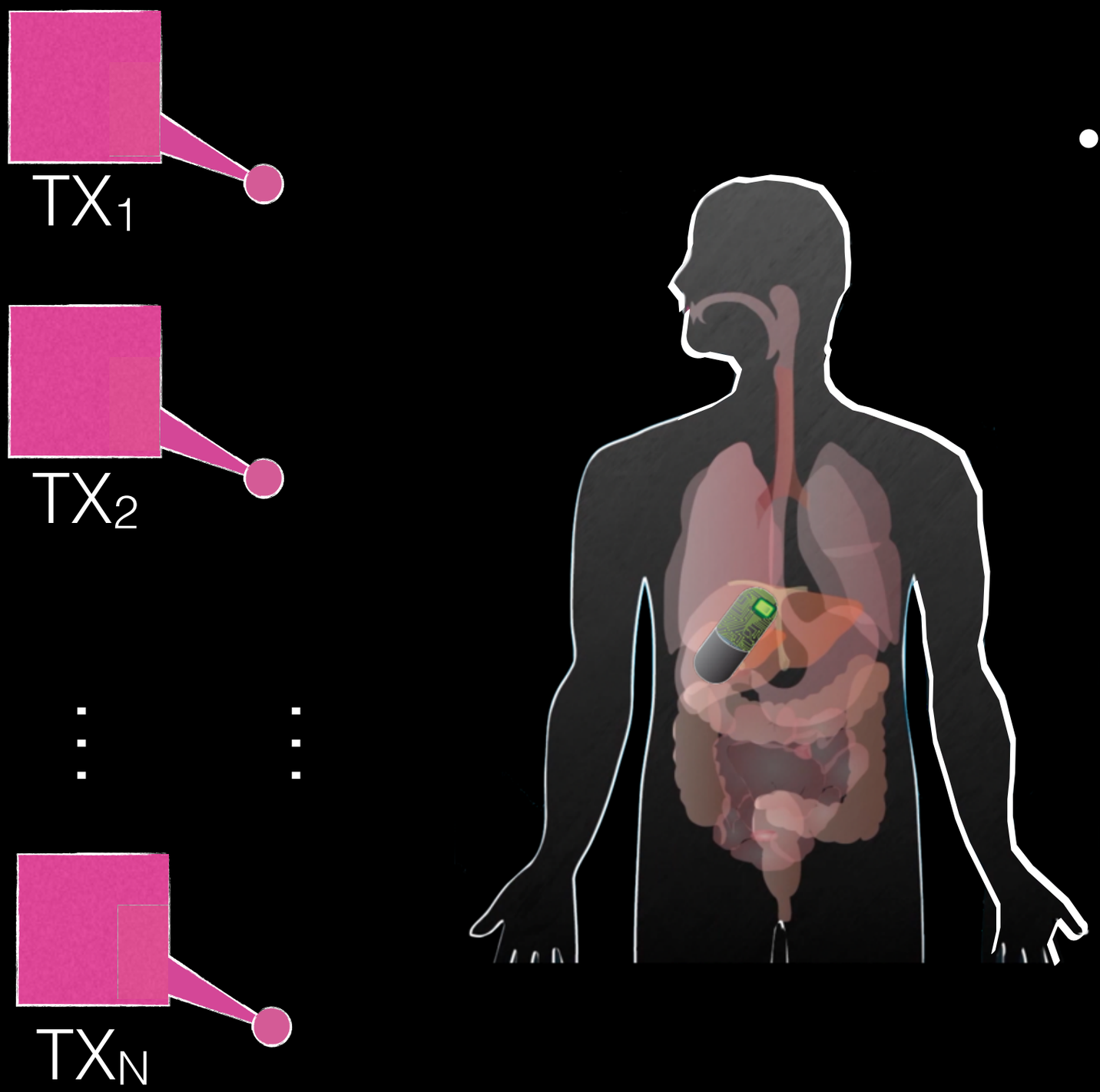

- Signals travel at different speeds in different tissues

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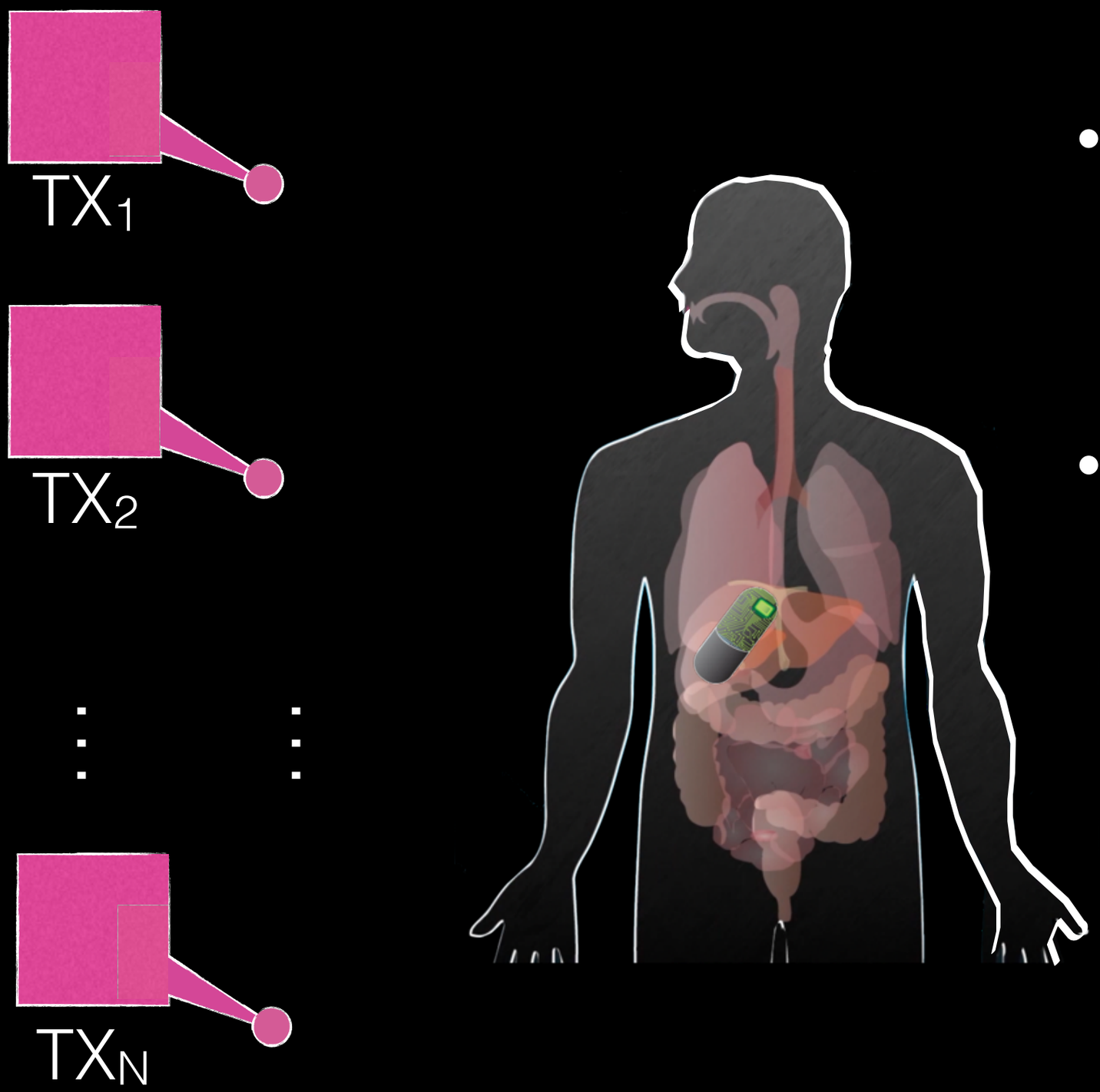

- Signals travel at different speeds in different tissues
- Signals reflect off organs, change angles, undergo diffraction.

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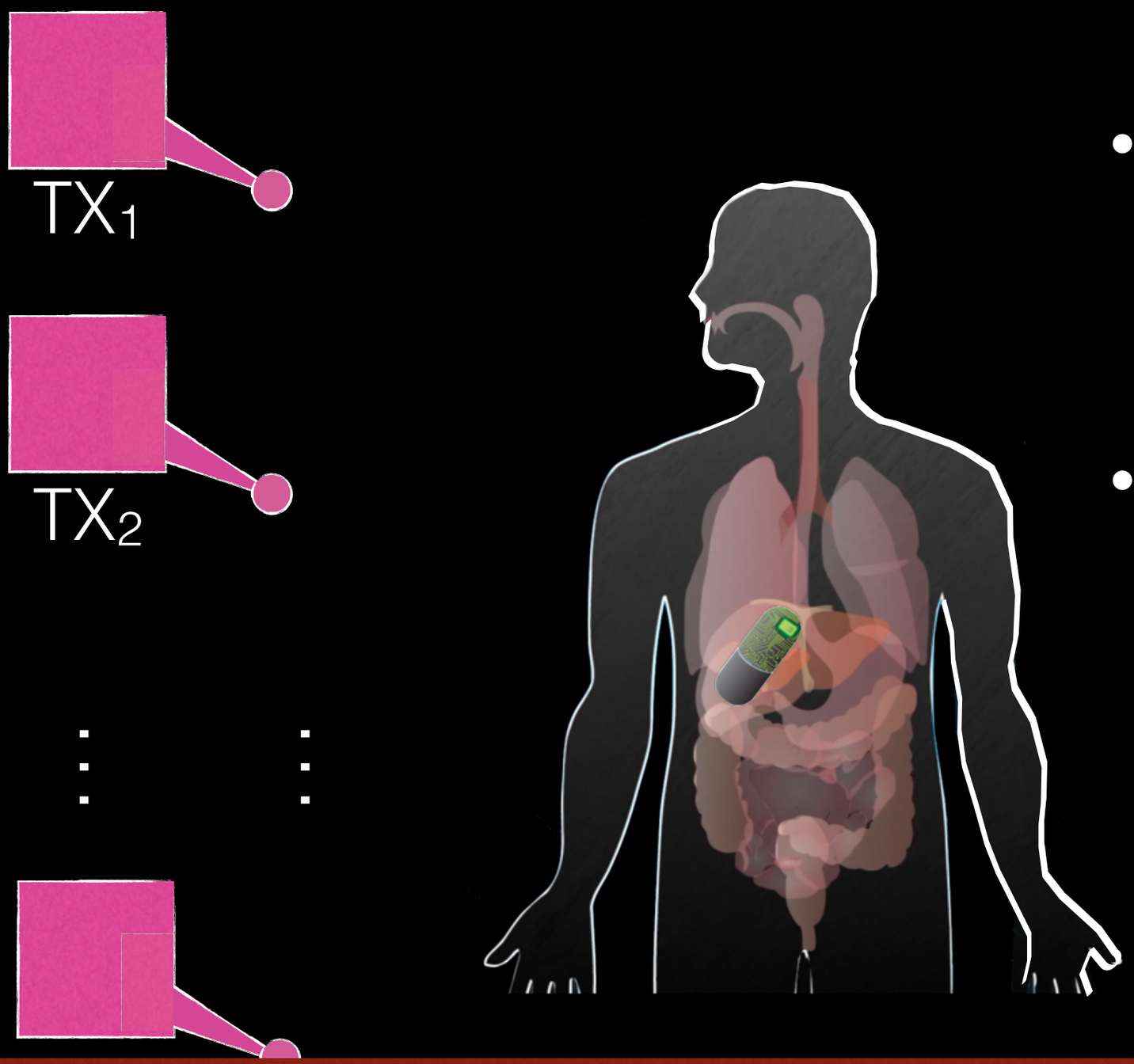

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- Signals reflect off organs, change angles, undergo diffraction.

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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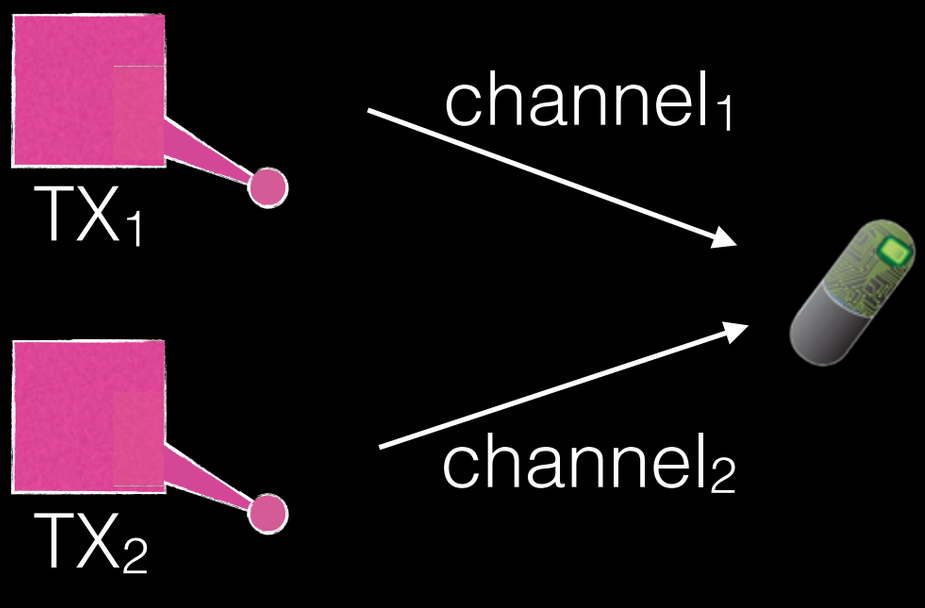
Solution: IVN introduces beamforming technology that can work under blind wireless channels

Traditional MIMO

IVN beamforming

Traditional MIMO



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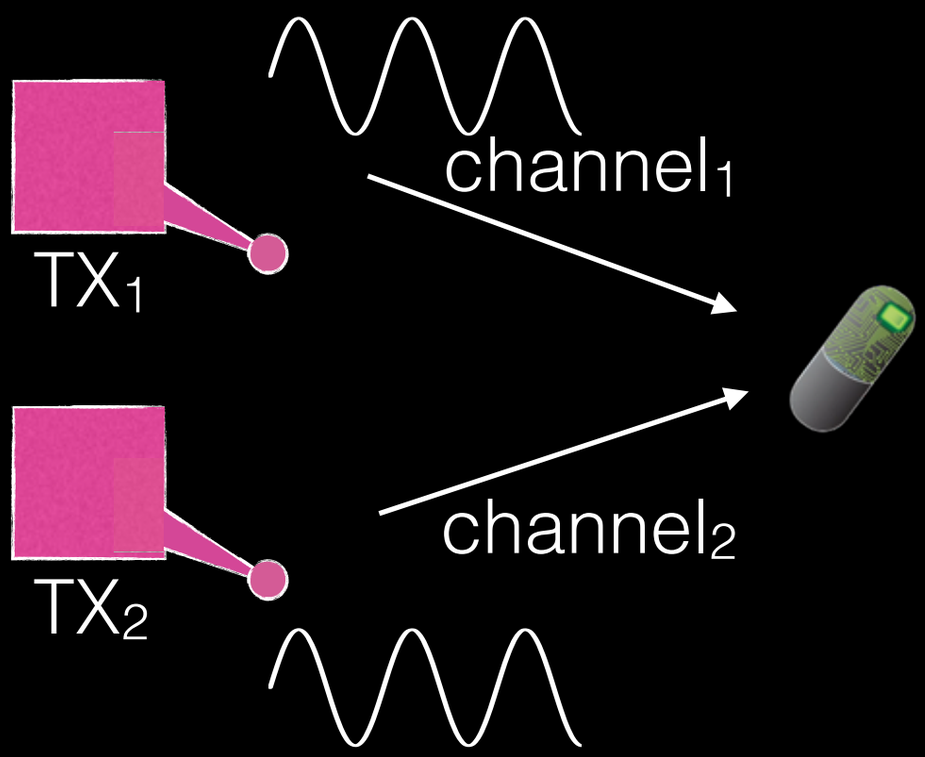

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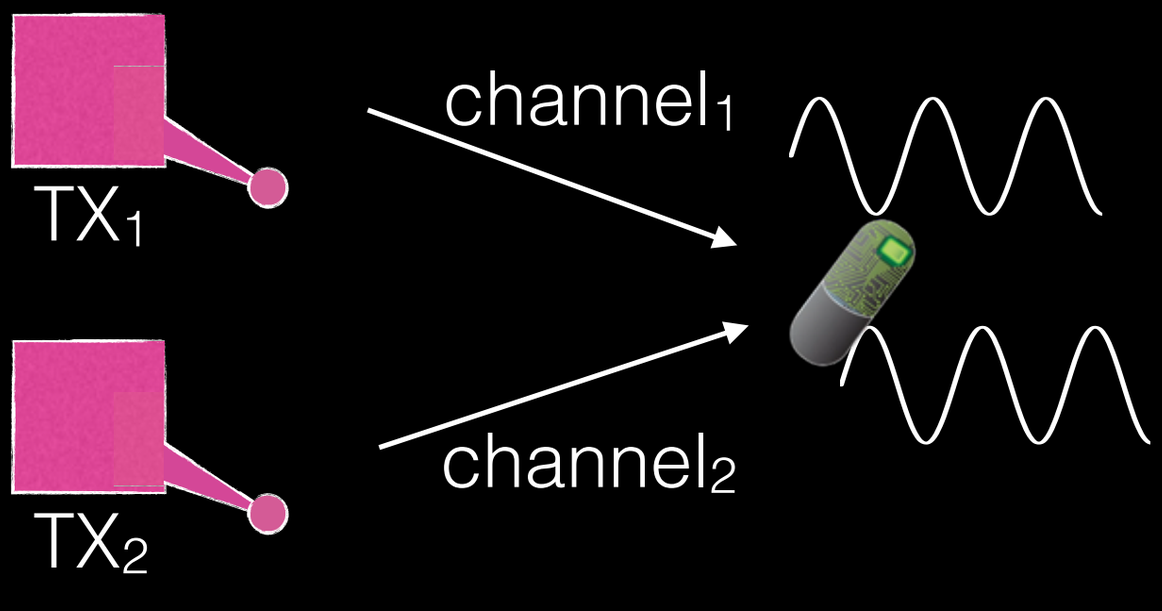

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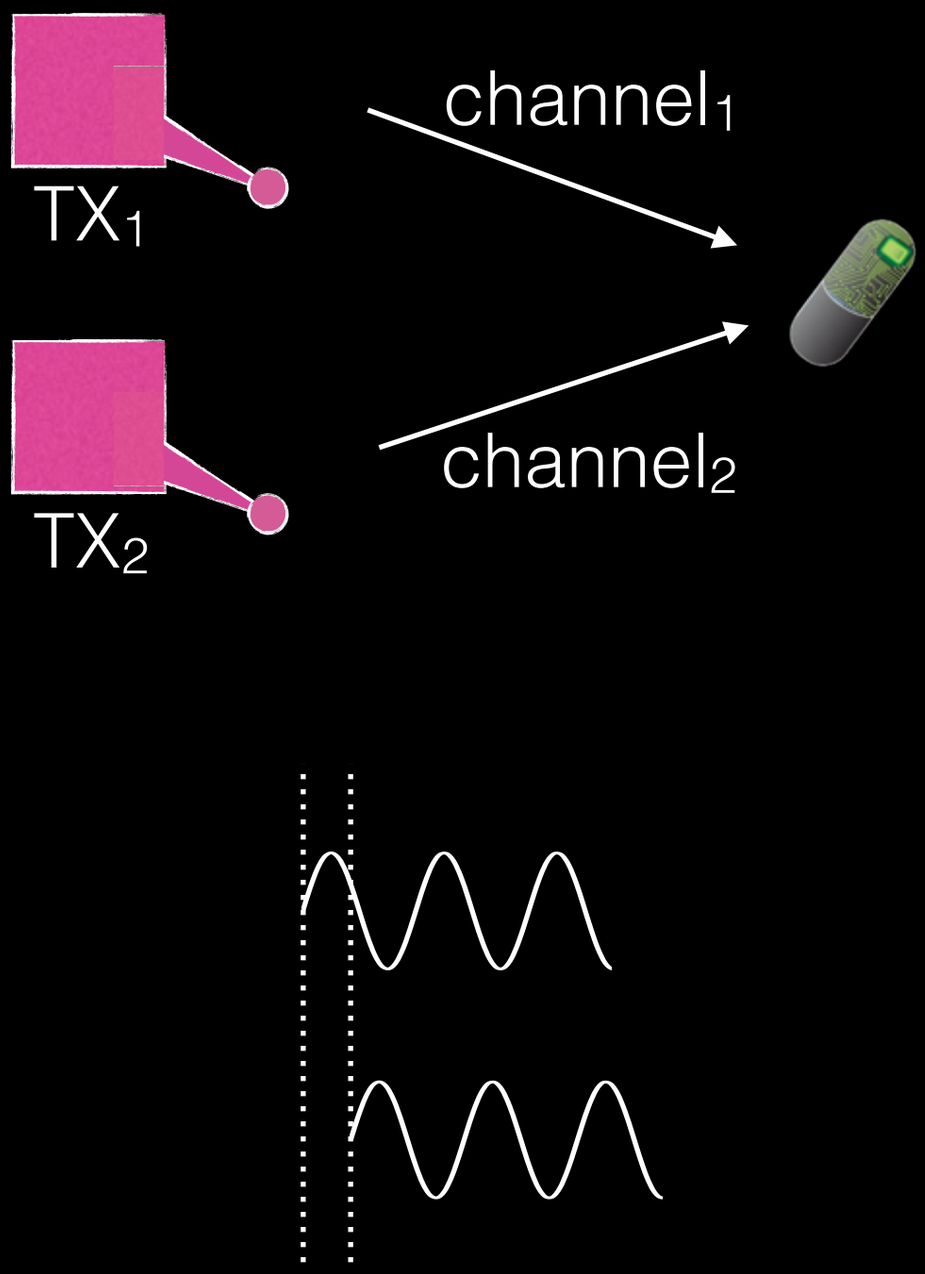

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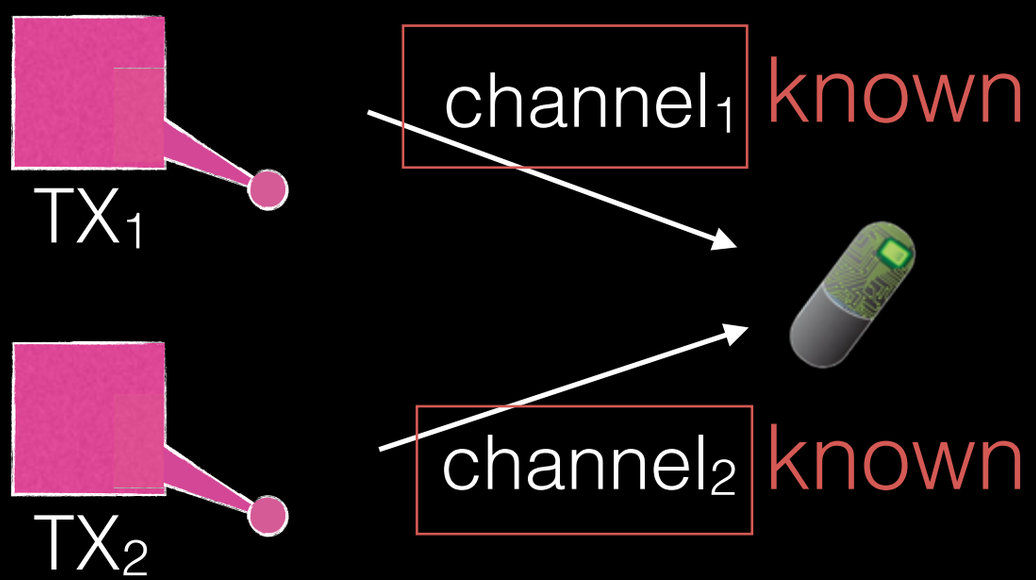

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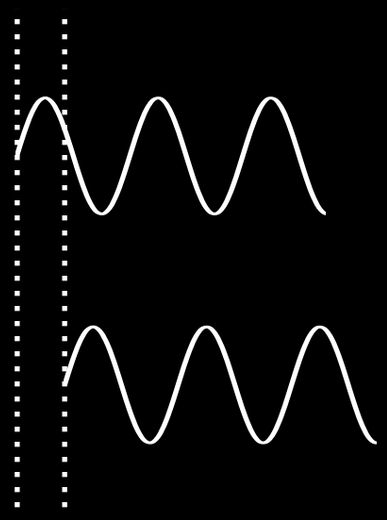

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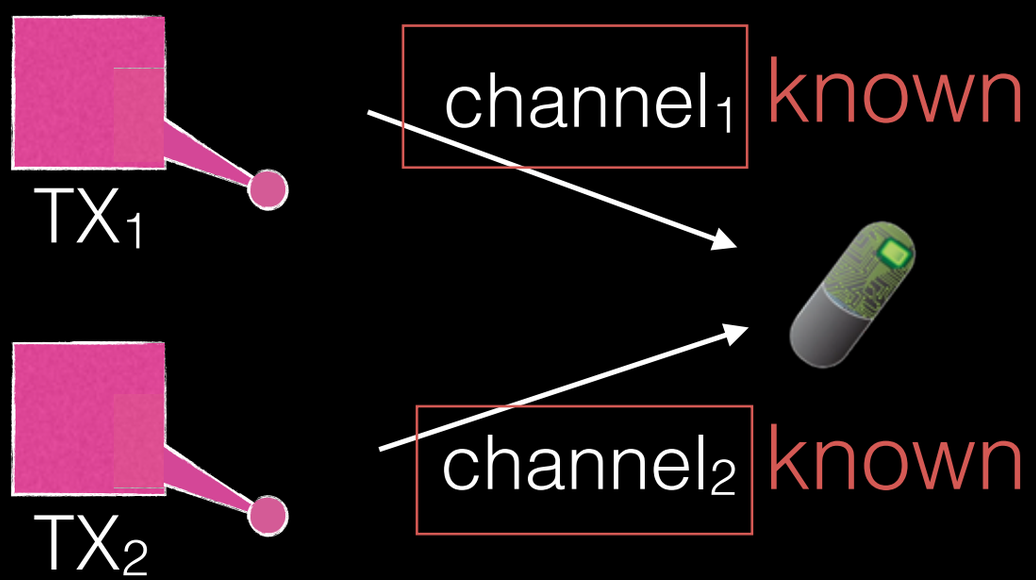

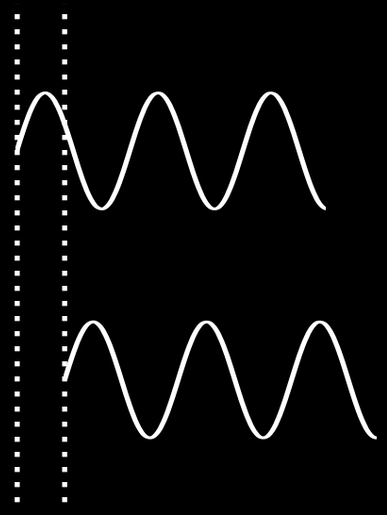

MIMO compensates signal
by knowing the channel

IVN beamforming

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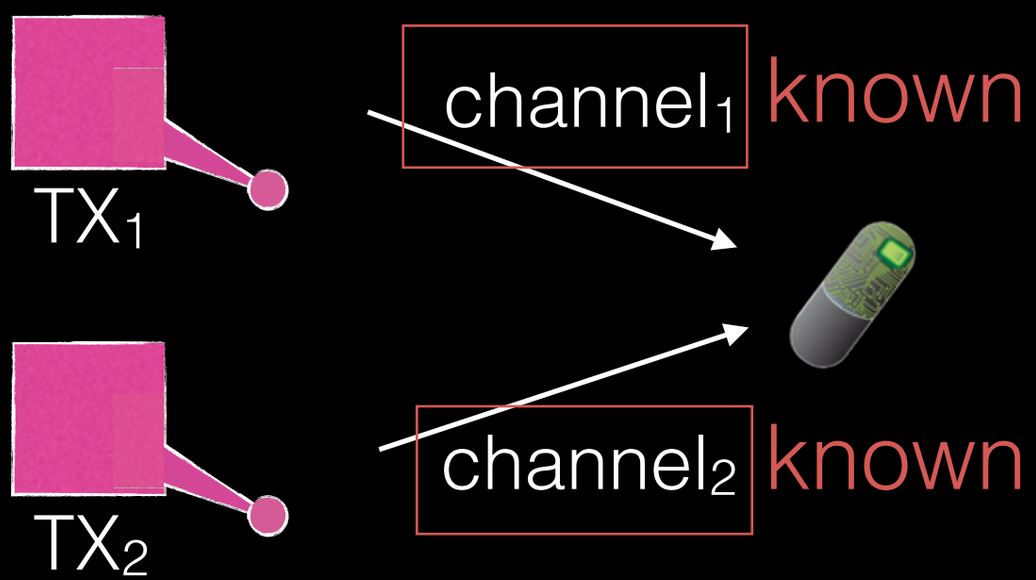

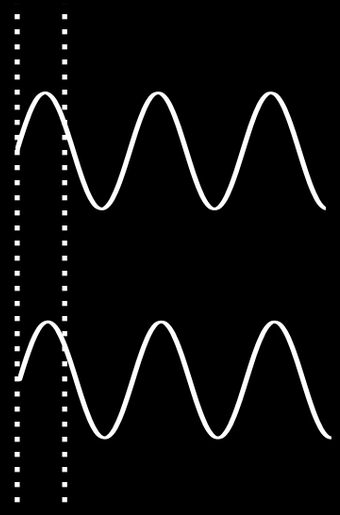

Signal
realigned

MIMO compensates signal
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IVN beamforming

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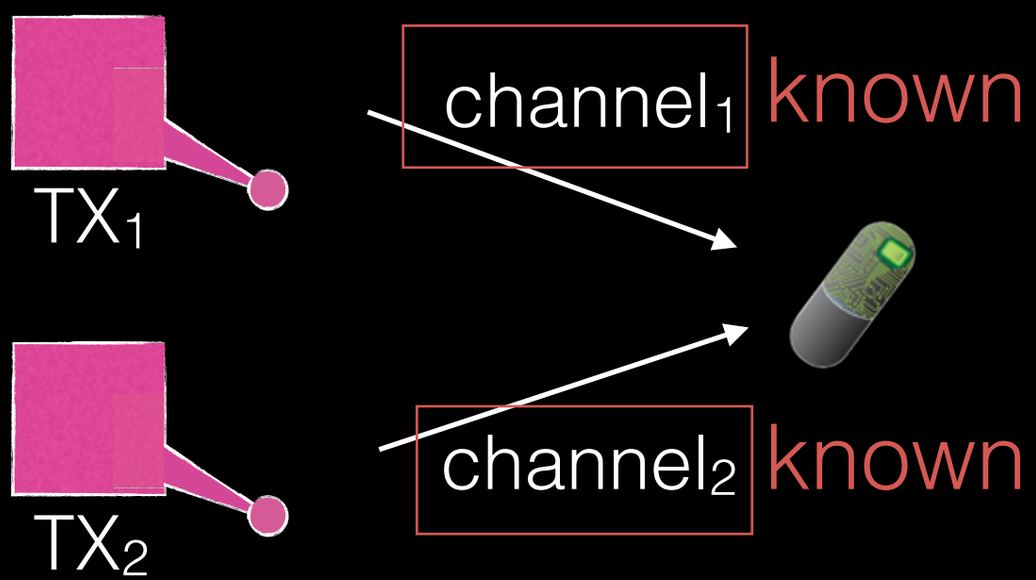

