BackFi: High Throughput WiFi Backscatter for IoT

Dinesh Bharadia*, Kiran Joshi*, Manikanta Kotaru, Sachin Katti
Stanford University
*co-primary authors

The Internet of Things (IoT) Vision

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The Internet of Things (IoT) Vision

Sense

Collect & Analyze

The Internet of Things (IoT) Vision

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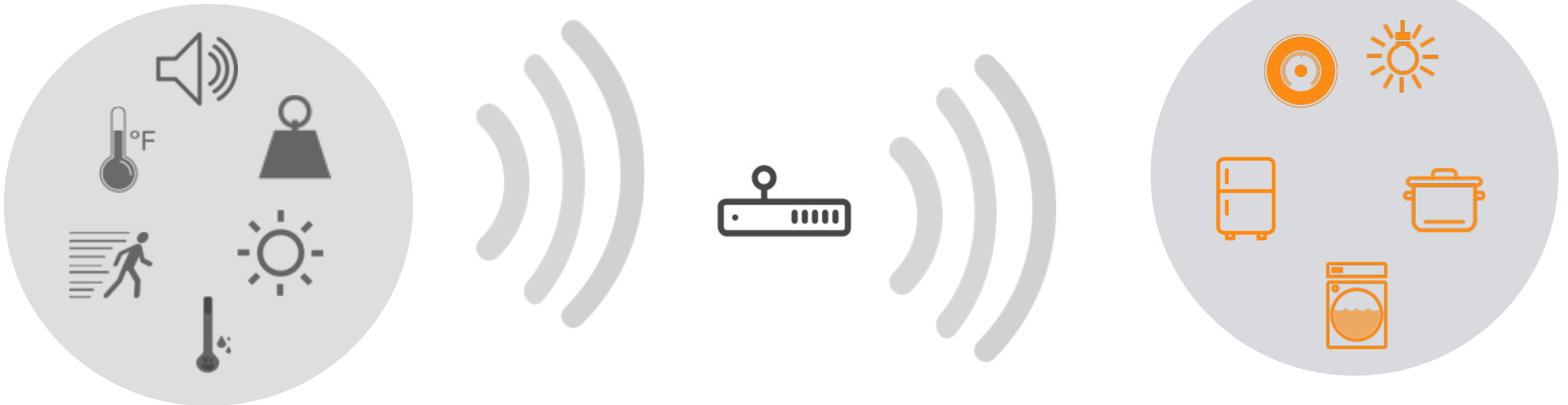
Collect & Analyze

Control



The Internet of Things (IoT) Vision

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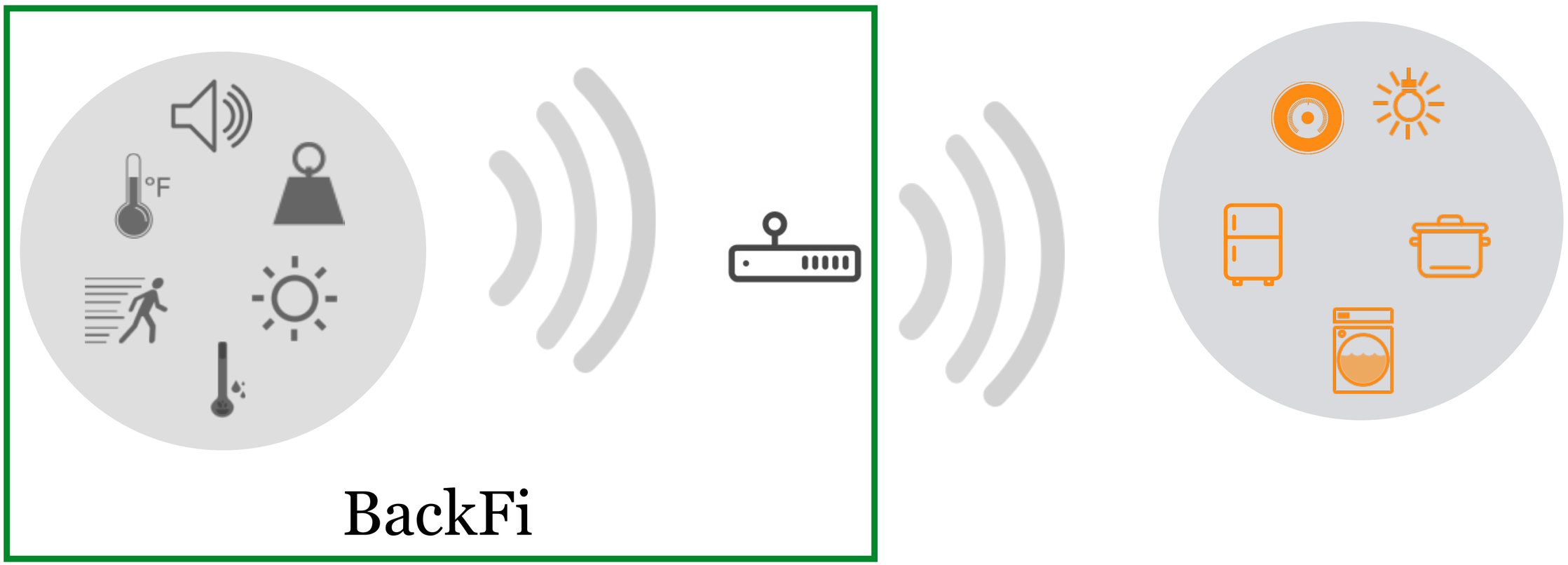
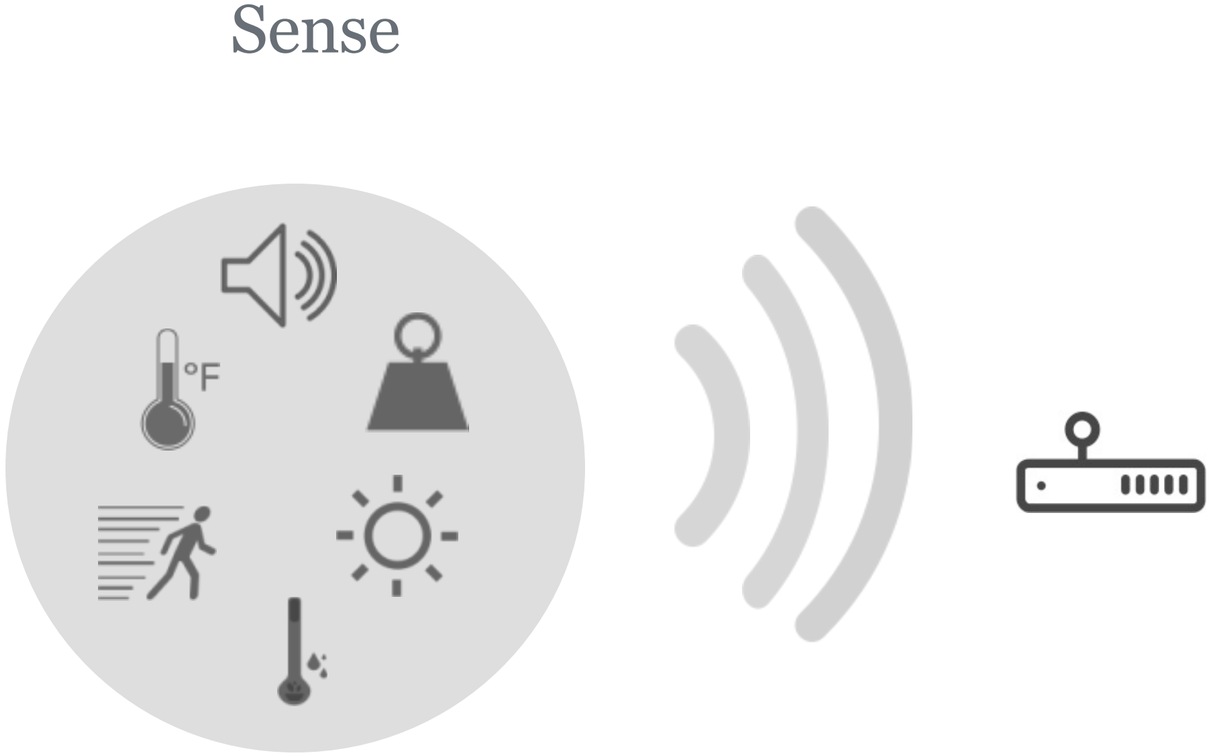


BackFi

What do we need for IoT Connectivity?



What do we need for IoT Connectivity?

Sense

Ubiquitous connectivity

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Ubiquitous connectivity

Low power

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- Ubiquitous connectivity
- Low power
- High uplink rate

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BackFi: *Ubiquitous, low power, high throughput connectivity for IoT sensors using ambient WiFi*

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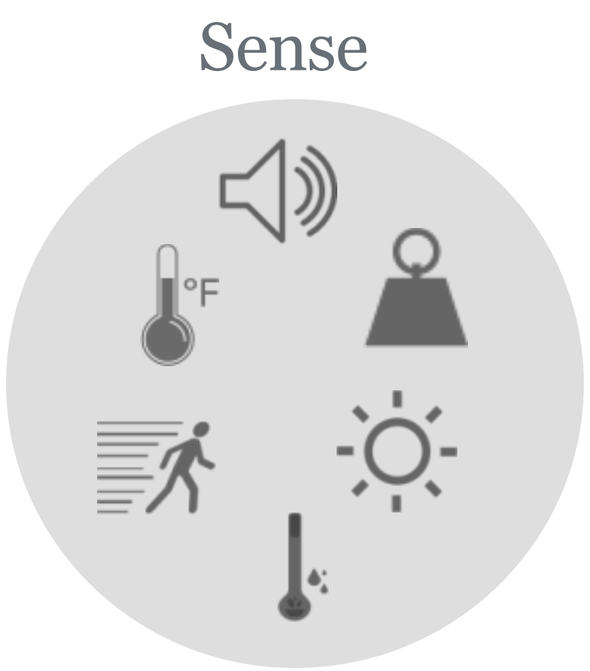

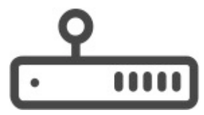

BackFi: *Ubiquitous, low power, high throughput connectivity for IoT sensors using ambient WiFi*

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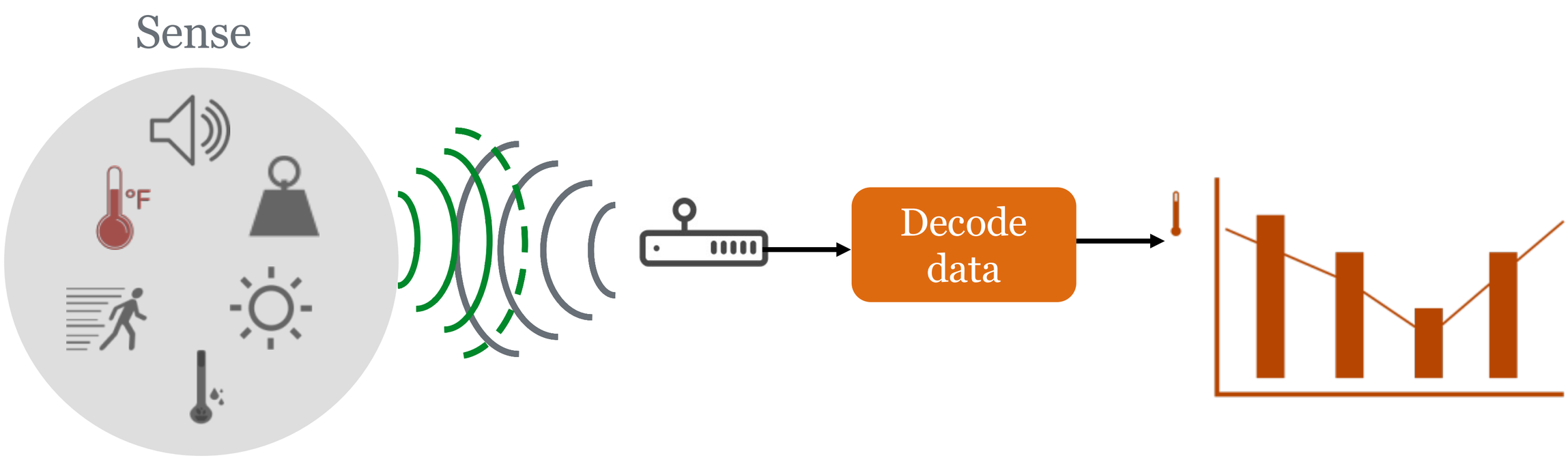

BackFi's Contributions

	Technical spec	Key enabling technique
Ubiquitous connectivity		
Low power		
High uplink rate		
Sufficient range		

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Low power	Less than 50 uW	Passive backscatter radios
High uplink rate	Up to 6.67 Mbps	Maximal ratio combining
Sufficient range	Up to 7m	Self-interference cancelation

Related Work

Related Work

Ubiquitous connectivity

Low power

High uplink rate

Sufficient range

Related Work

	WiFi-Backscatter
Ubiquitous connectivity	
Low power	
High uplink rate	
Sufficient range	

WiFi Backscatter:

H. Ishizaki, et. al. "A Battery-less WiFi-BER modulated data transmitter with ambient radio-wave energy harvesting"

B. Kellogg et. al. "Wi-Fi Backscatter: Internet Connectivity for RF-Powered Devices"

Related Work

	WiFi-Backscatter
Ubiquitous connectivity	✓
Low power	✓
High uplink rate	✗
Sufficient range	✗

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Related Work

	WiFi-Backscatter	RFID-based
Ubiquitous connectivity	✓	
Low power	✓	
High uplink rate	✗	
Sufficient range	✗	

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RFID based:
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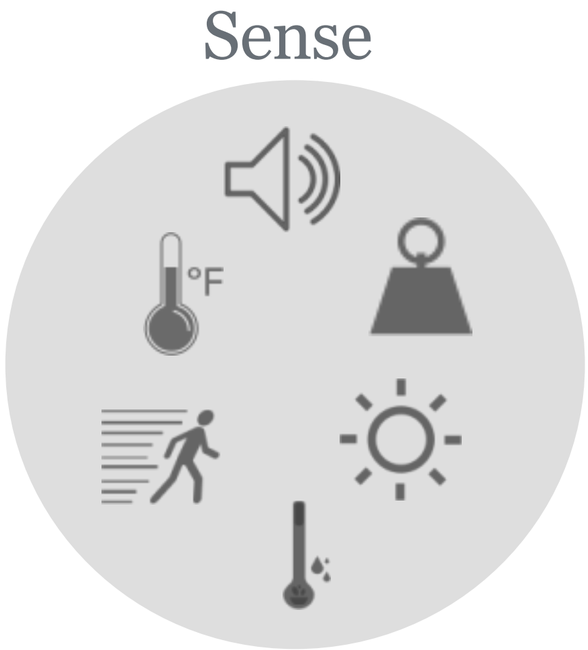
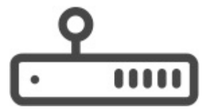


BackFi's Overview

Sense



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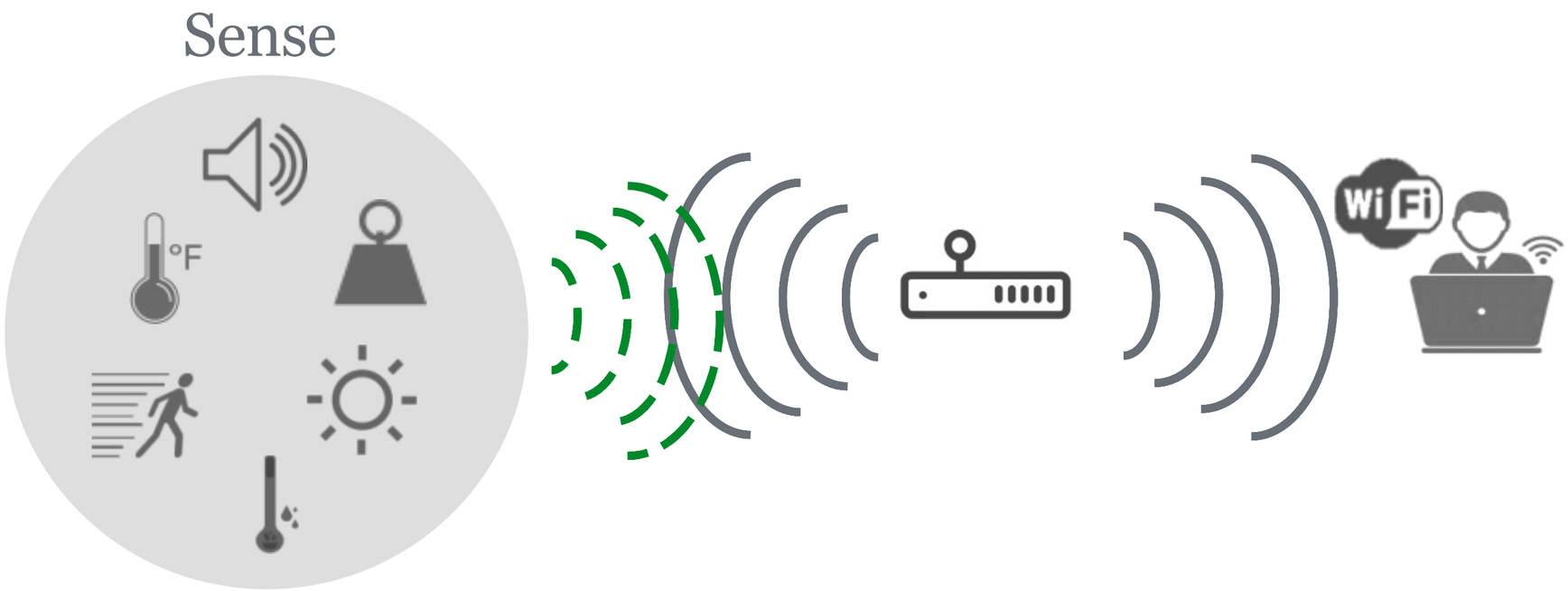

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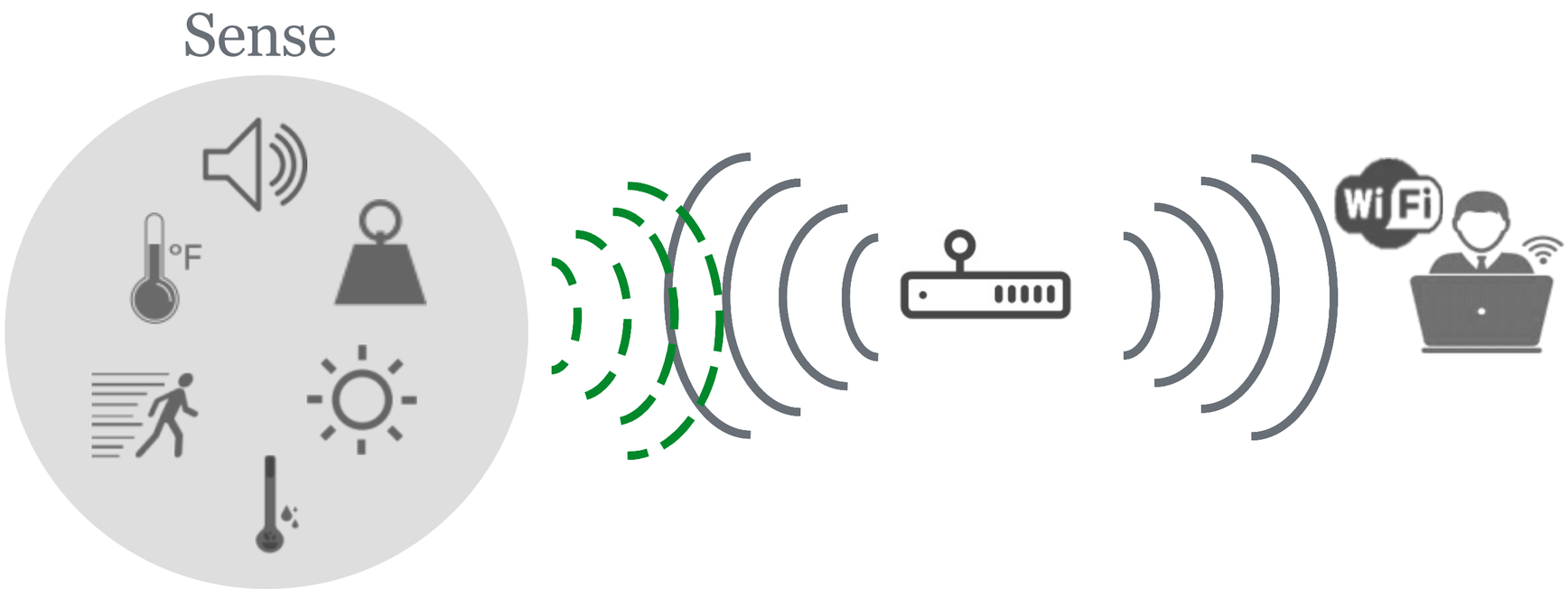
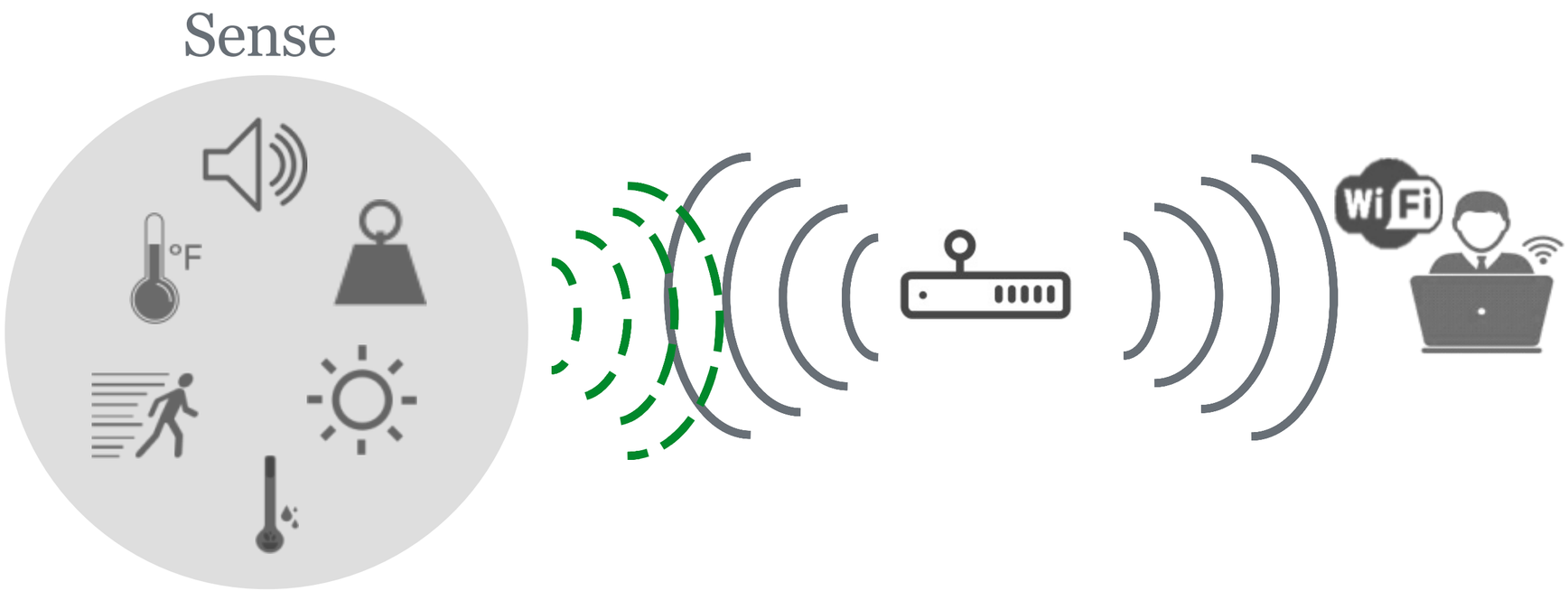