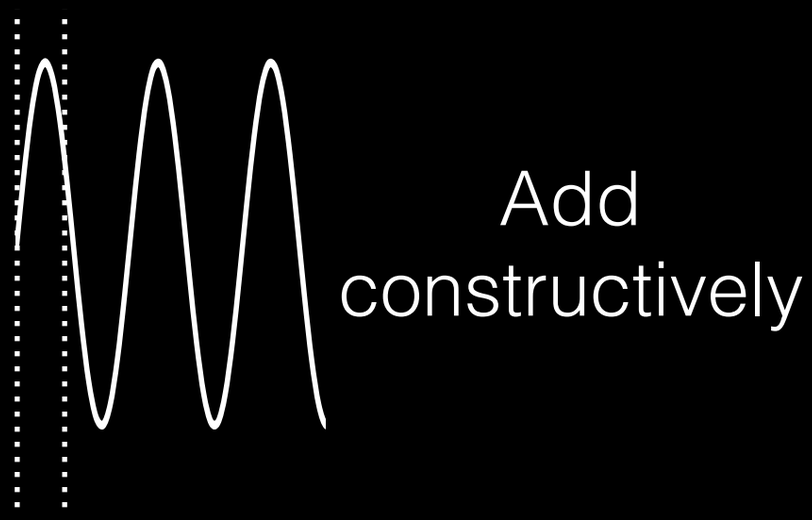

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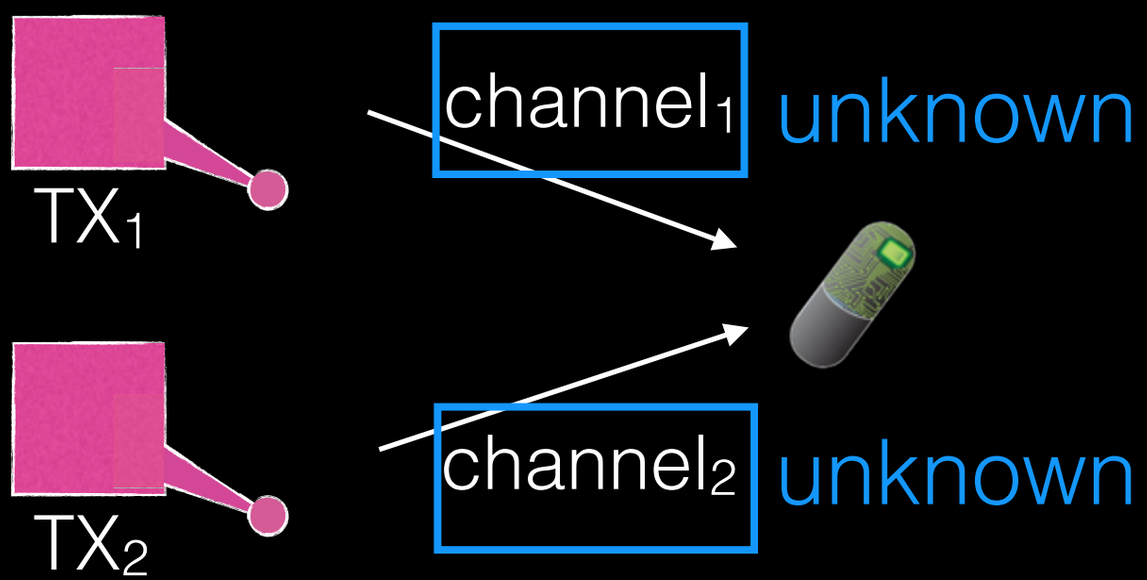
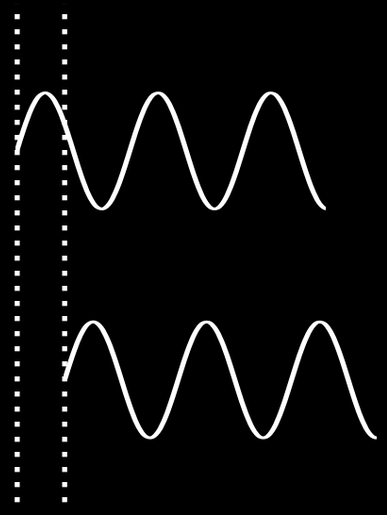
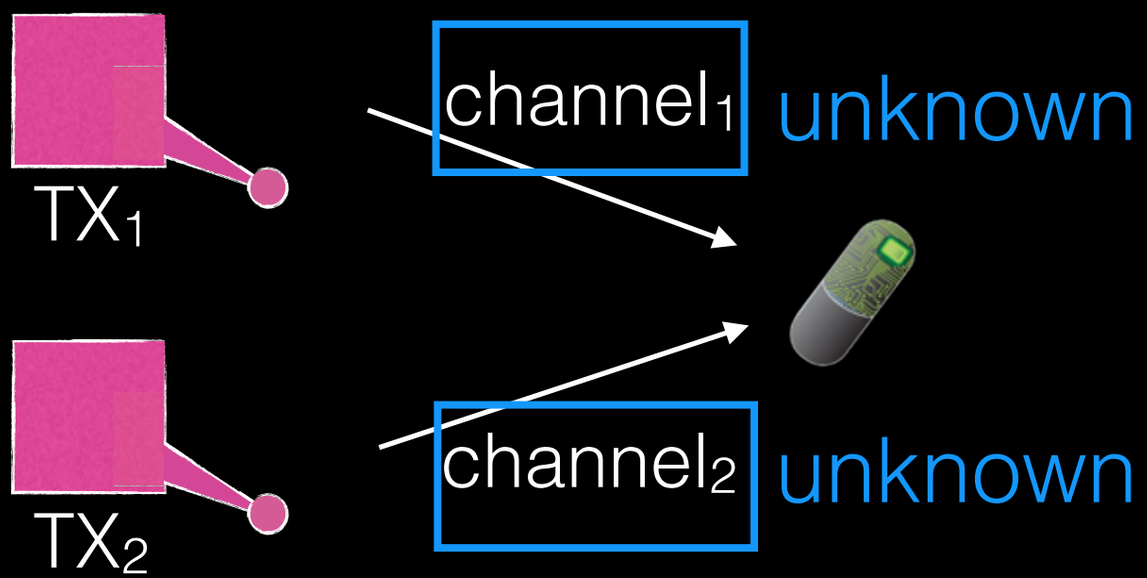


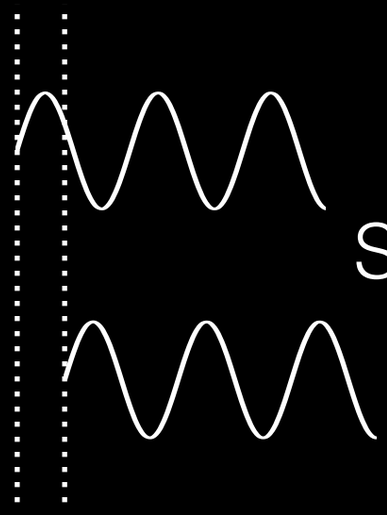


Signal misalignment cannot be compensated

IVN beamforming

Traditional MIMO



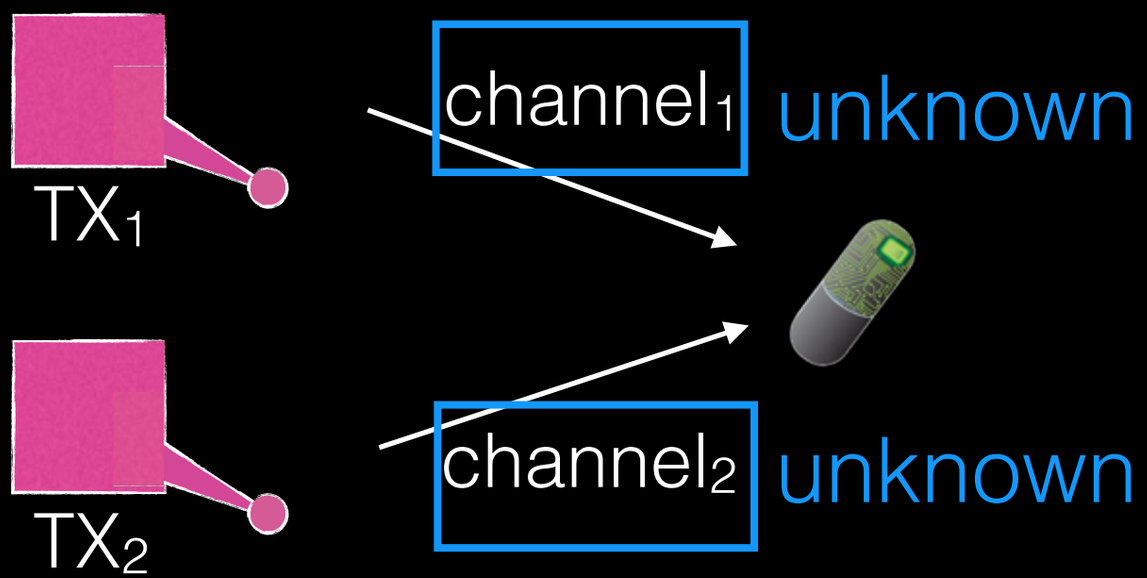


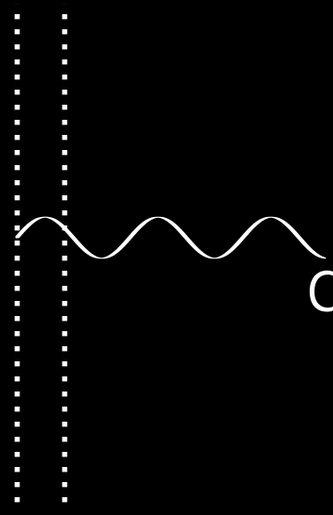
Signals remain
mis-aligned

Signal misalignment cannot
be compensated

IVN beamforming

Traditional MIMO





Add
destructively

Signal misalignment cannot
be compensated

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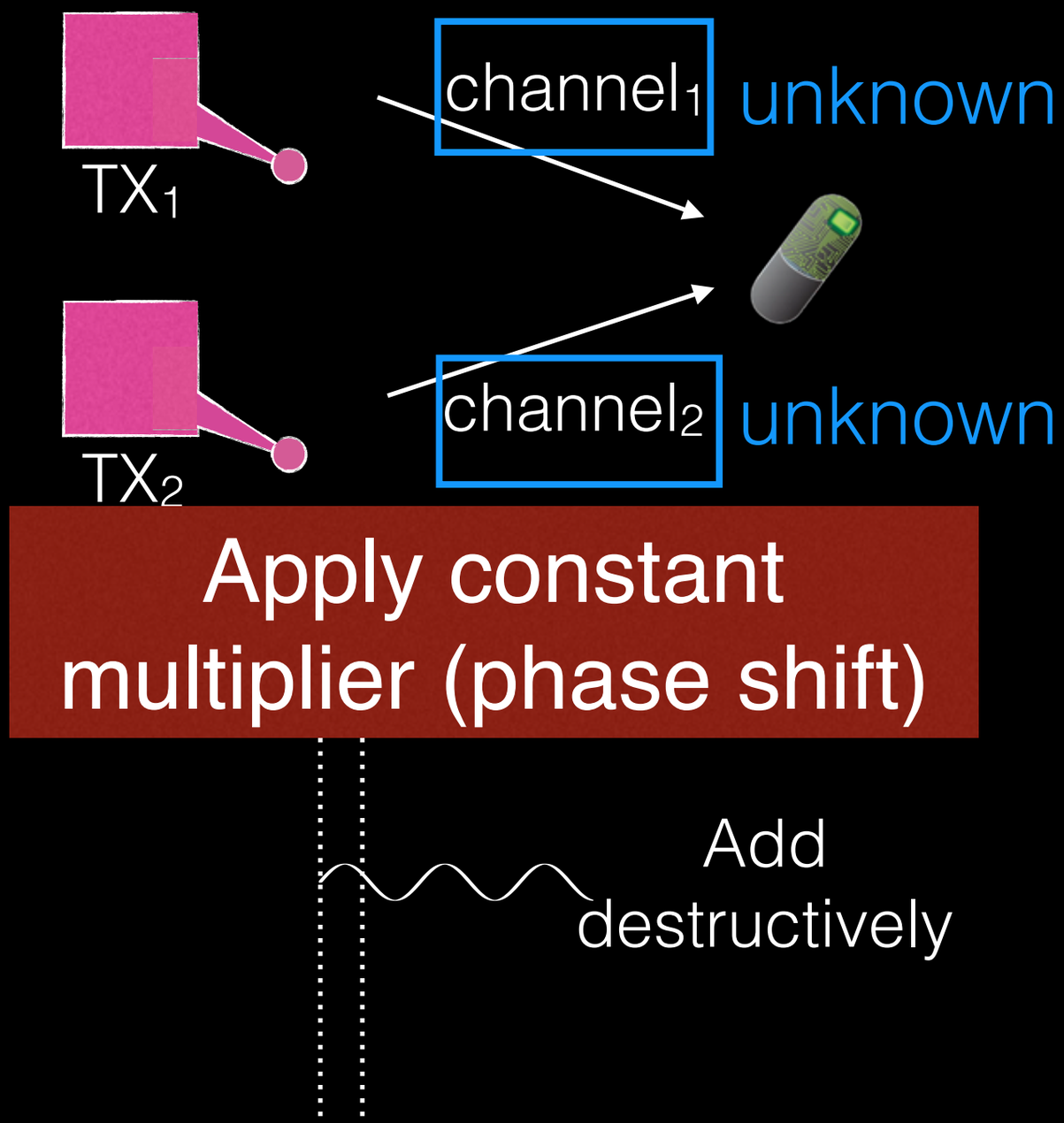

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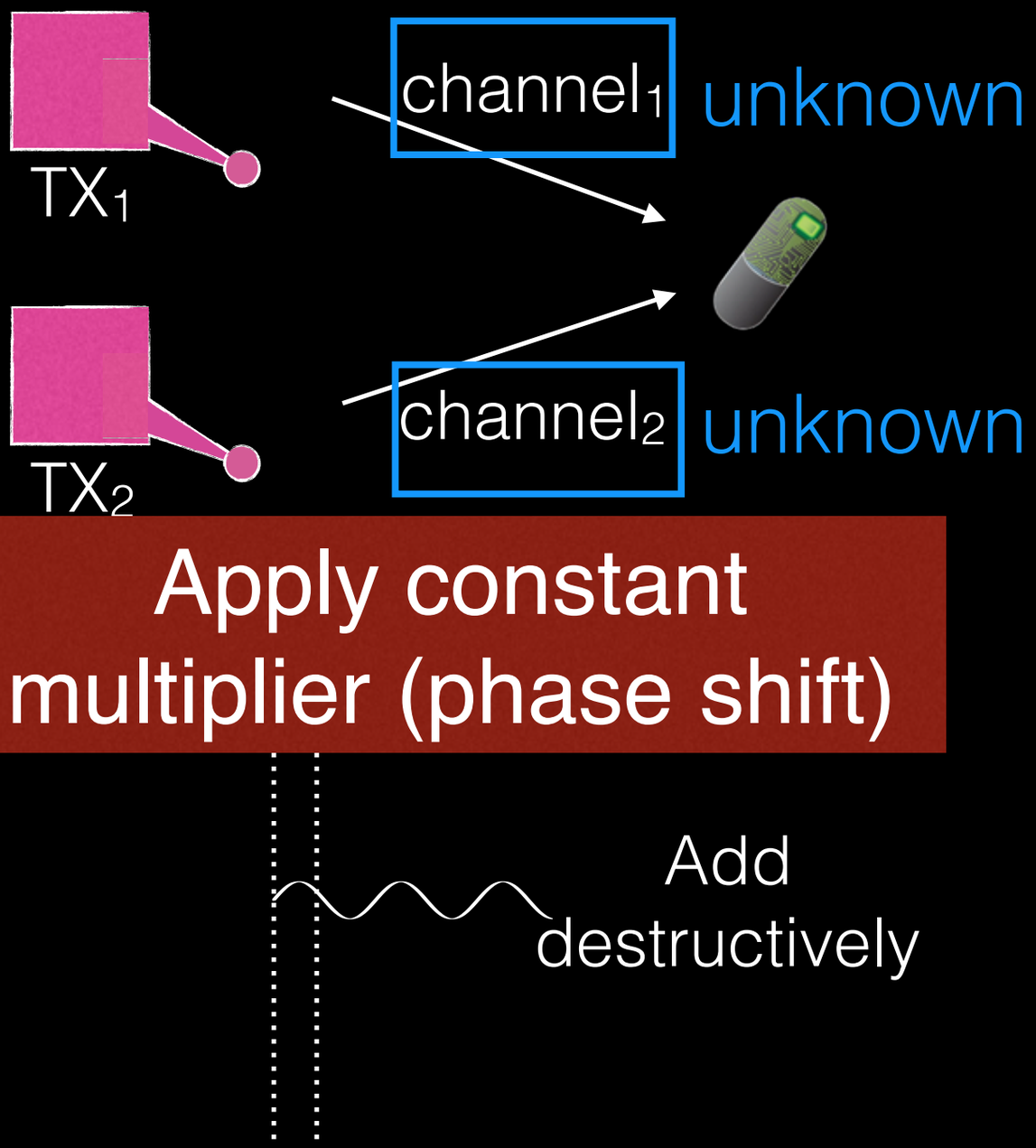
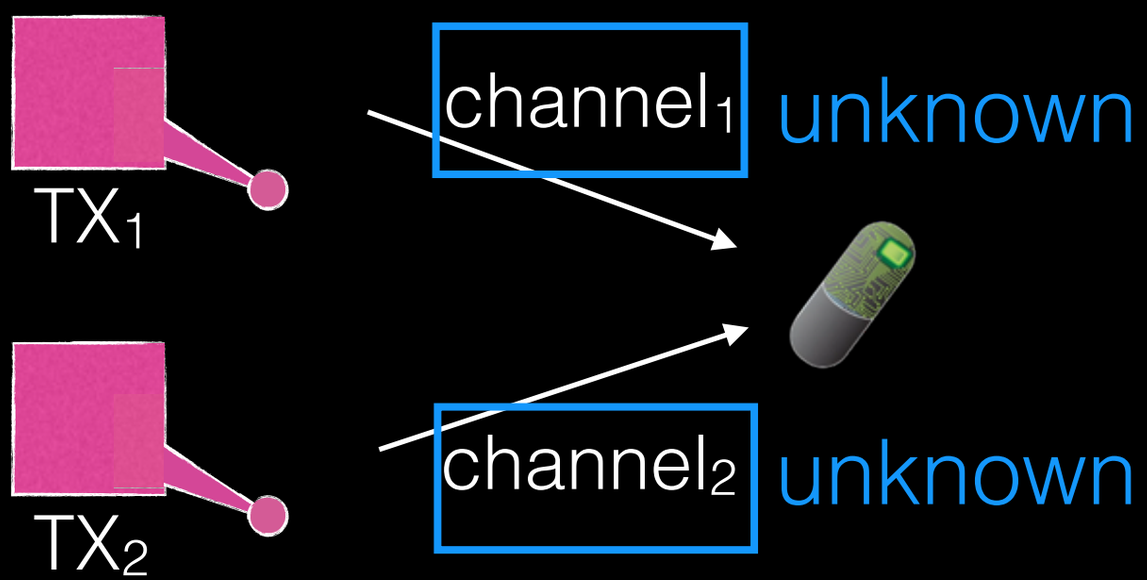
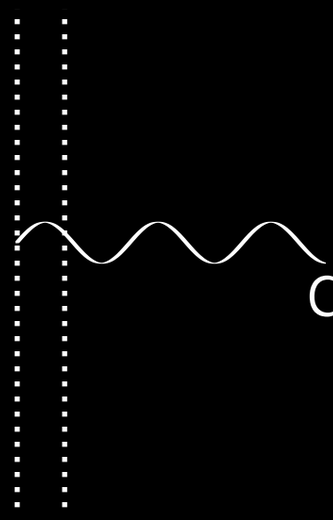


IVN beamforming

Apply time-varying multiplier (frequency shift)

Apply constant multiplier (phase shift)

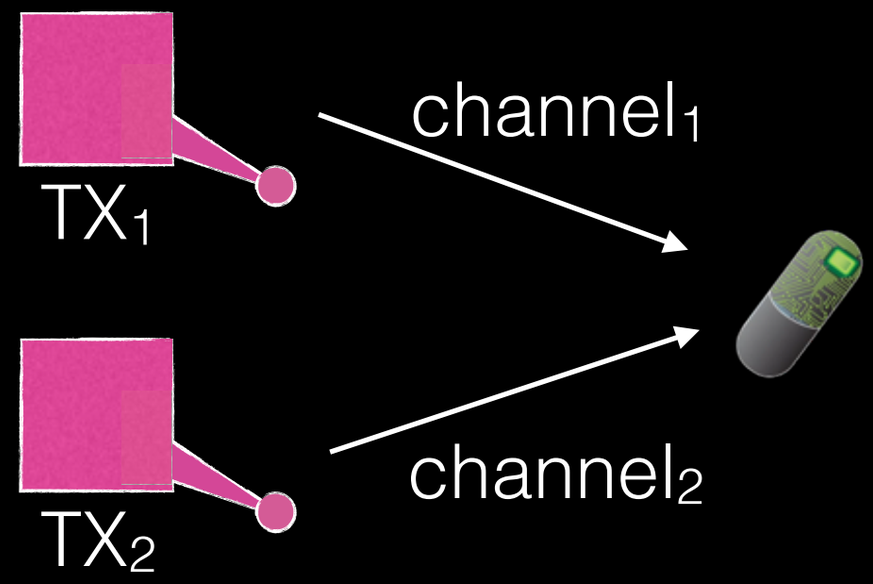




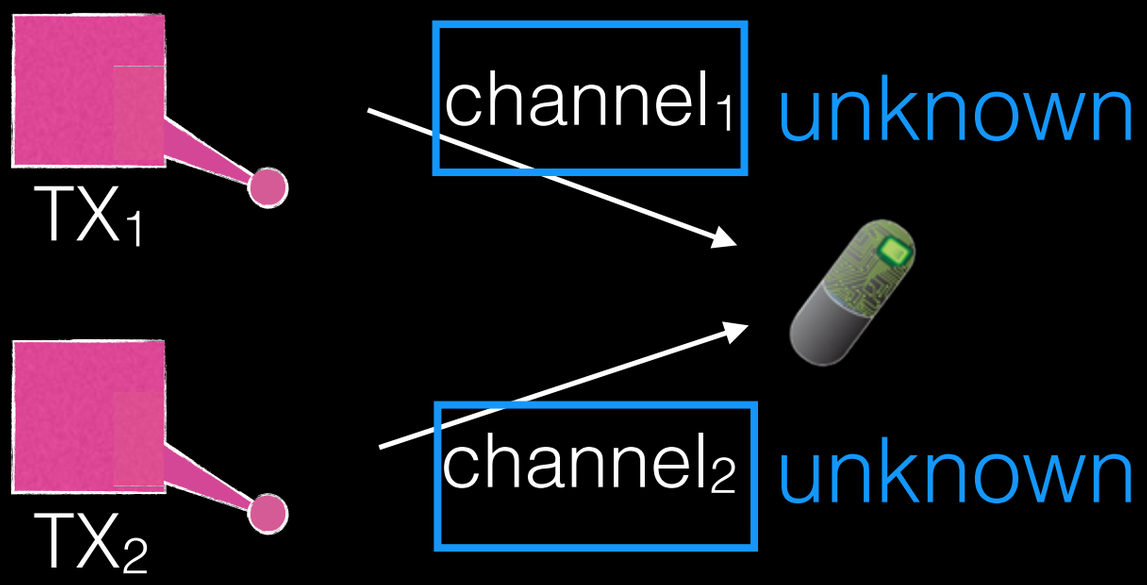
Add destructively

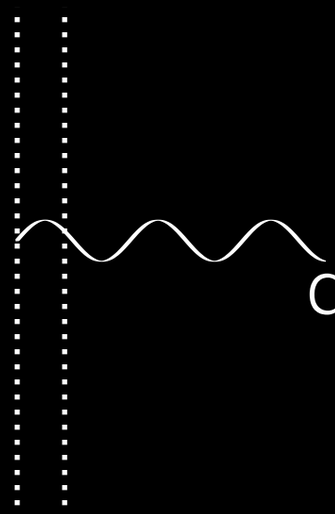
Signal misalignment cannot be compensated

Apply time-varying multiplier (frequency shift)



Apply constant multiplier (phase shift)

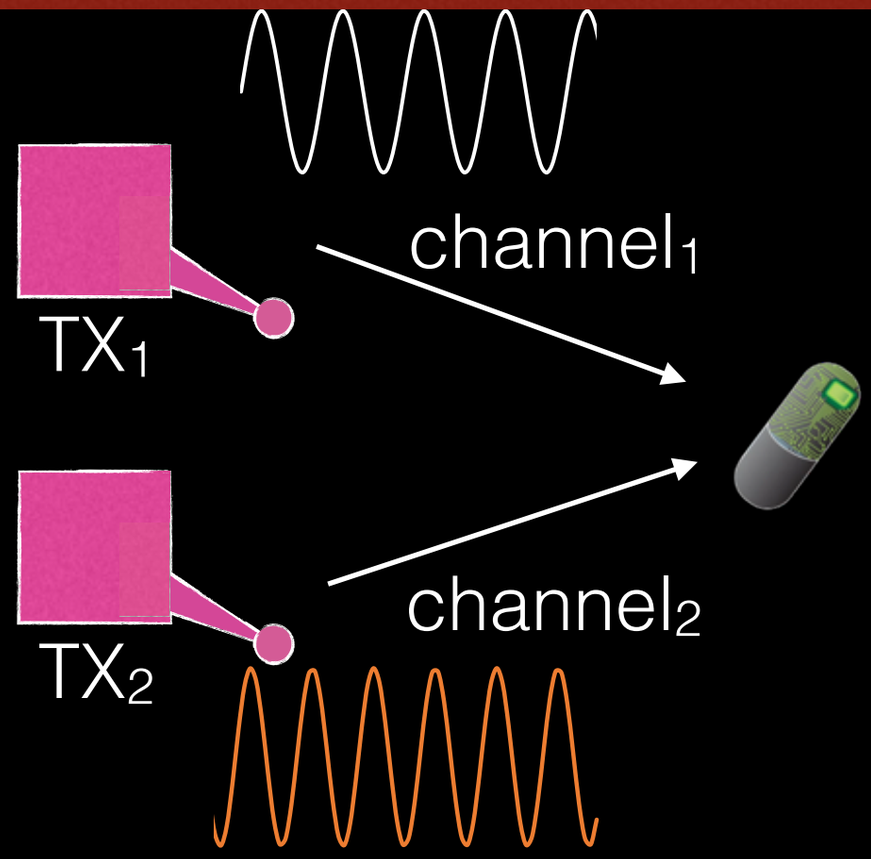




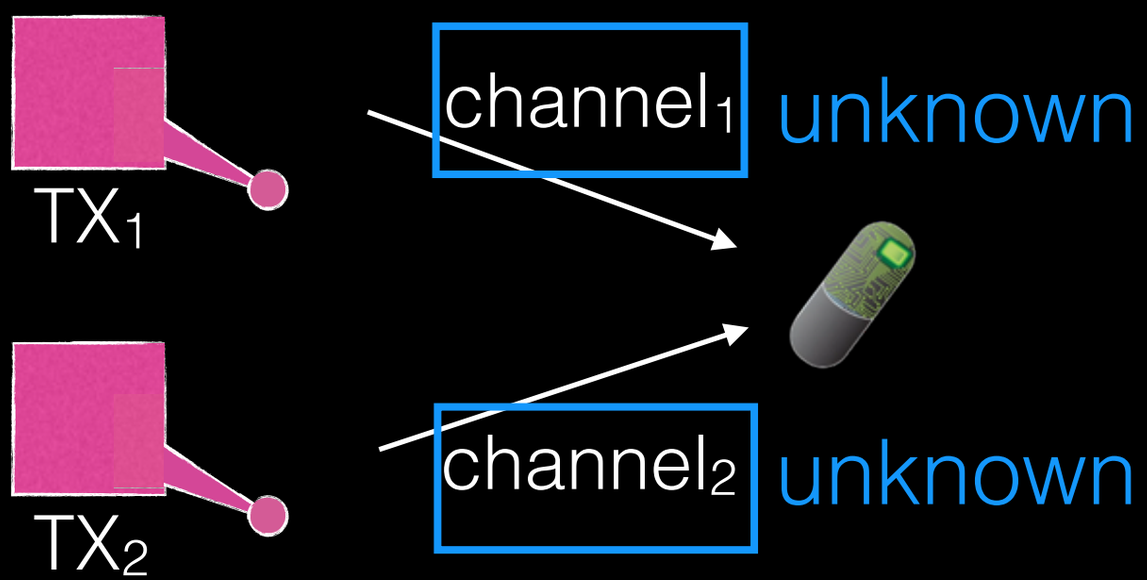
Add destructively

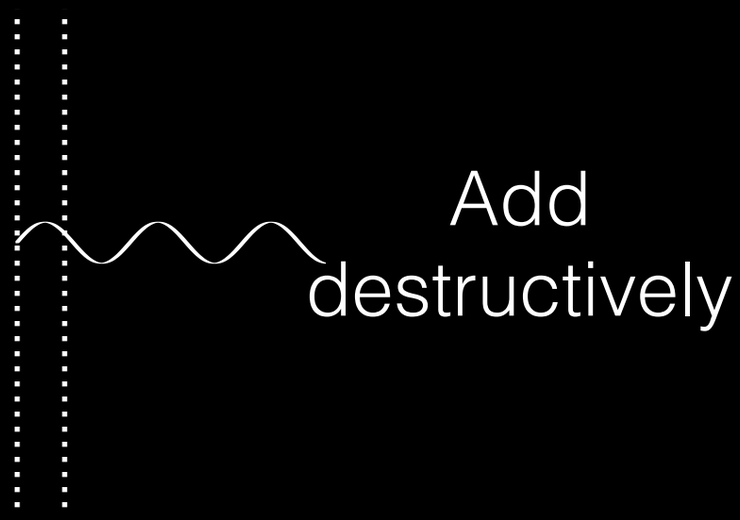
Signal misalignment cannot be compensated

Apply time-varying multiplier (frequency shift)



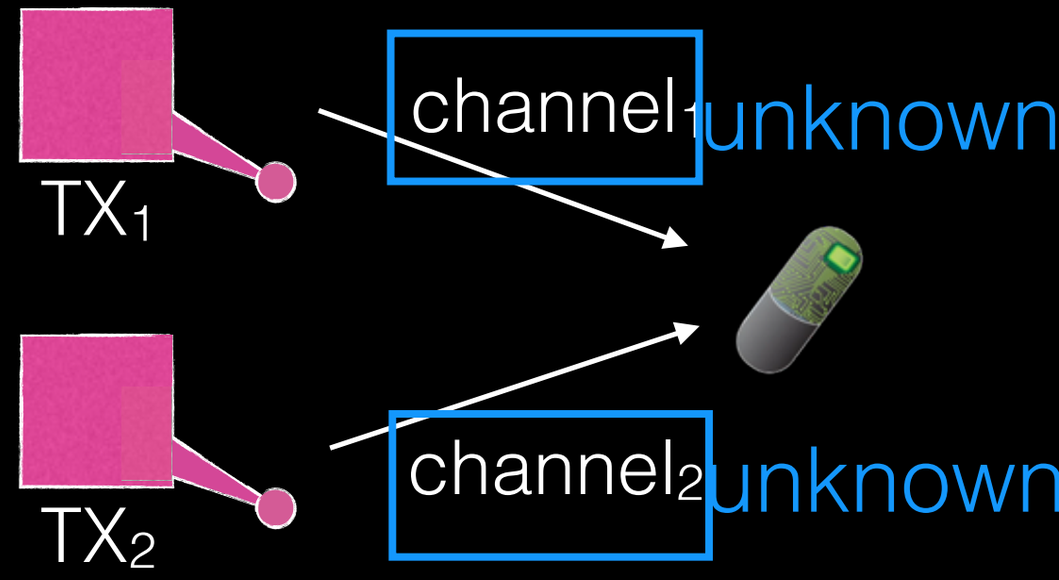
Traditional MIMO

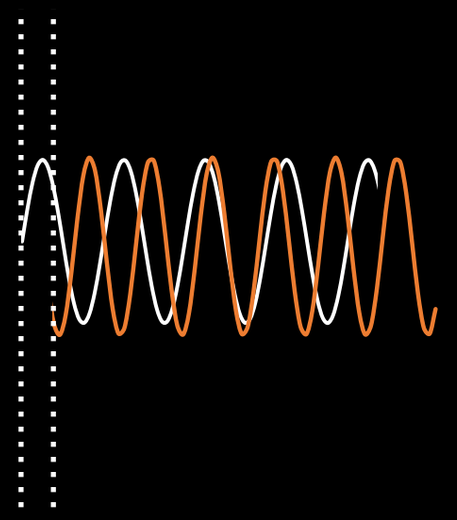




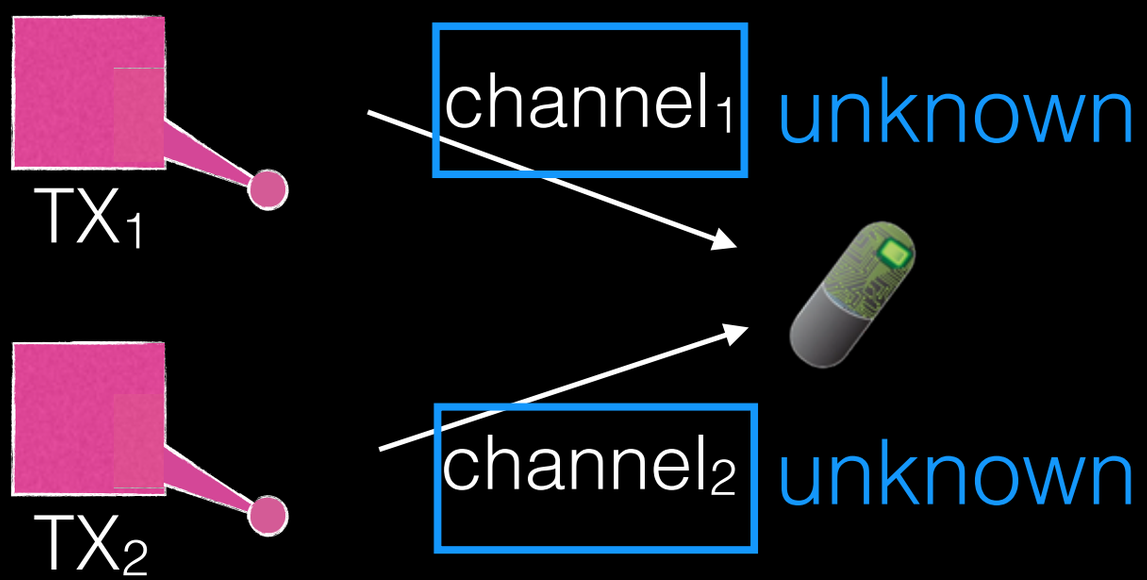
Signal misalignment cannot be compensated

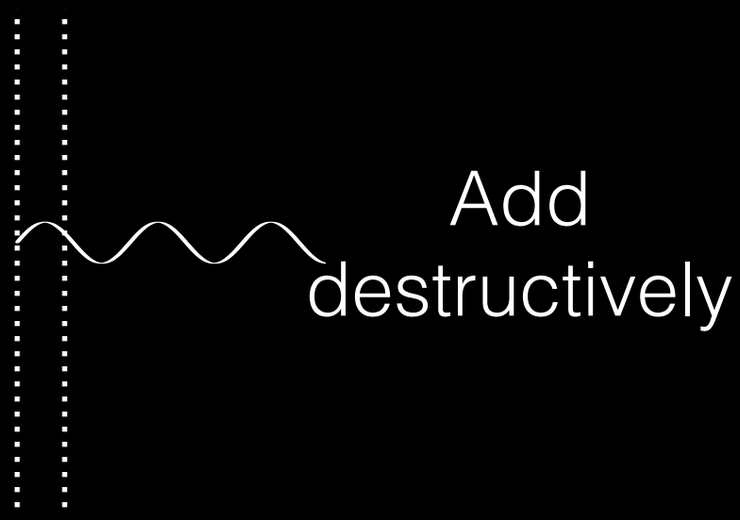
IVN beamforming





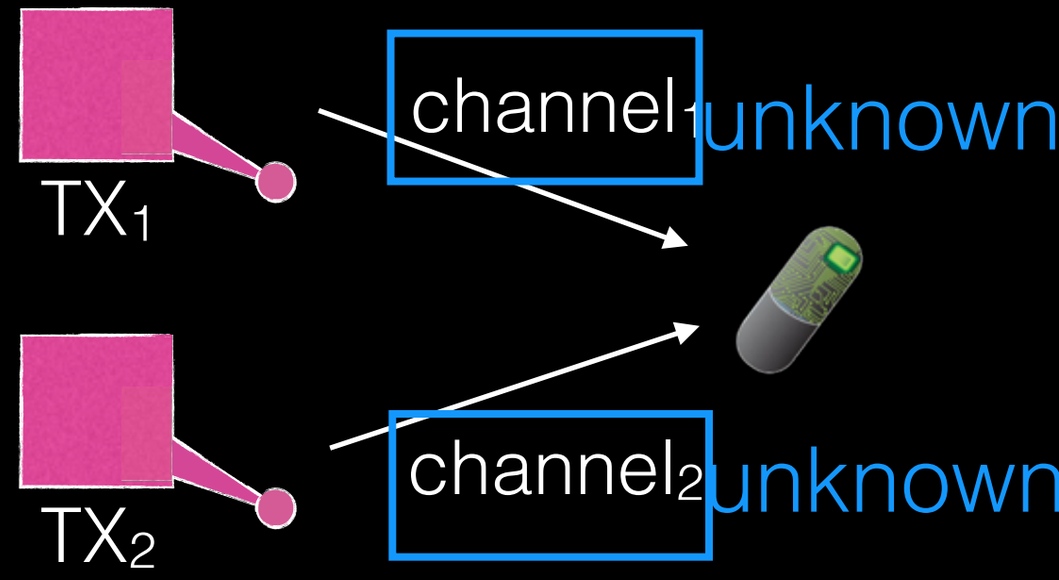
Traditional MIMO

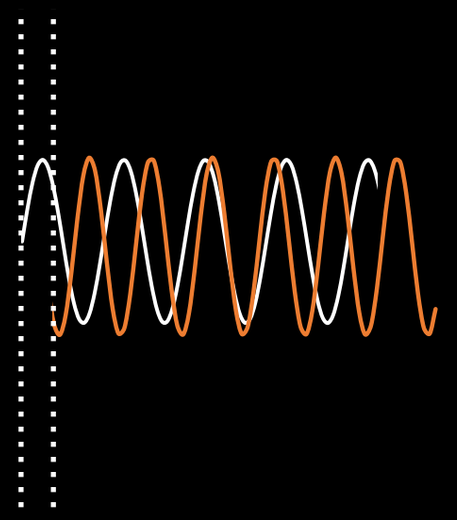




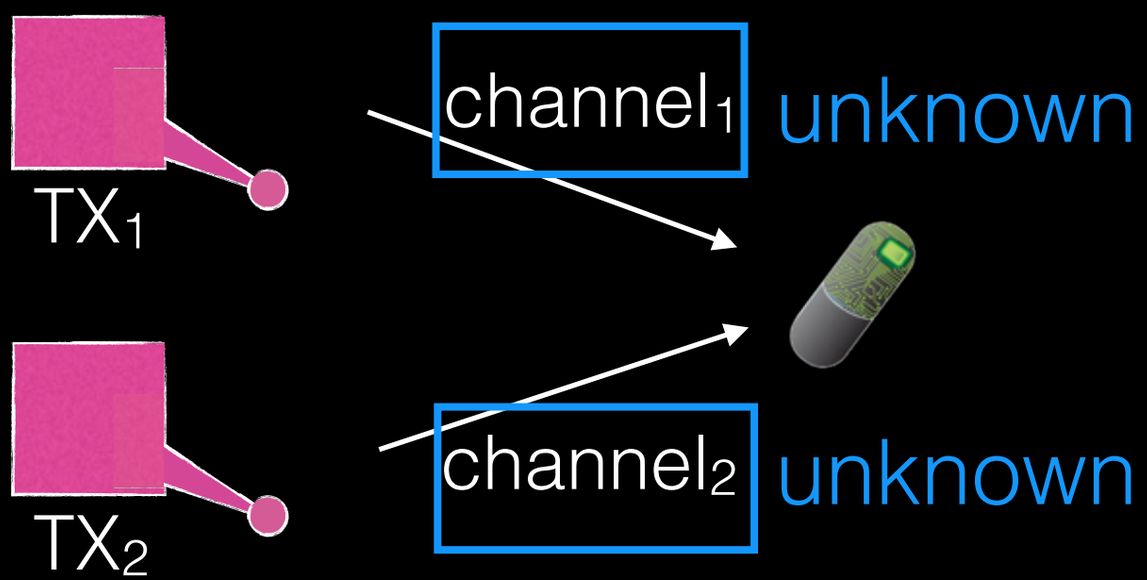
Signal misalignment cannot be compensated

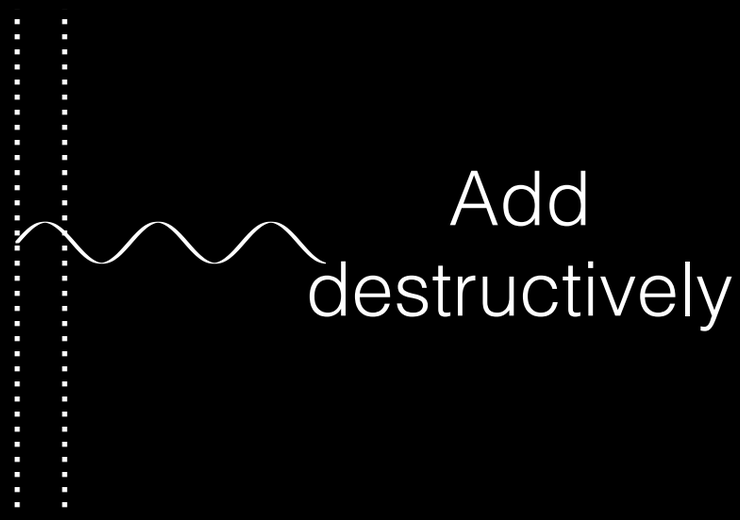
IVN beamforming





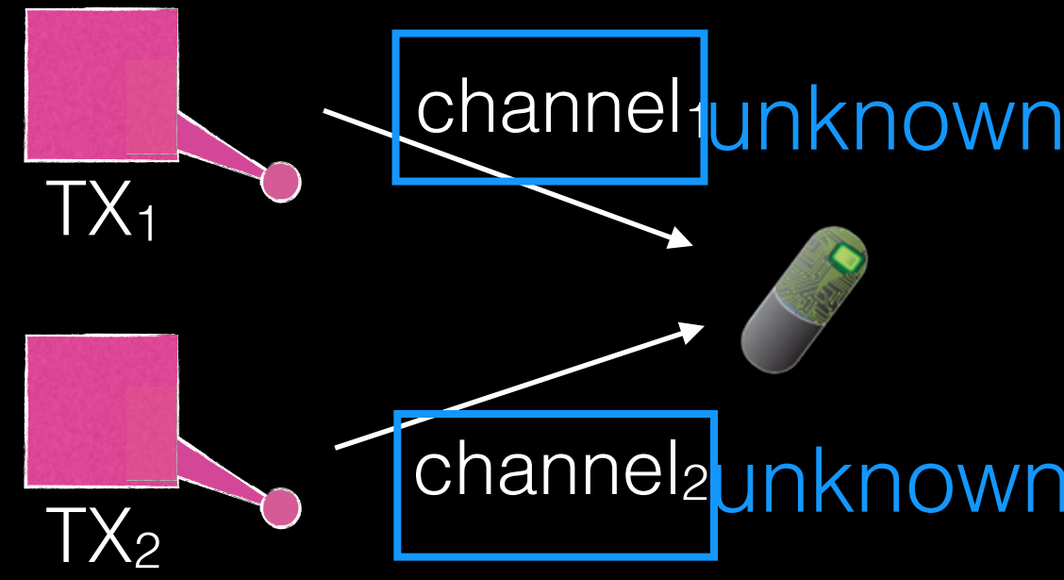
Traditional MIMO

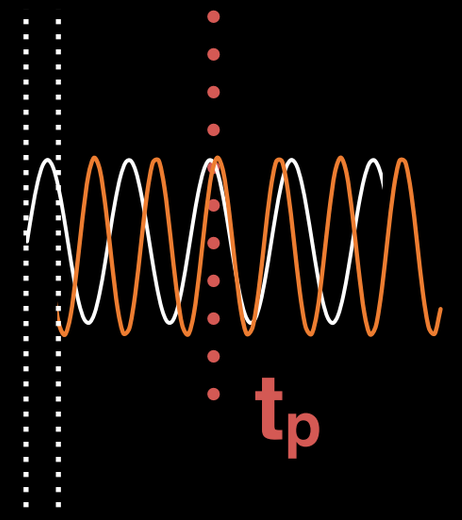




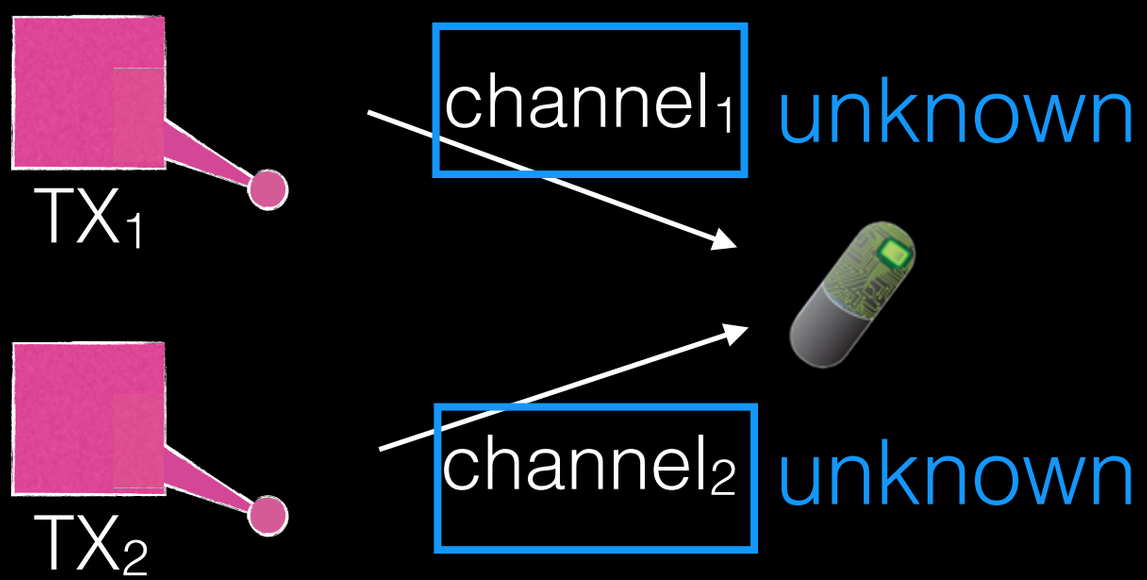
Signal misalignment cannot be compensated

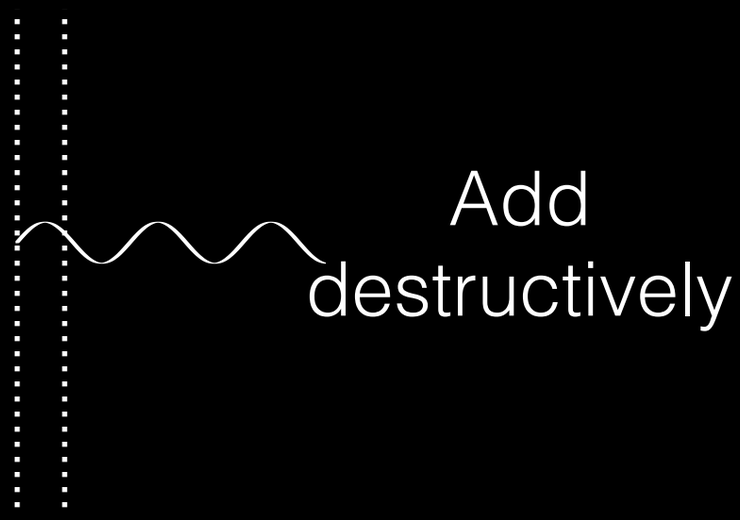
IVN beamforming





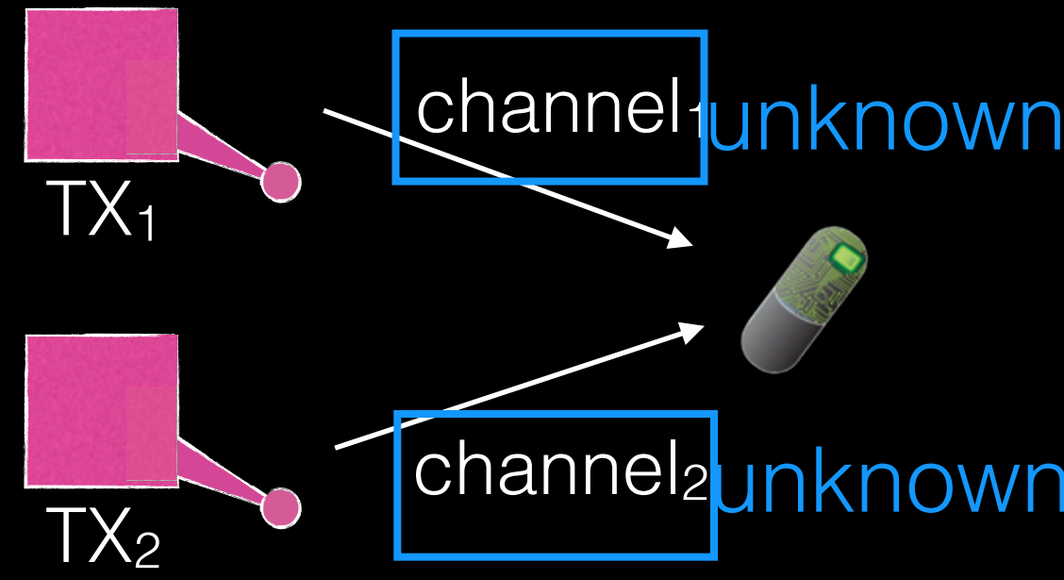
Traditional MIMO

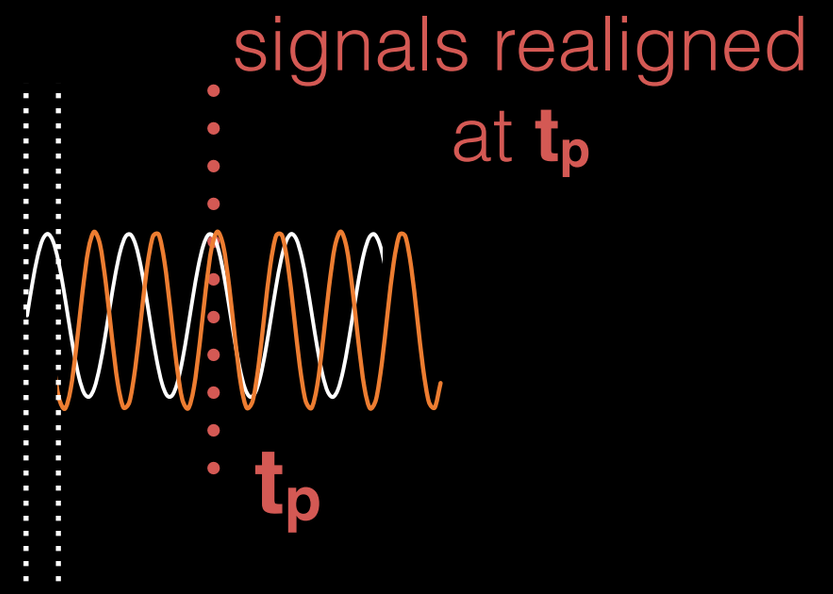




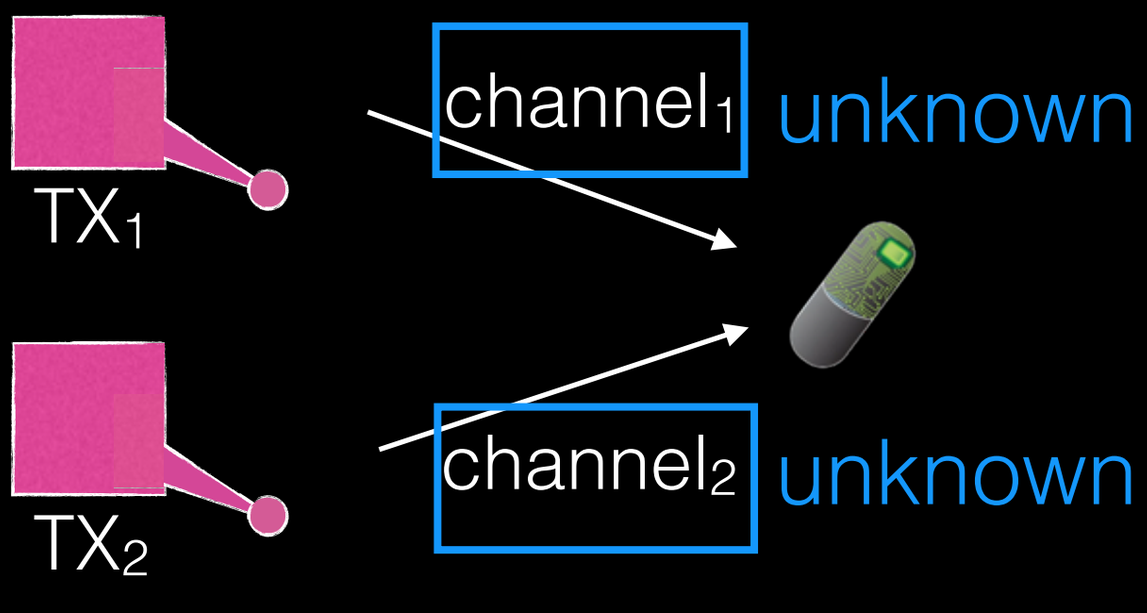
Signal misalignment cannot be compensated

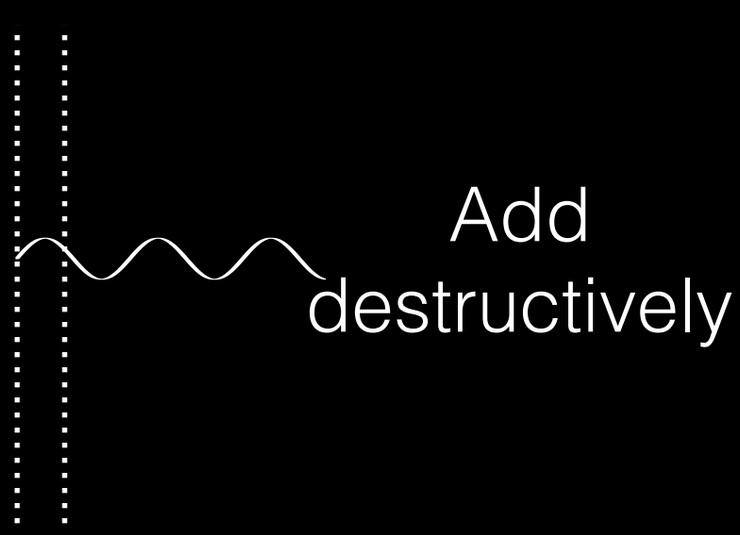
IVN beamforming





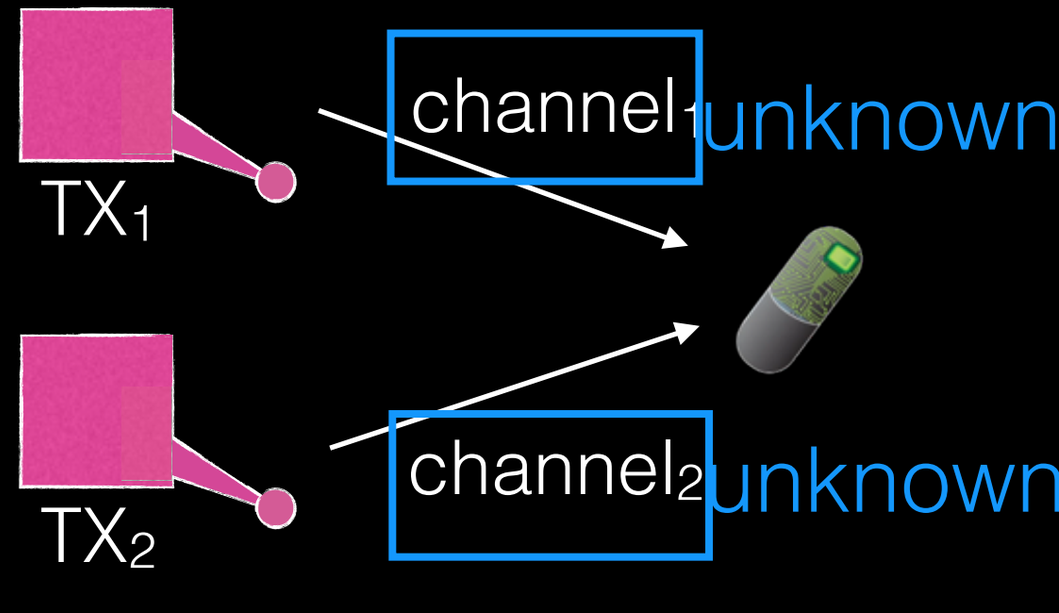
Traditional MIMO

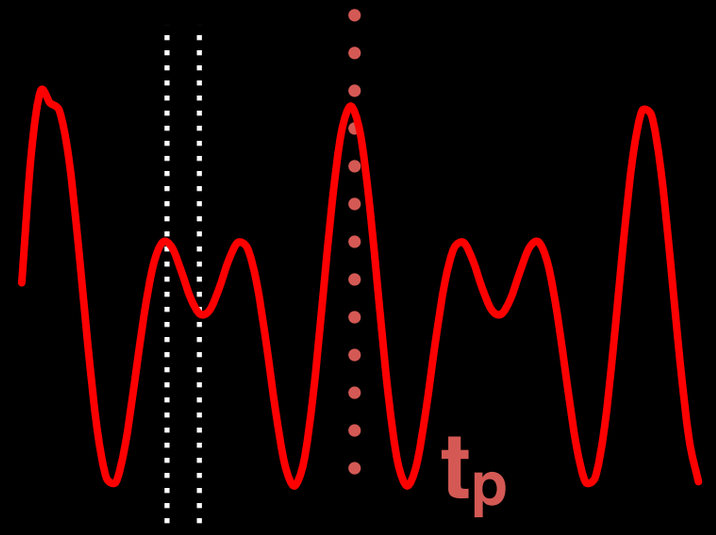




Signal misalignment cannot be compensated

IVN beamforming

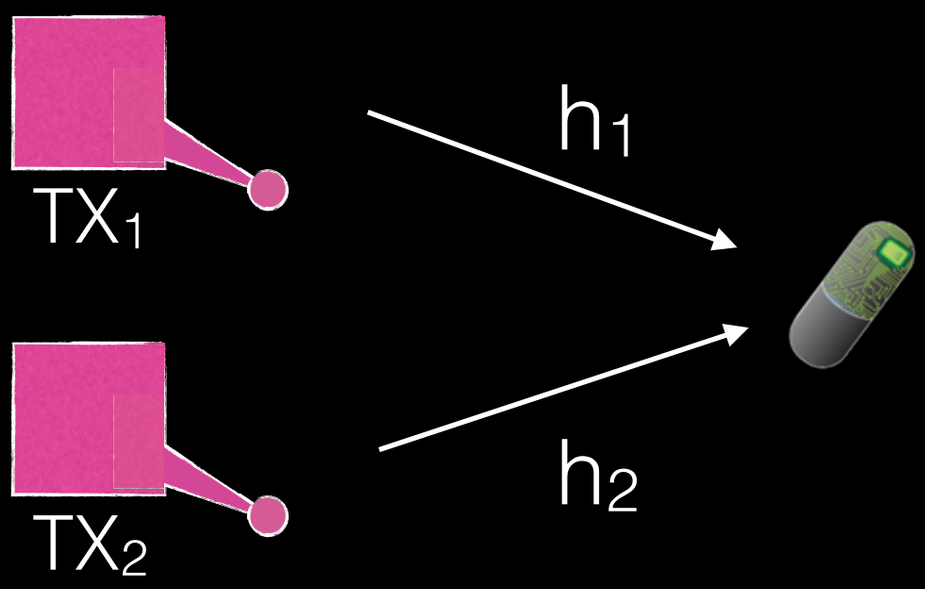




Power boosting at a particular time

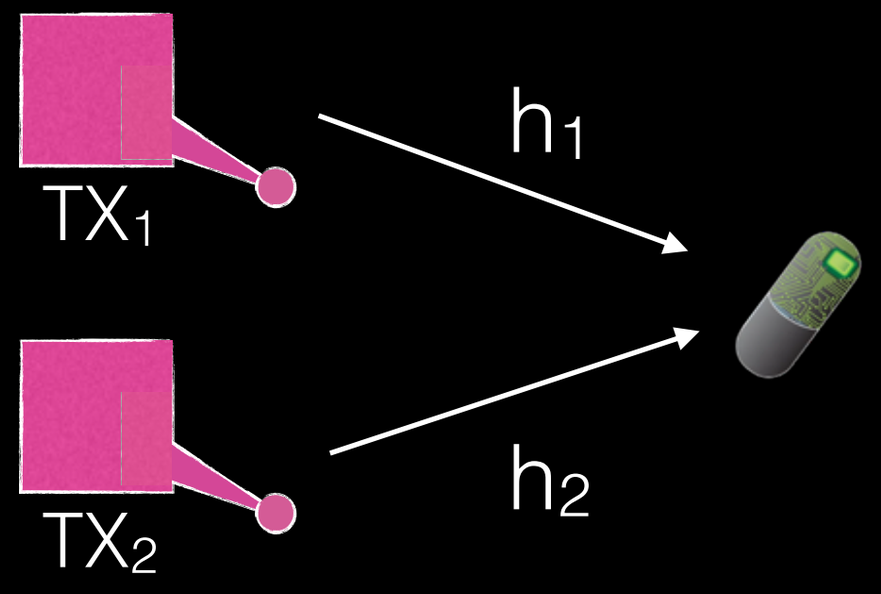
Traditional MIMO

Apply constant multiplier
(phase shift)