IoT Sensor

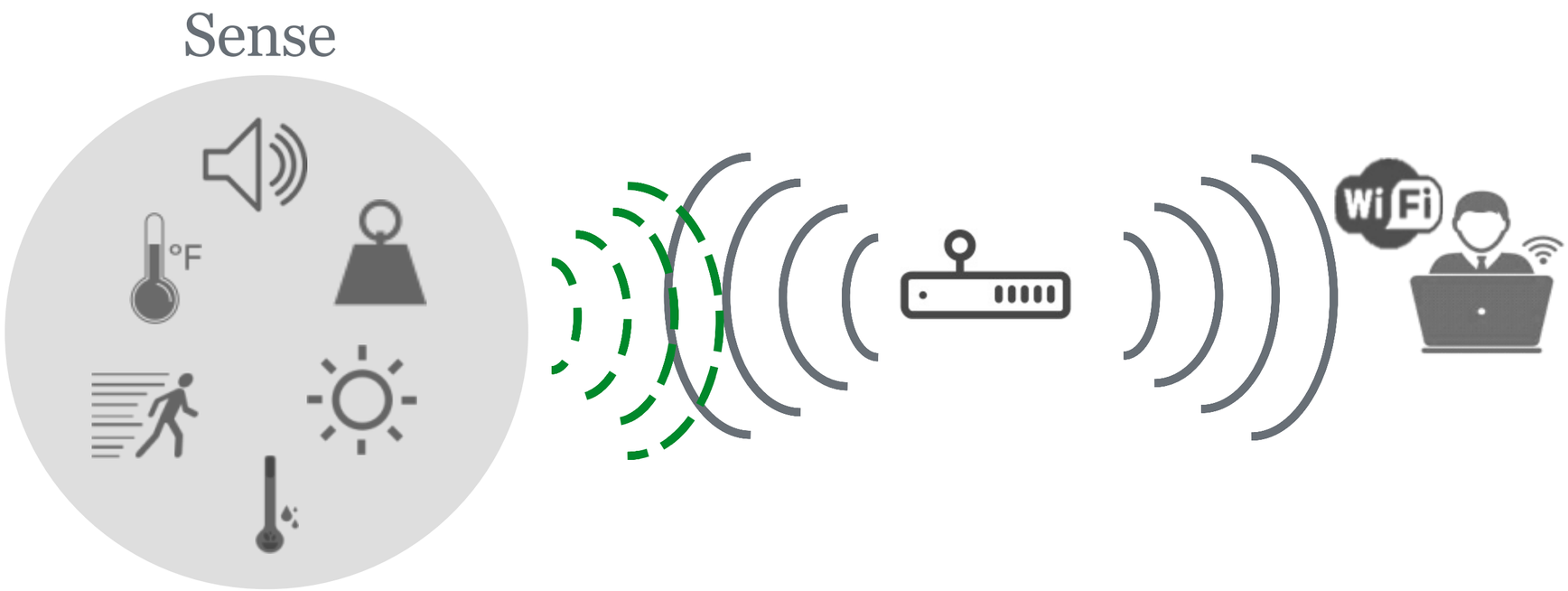
BackFi's Overview



IoT Sensor

BackFi AP

BackFi's Overview



IoT Sensor

BackFi AP

IoT Sensor Design

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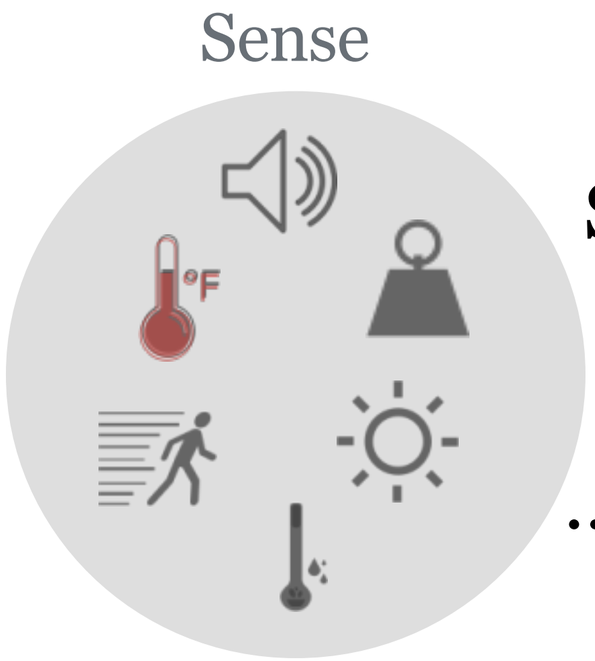
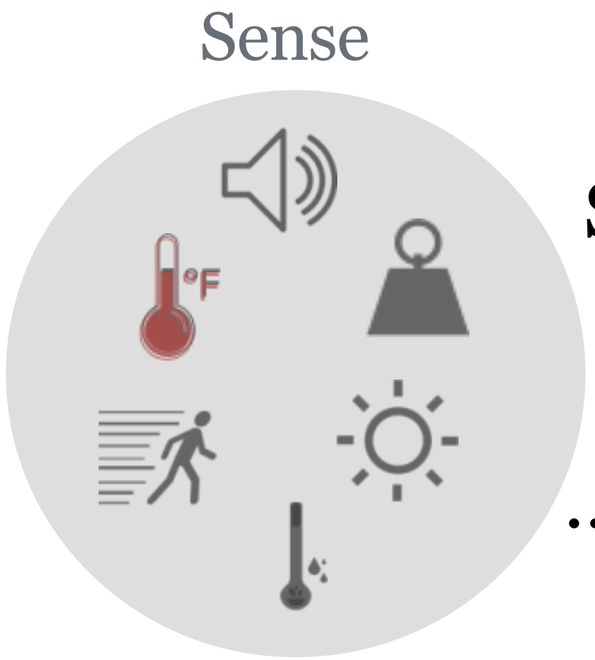


Sensor data

...10101010...

IoT Sensor Design



Sensor data

0 to -1

1 to +1

...10101010...

IoT Sensor Design

Sense

Sensor data

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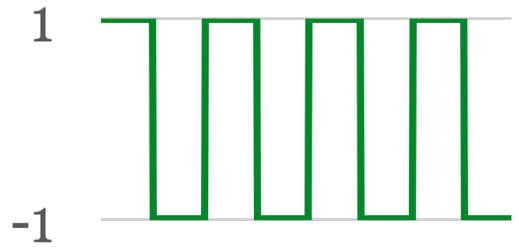
Data modulation



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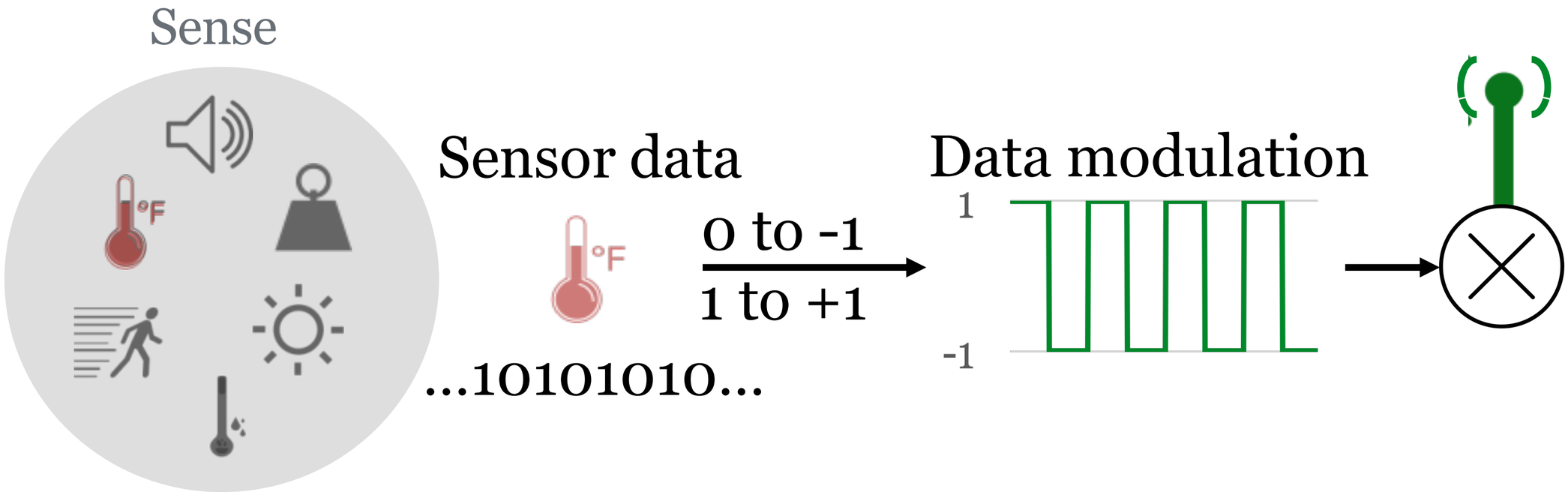

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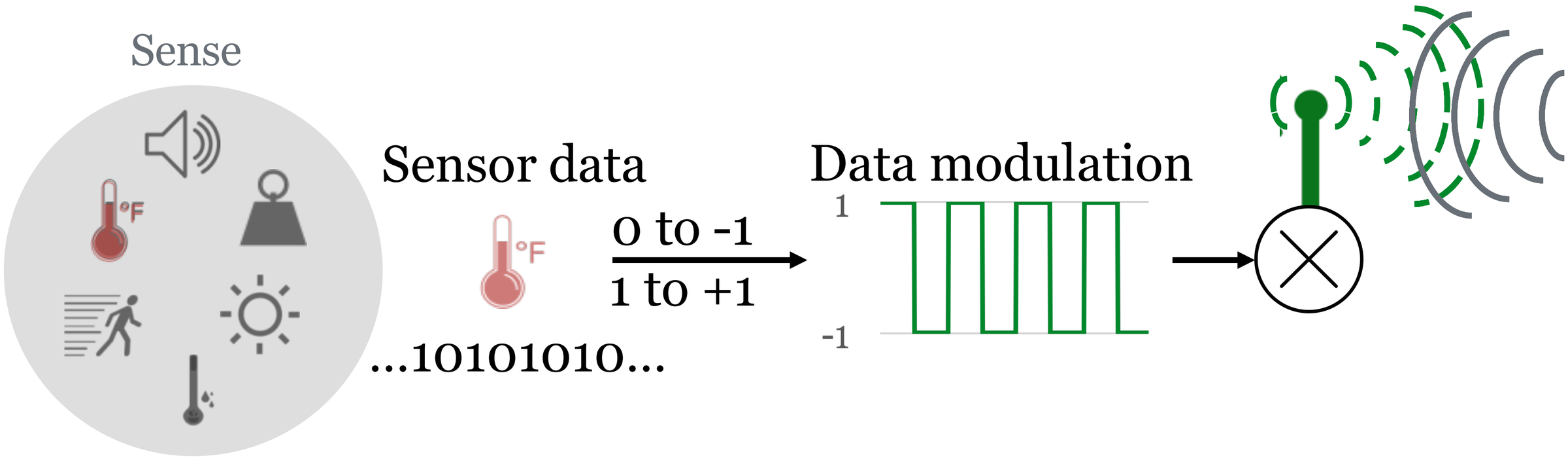

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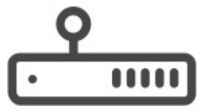

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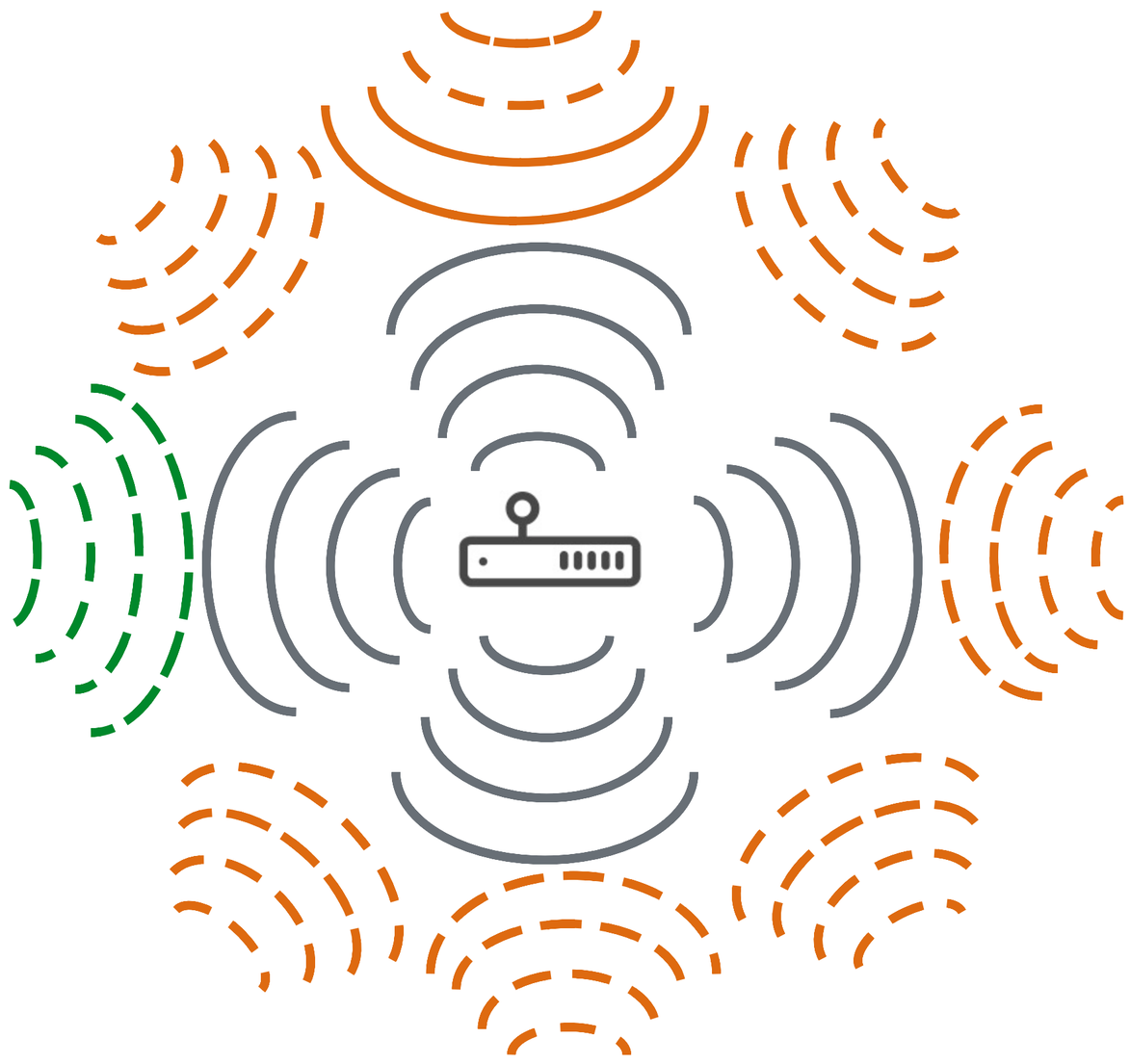

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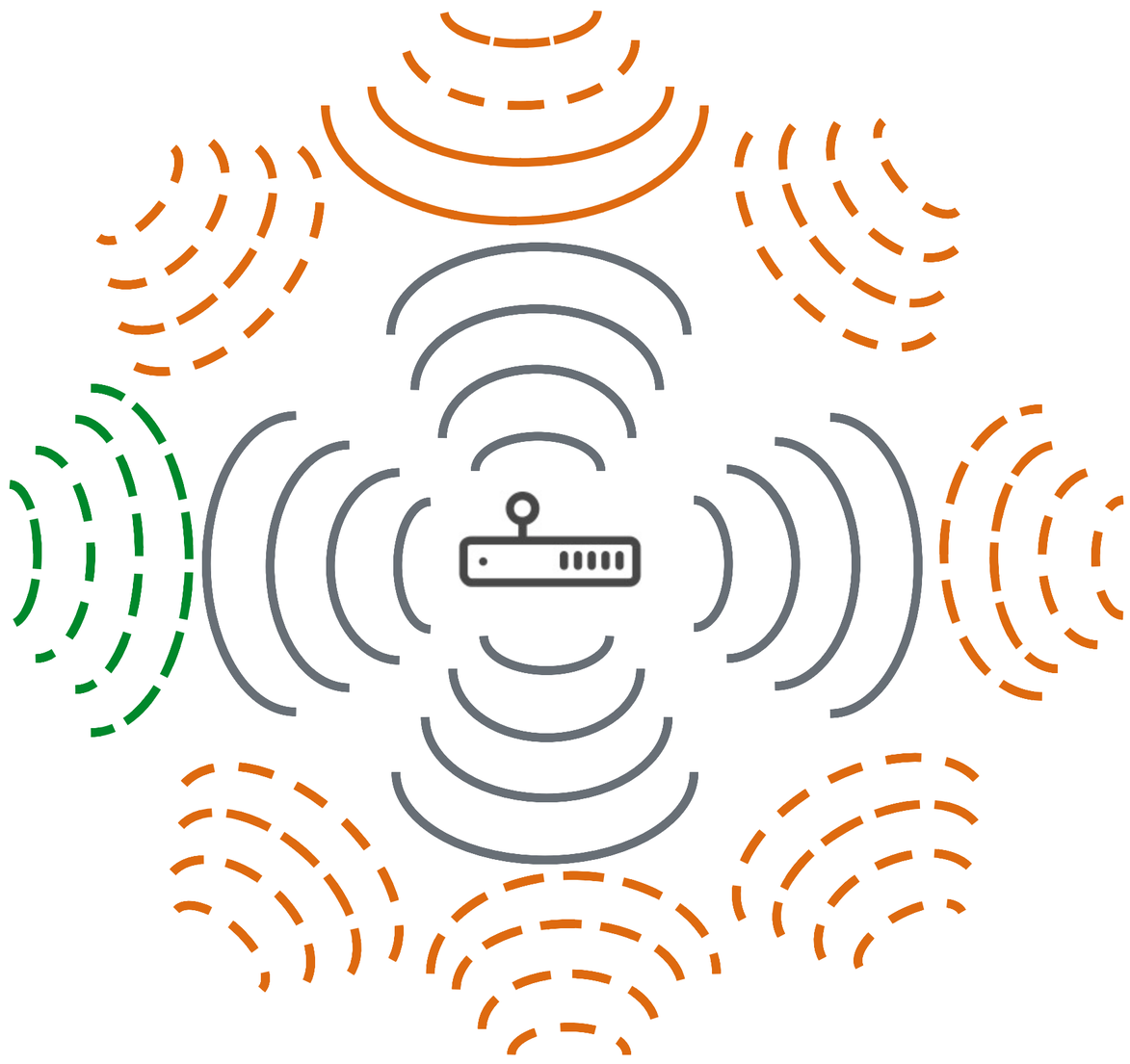