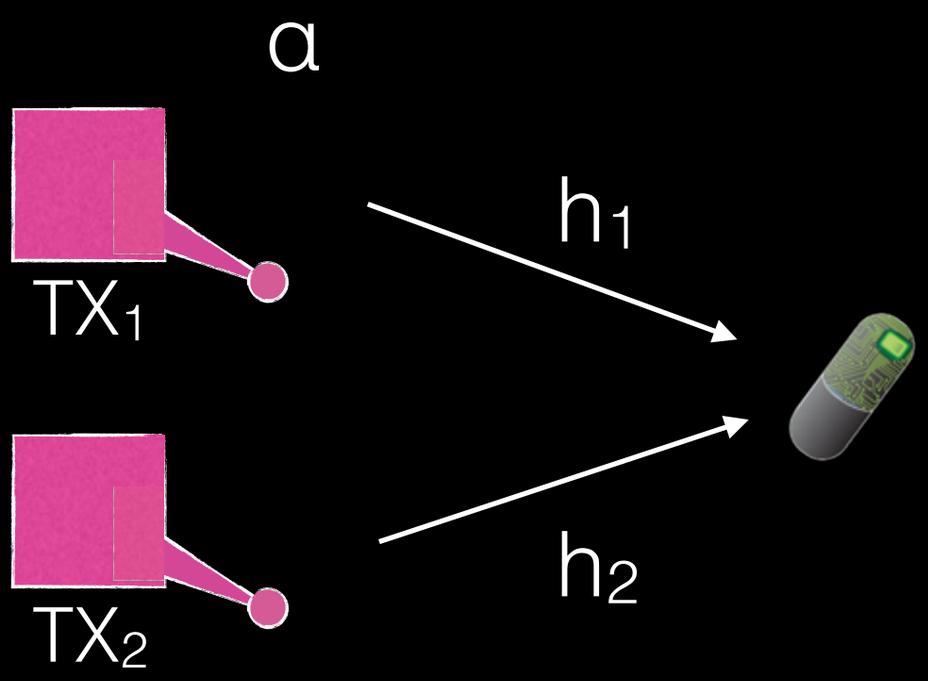
IVN beamforming

Apply time-varying multiplier
(frequency shift)



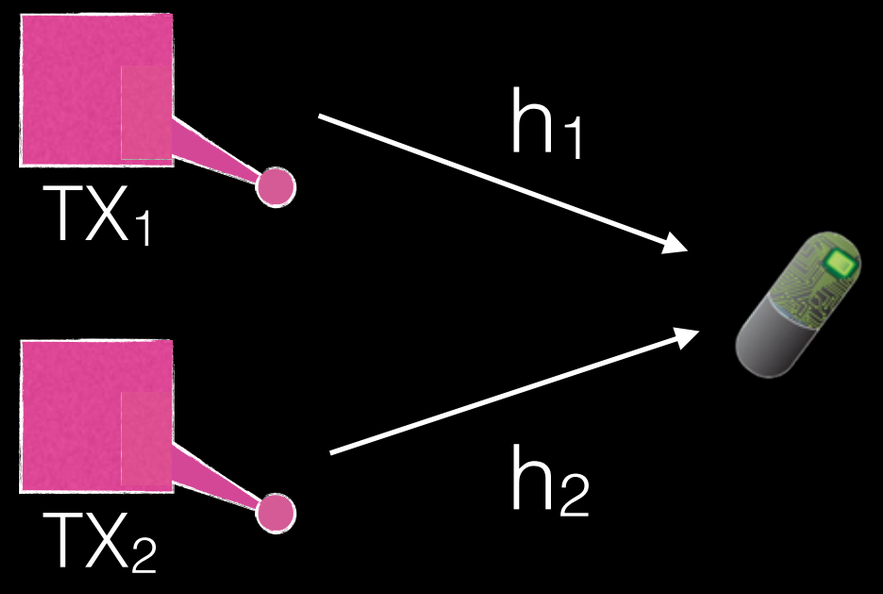
Traditional MIMO

Apply constant multiplier
(phase shift)



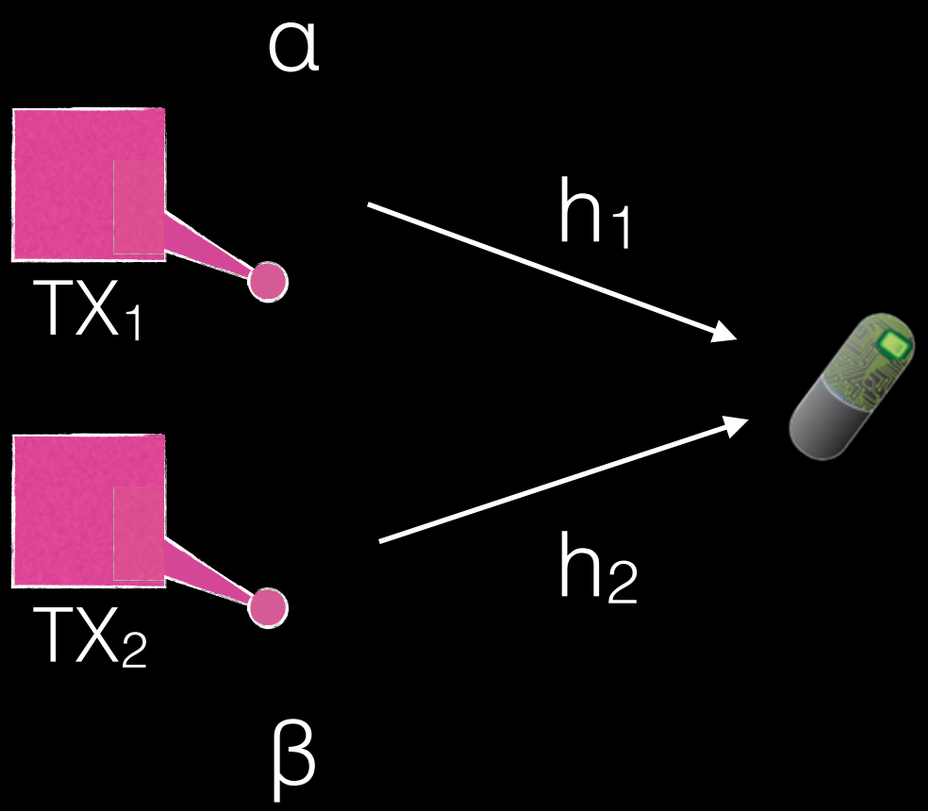
IVN beamforming

Apply time-varying multiplier
(frequency shift)



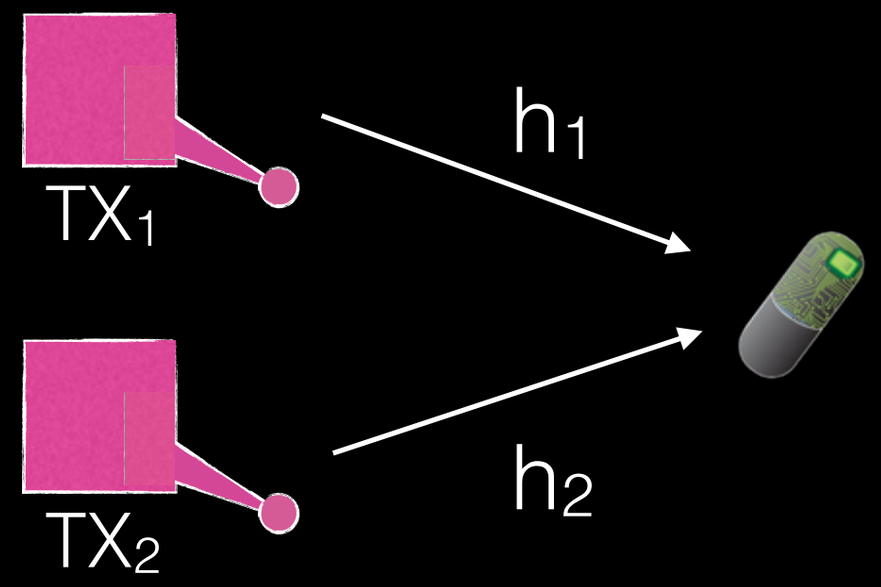
Traditional MIMO

Apply constant multiplier
(phase shift)



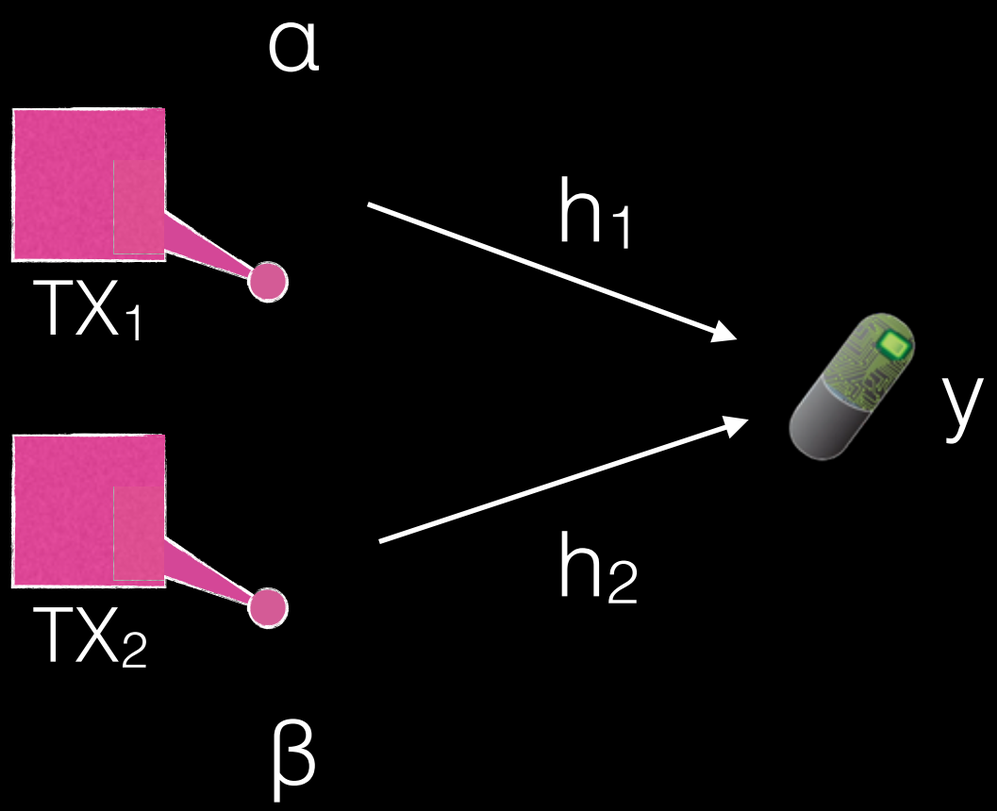
IVN beamforming

Apply time-varying multiplier
(frequency shift)



Traditional MIMO

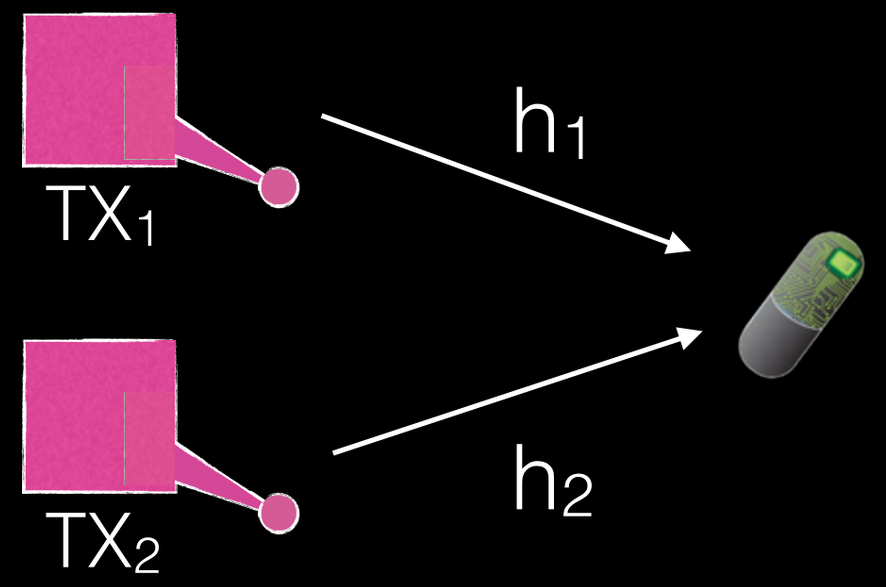
Apply constant multiplier
(phase shift)



$$y = \alpha h_1 + \beta h_2$$

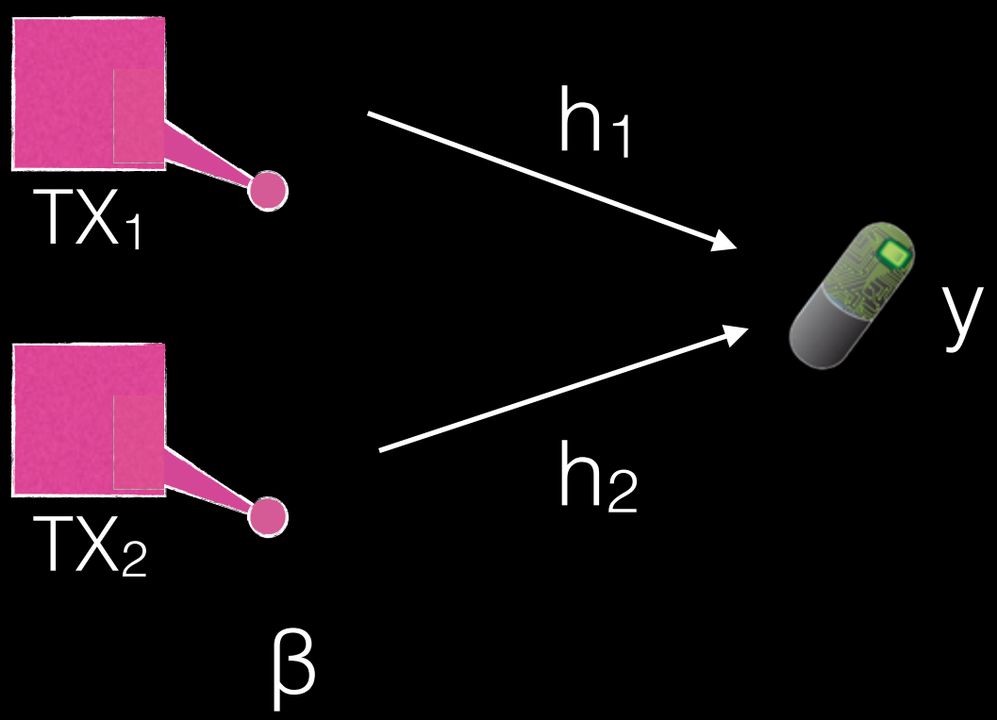
IVN beamforming

Apply time-varying multiplier
(frequency shift)



Traditional MIMO

Apply constant multiplier (phase shift)

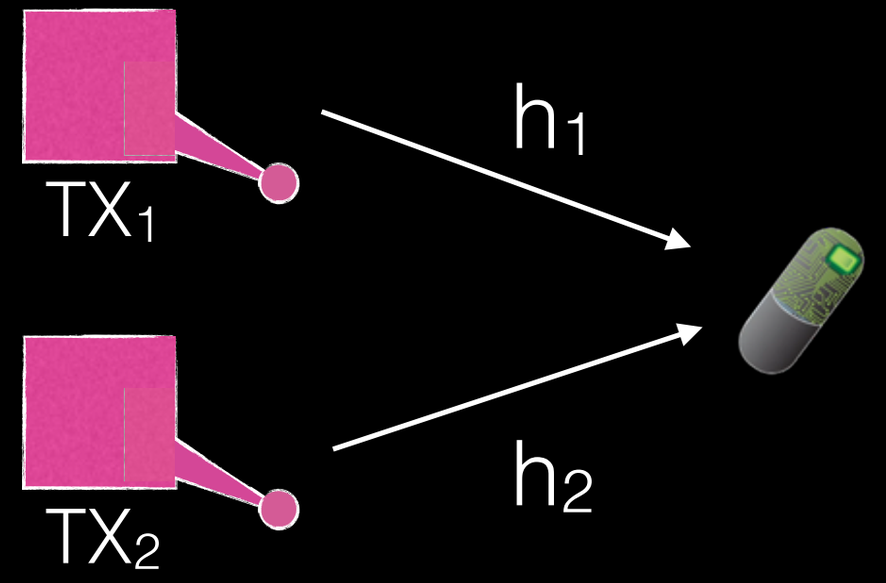


$$y = \alpha h_1 + \beta h_2$$

IVN beamforming

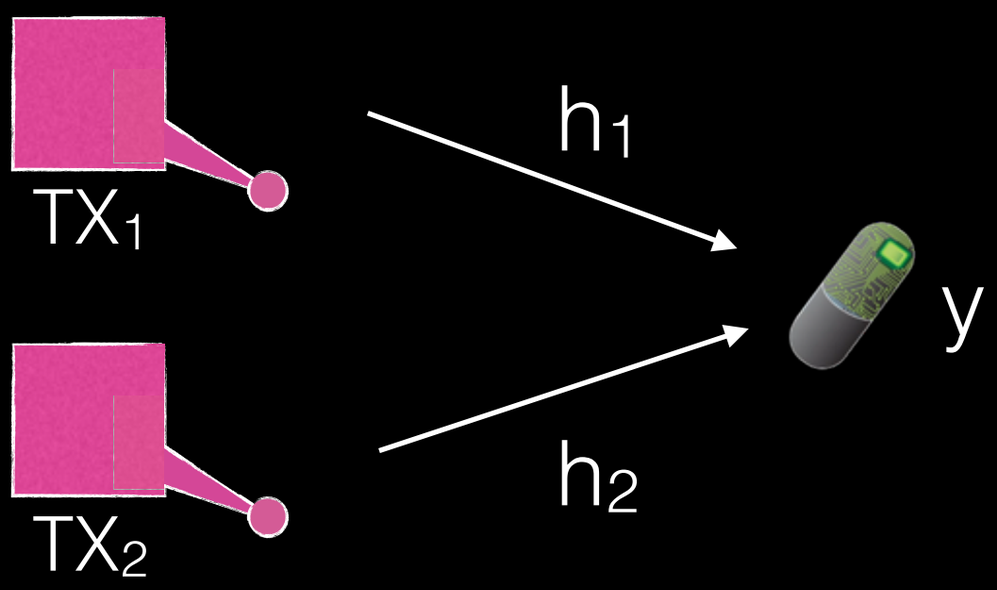
Apply time-varying multiplier (frequency shift)

$$\alpha(t) = \alpha \times \exp(j\omega_1 t)$$



Traditional MIMO

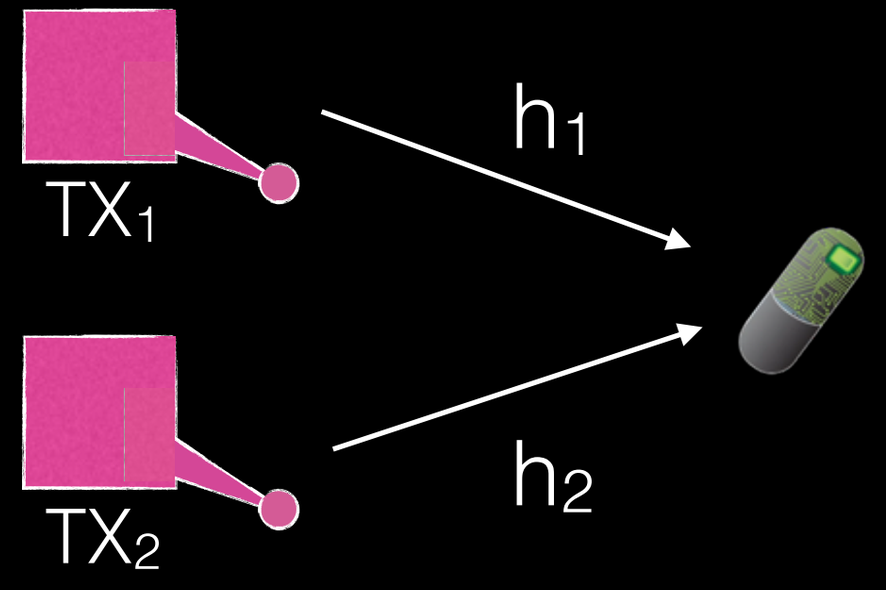
Apply constant multiplier (phase shift)



$$y = \alpha h_1 + \beta h_2$$

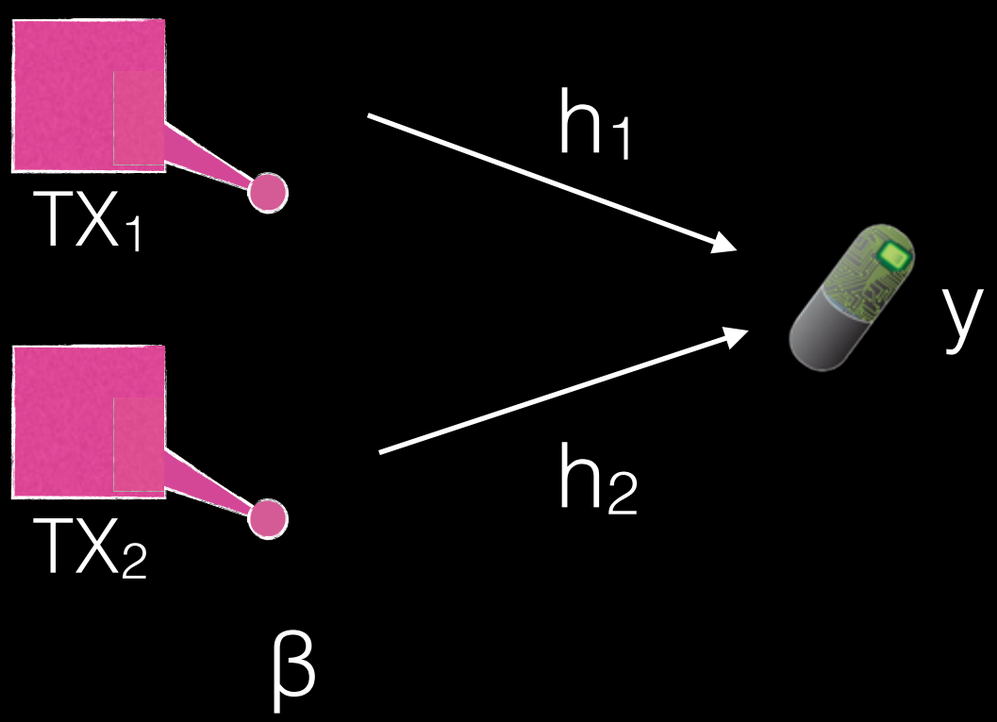
IVN beamforming

Apply time-varying multiplier (frequency shift)



Traditional MIMO

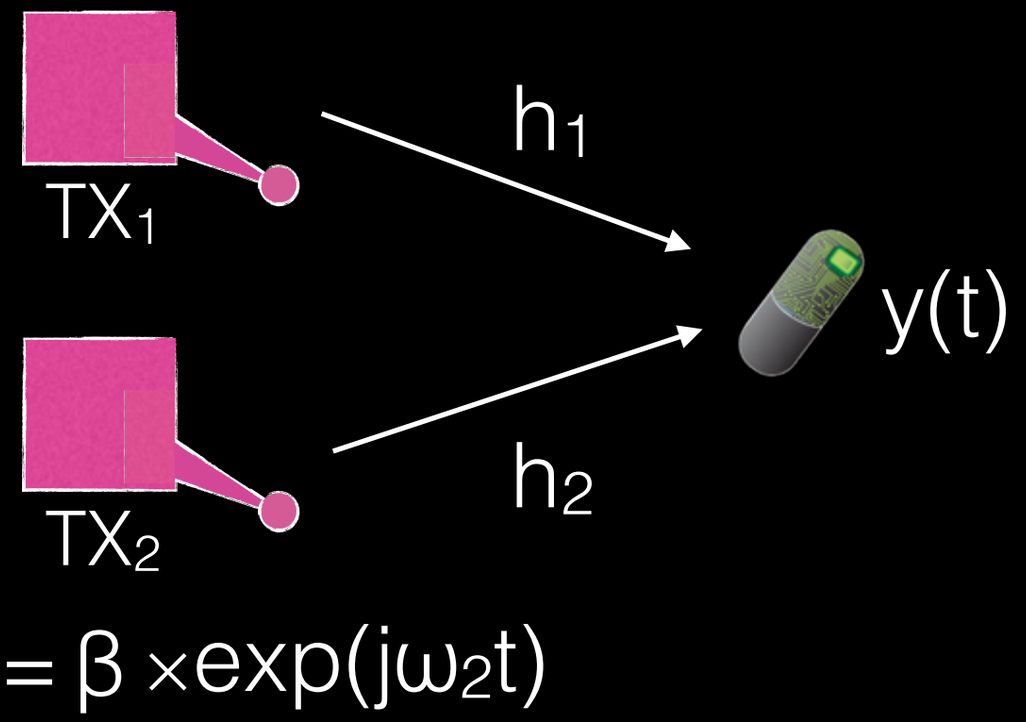
Apply constant multiplier (phase shift)



$$y = \alpha h_1 + \beta h_2$$

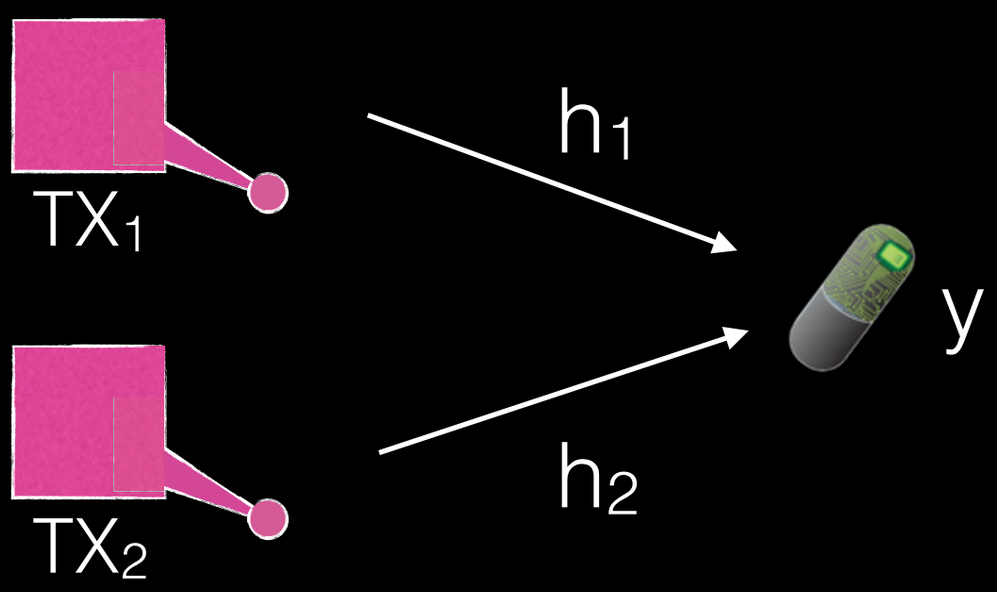
IVN beamforming

Apply time-varying multiplier (frequency shift)



Traditional MIMO

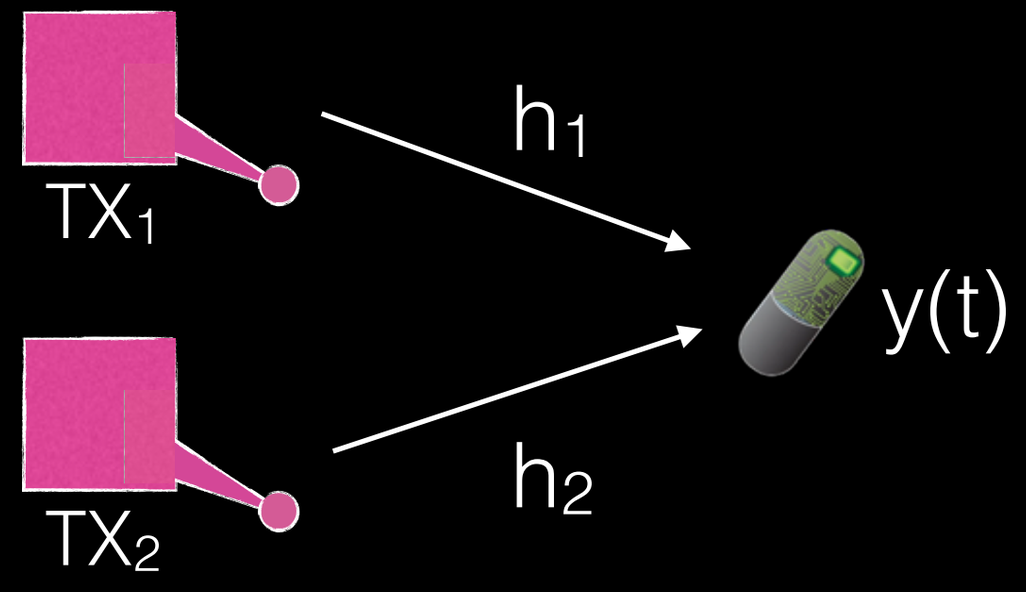
Apply constant multiplier (phase shift)



$$y = \alpha h_1 + \beta h_2$$

IVN beamforming

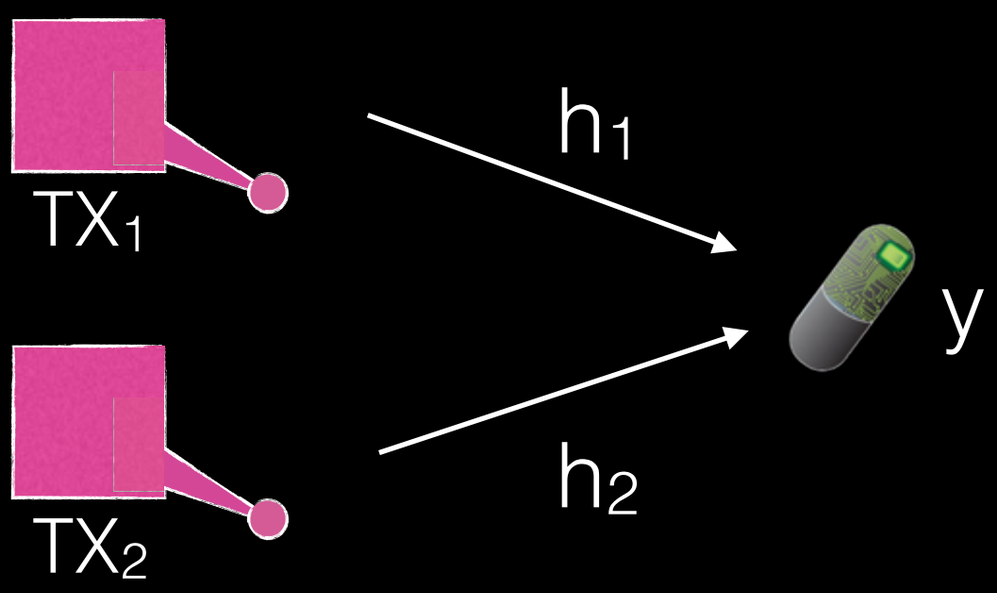
Apply time-varying multiplier (frequency shift)



$$y(t) = \alpha h_1 e^{j\omega_1 t} + \beta h_2 e^{j\omega_2 t}$$

Traditional MIMO

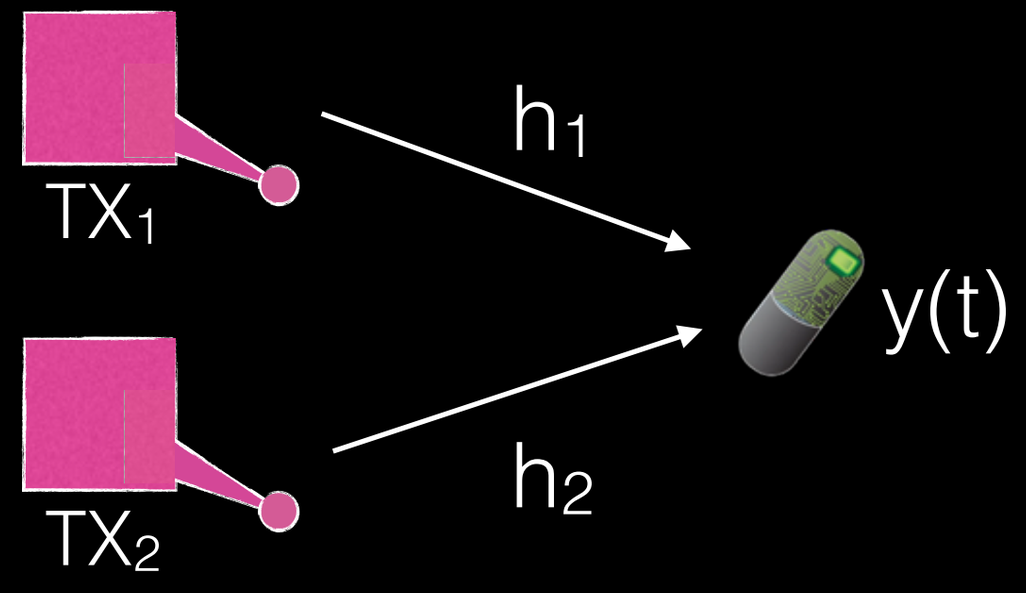
Apply constant multiplier (phase shift)



$$y = \alpha h_1 + \beta h_2$$

IVN beamforming

Apply time-varying multiplier (frequency shift)

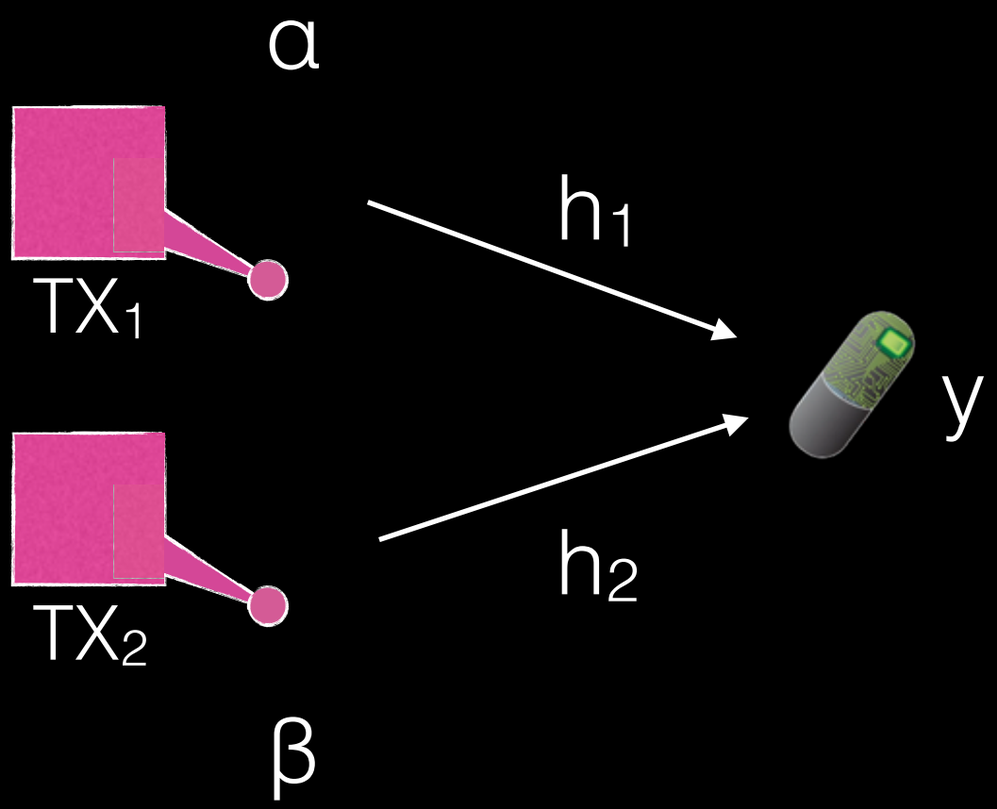


$$y(t) = \alpha h_1 e^{j\omega_1 t} + \beta h_2 e^{j\omega_2 t}$$

Mathematically, IVN introduces a time-varying channel

Traditional MIMO

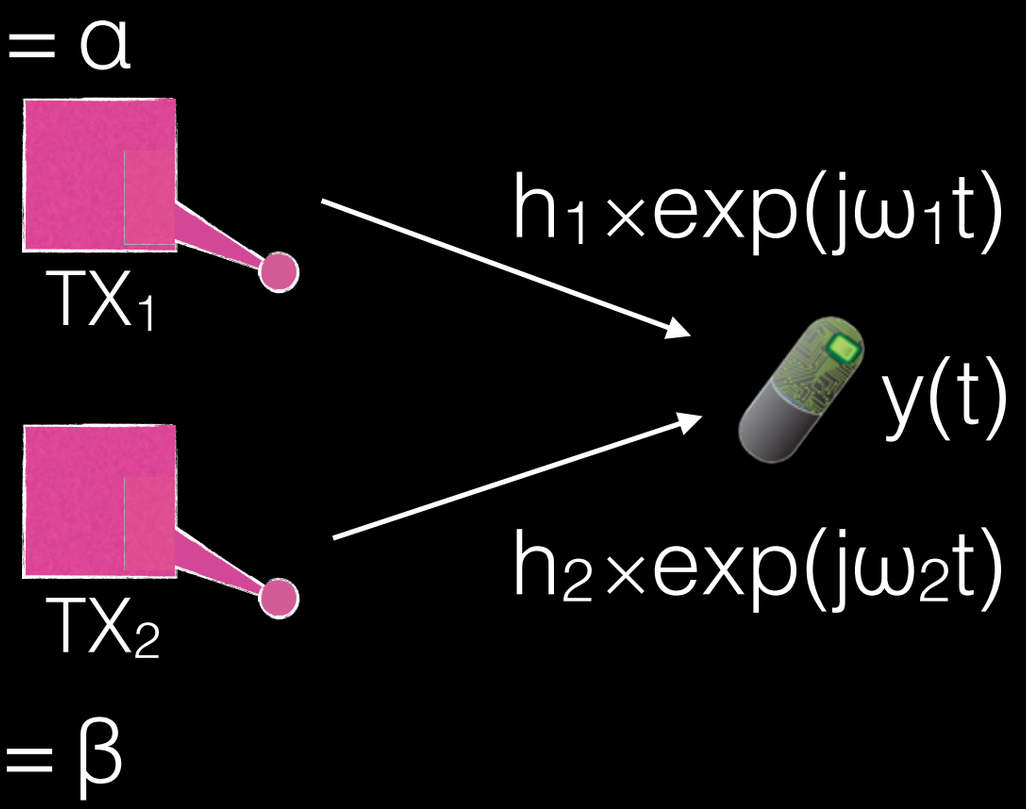
Apply constant multiplier (phase shift)



$$y = \alpha h_1 + \beta h_2$$

IVN beamforming

Apply time-varying multiplier (frequency shift)

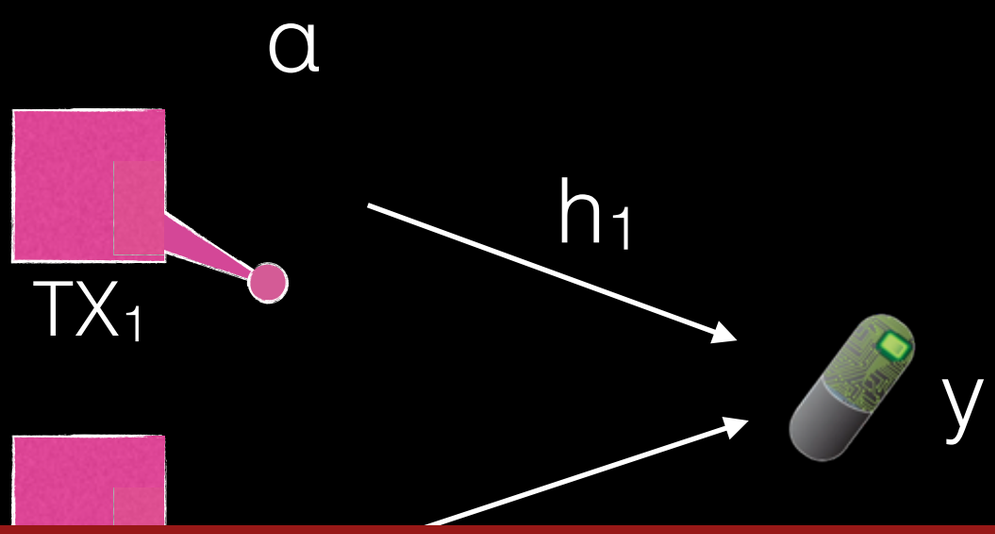


$$y(t) = \alpha h_1 e^{j\omega_1 t} + \beta h_2 e^{j\omega_2 t}$$
$$= \alpha h_1(t) + \beta h_2(t)$$

Mathematically, IVN introduces a time-varying channel

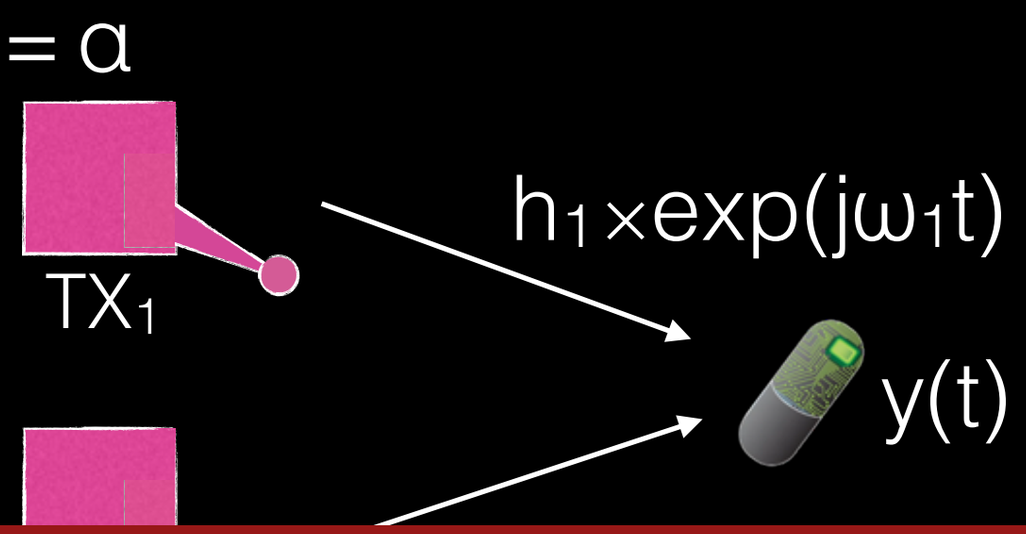
Traditional MIMO

Apply constant multiplier (phase shift)



IVN beamforming

Apply time-varying multiplier (frequency shift)



IVN's beamformer introduces frequency shifts to focus power under blind channel conditions

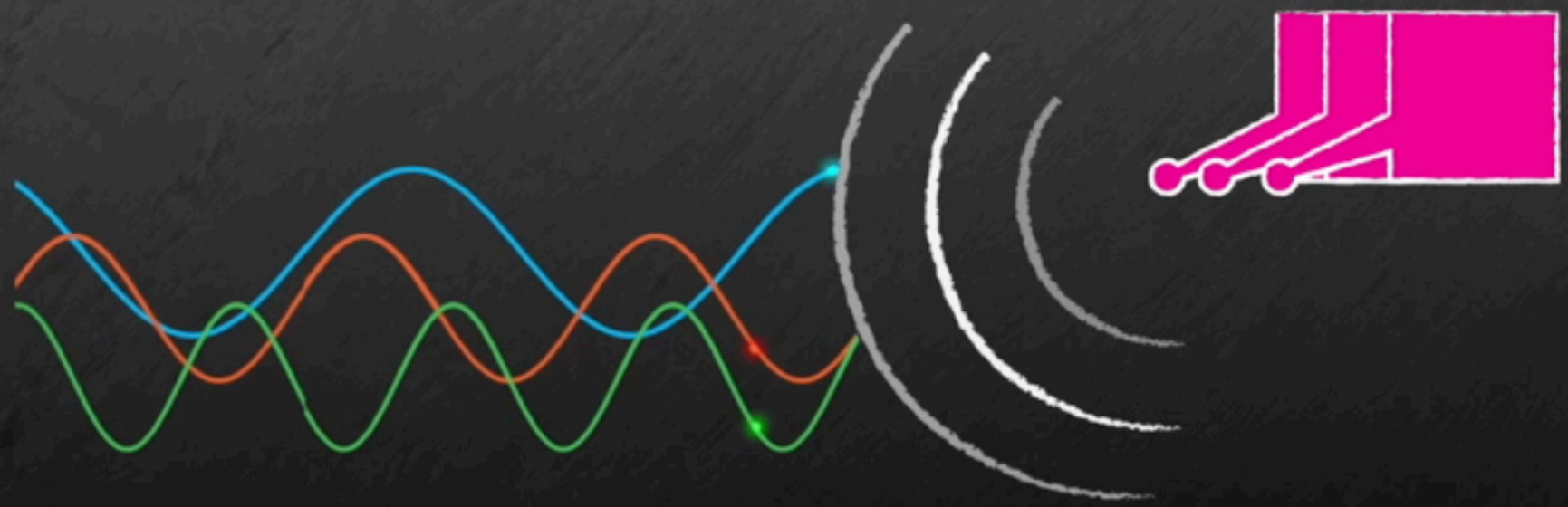
$$y = \alpha h_1 + \beta h_2$$

$$y(t) = \alpha h_1 e^{j\omega_1 t} + \beta h_2 e^{j\omega_2 t}$$
$$= \alpha h_1(t) + \beta h_2(t)$$

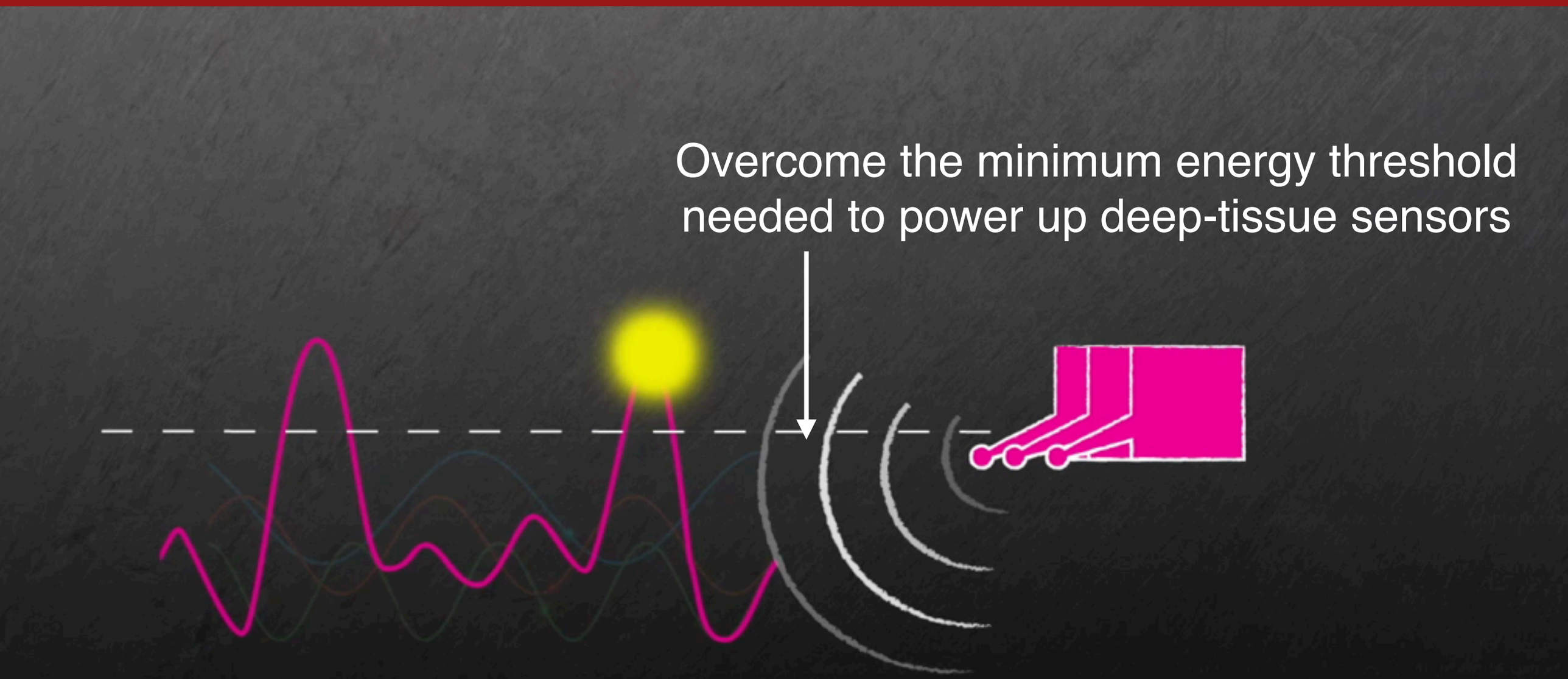
Mathematically, IVN introduces a time-varying channel

IVN's beamformer introduces frequency shifts to focus power under blind channel conditions

IVN's beamformer introduces frequency shifts to focus power under blind channel conditions



IVN's beamformer introduces frequency shifts to focus power under blind channel conditions



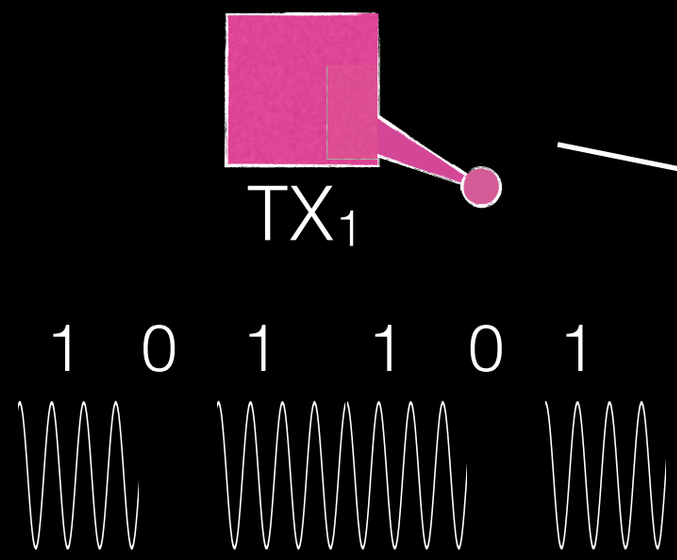
Deep-Tissue Communication

Deep-Tissue Communication

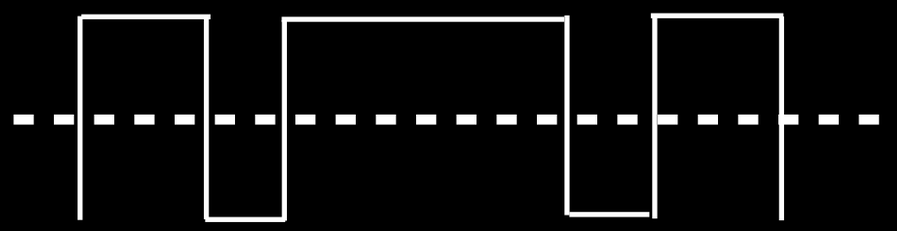
IVN leverages backscatter, the most energy-efficient communication technology

Deep-Tissue Communication

IVN leverages backscatter, the most energy-efficient communication technology



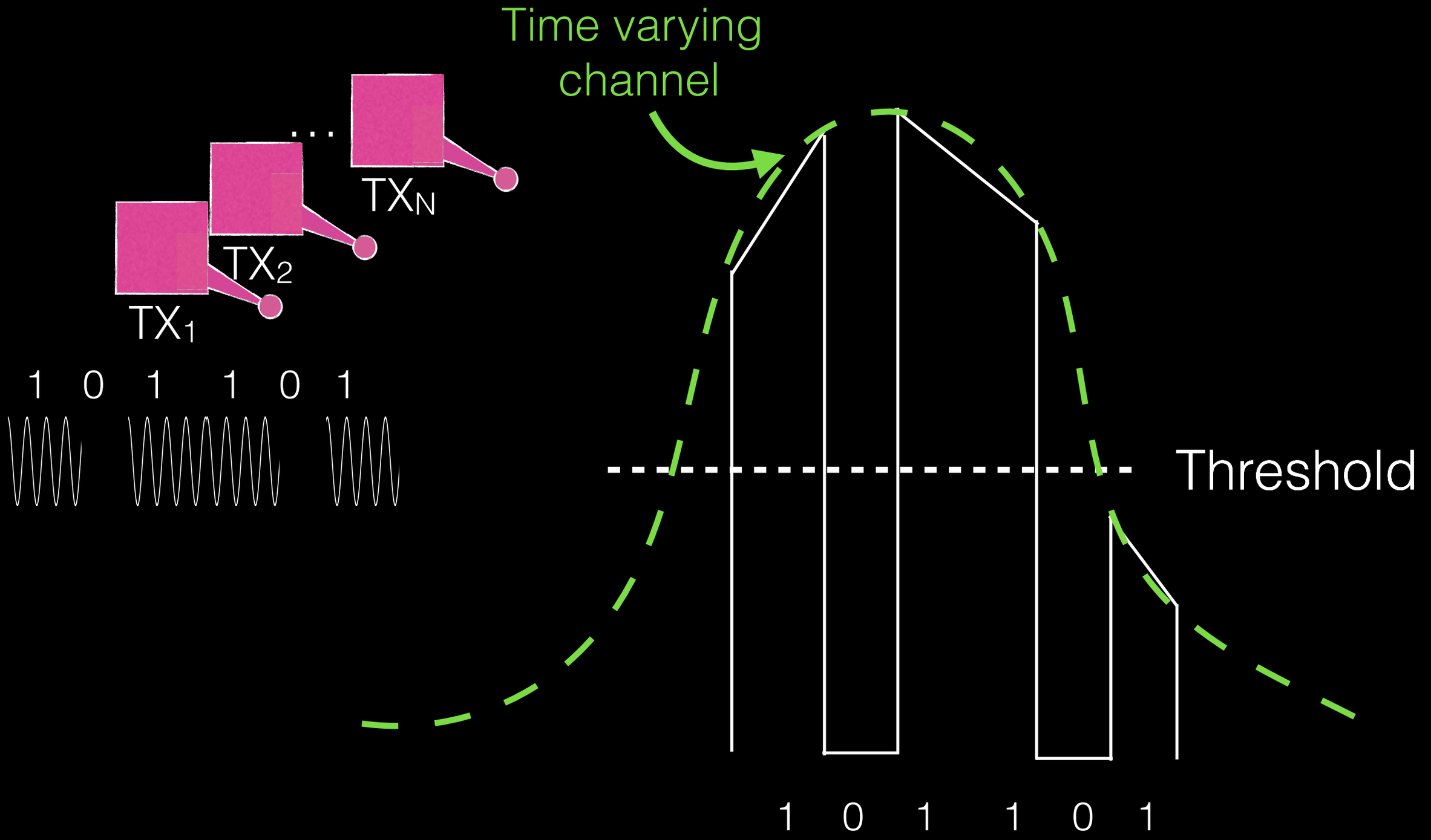
Energy Envelope



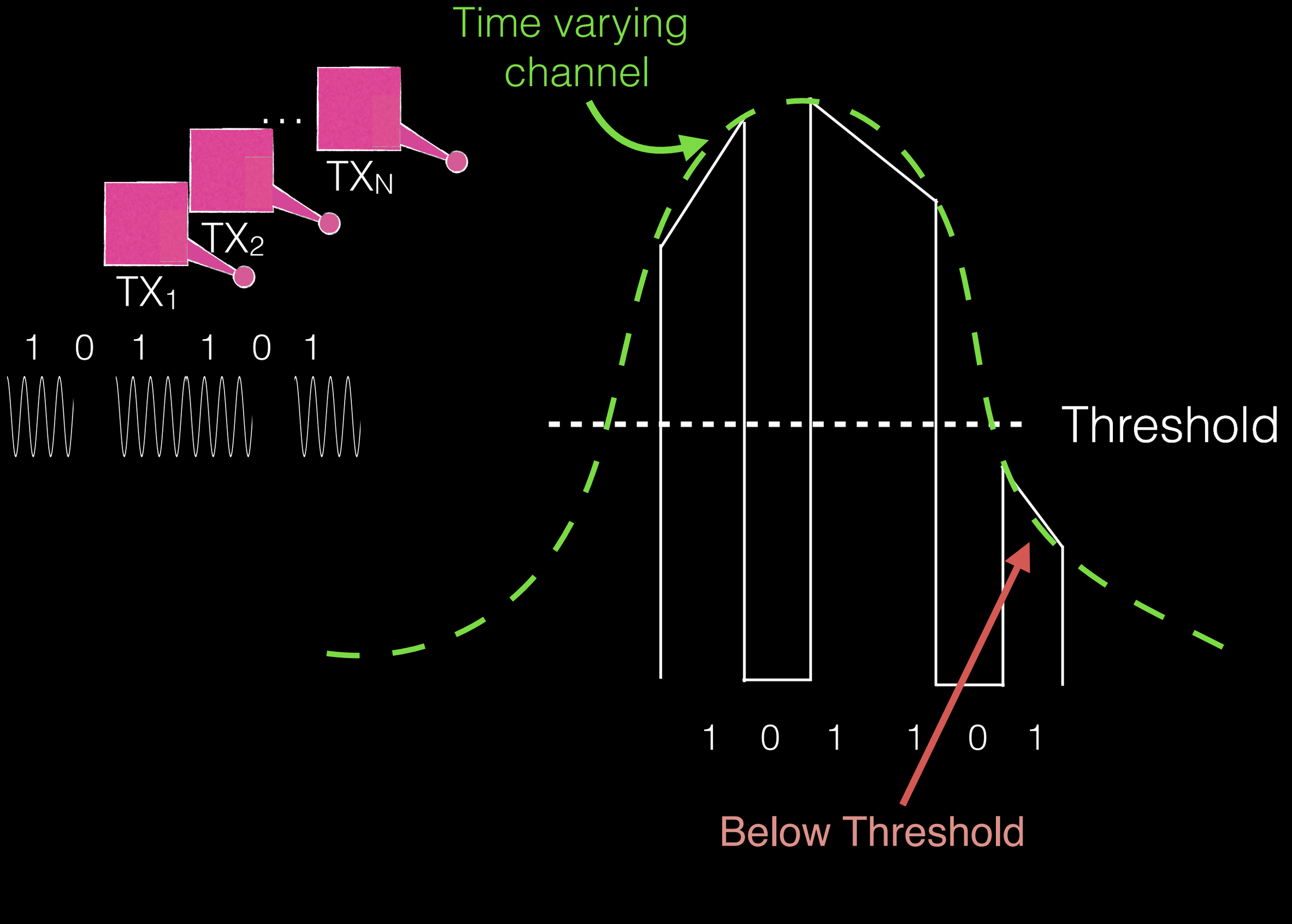
Threshold

1 0 1 1 0 1

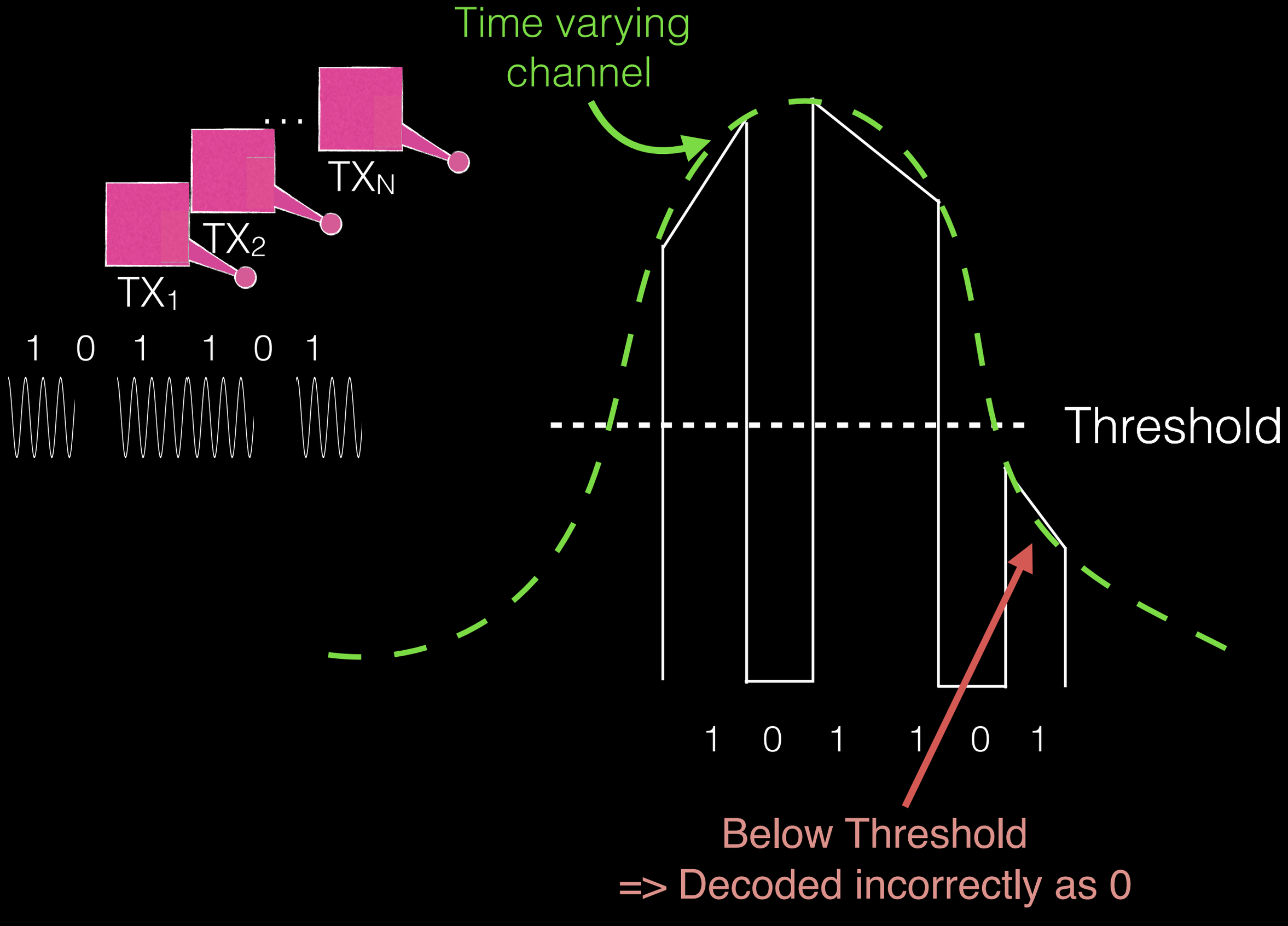
Energy Thresholding with IVN's Beamformer