Received signal = Sensor backscatter + Environmental reflections

Challenge 1: Strong Environmental Reflections

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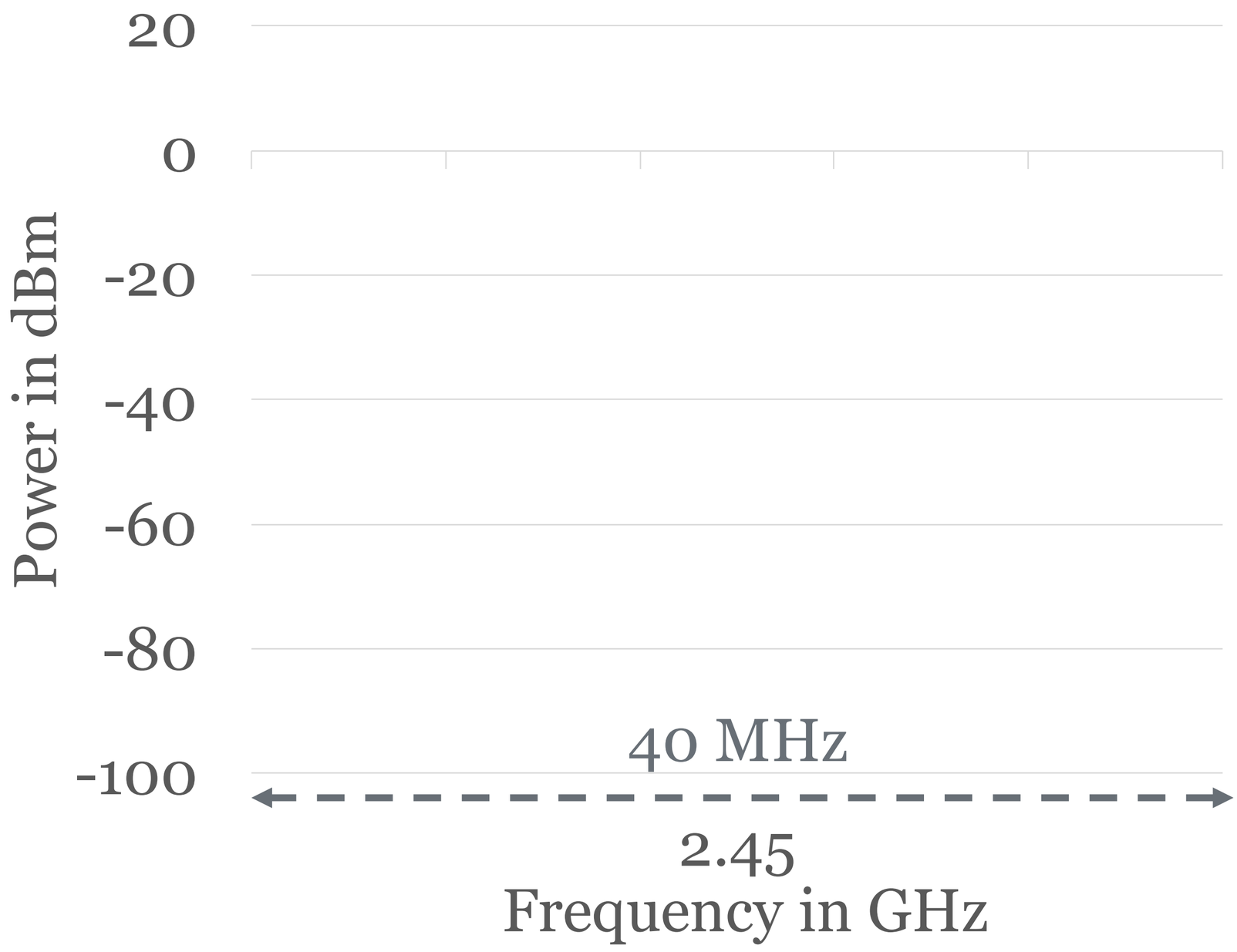

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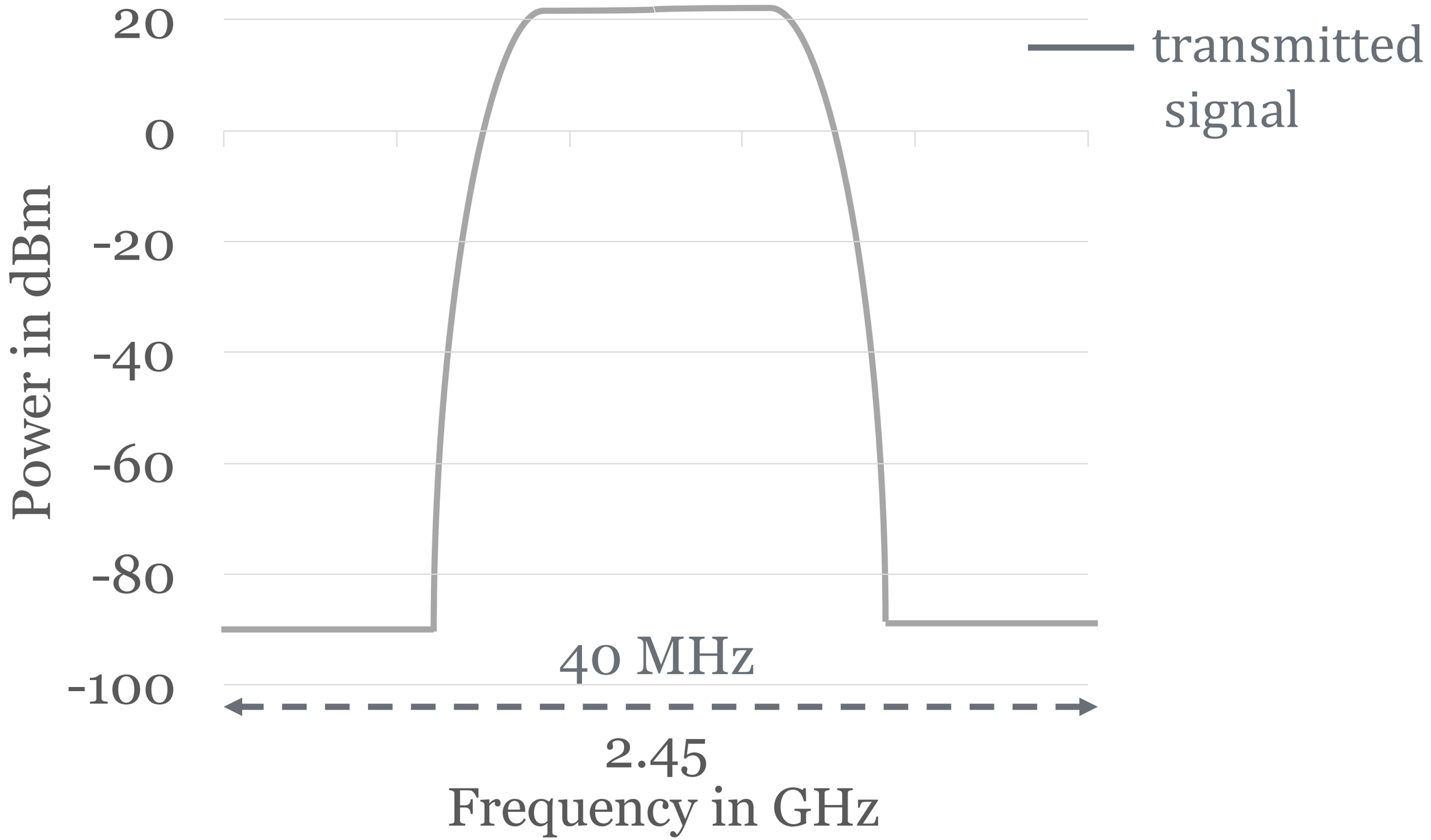

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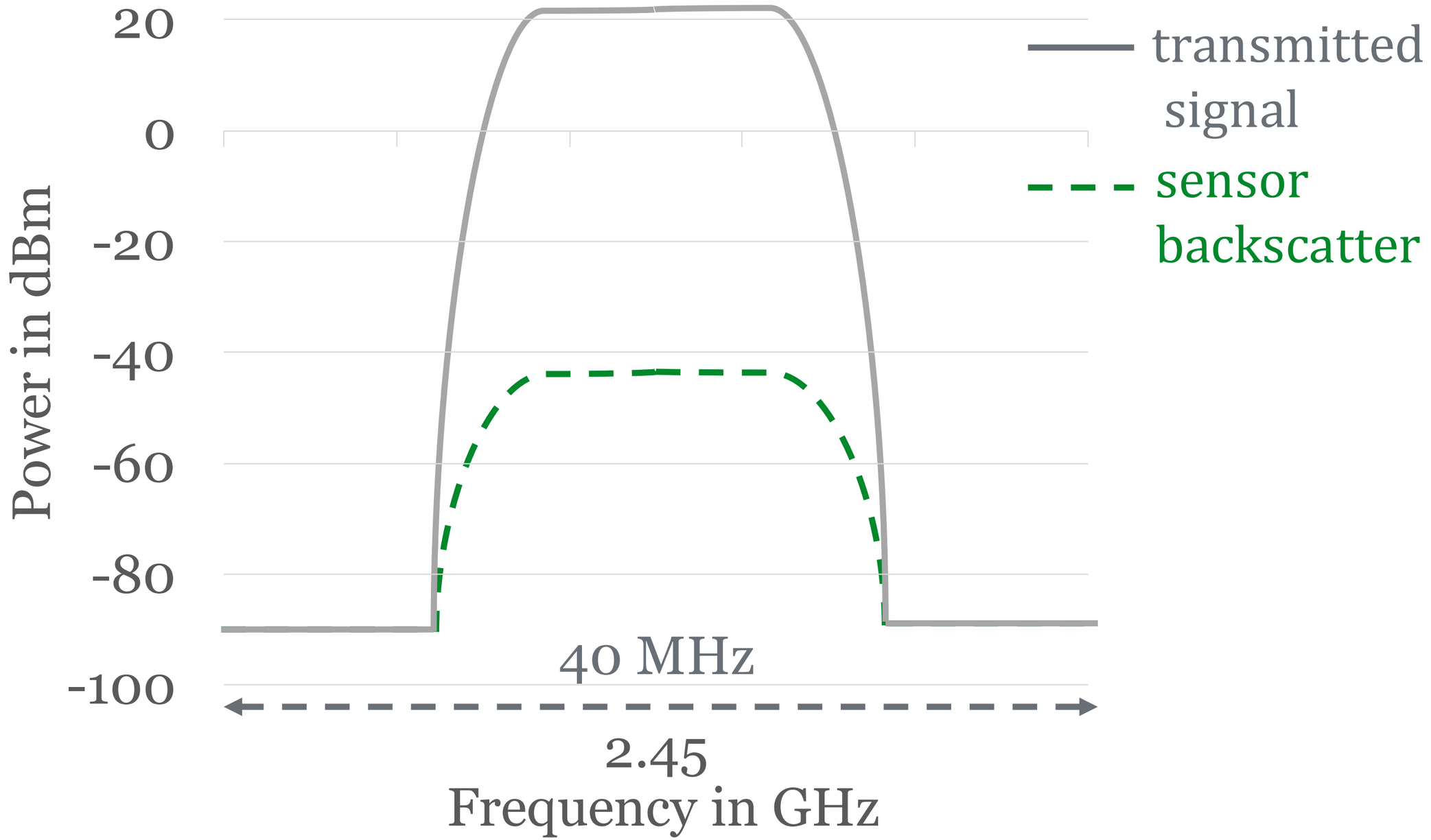

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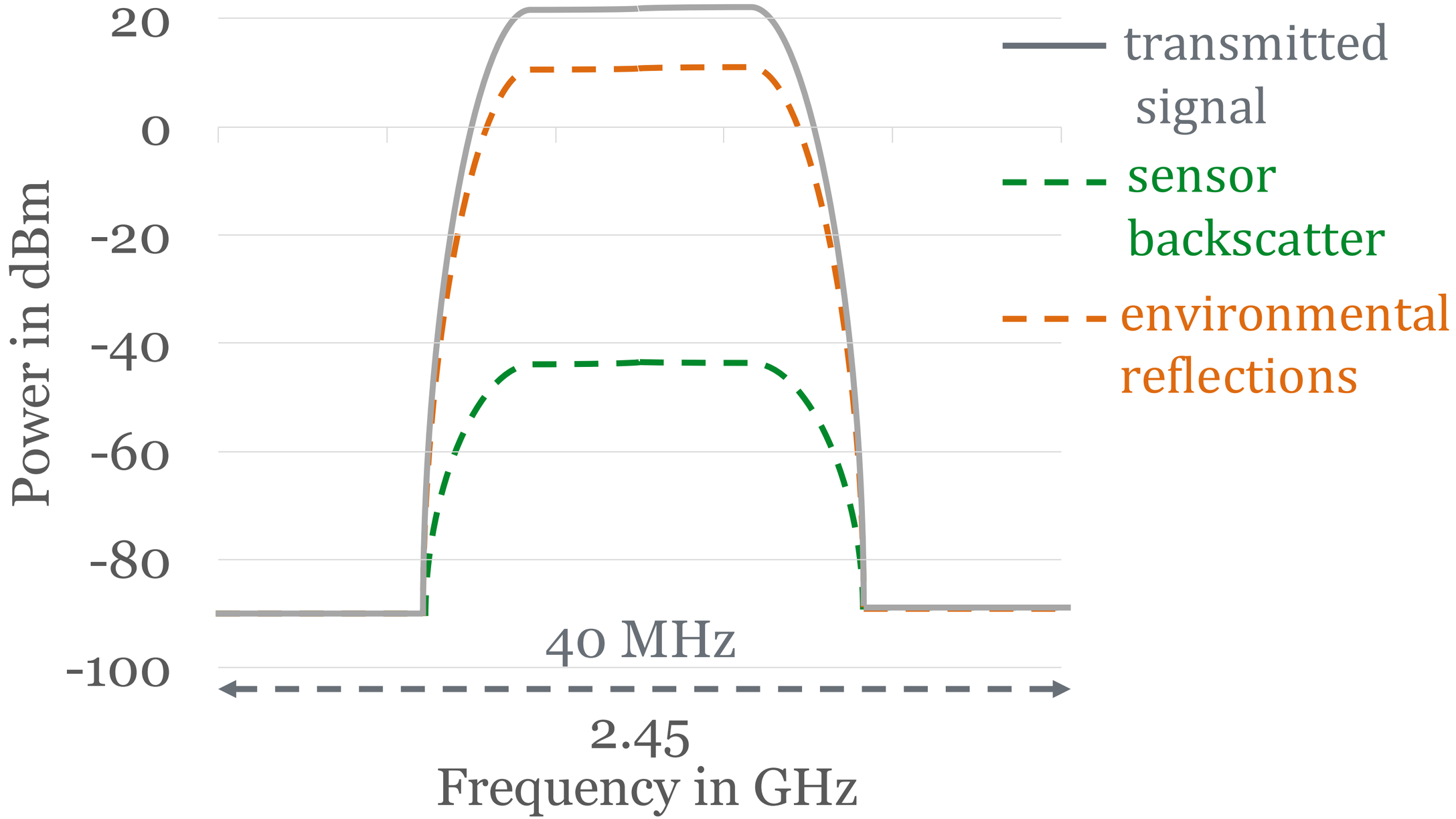

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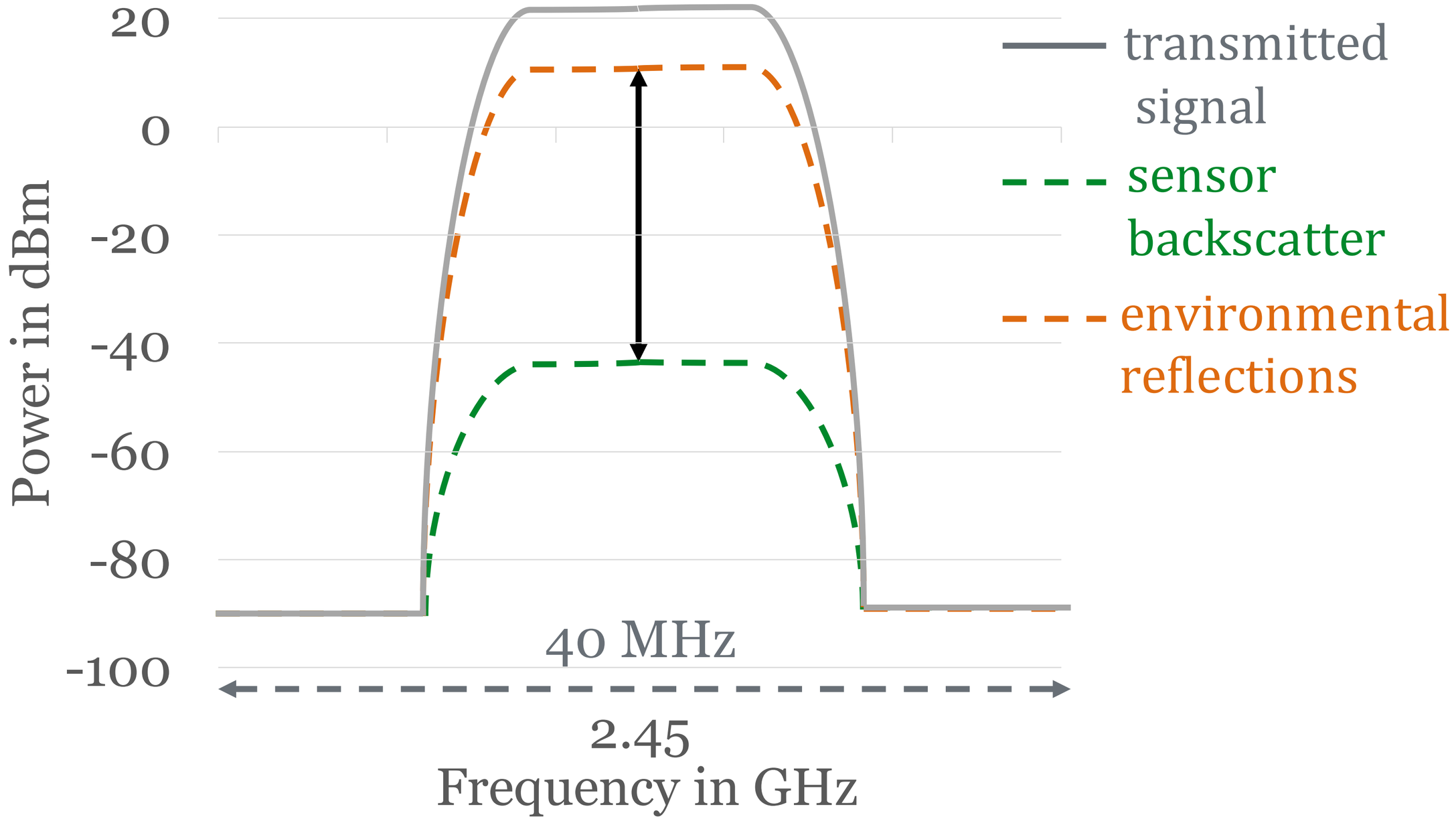

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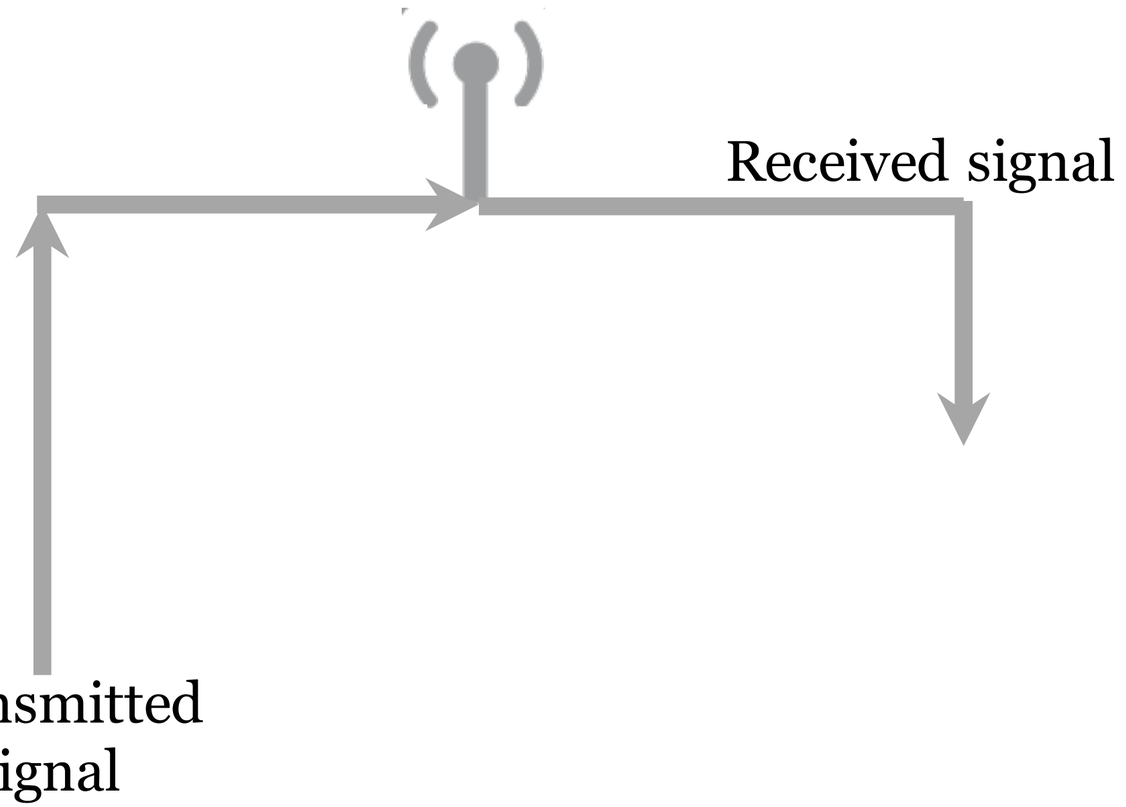