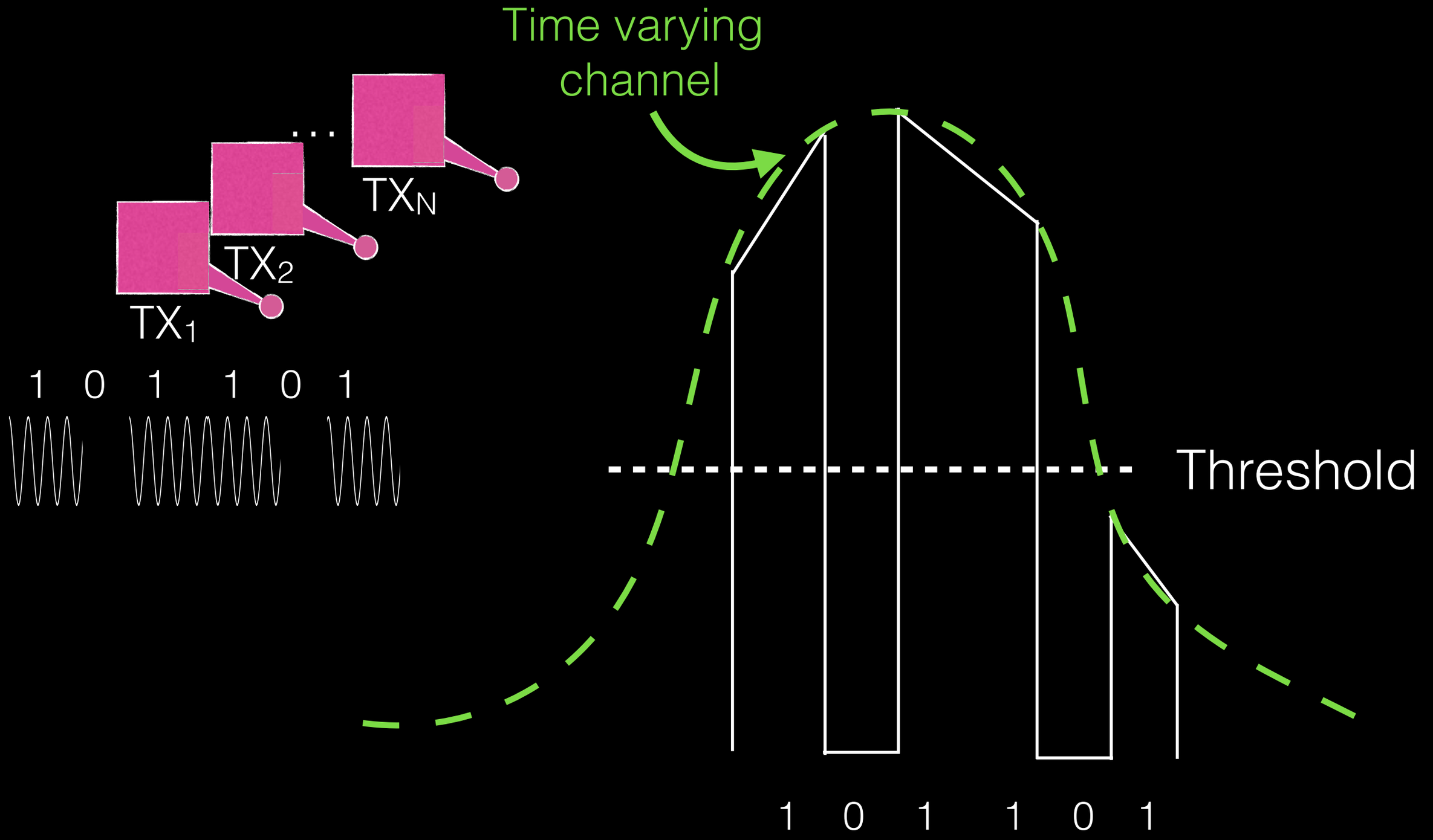
Energy Thresholding with IVN's Beamformer



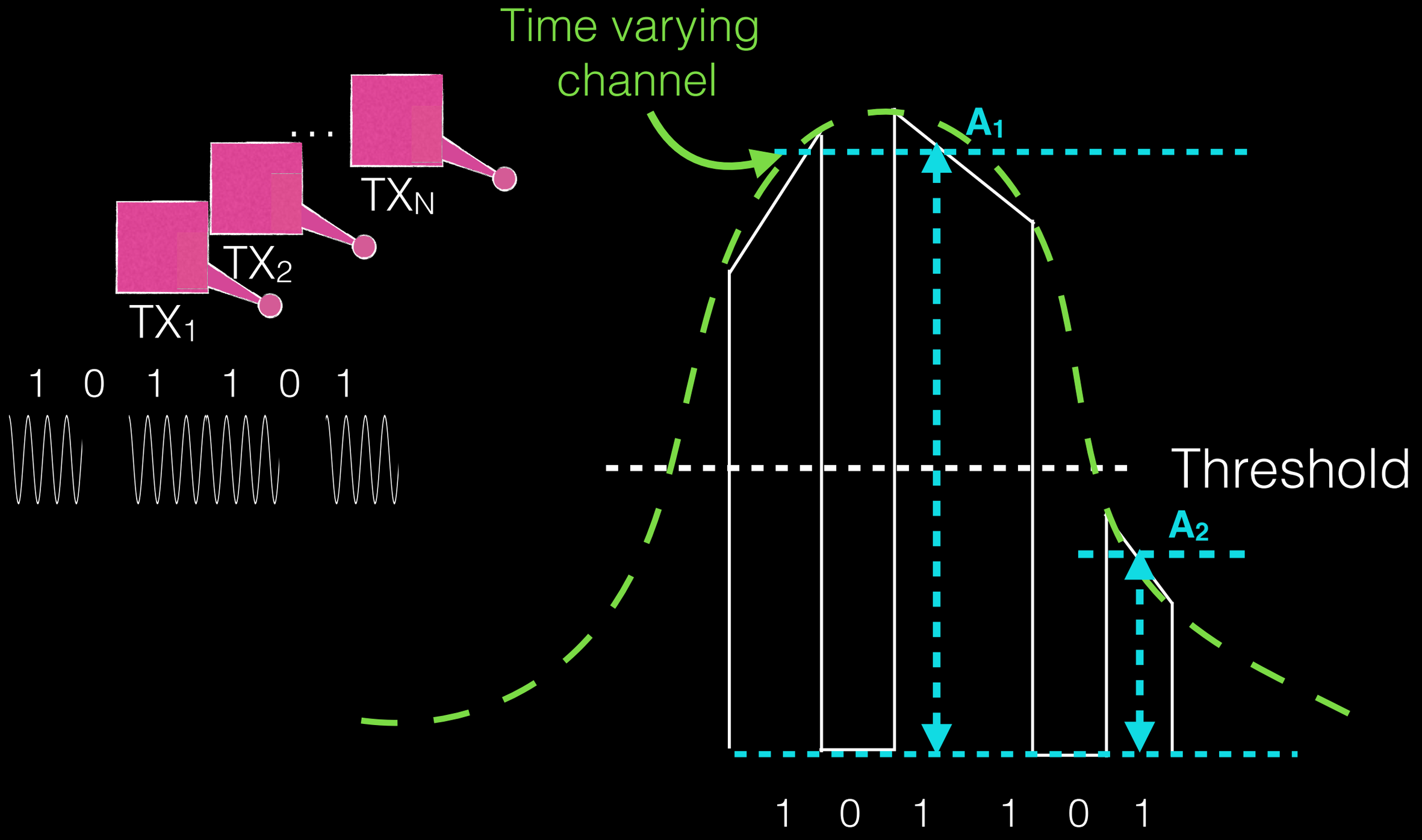
Energy Thresholding with IVN's Beamformer



Energy Thresholding with IVN's Beamformer



Energy Thresholding with IVN's Beamformer



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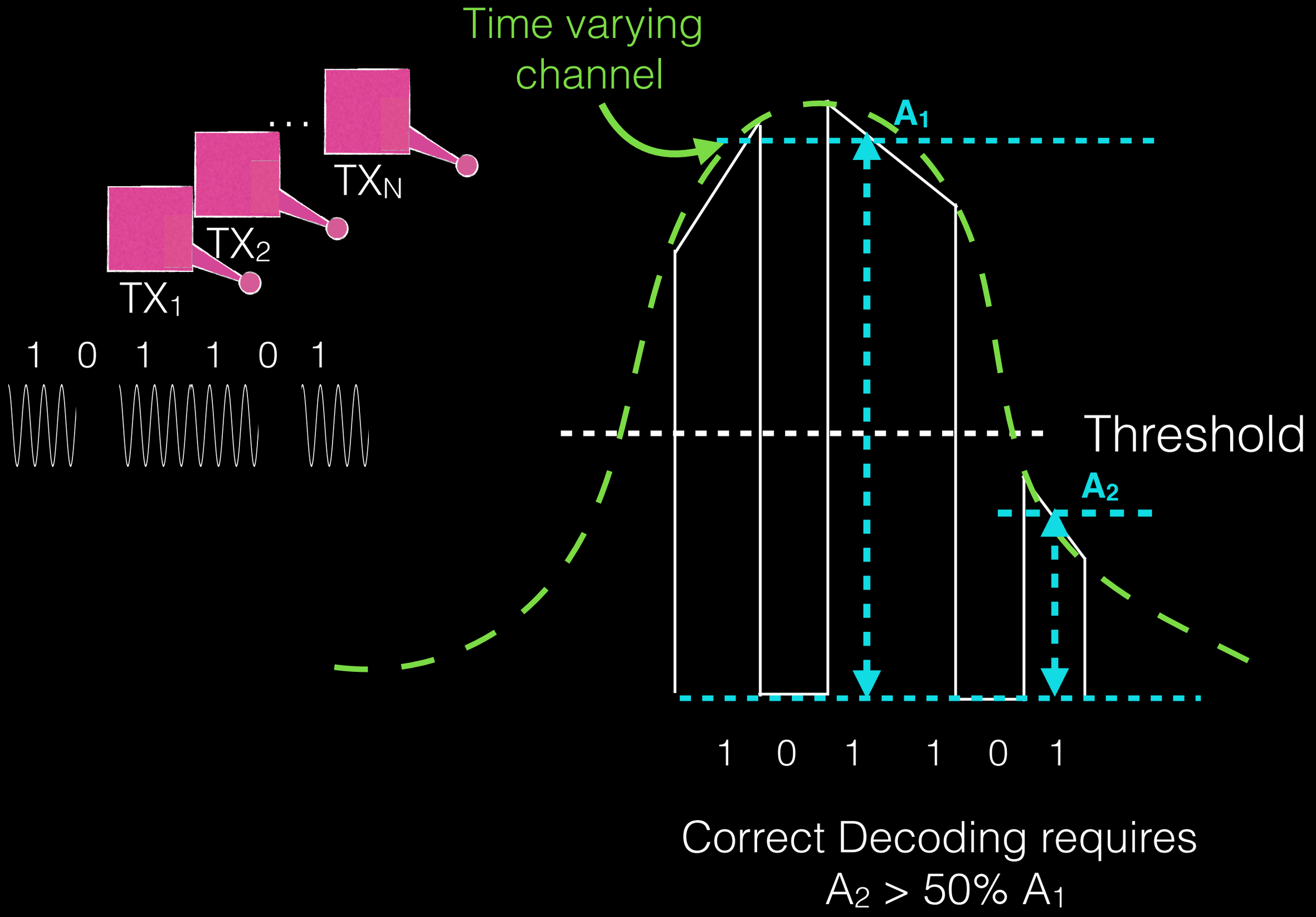
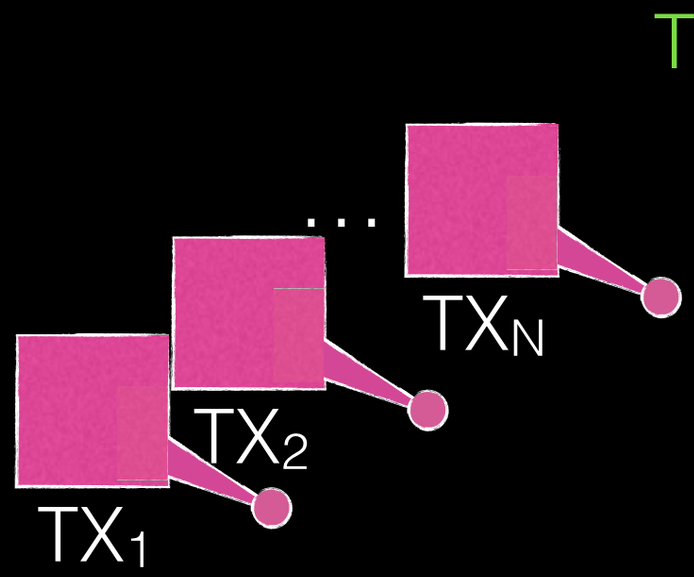
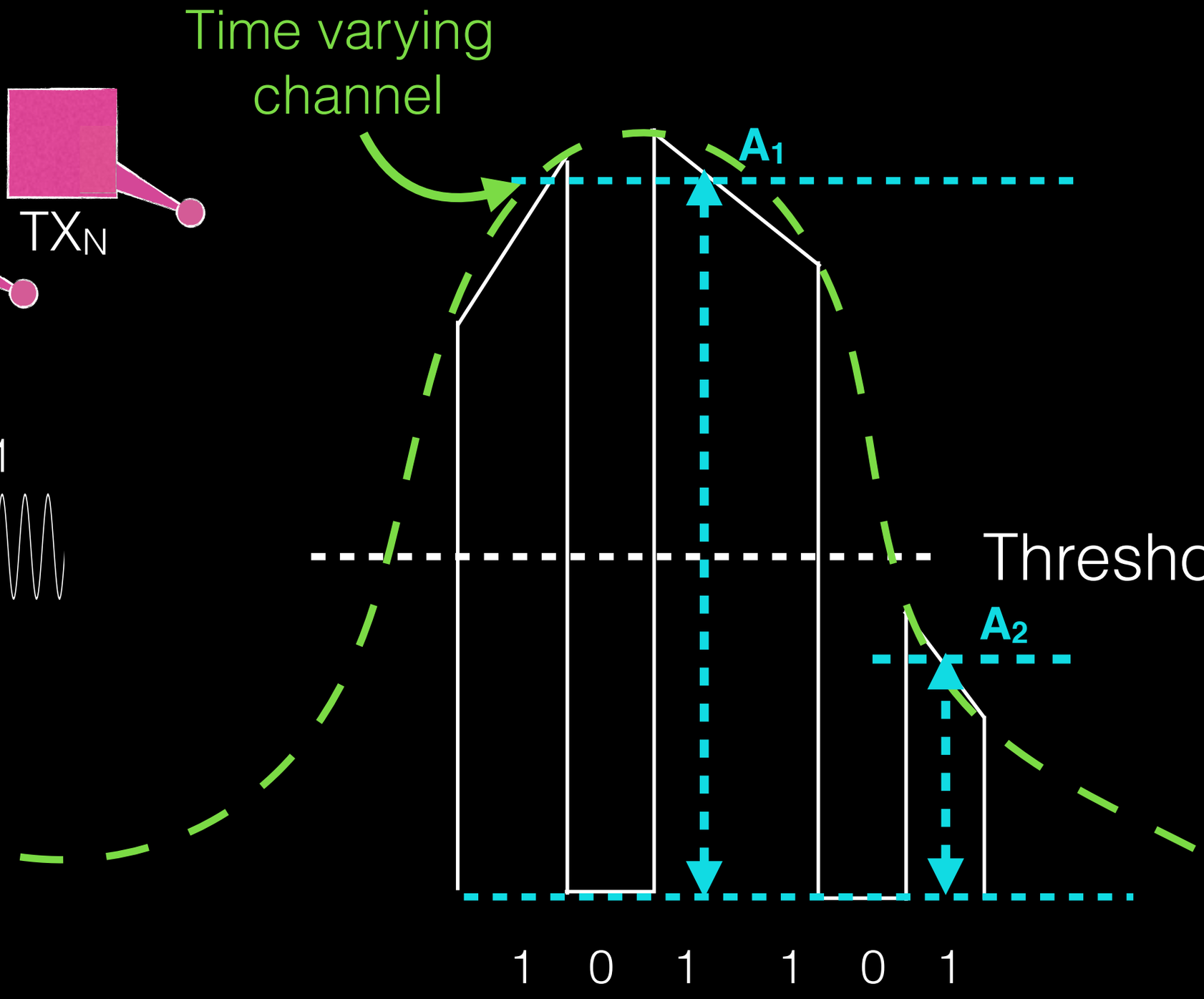


Correct Decoding requires
$A_2 > 50\% A_1$

Energy Thresholding with IVN's Beamformer

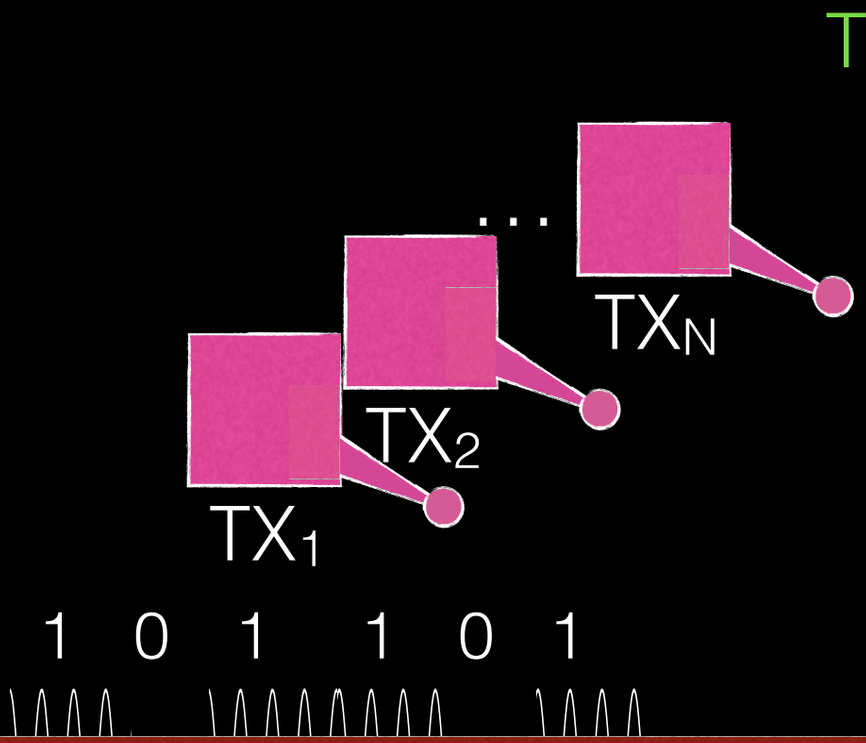




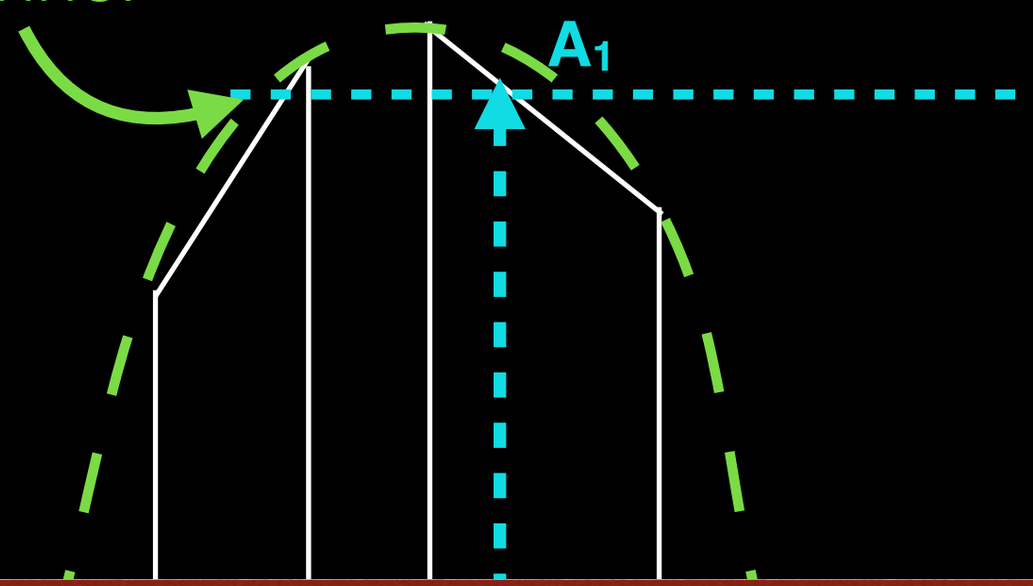
$$\frac{1}{N}\sum_{i=2}^{N}\Delta f_i{}^2 < \frac{1}{4\pi^2\,(T_{cmd})^2}$$

Correct Decoding requires
$A_2 > 50\%\ A_1$

Energy Thresholding with IVN's Beamformer



Time varying channel

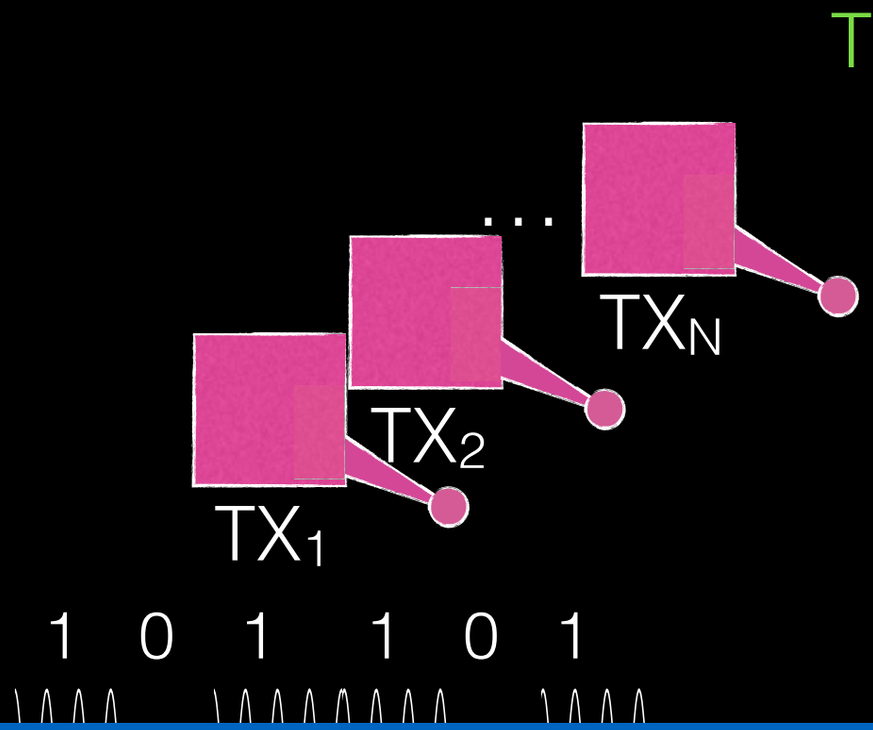


We formulate frequency selection as an optimization problem to maximize peak power with communication constraints

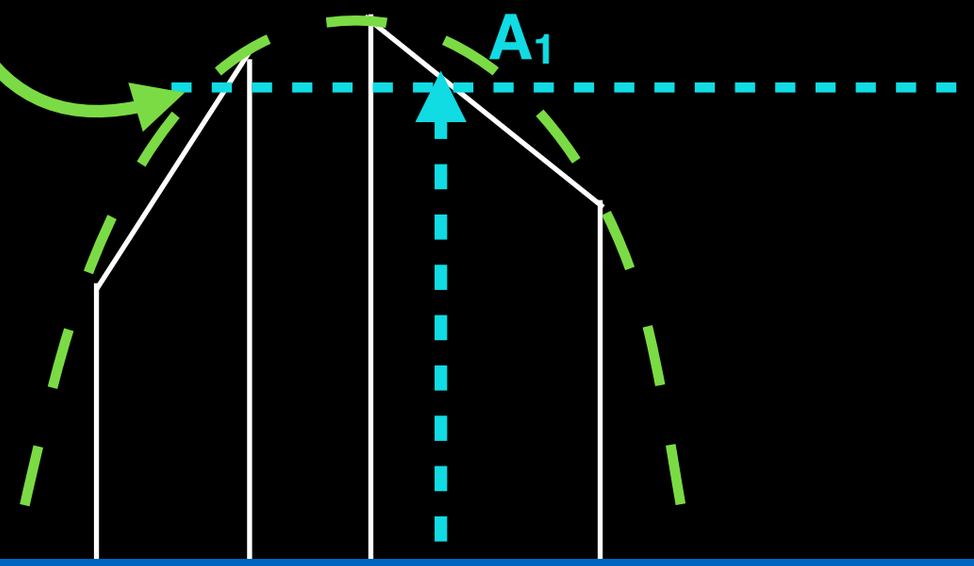
$$\frac{1}{N}\sum_{i=2}^{N}\Delta f_i^{\,2} < \frac{1}{4\pi^2\,(T_{cmd})^2}$$

Correct Decoding requires
$A_2 > 50\%\ A_1$

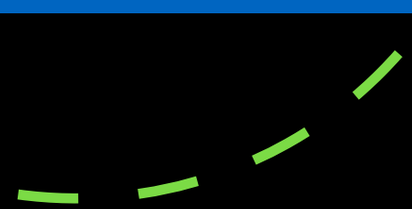
Energy Thresholding with IVN's Beamformer

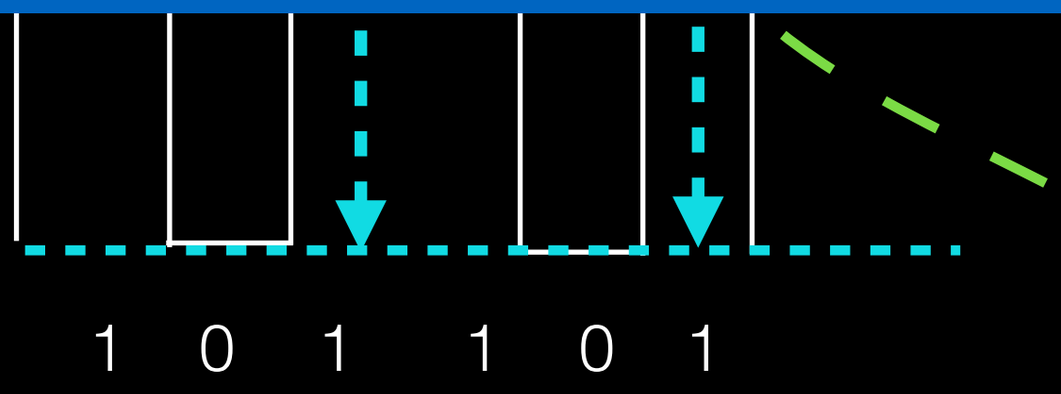


Time varying channel



Extend IVN to enable two-way communication with multiple deep-tissue sensors





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

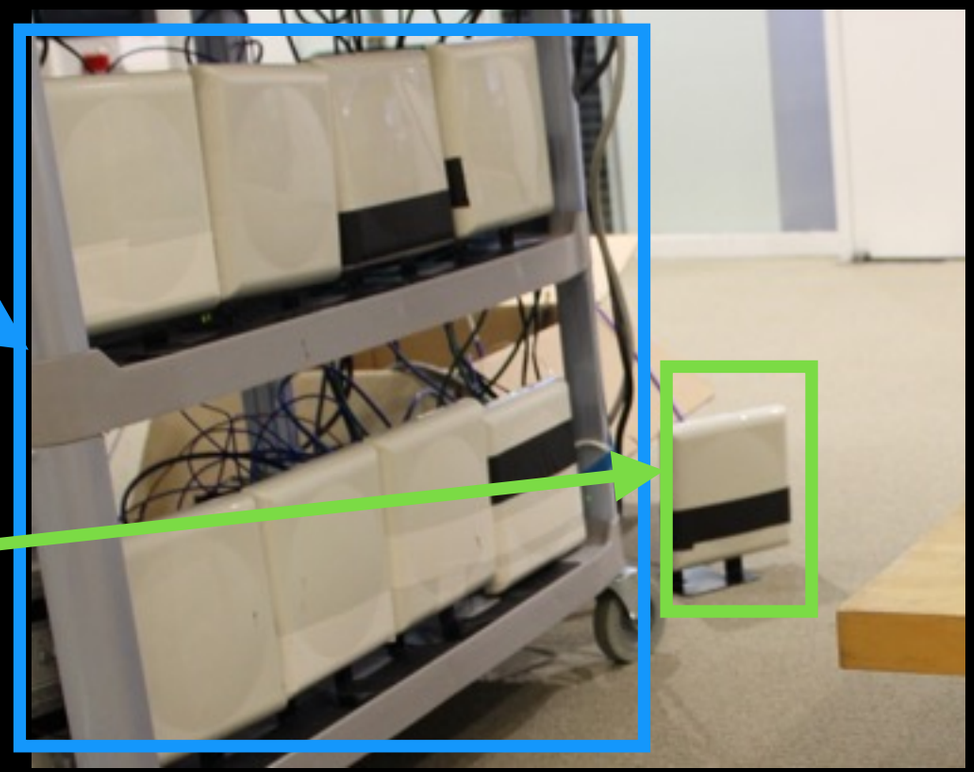
Correct Decoding requires
$A_2 > 50\%\ A_1$

Implementation & Evaluation

Implementation

IVN's Multi-antenna beamformer

- USRP N210 software defined radios with SBX daughterboard
- 6-dBi patch antennas
- Transmit around 900MHz



Out-of-band reader

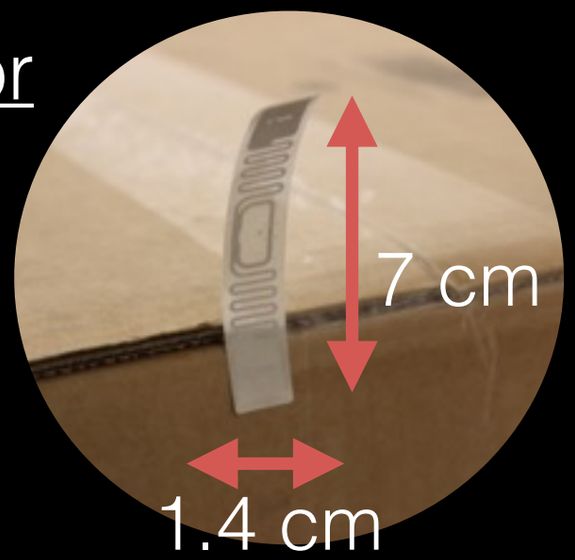
- Deals with self-interference on uplink

Beamforming and communication algorithms written in the USRP driver

Baseline: Multi-antenna transmitter (MIMO) using same setup

Standard sensor

Avery Dennison
AD-238u8 RFID



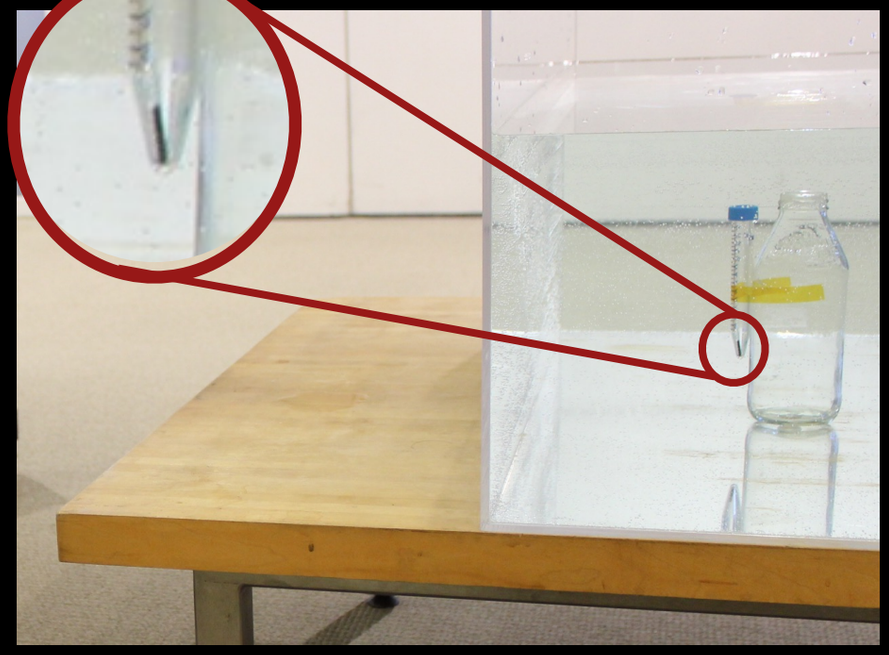
Miniature sensor

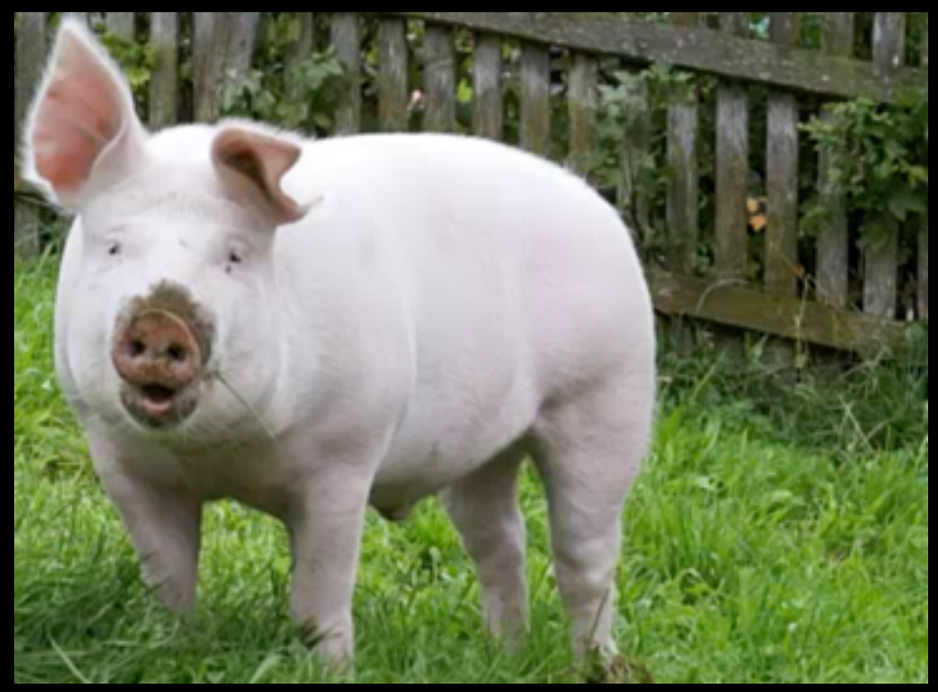
Xerafy Dash-On
XS

Evaluation

- <u>In-Vitro:</u> Out-of-body Liquids and Simulated Fluids
  - Water, gastric fluid, intestinal fluid
- <u>Ex-Vivo:</u> Various animal tissues (performed outside animals)
  - Pork meat, chicken breast, beef meat
- <u>In-Vivo:</u> Experiment inside living animal
  - Living yorkshire pig

miniature tag





Can IVN deliver the multi-antenna power gain?