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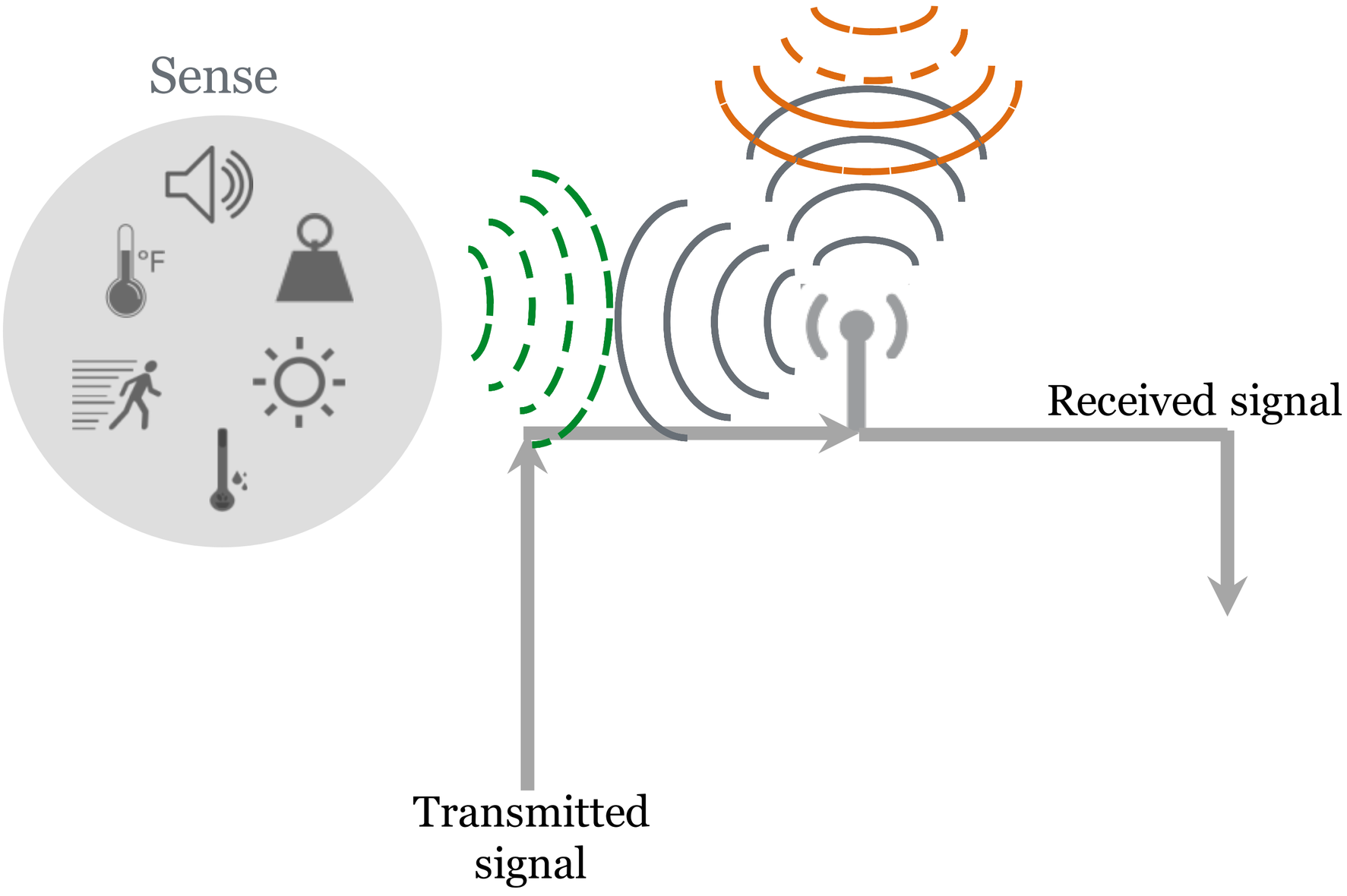

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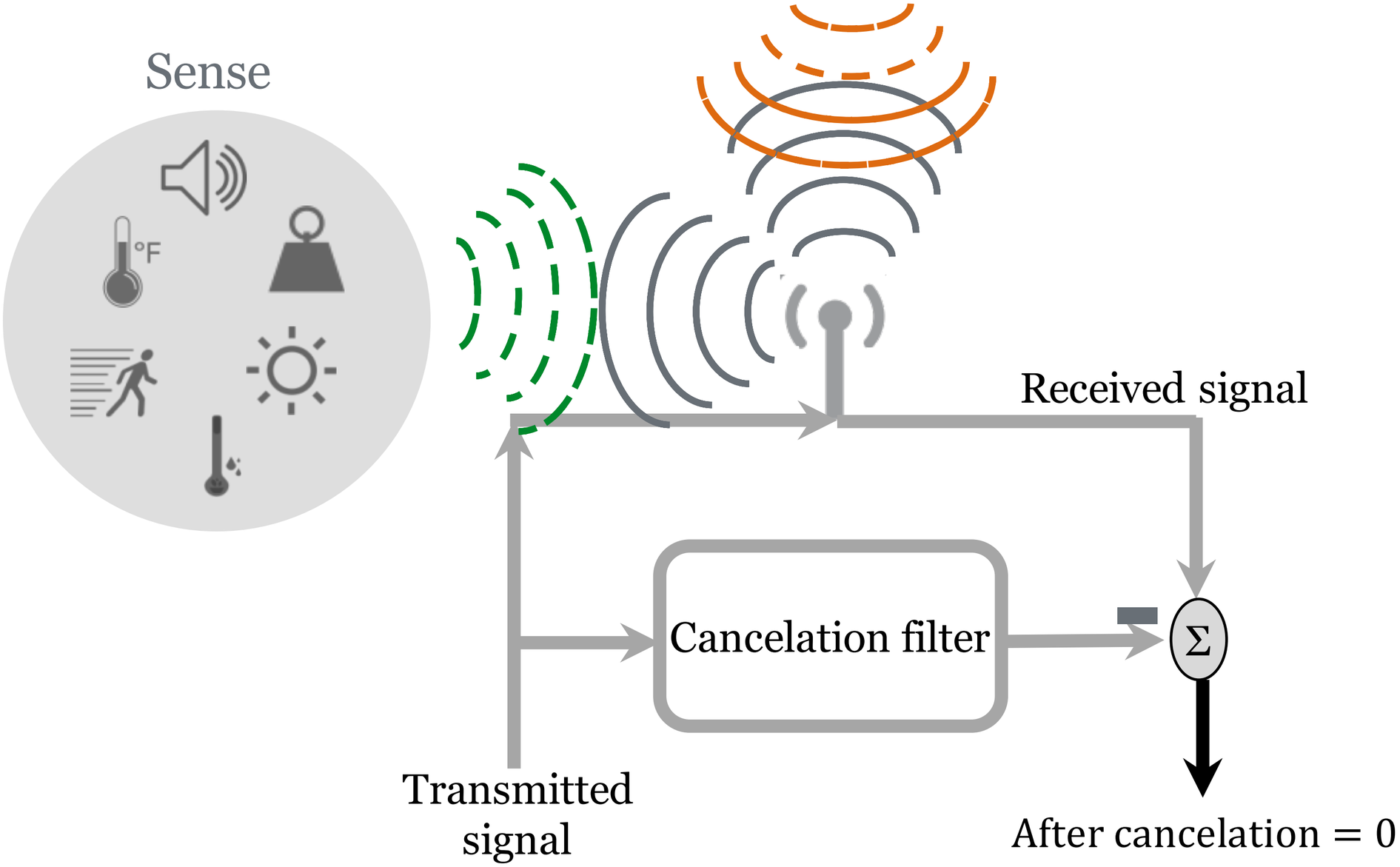

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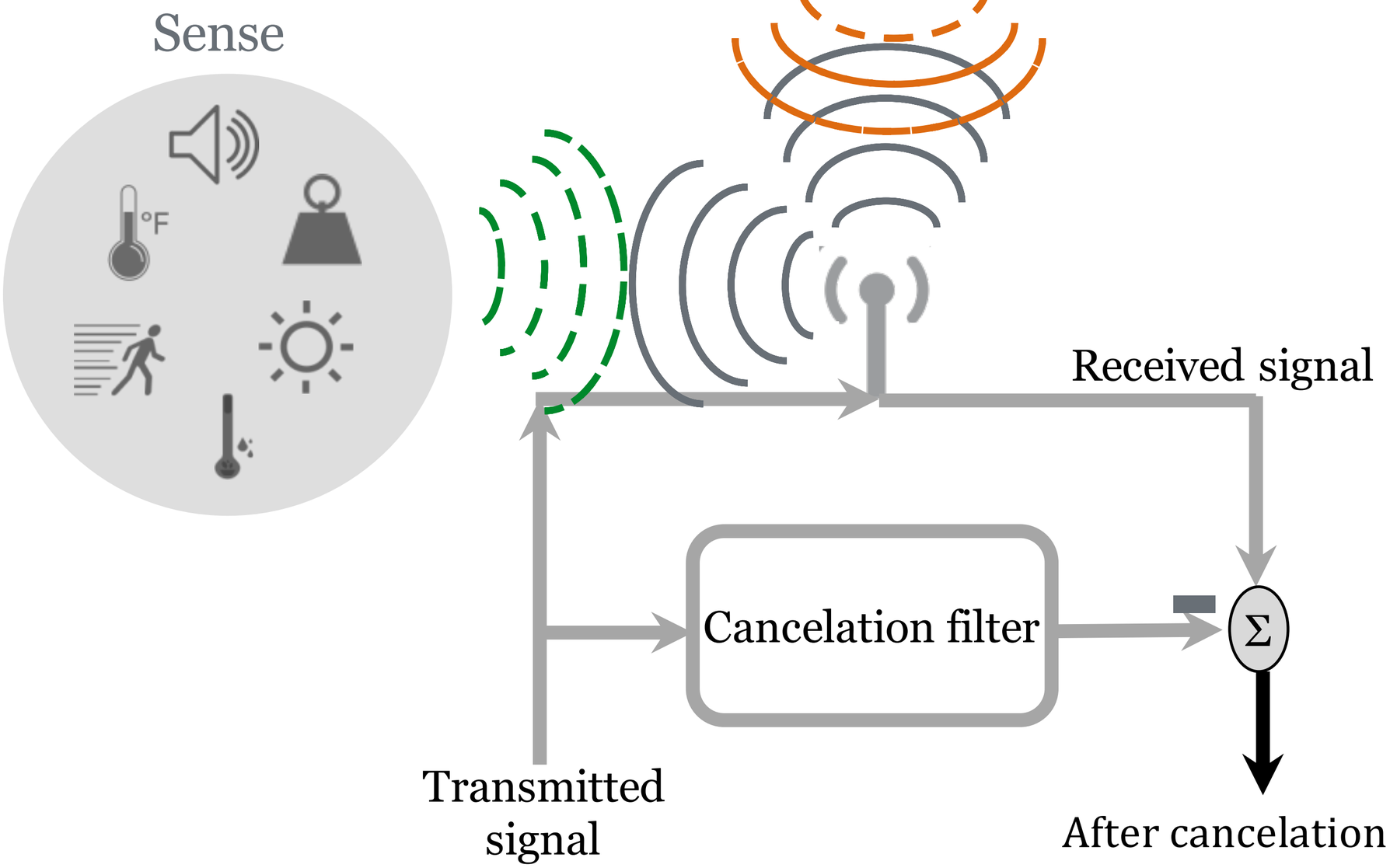

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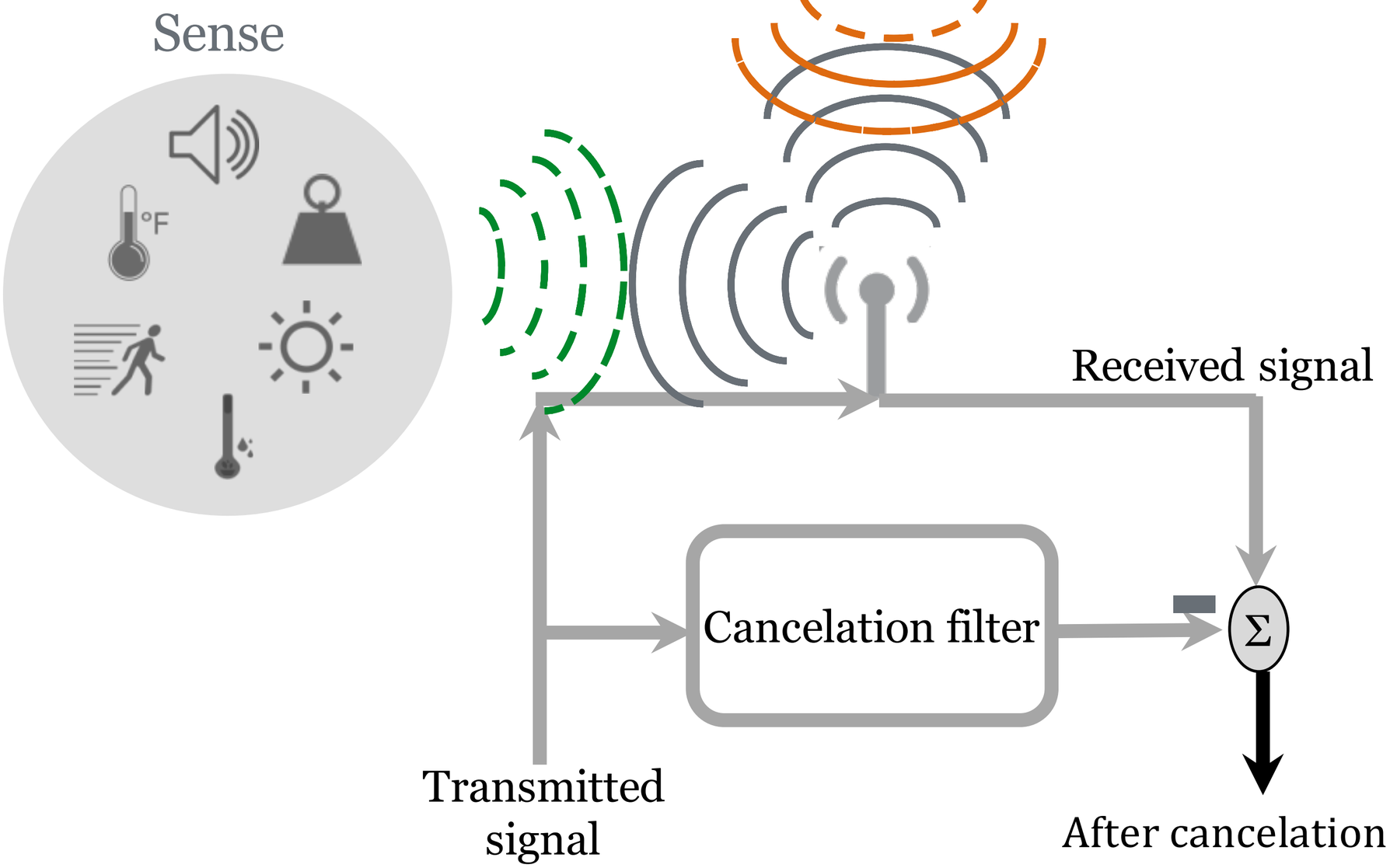
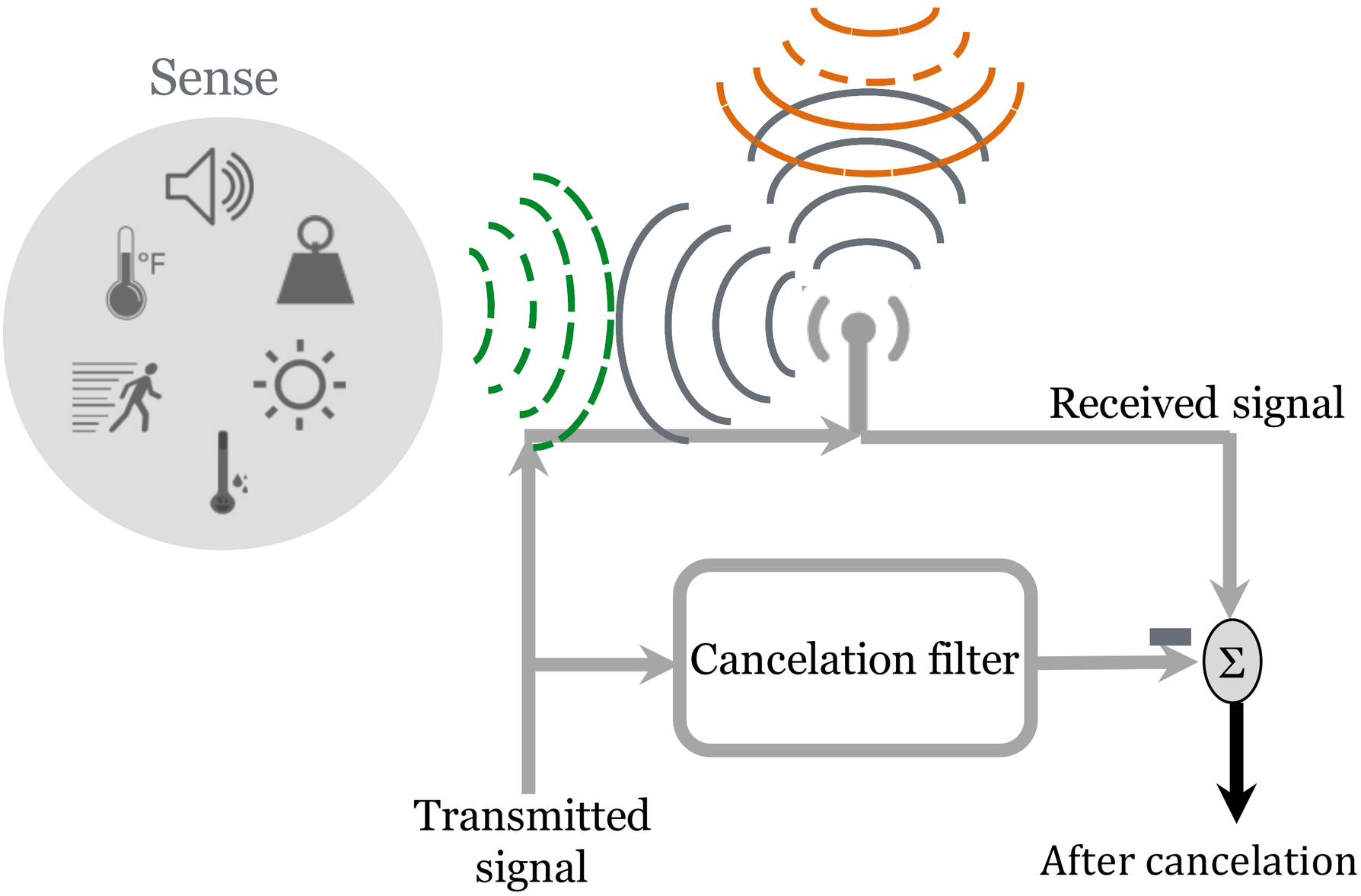


Received signal = Sensor backscatter + Environmental reflections

After cancelation = 0

Eliminating environmental reflections



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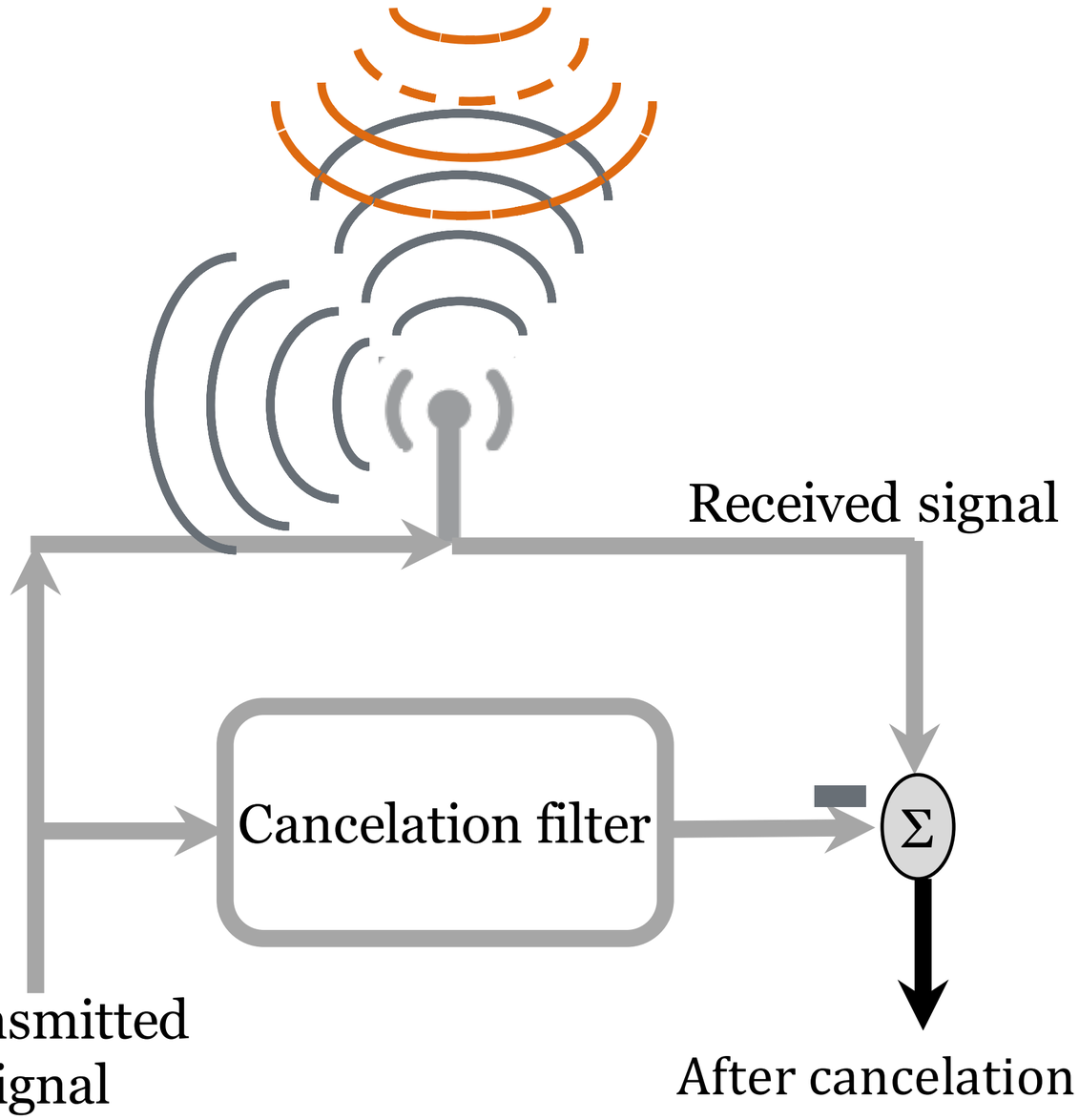
Eliminating environmental reflections

Turn off the backscatter



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Eliminating environmental reflections

Sense

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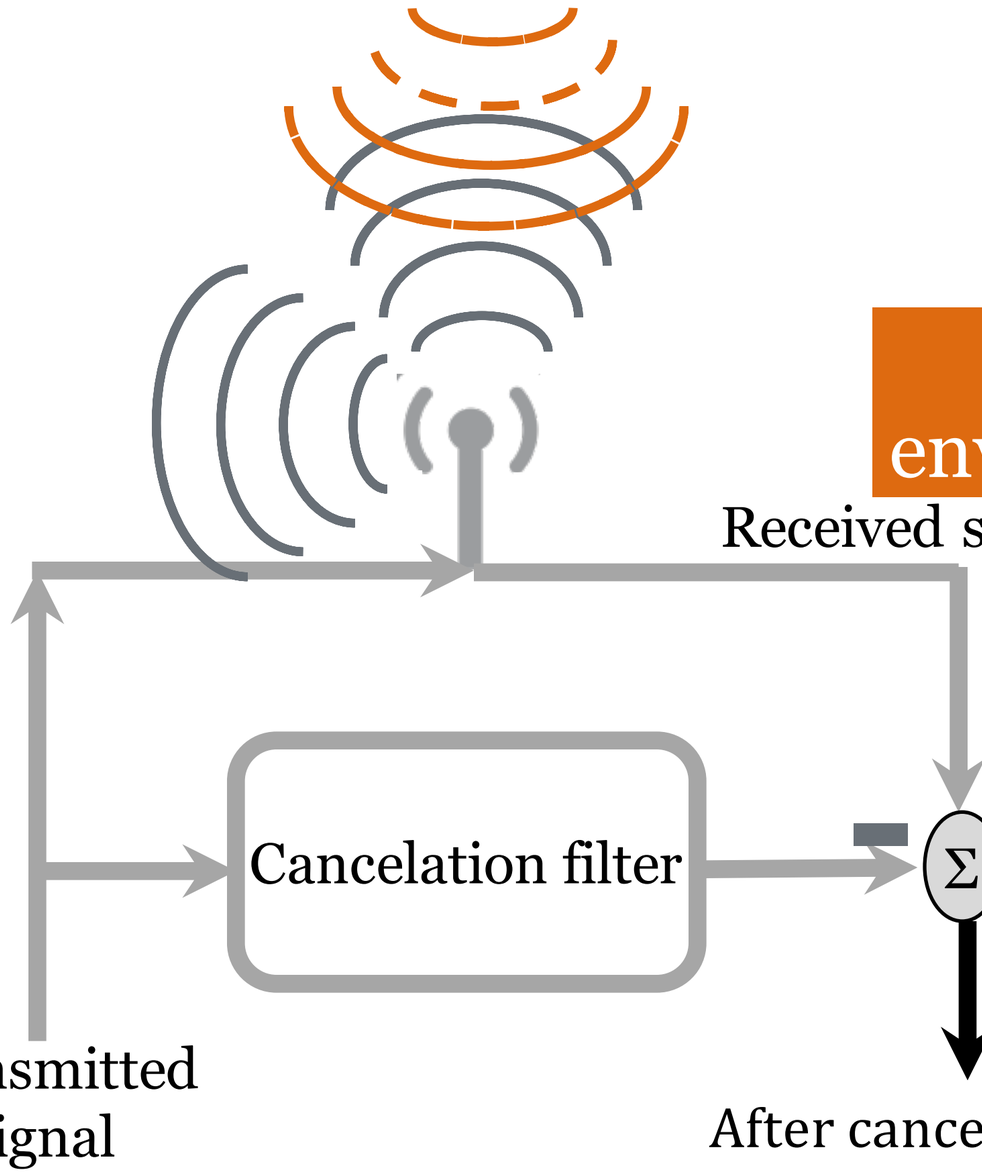

Estimate the environmental reflections

Received signal = Sensor backscatter + Environmental reflections

Eliminating environmental reflections

Sense

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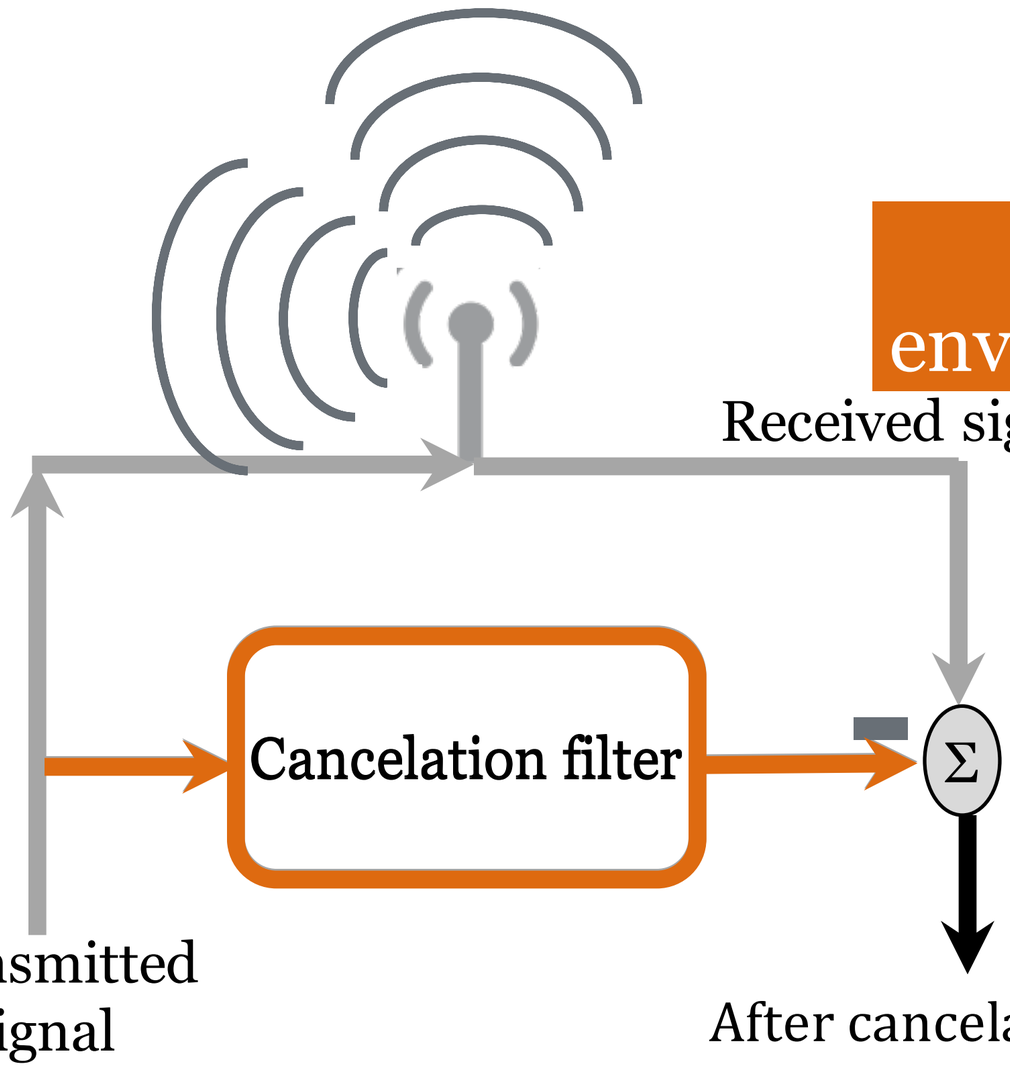

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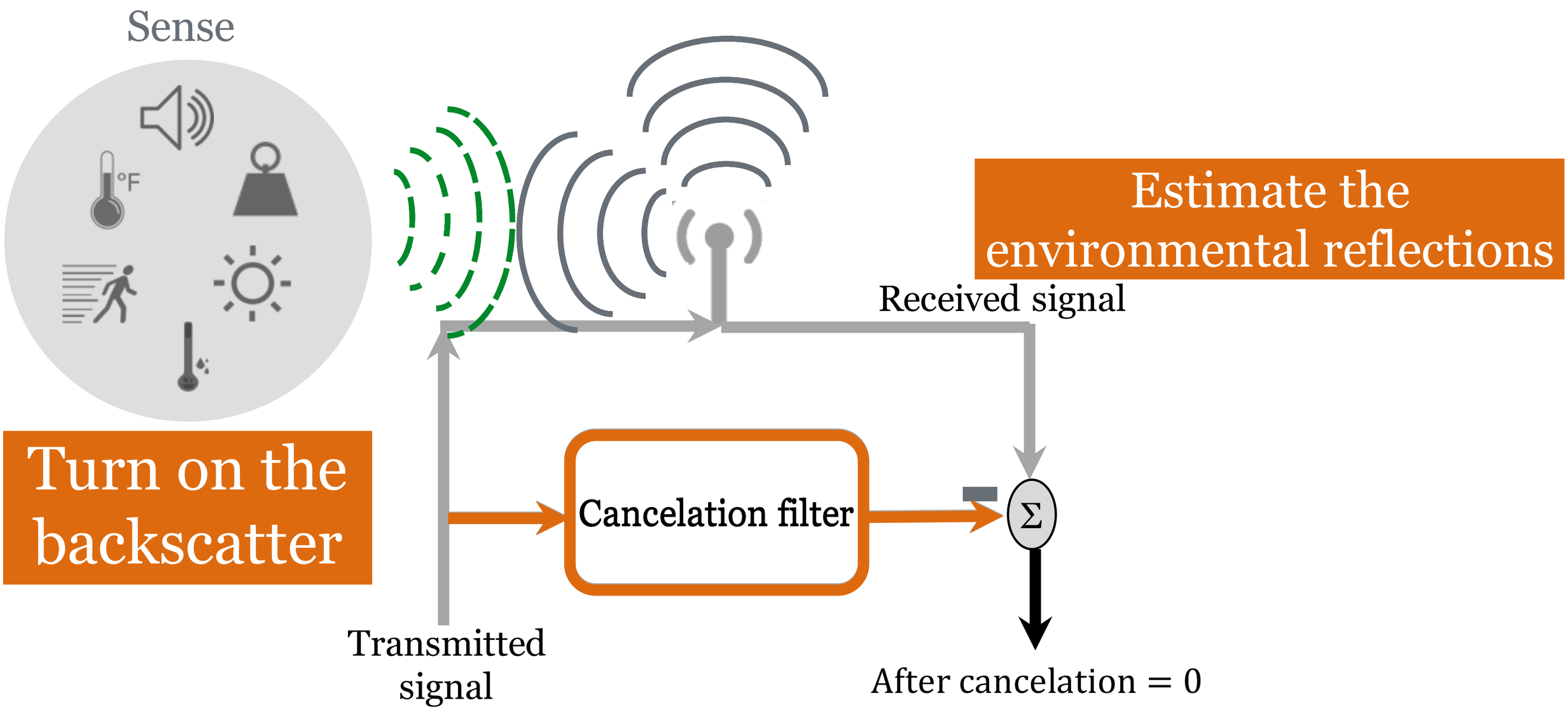

Received signal = Sensor backscatter + Environmental reflections

After cancelation = Sensor backscatter

Challenge 2: Inferring IoT Sensor Data

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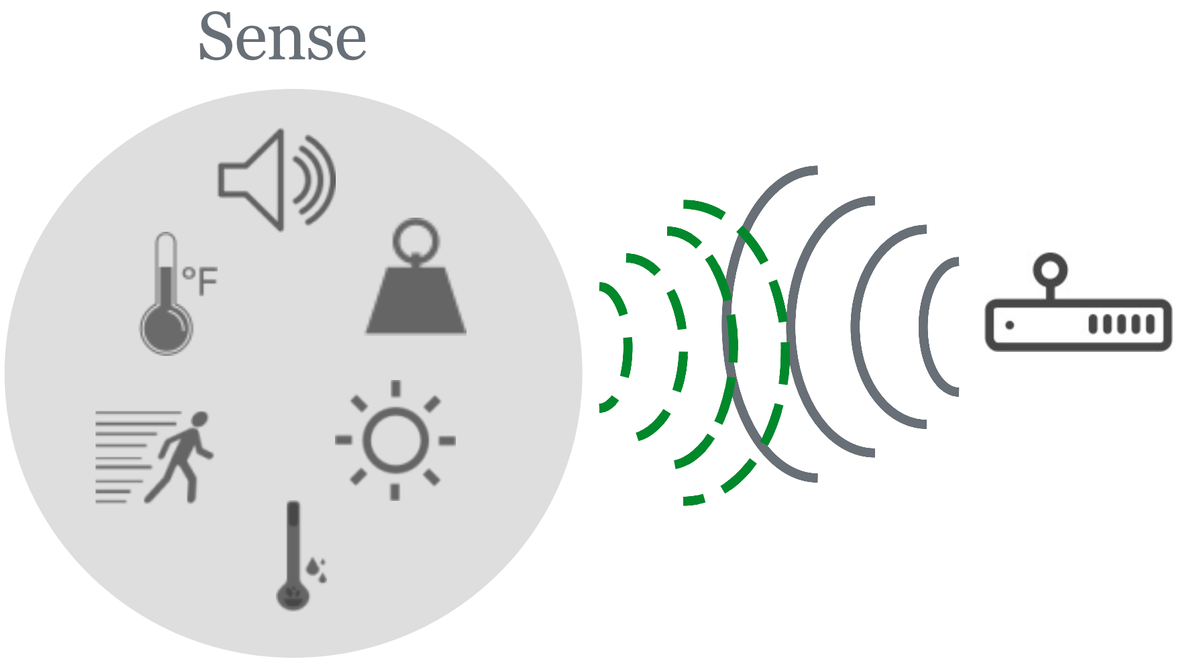
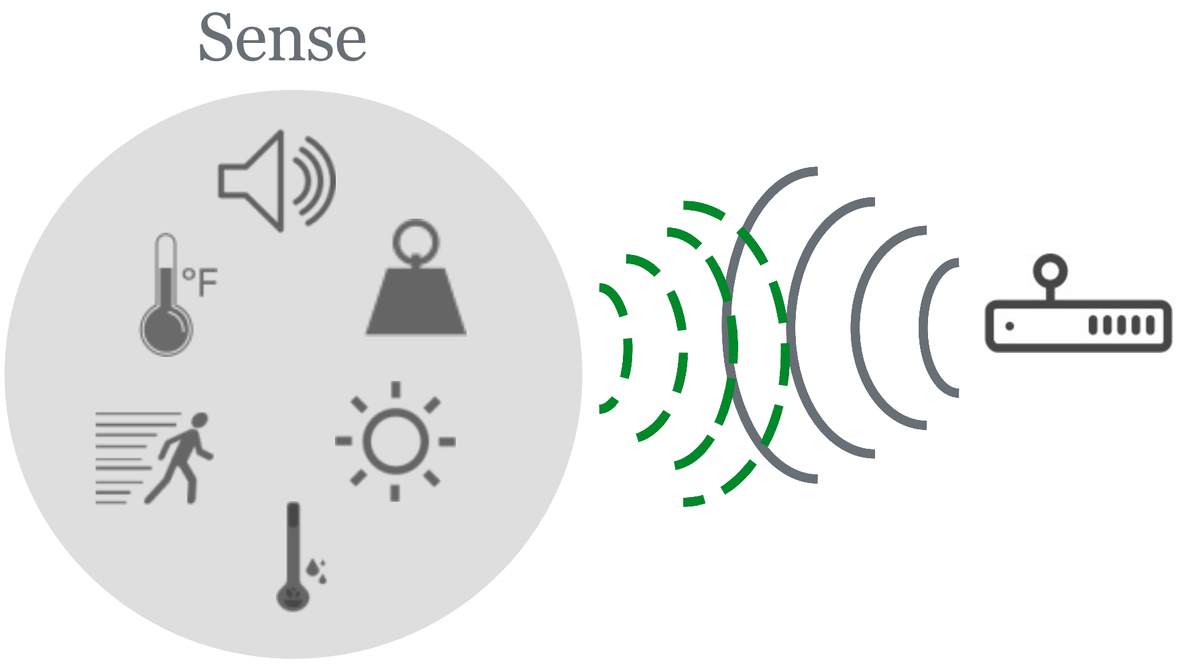


Sensor backscatter is function of:

Challenge 2: Inferring IoT Sensor Data



Sensor backscatter is function of:

- Transmitted signal

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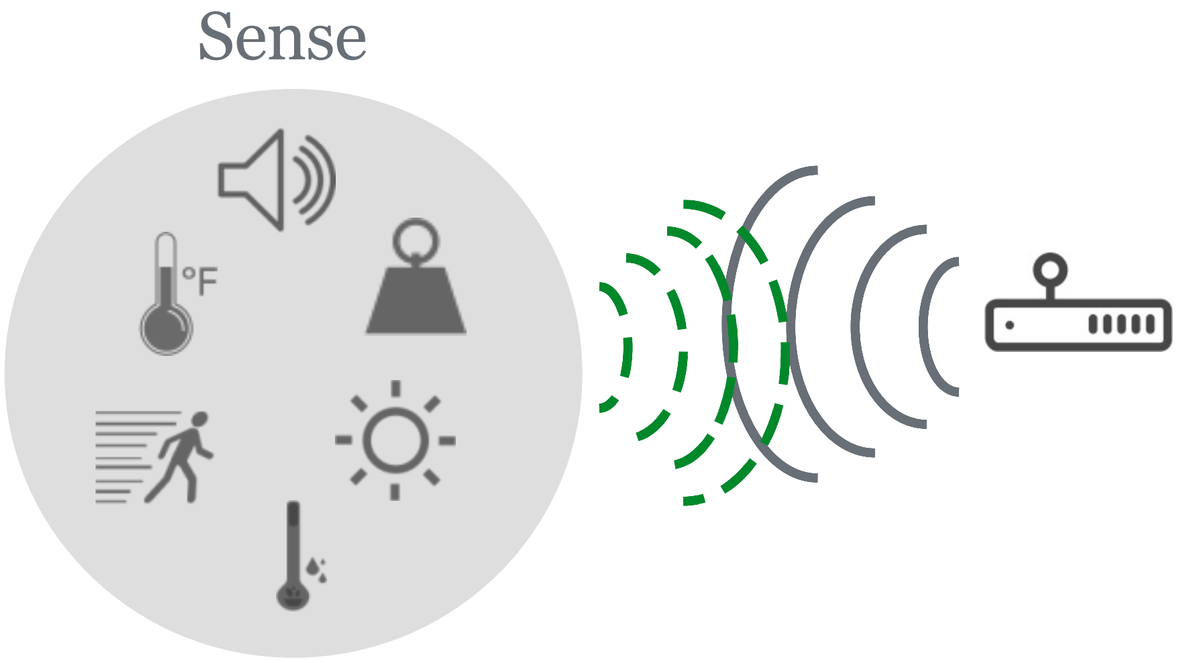

Sensor backscatter is function of:

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- IoT sensor data

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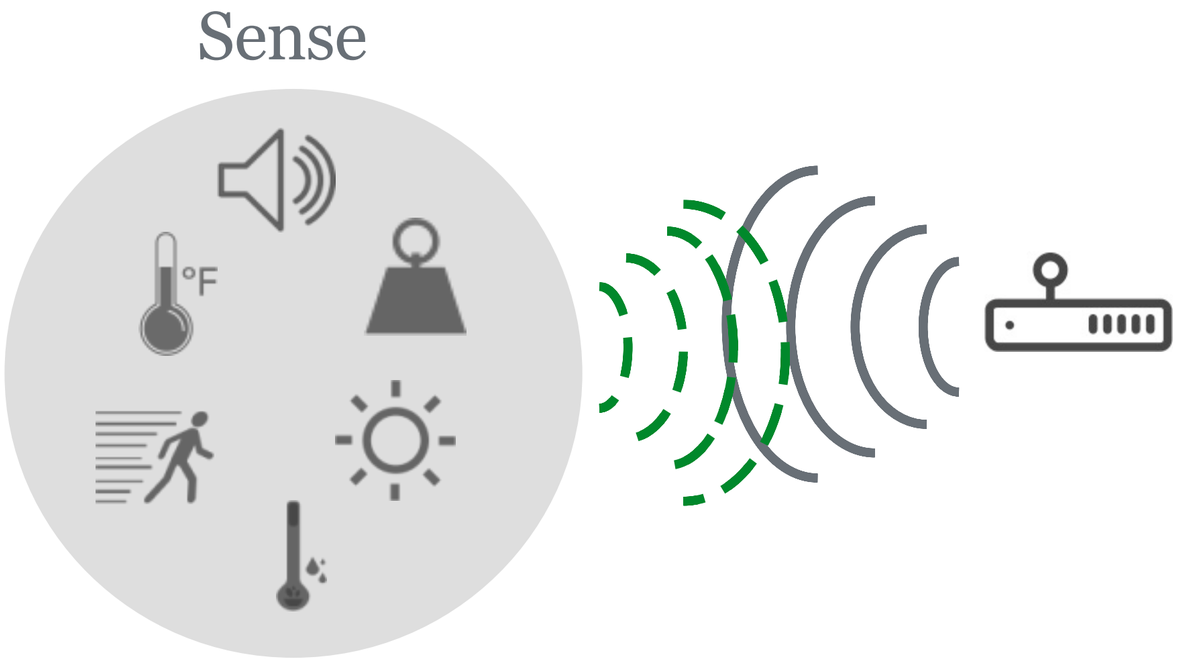
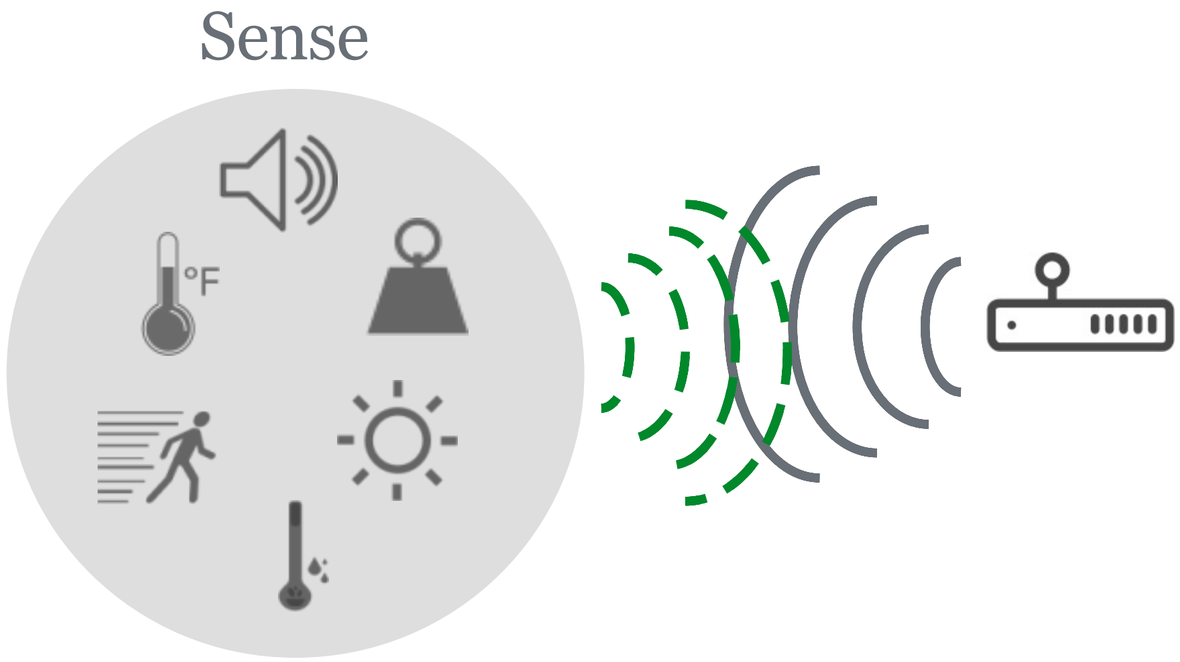


Sensor backscatter is function of:

- Transmitted signal
- IoT sensor data
- Wireless channel distortions

Challenge 2: Inferring IoT Sensor Data



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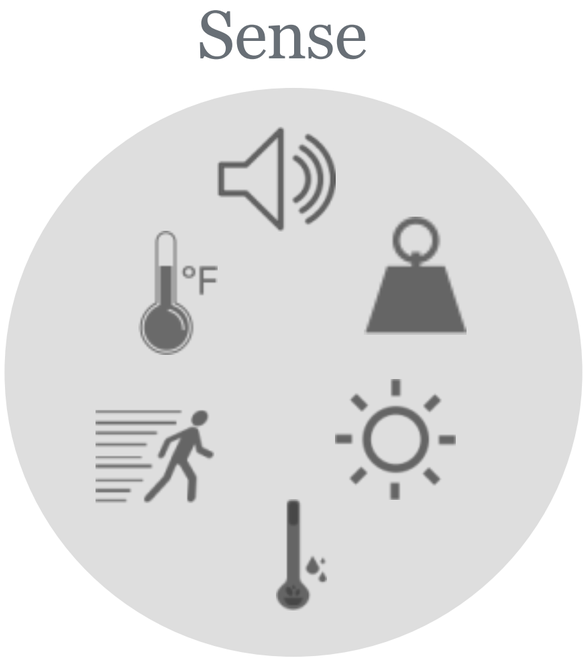
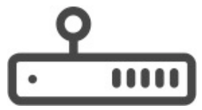
- Transmitted signal ✓
- IoT sensor data ?
- Wireless channel distortions ?