Can IVN deliver the multi-antenna power gain?

Experiment: Test 10-antenna beamformer in different tissues

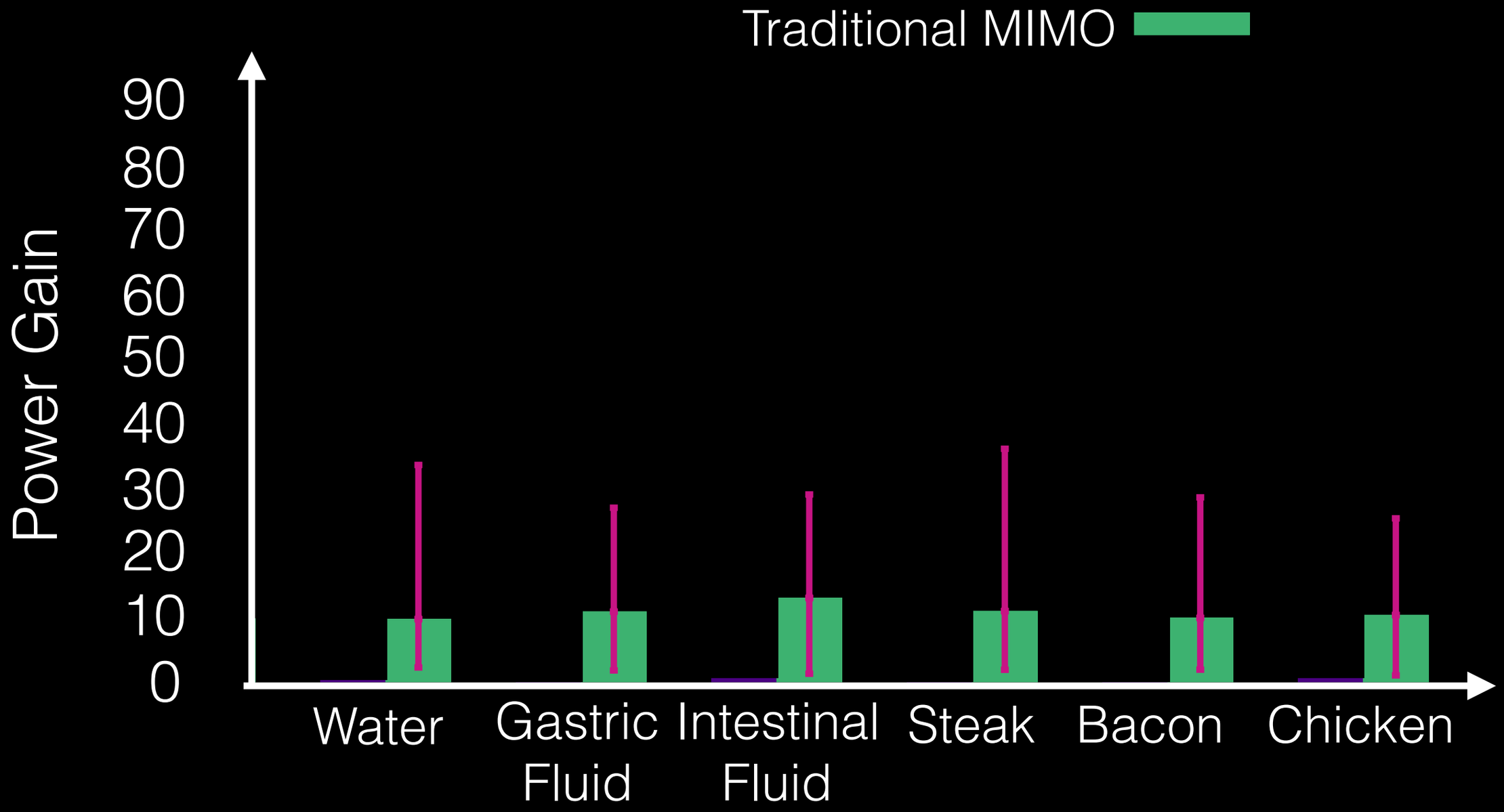
Can IVN deliver the multi-antenna power gain?

Experiment: Test 10-antenna beamformer in different tissues

Measured as ratio of the peak power of the multi-antenna beamformer to that of a single-antenna transmitter

Can IVN deliver the multi-antenna power gain?

Experiment: Test 10-antenna beamformer in different tissues



Can IVN deliver the multi-antenna power gain?

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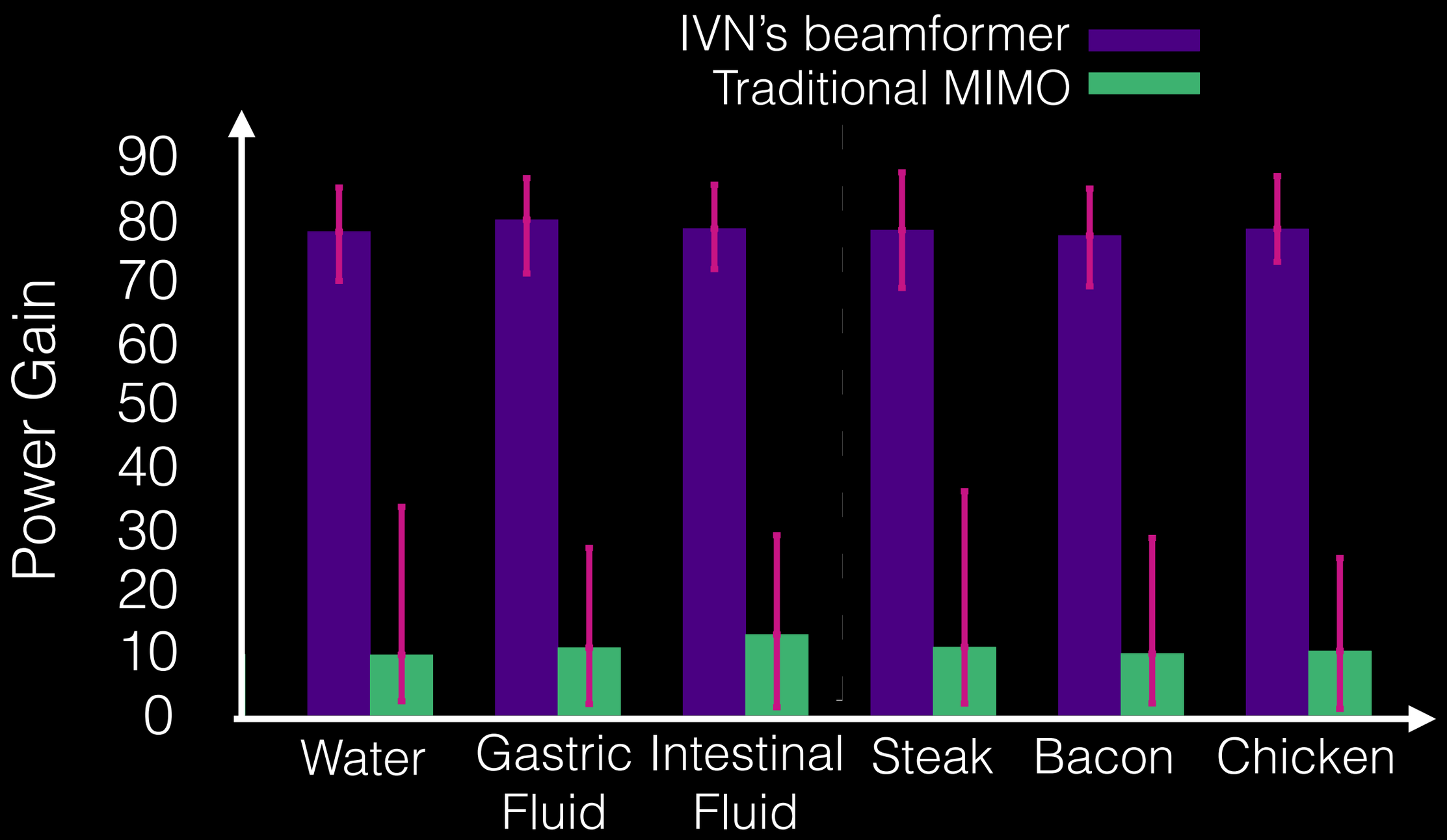

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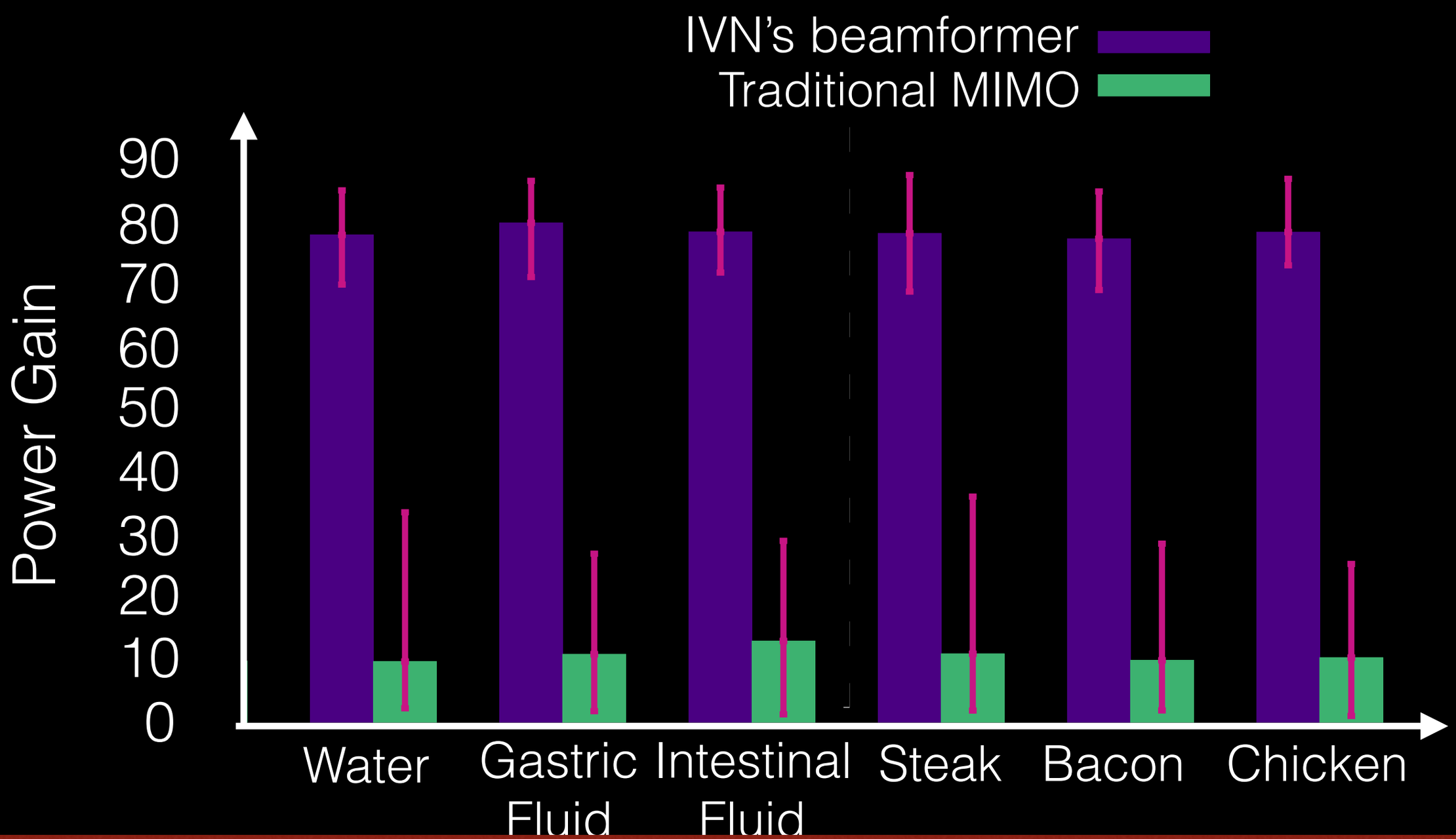

IVN can deliver MIMO gains under blind channel conditions to deep tissue battery-free sensors

Communication Depth inside Water (Standard Sensor)

Experiment: Vary the depth of a standard battery-fee sensor (i.e., RFID) inside water and evaluate our ability to communicate with it

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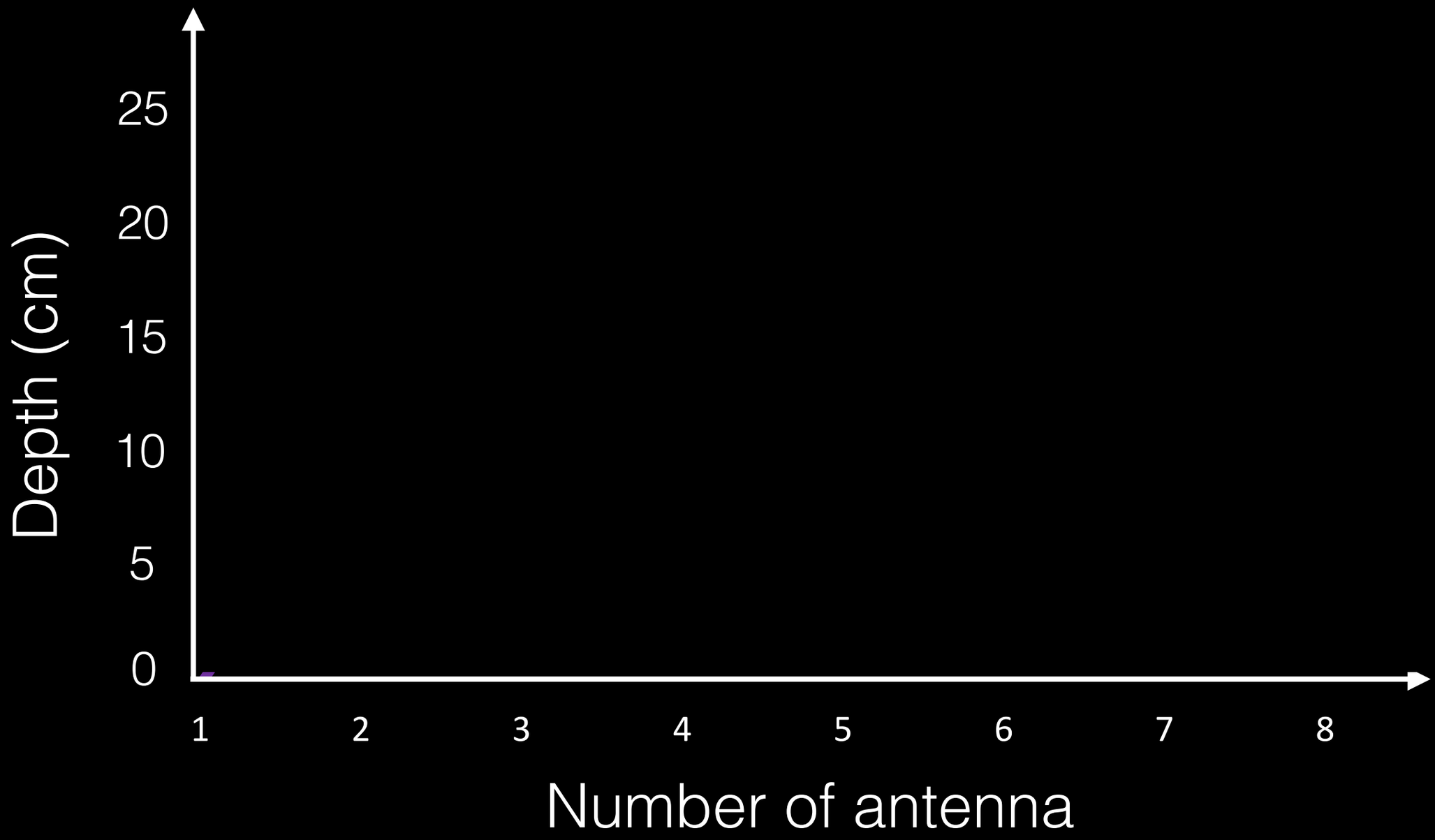
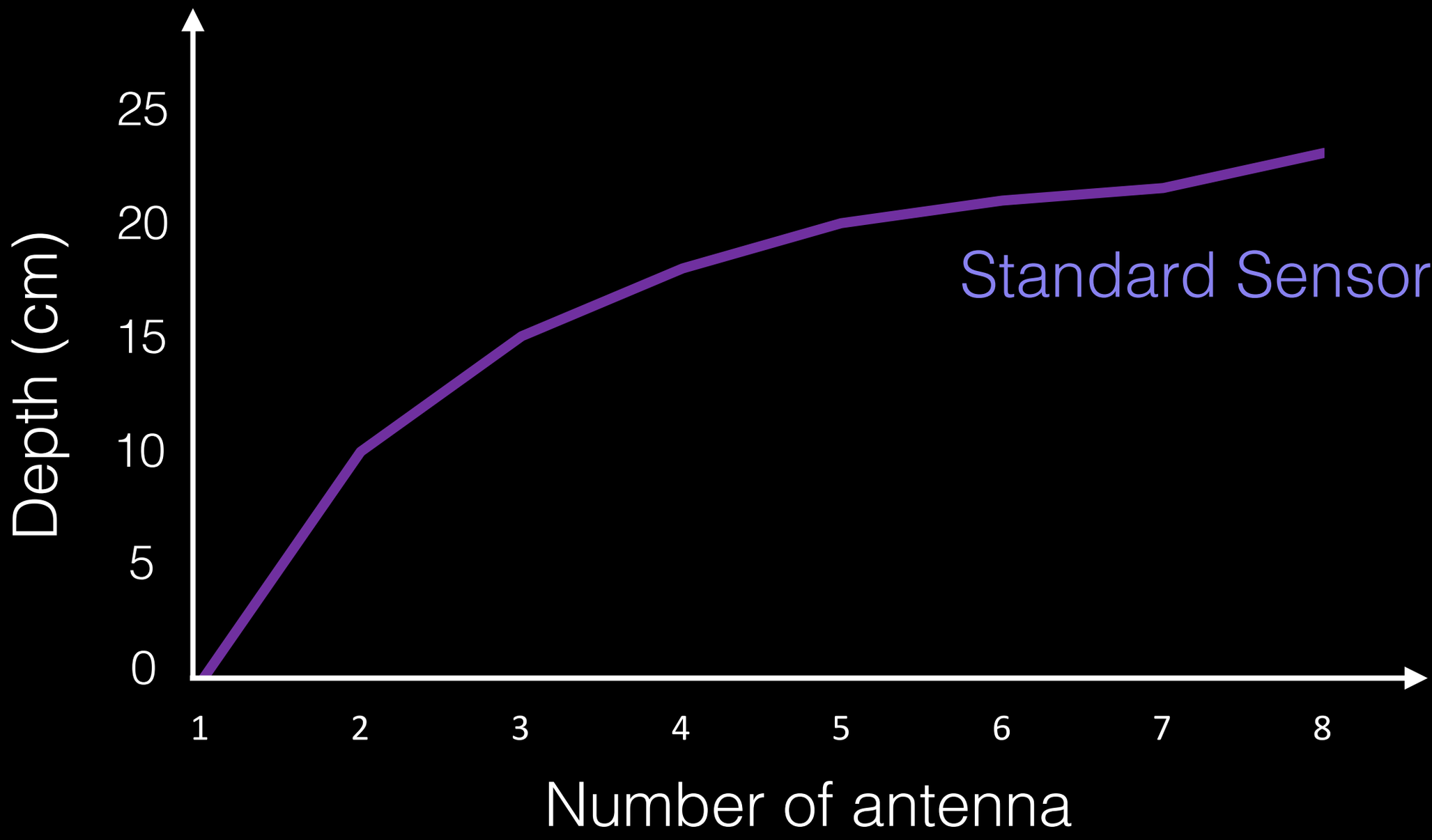


Communication Depth inside Water (Standard Sensor)

Experiment: Vary the depth of a standard battery-fee sensor (i.e., RFID) inside water and evaluate our ability to communicate with it

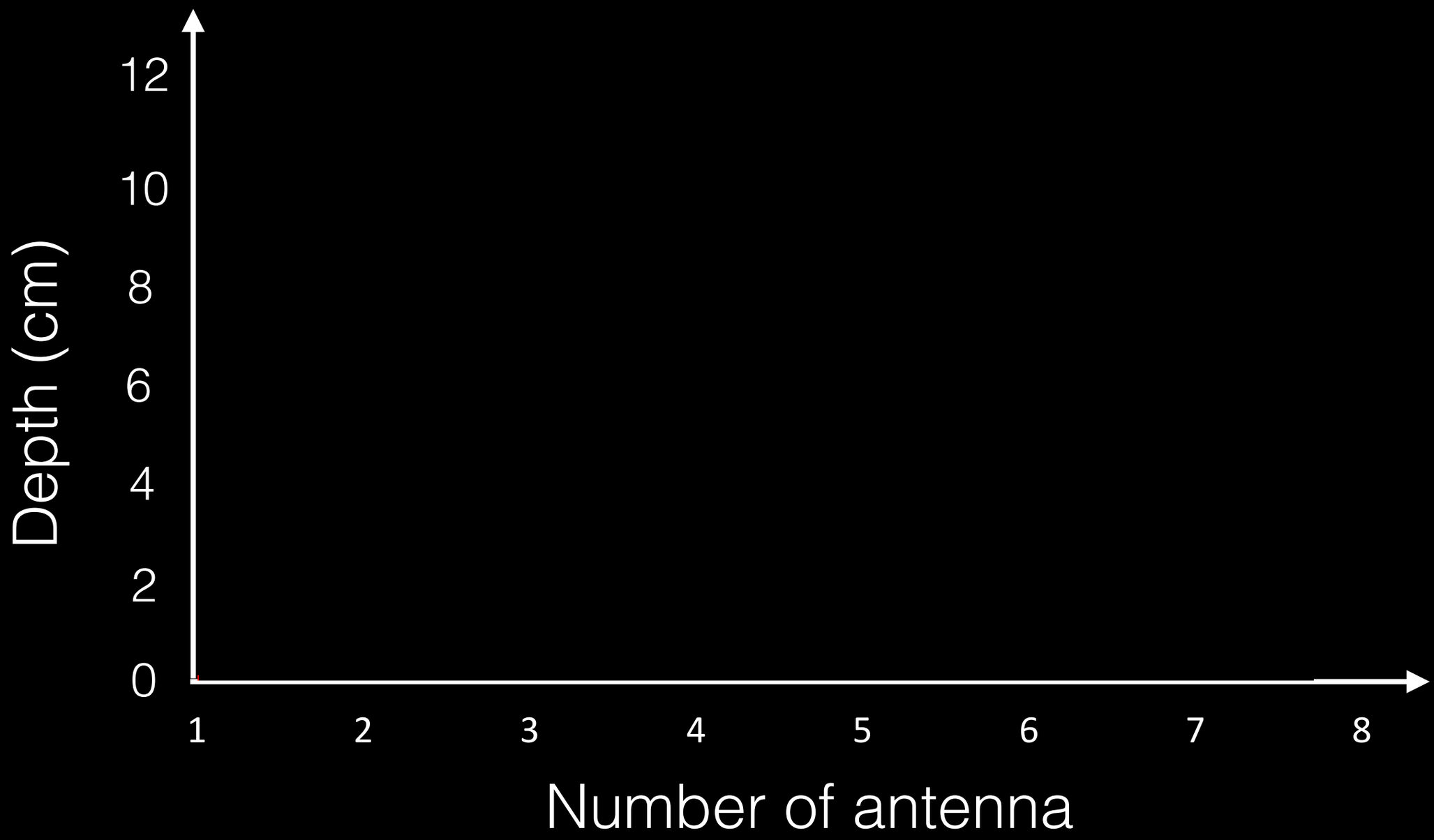


Communication Depth inside Water (Miniature Sensor)

Experiment: Vary the depth of a miniature battery-fee sensor inside water and evaluate our ability to communicate with it

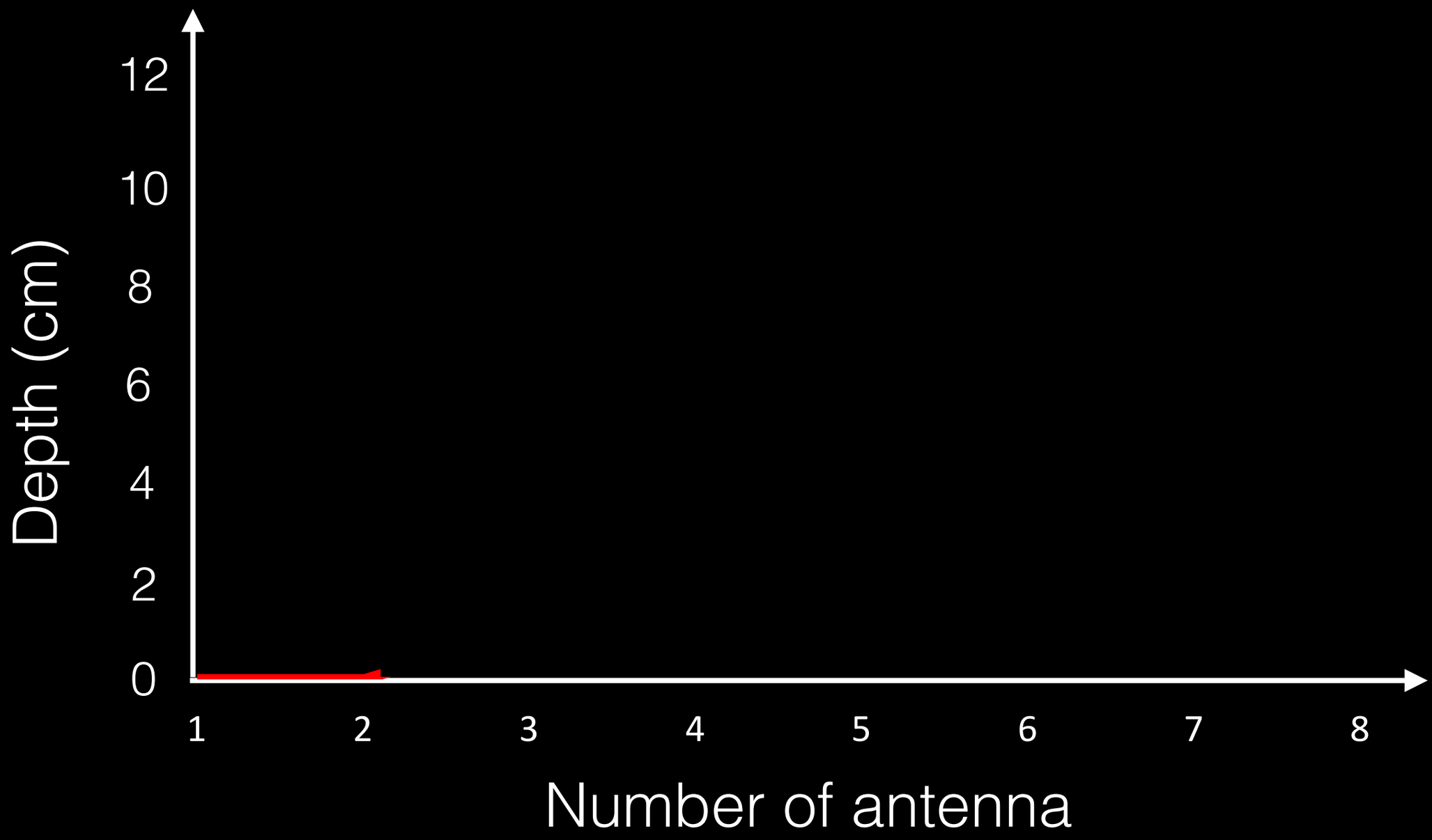
Communication Depth inside Water (Miniature Sensor)