Modeling Sensor Backscatter

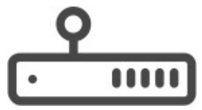




Modeling Sensor Backscatter

Sense

Transmitted signal = x



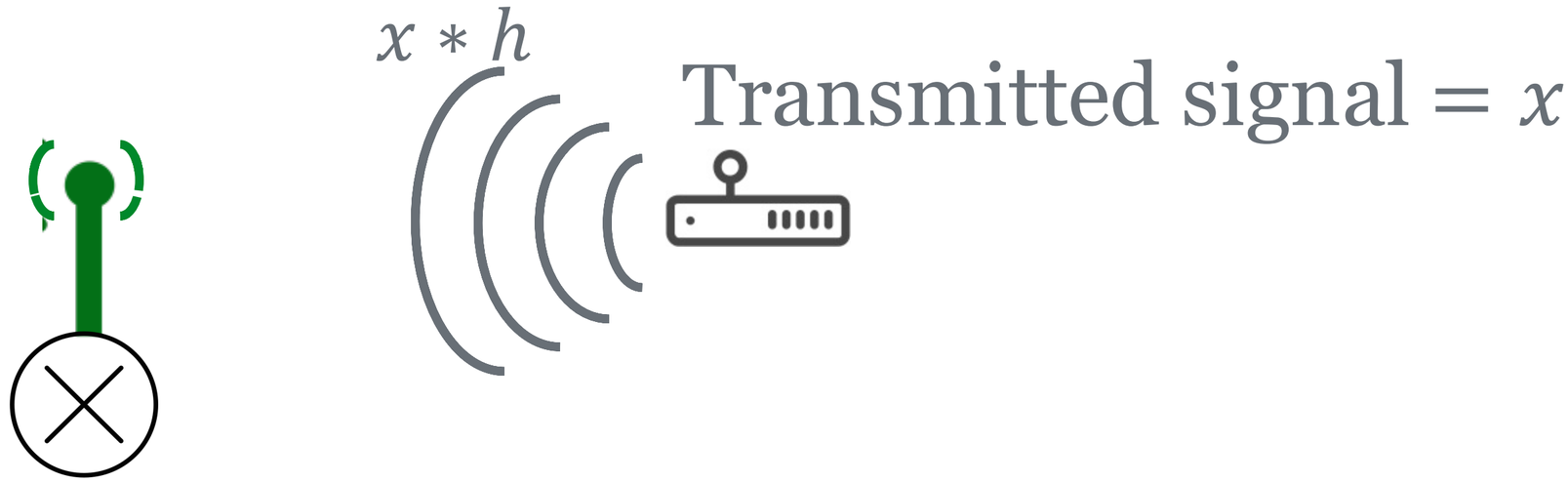
Modeling Sensor Backscatter

Sense

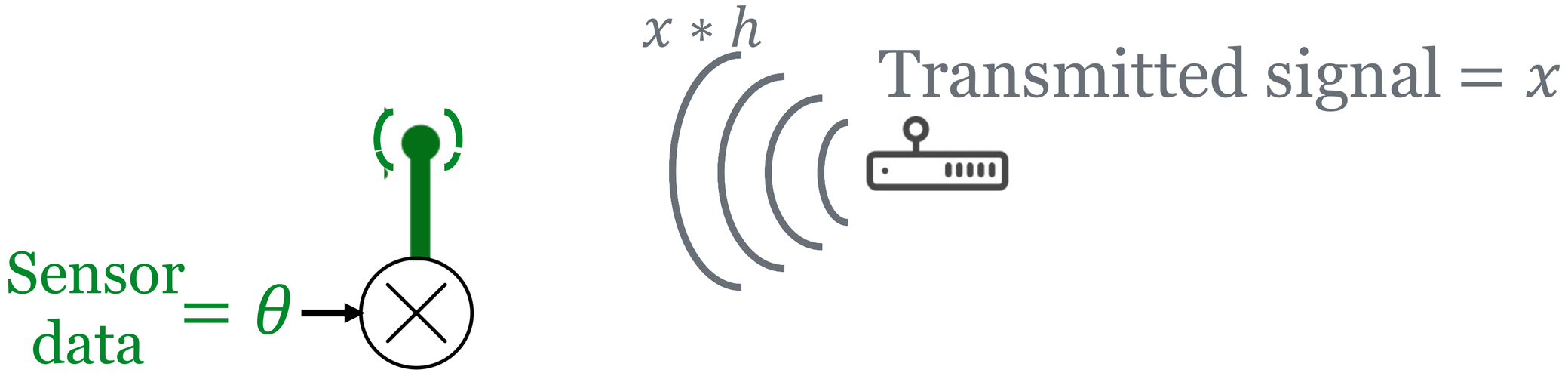
$x * h$

Transmitted signal $= x$

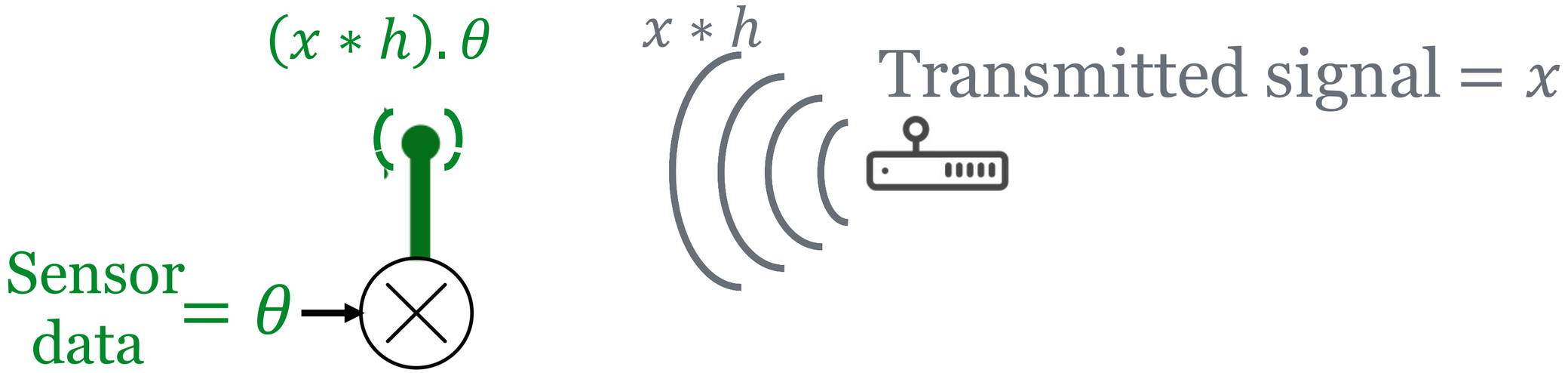
Modeling Sensor Backscatter



Modeling Sensor Backscatter



Modeling Sensor Backscatter



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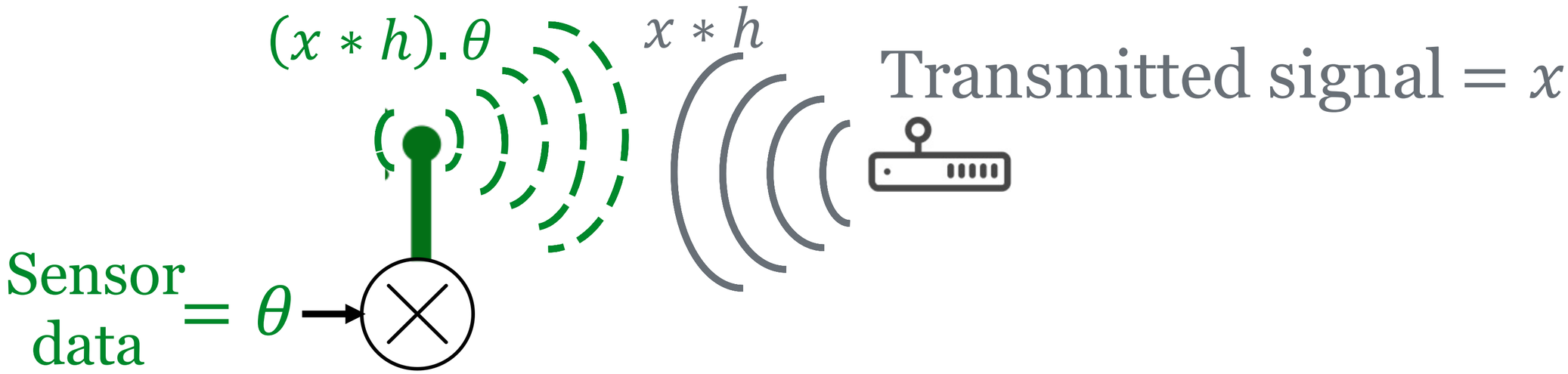
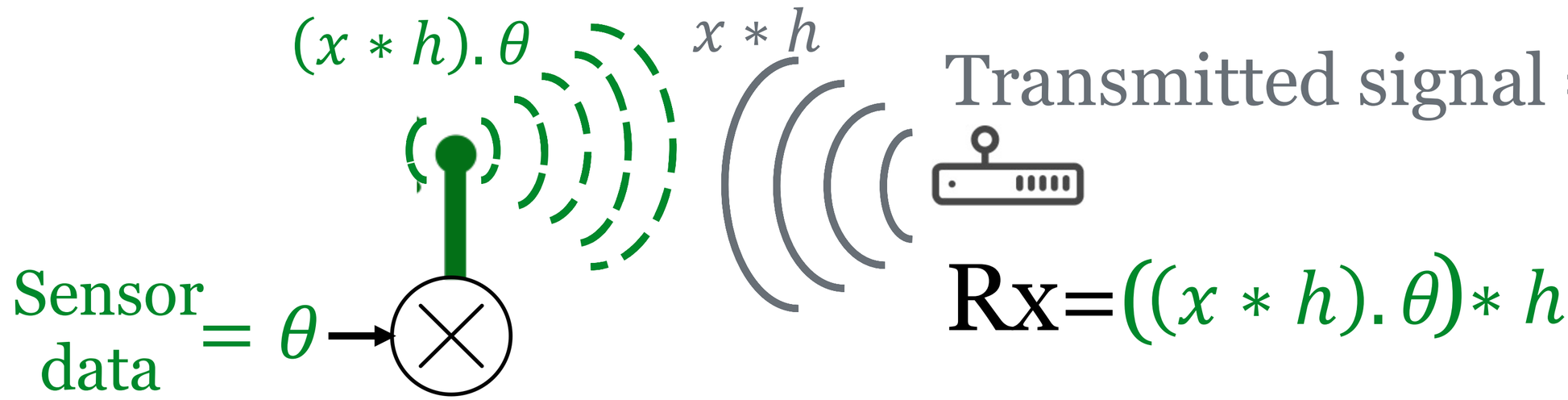
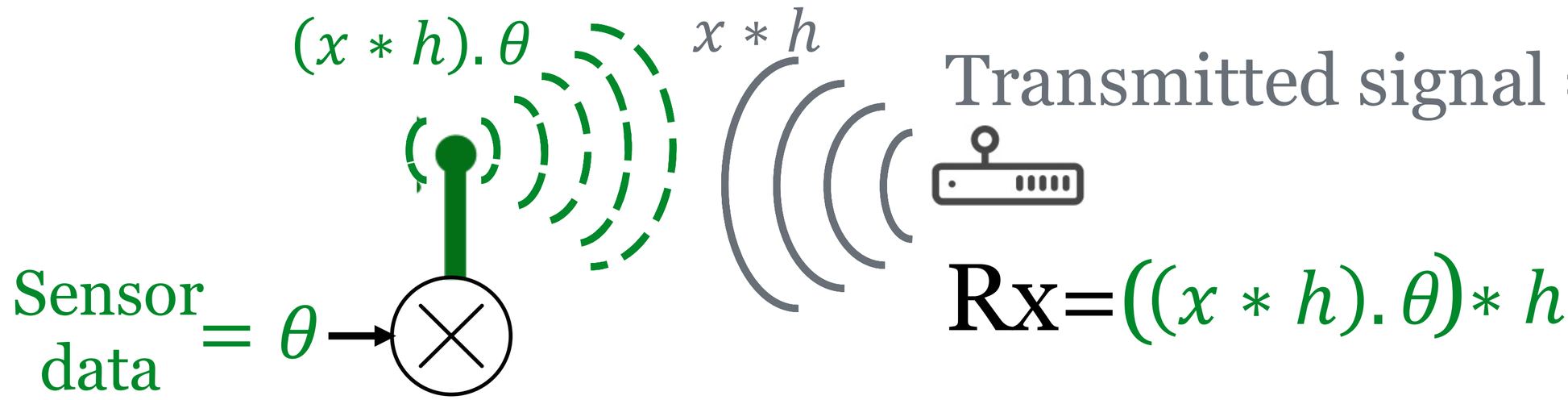


Modeling Sensor Backscatter



Rx $=$ sensor backscatter $= ((x * h).\theta) * h$

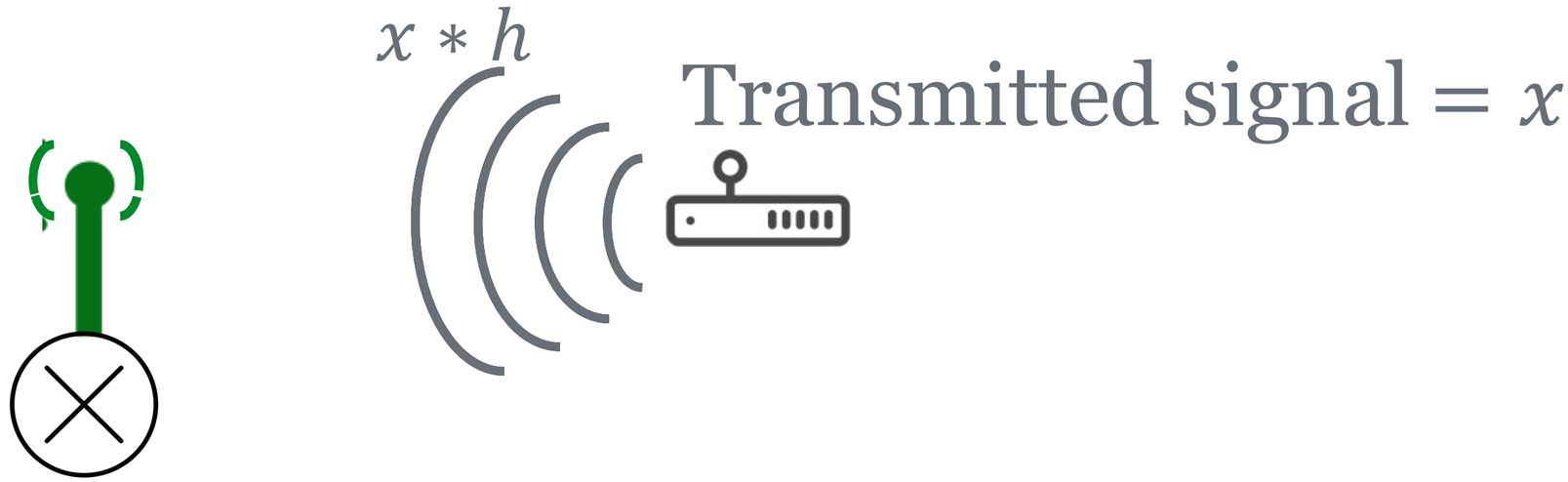
Modeling Sensor Backscatter



Rx $=$ sensor backscatter $= ((x * h).\theta) * h$

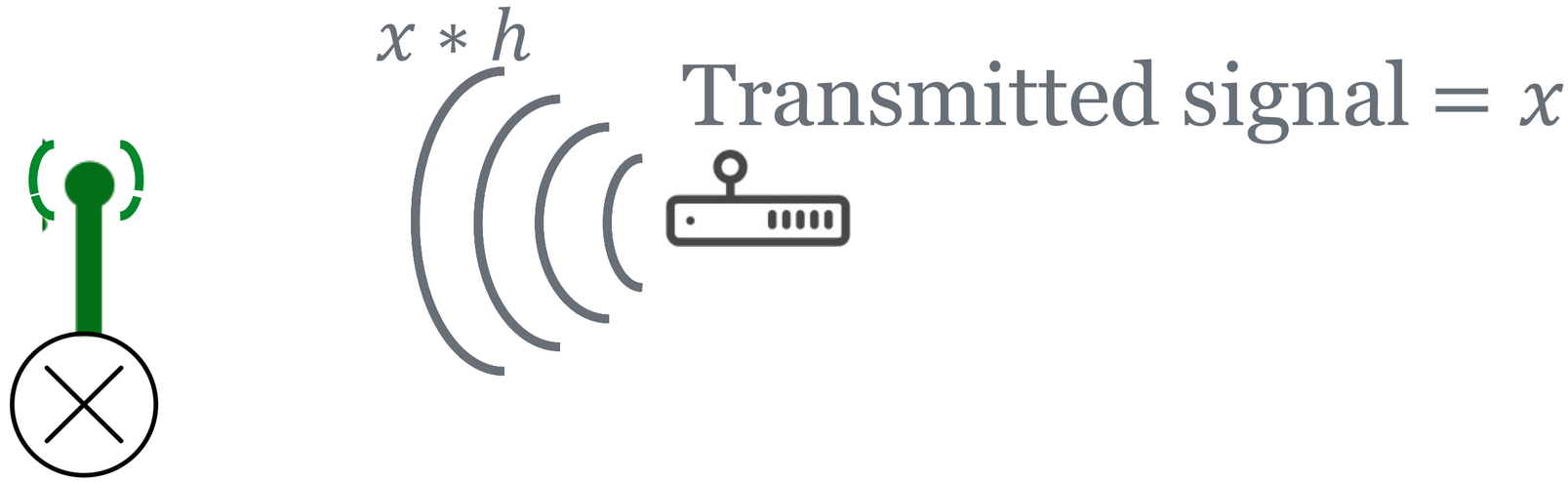
✔ ? ? ?

Estimating Backscatter Channel



Estimating Backscatter Channel

Use predefined sequence of sensor data θ to estimate channel



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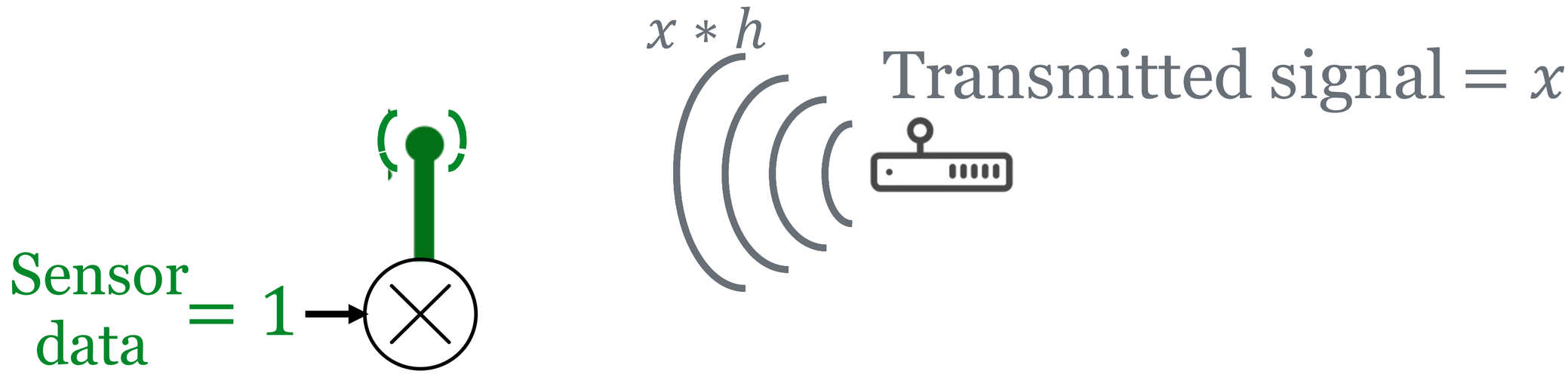

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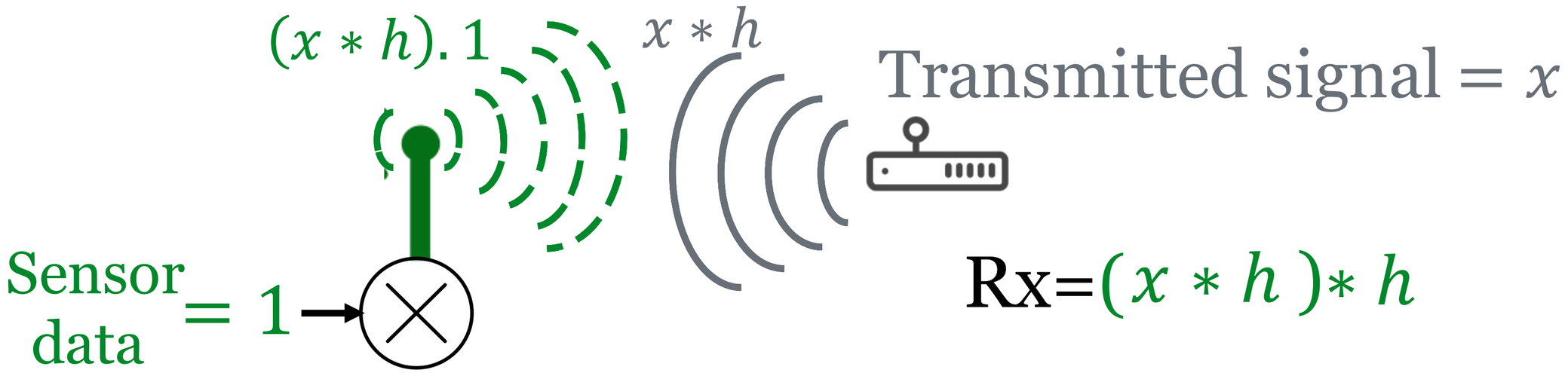

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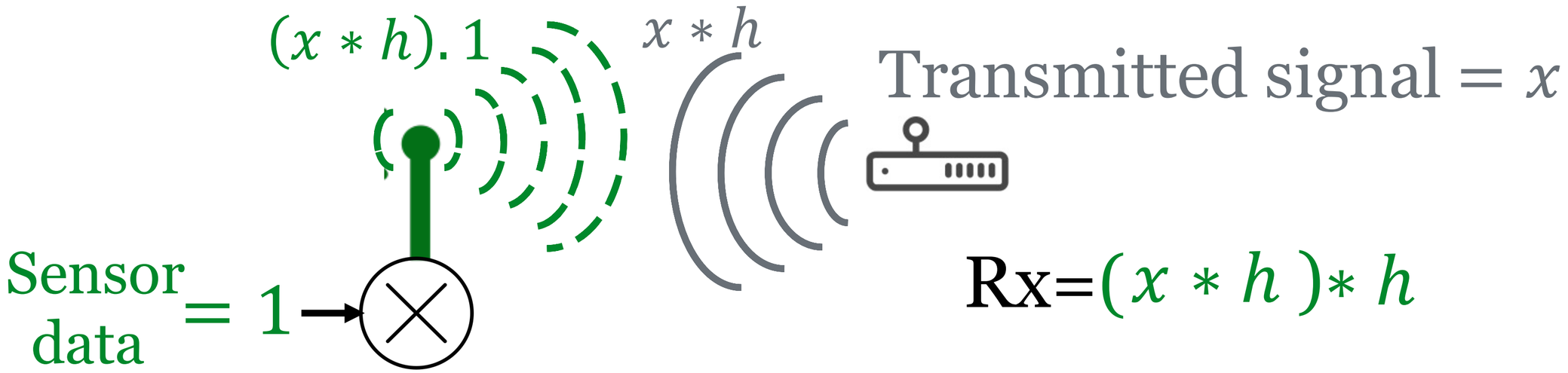
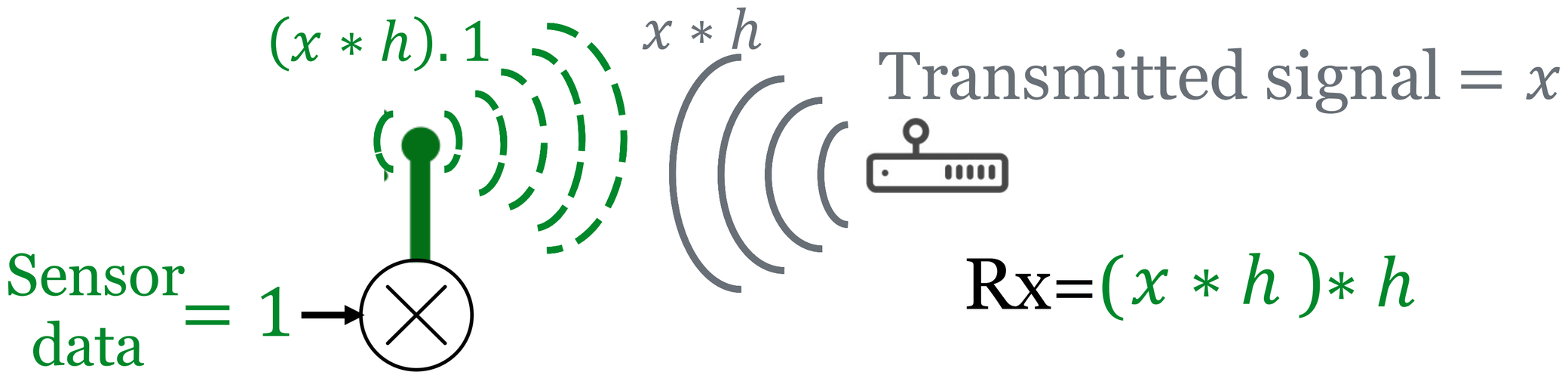


Rx $=$ sensor backscatter $=$ $x * (h * h)$ ✔

Estimating Backscatter Channel

Use predefined sequence of sensor data θ to estimate channel

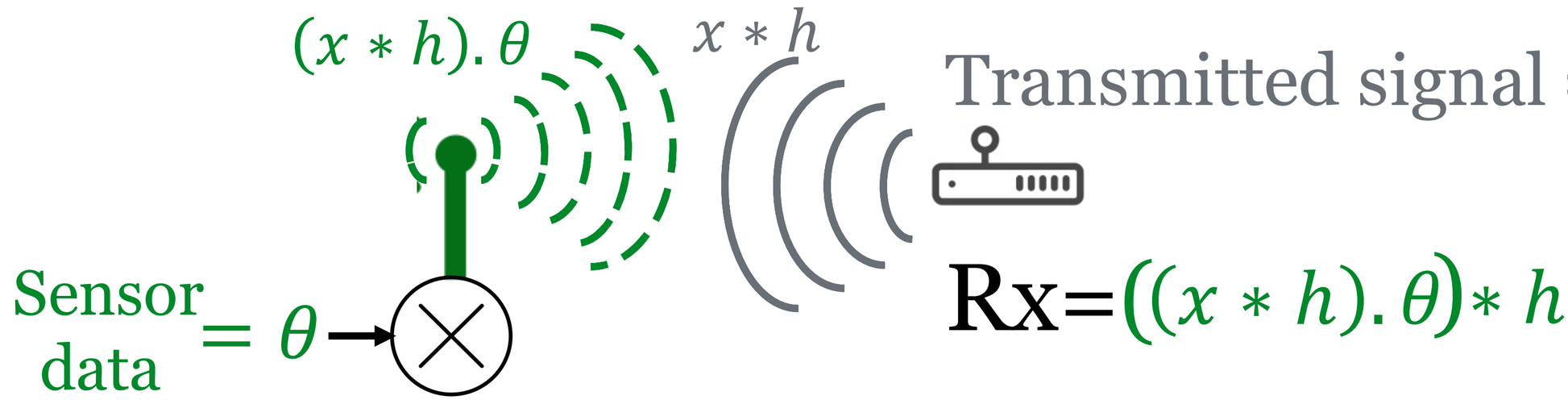


Rx $=$ sensor backscatter $=$ $x * (h * h)$

✔

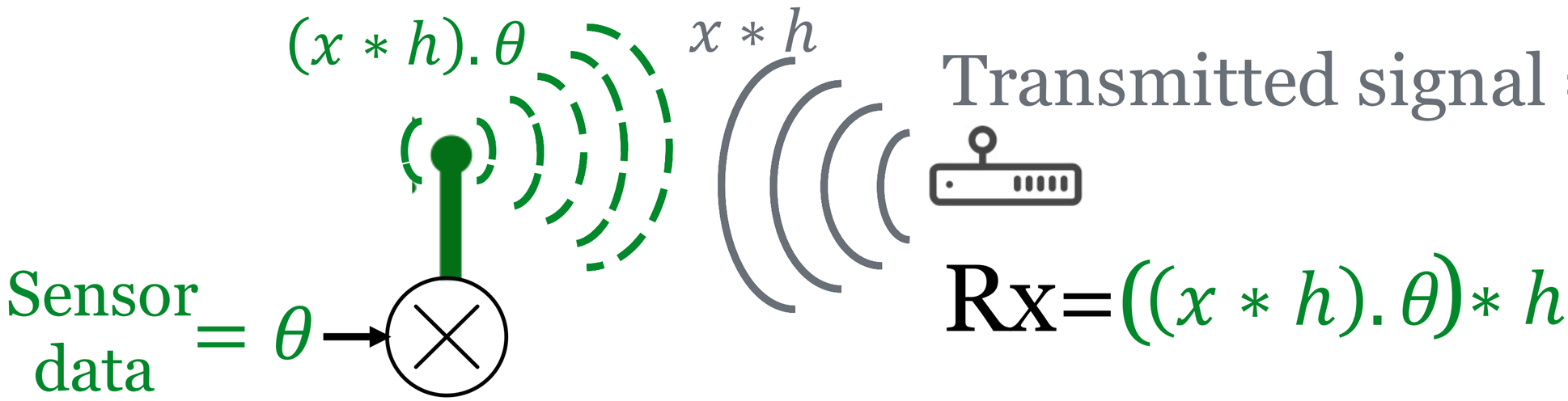
Estimate h

Modeling Sensor Backscatter



Rx = sensor backscatter =

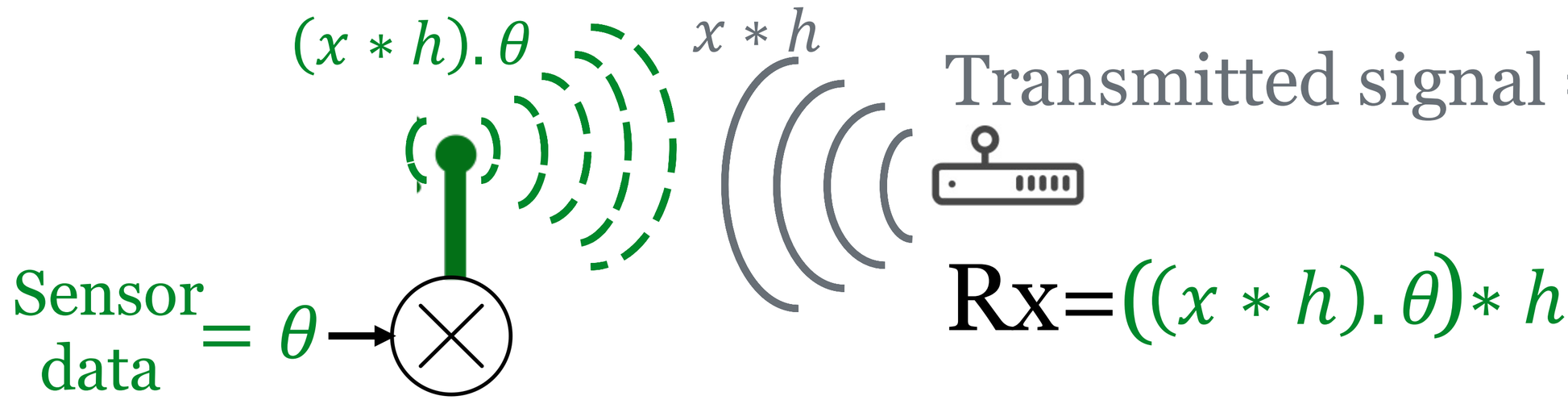
Modeling Sensor Backscatter



Rx $=$ sensor backscatter $= ((x * h).\theta) * h$

✔ ? ? ?

Modeling Sensor Backscatter



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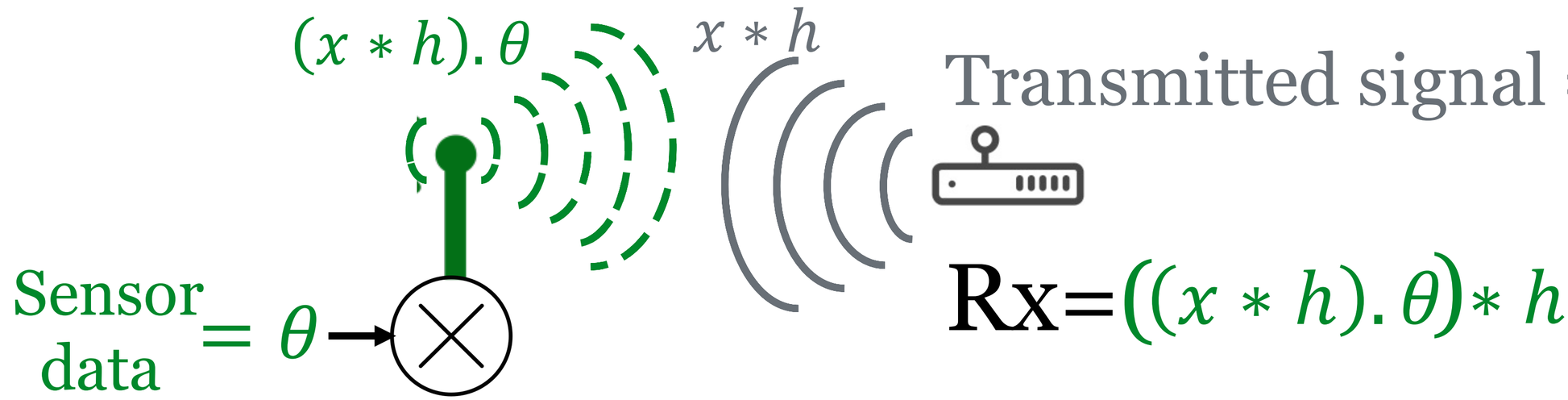
✔ ✔ ? ✔