<u>Experiment:</u> Vary the depth of a miniature battery-fee sensor inside water and evaluate our ability to communicate with it



Communication Depth inside Water (Miniature Sensor)

Experiment: Vary the depth of a miniature battery-fee sensor inside water and evaluate our ability to communicate with it



Communication Depth inside Water (Miniature Sensor)

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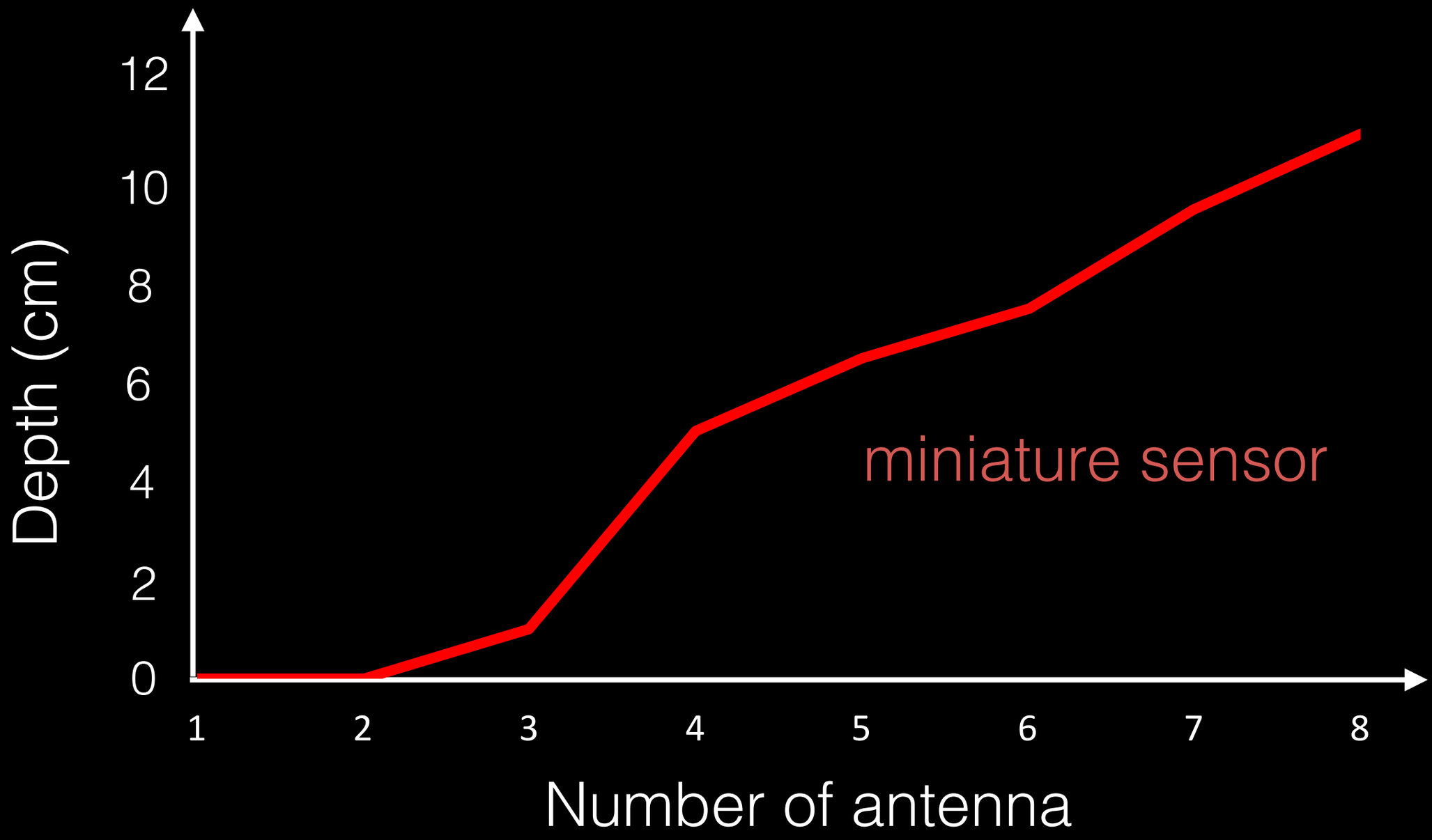
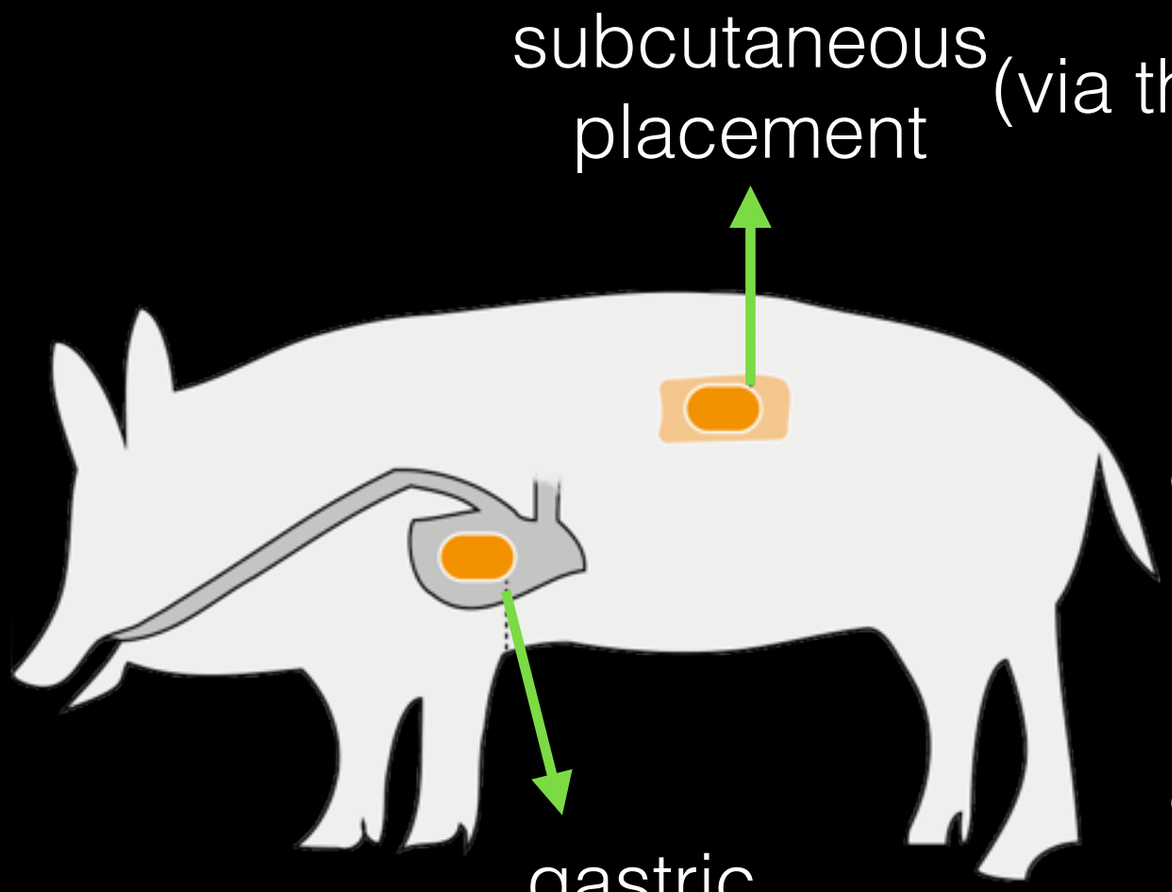


In-Vivo Evaluation with Living Animal



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

In-Vivo Evaluation with Living Animal

In-Vivo Evaluation with Living Animal

Experiment: Send command to a deep-tissue sensor and measure its response to IVN

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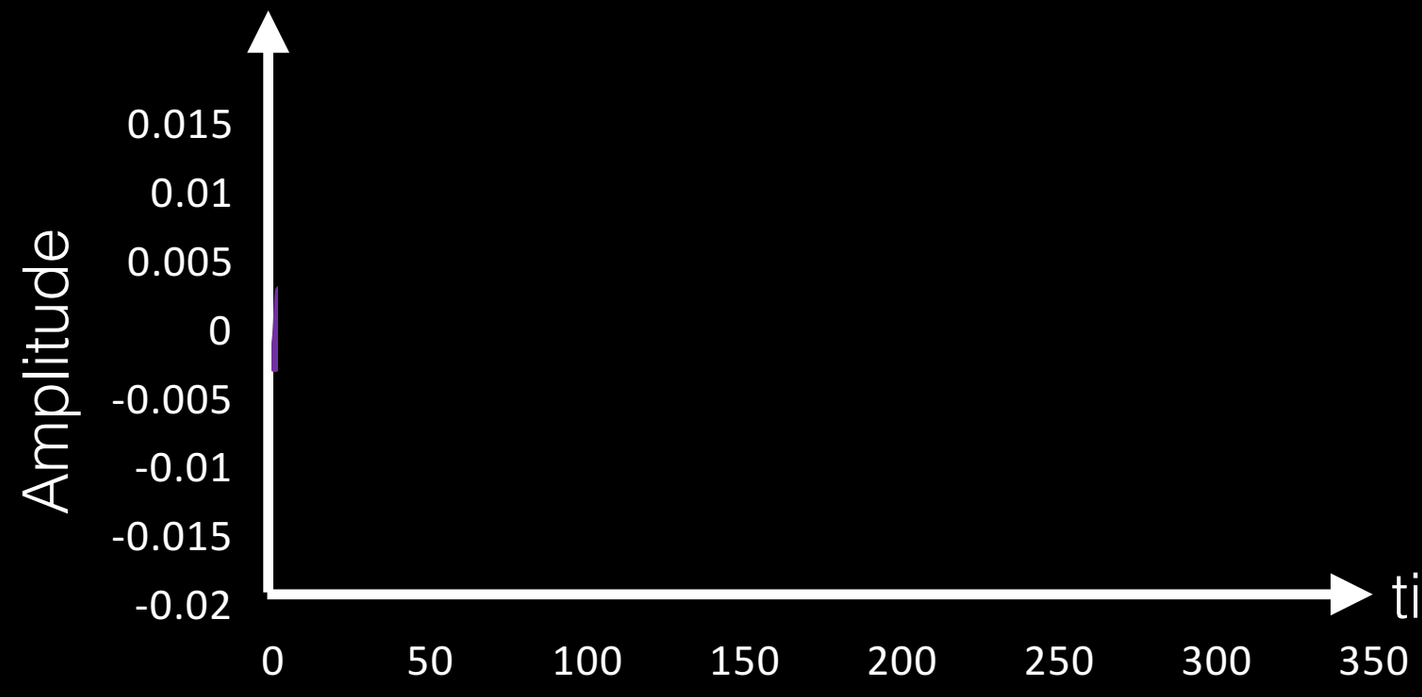
In-Vivo Evaluation with Living Animal

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

Standard sensor placed in stomach



In-Vivo Evaluation with Living Animal

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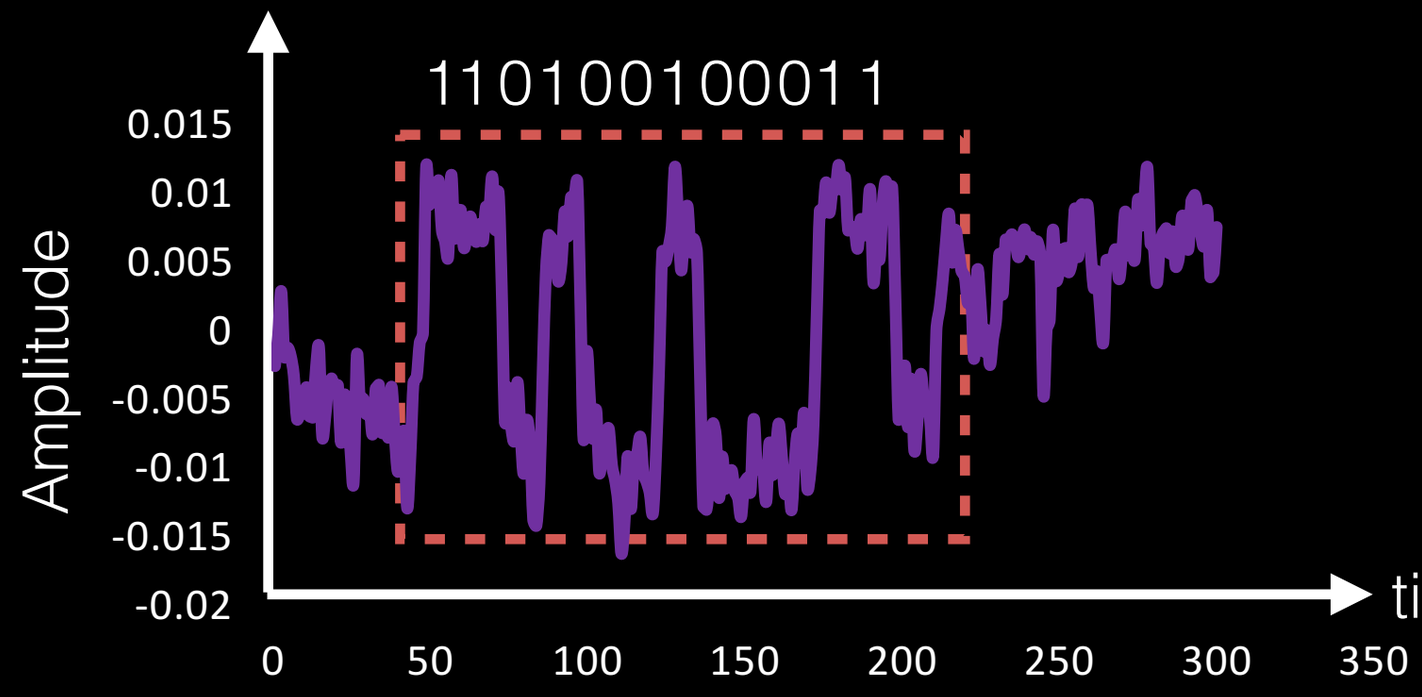

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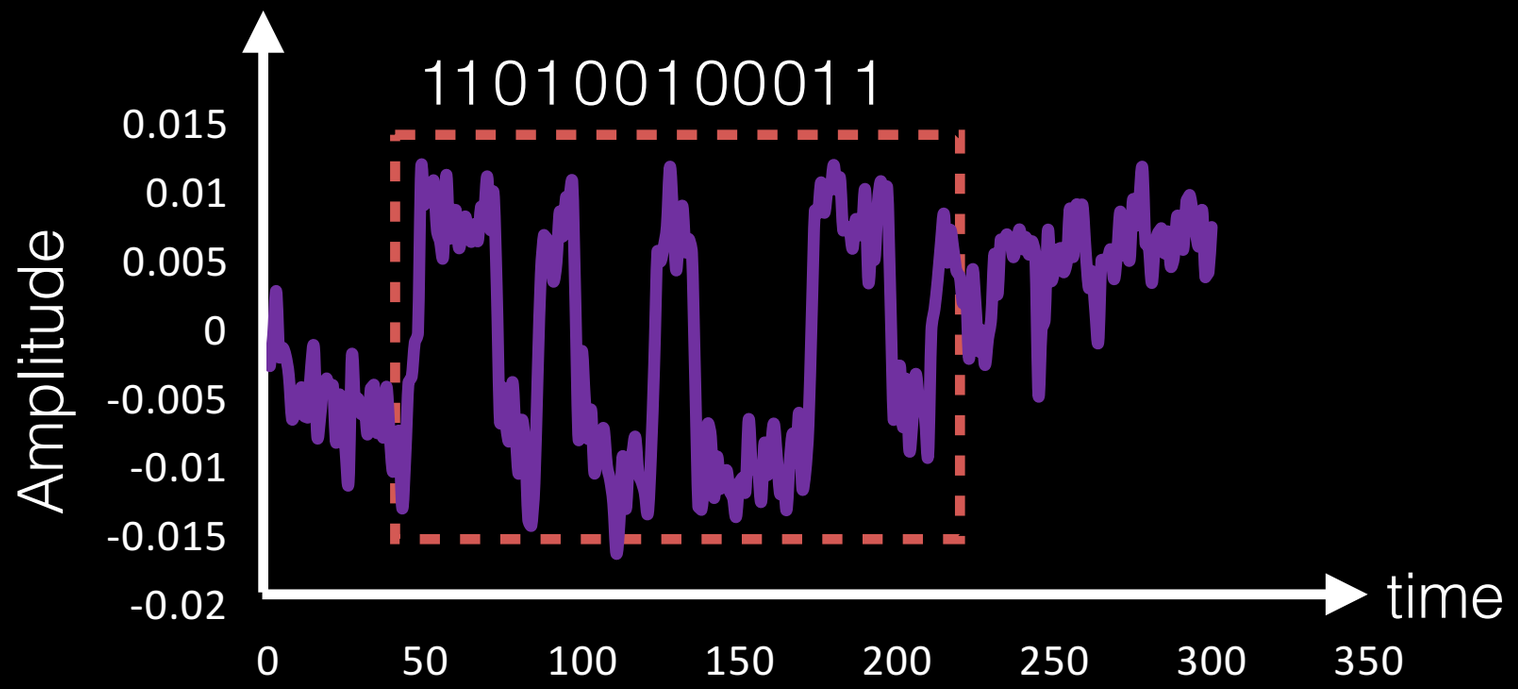
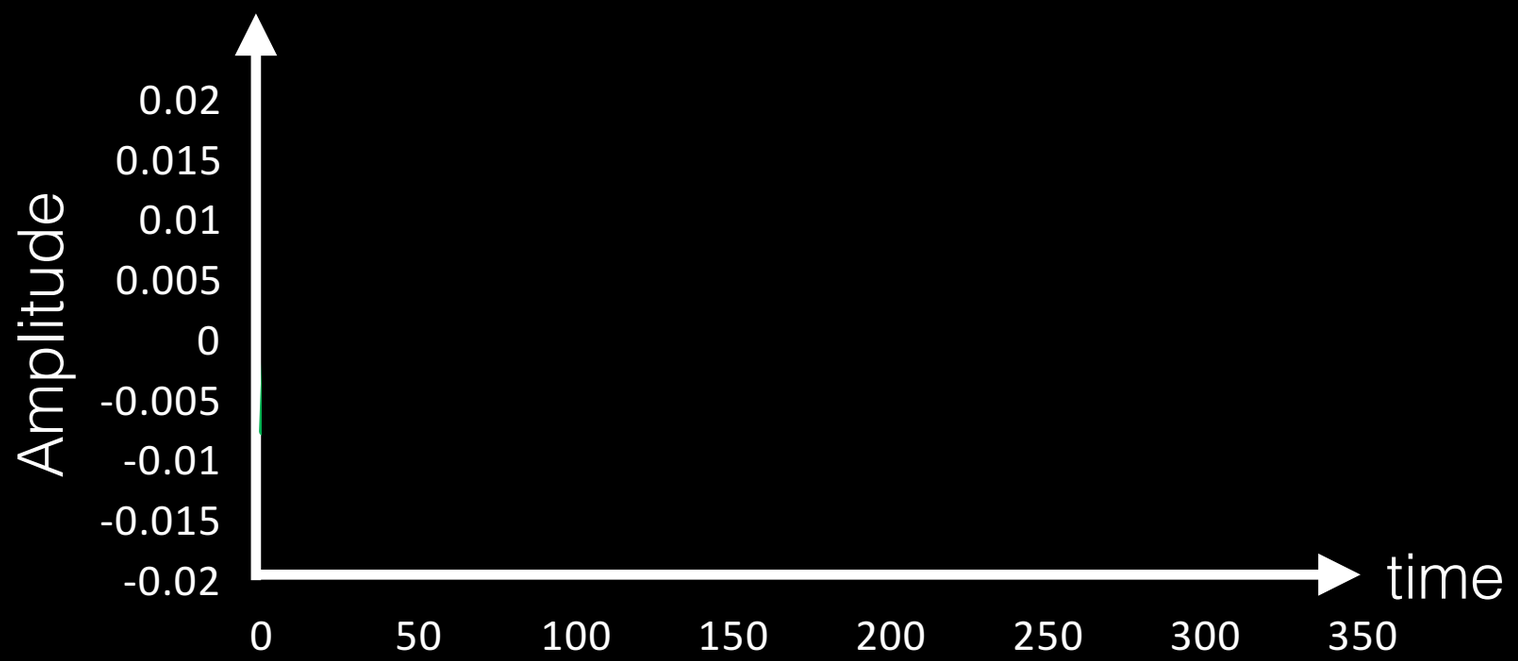


Miniature sensor placed subcutaneously



In-Vivo Evaluation with Living Animal

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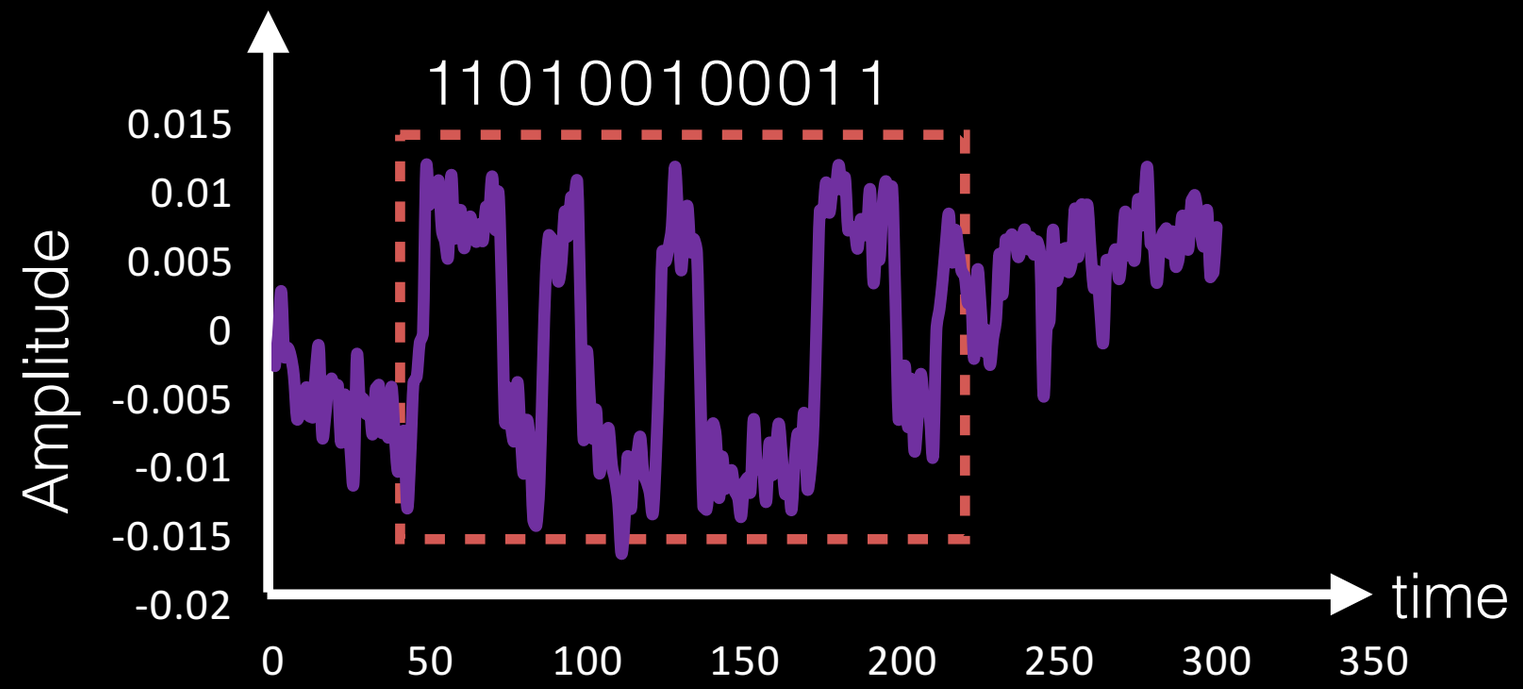
Standard sensor placed in stomach



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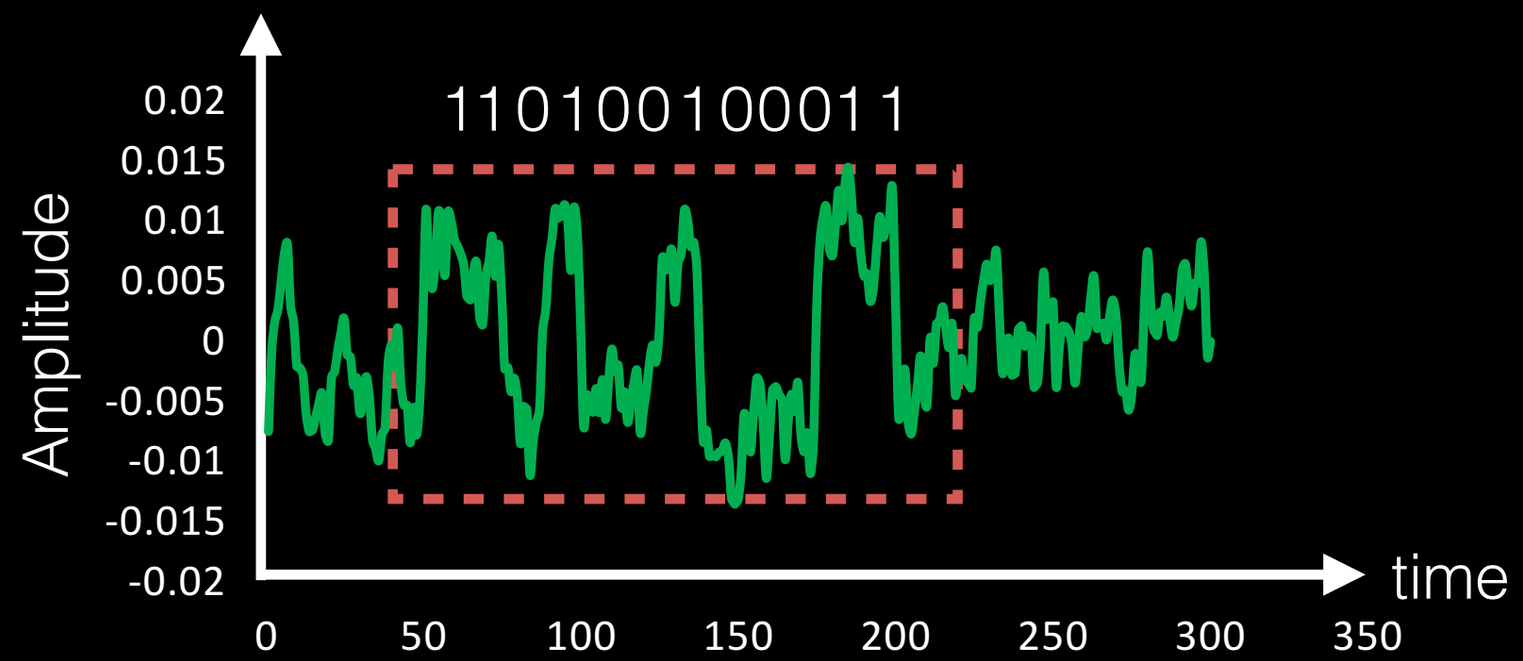

In-Vivo Evaluation with Living Animal

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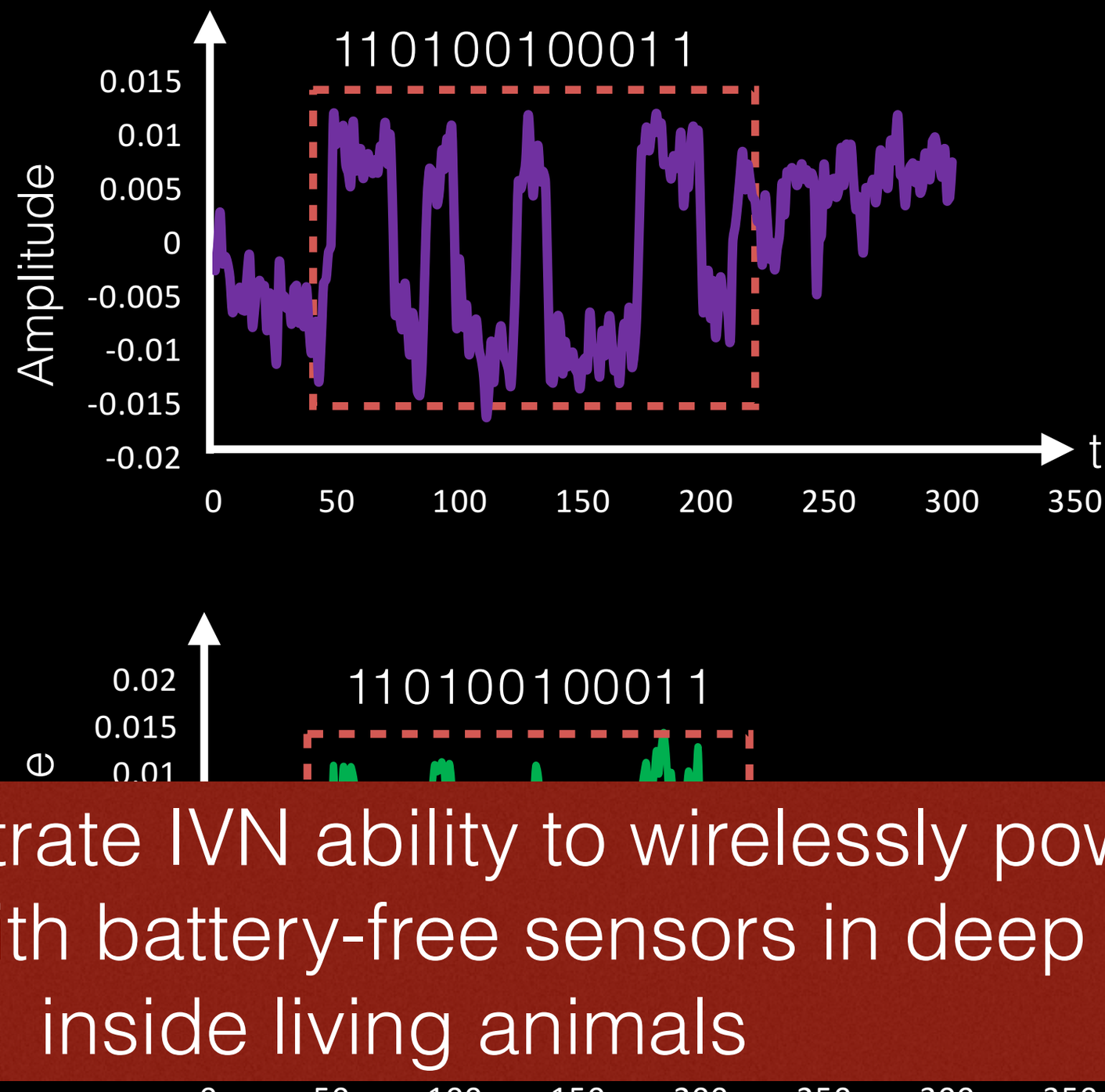

Results demonstrate IVN ability to wirelessly power and communicate with battery-free sensors in deep tissues inside living animals

Conclusion

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- IVN enables powering and communication with battery-free deep-tissue implants

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- New technology that enables beamforming to deep-tissues under blind wireless channel

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Conclusion

- IVN enables powering and communication with battery-free deep-tissue implants
- New technology that enables beamforming to deep-tissues under blind wireless channel
- IVN tested in tissues and in live animals
- Open up possibilities for wireless networking to help curing medical diseases like Parkinson's and Alzheimer's