Modeling Sensor Backscatter

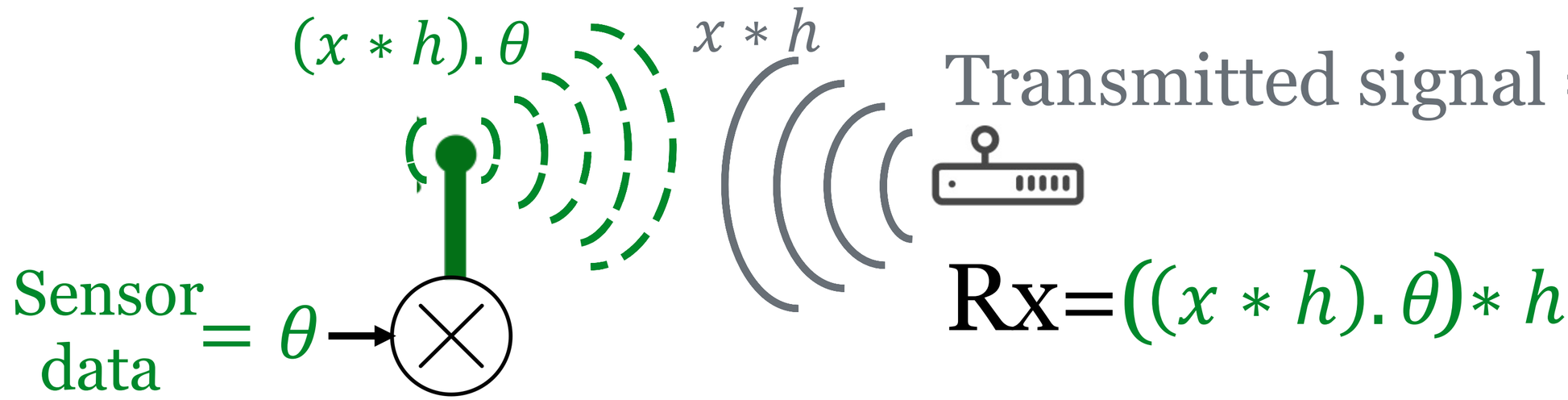


Rx $=$ sensor backscatter $= ((x * h).\theta) * h$

✔ ✔ ? ✔

Incoming signal z $= (x * h)$

Modeling Sensor Backscatter



Rx $=$ sensor backscatter $= ((x * h).\theta) * h$

✔ ✔ ? ✔

Incoming signal z $= (x * h)$

sensor backscatter $= (\quad z.\theta \quad) * h$

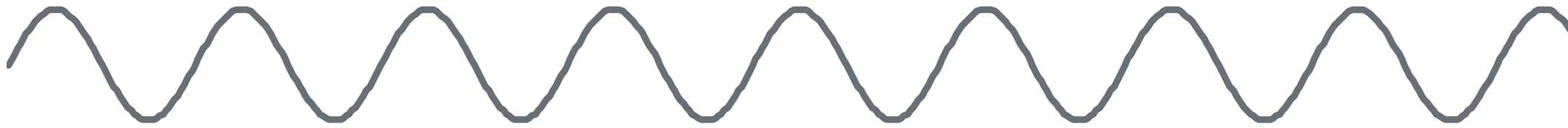
Demodulating θ from Sensor Backscatter

Sensor Backscatter = $\{z.\theta\} * h$

Demodulating θ from Sensor Backscatter

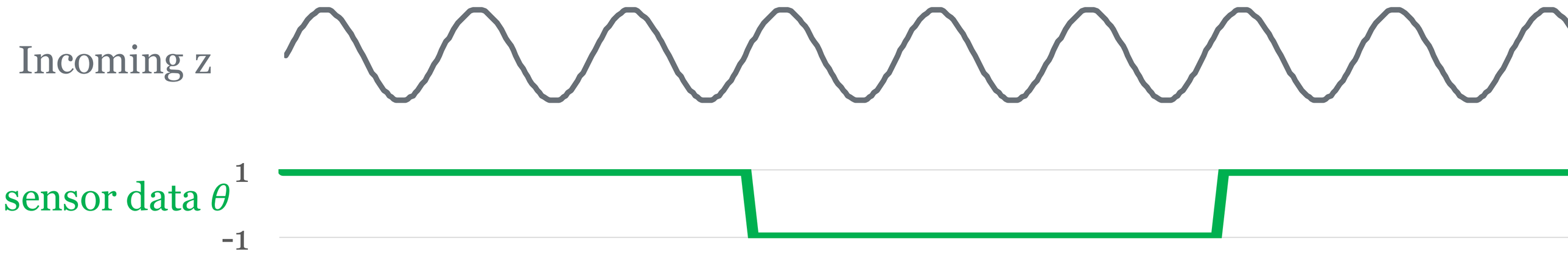
Sensor Backscatter = $\{z.\theta\} * h$

Incoming z



Demodulating θ from Sensor Backscatter

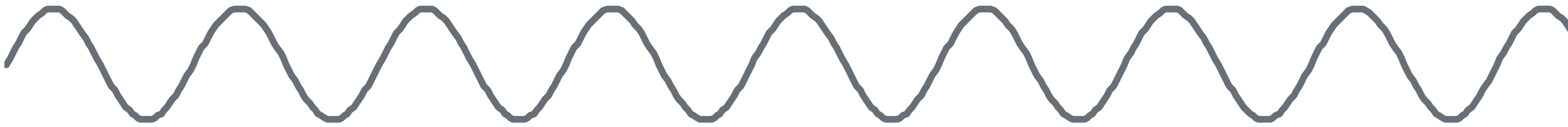
Sensor Backscatter = $\{z.\theta\} * h$



Demodulating θ from Sensor Backscatter

Sensor Backscatter = $\{z.\theta\} * h$

Incoming z

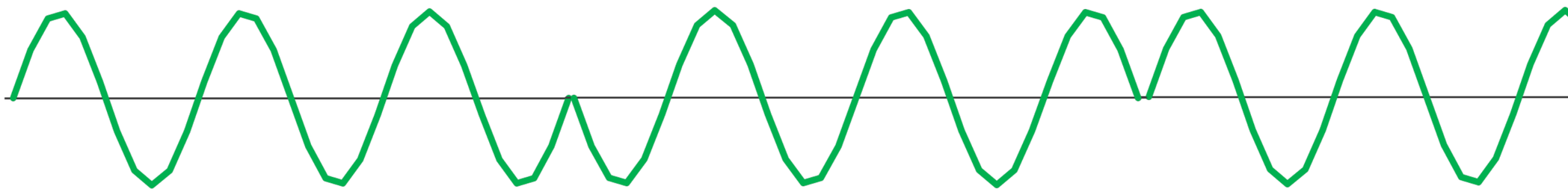


sensor data θ

1

-1

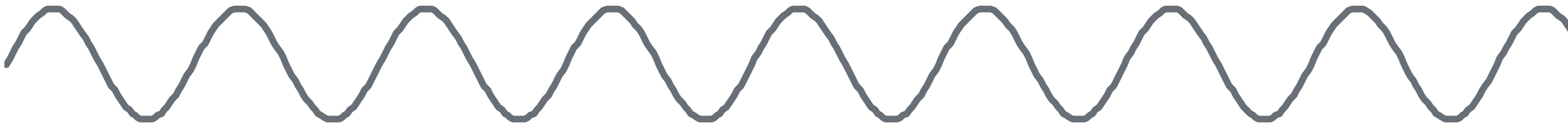
sensor backscatter



Demodulating θ from Sensor Backscatter

Sensor Backscatter = $\{z.\theta\} * h$

Incoming z

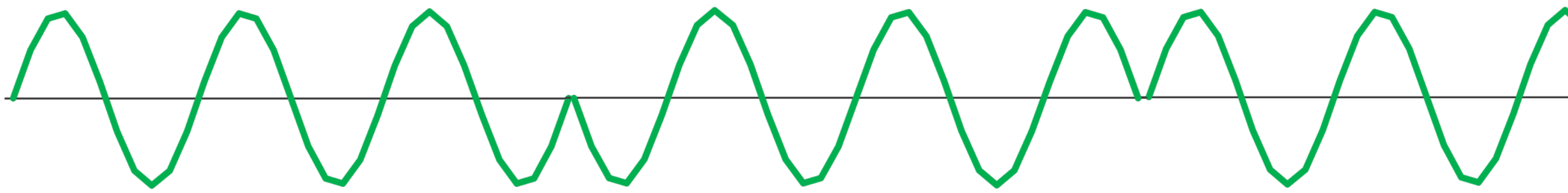


sensor data θ

1

-1

sensor backscatter



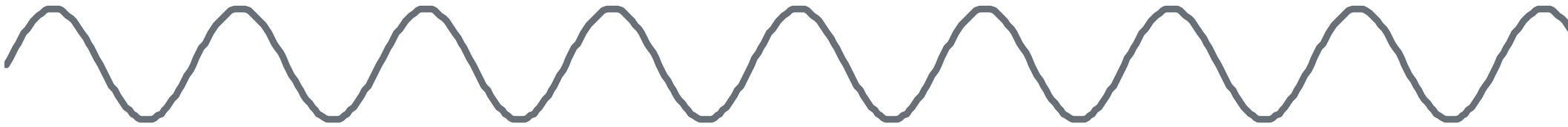
WiFi AP
sampling rate
40 Msps

IoT sensor
Information switching rate
2 Msps

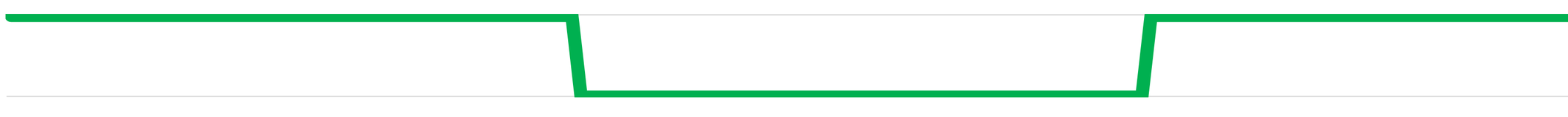
Demodulating θ from Sensor Backscatter

Sensor Backscatter = $\{z.\theta\} * h$

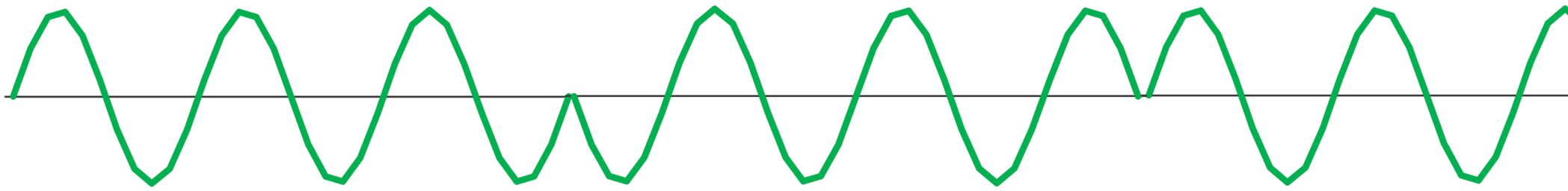
Incoming z



sensor data θ



sensor backscatter

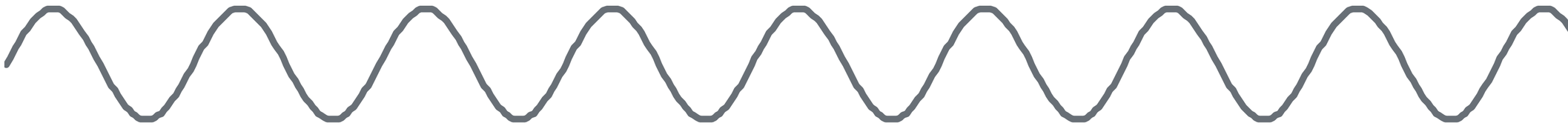


WiFi AP sampling rate 40 Msps = 20 × IoT sensor Information switching rate 2 Msps

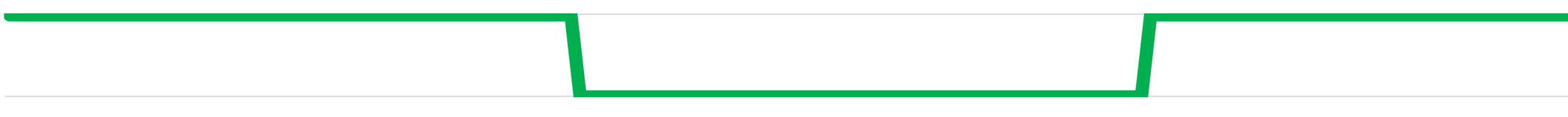
Demodulating θ from Sensor Backscatter

Sensor Backscatter = $\{z.\theta\} * h$

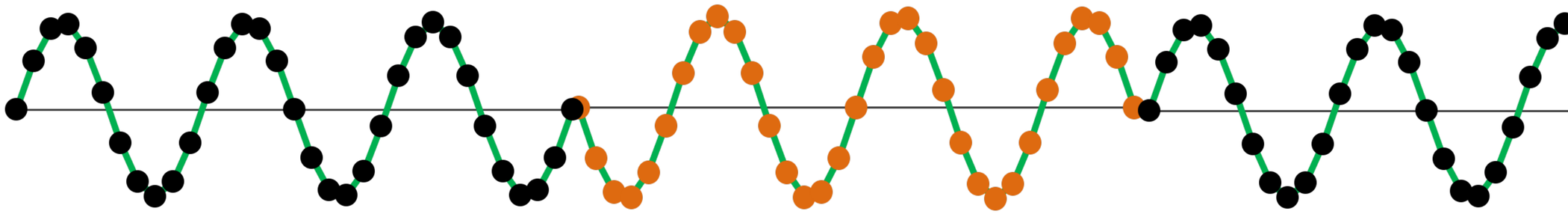
Incoming z



sensor data θ



sensor backscatter



WiFi AP sampling rate 40 Msps = 20 × IoT sensor Information switching rate 2 Msps

Demodulating θ from Sensor Backscatter

Sensor Backscatter = $\{z.\theta\} * h$

Incoming z

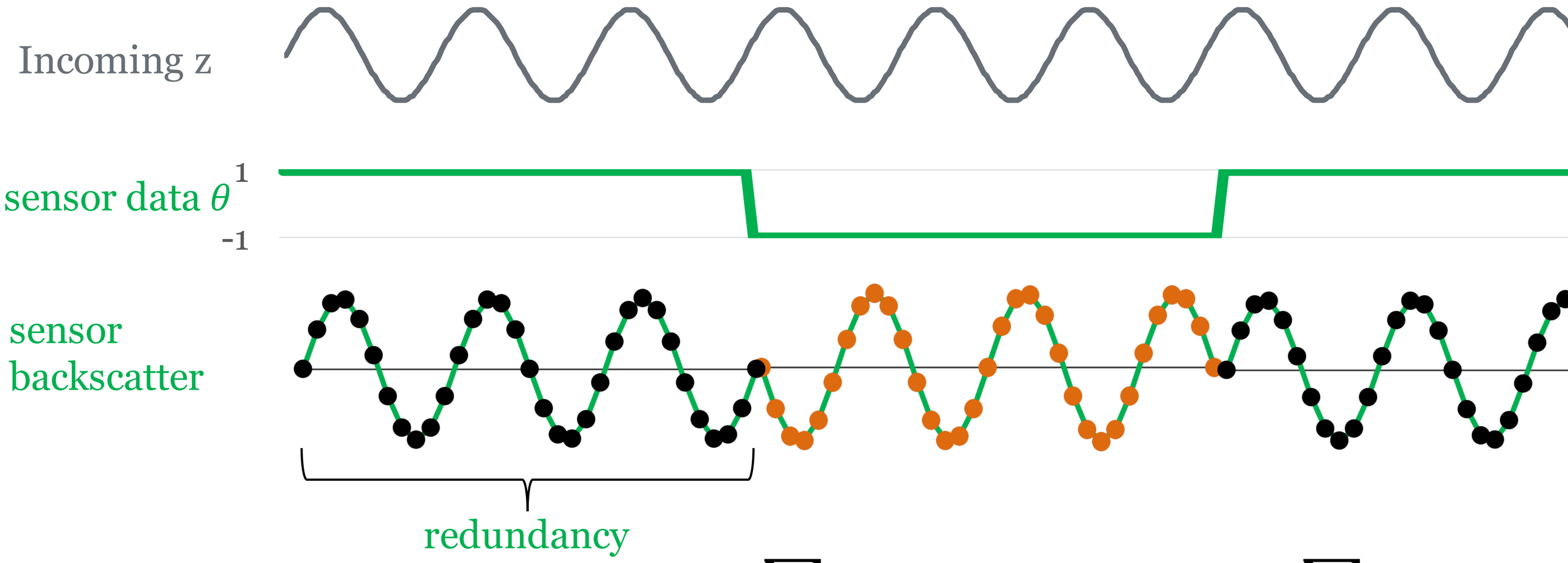
sensor data θ 1 -1

sensor backscatter

redundancy

Demodulating θ from Sensor Backscatter

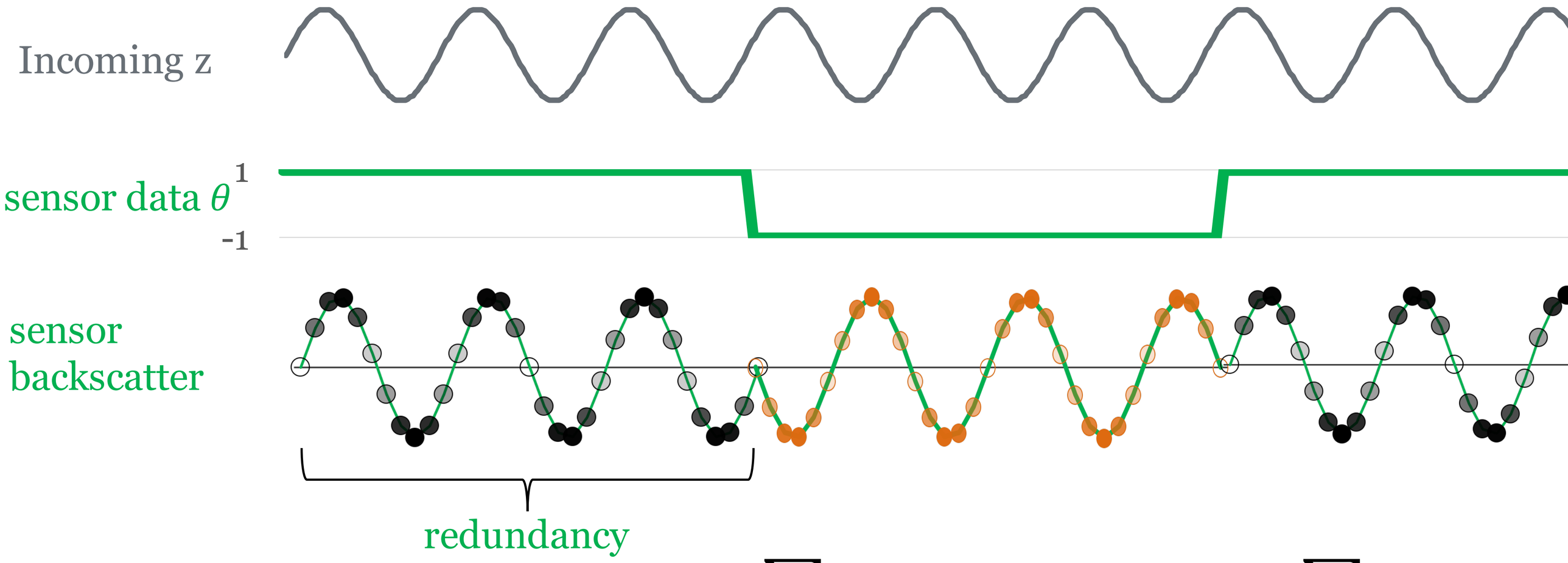
Sensor Backscatter = $\{z.\theta\} * h$



$$Maximal\ Ratio\ Combining = \sum weights\ * samples = \sum w_i\ * s_i$$

Demodulating θ from Sensor Backscatter

Sensor Backscatter = $\{z.\theta\} * h$



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Demodulating θ from Sensor Backscatter

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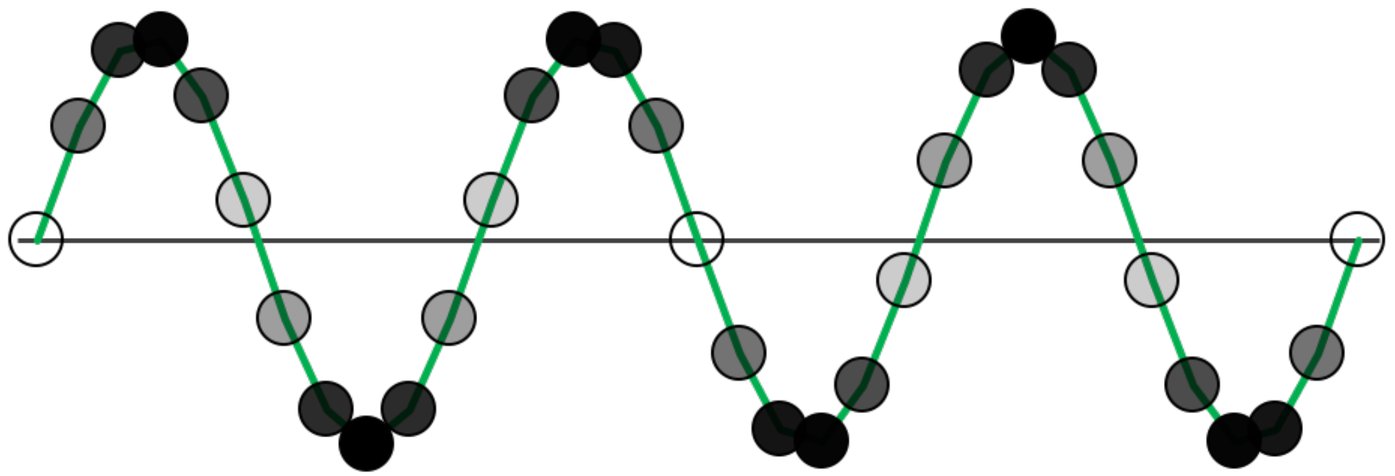
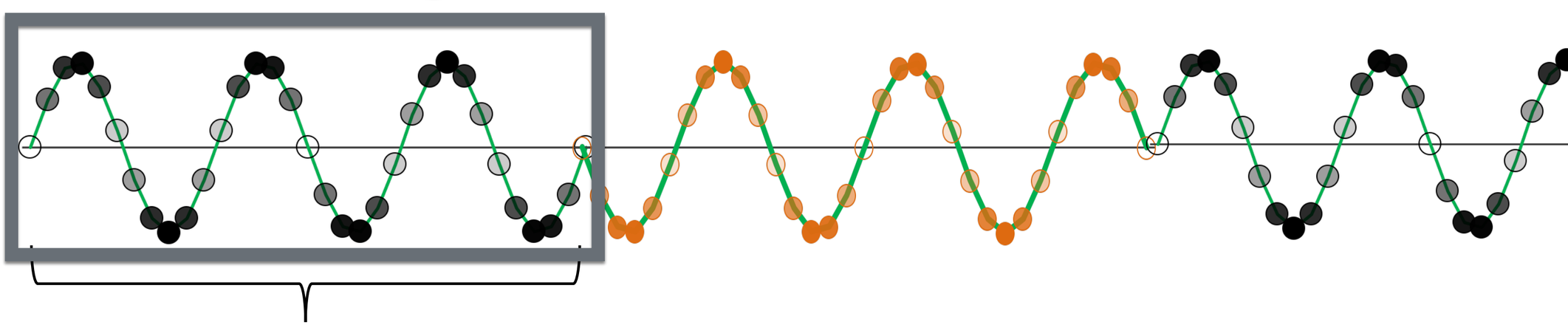


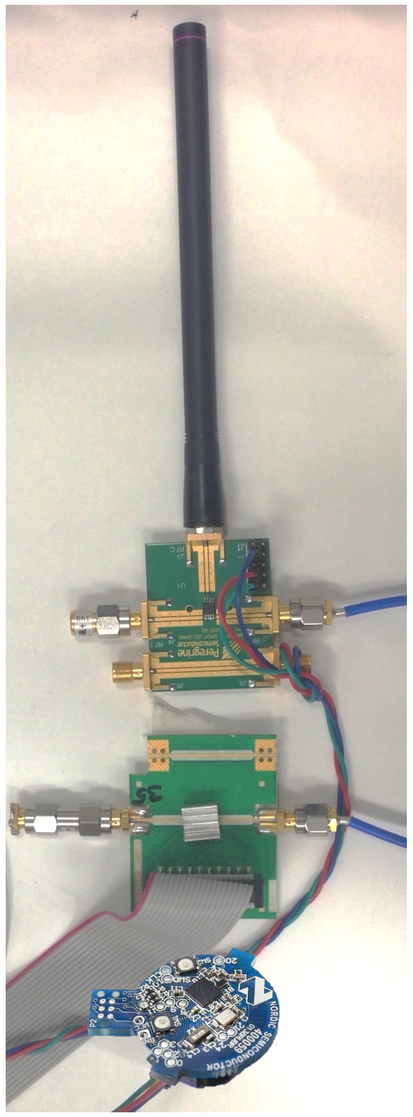
sensor backscatter



$$Maximal\ Ratio\ Combining = \sum weights\ * samples = \sum w_i\ * s_i$$

BackFi Prototype

BackFi Prototype

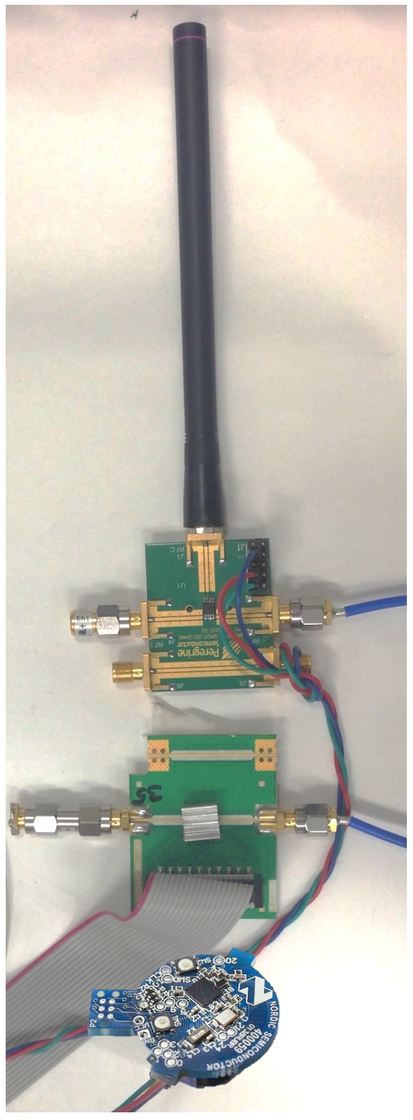


BackFi Prototype

Antenna

Modulator

Digital control board



BackFi Prototype

Antenna

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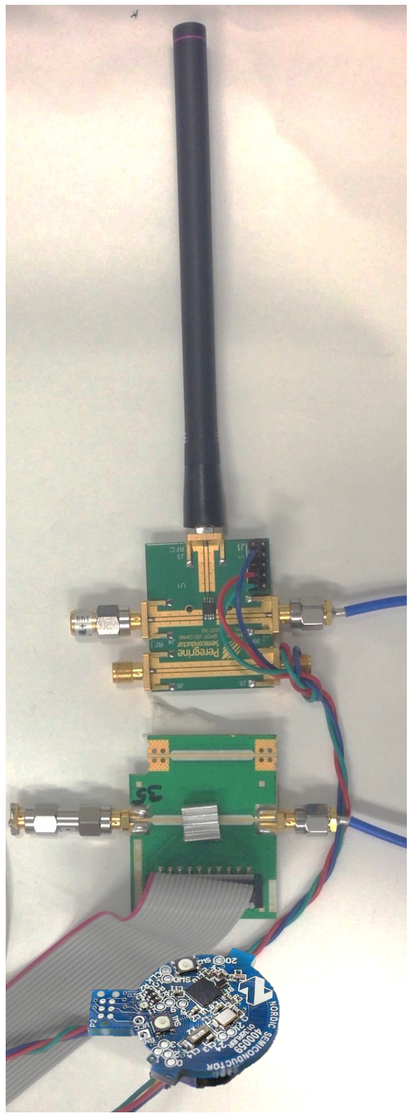


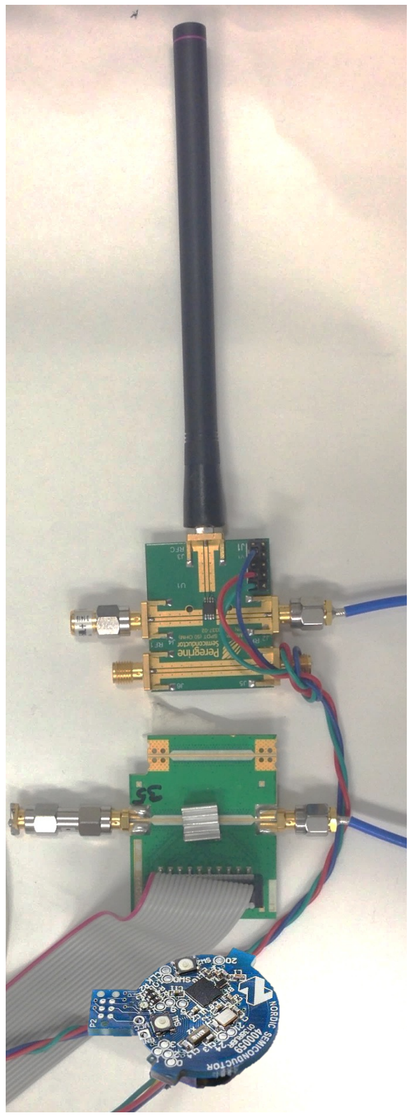
WiFi Backscatter radio with BPSK, QPSK & 16 PSK

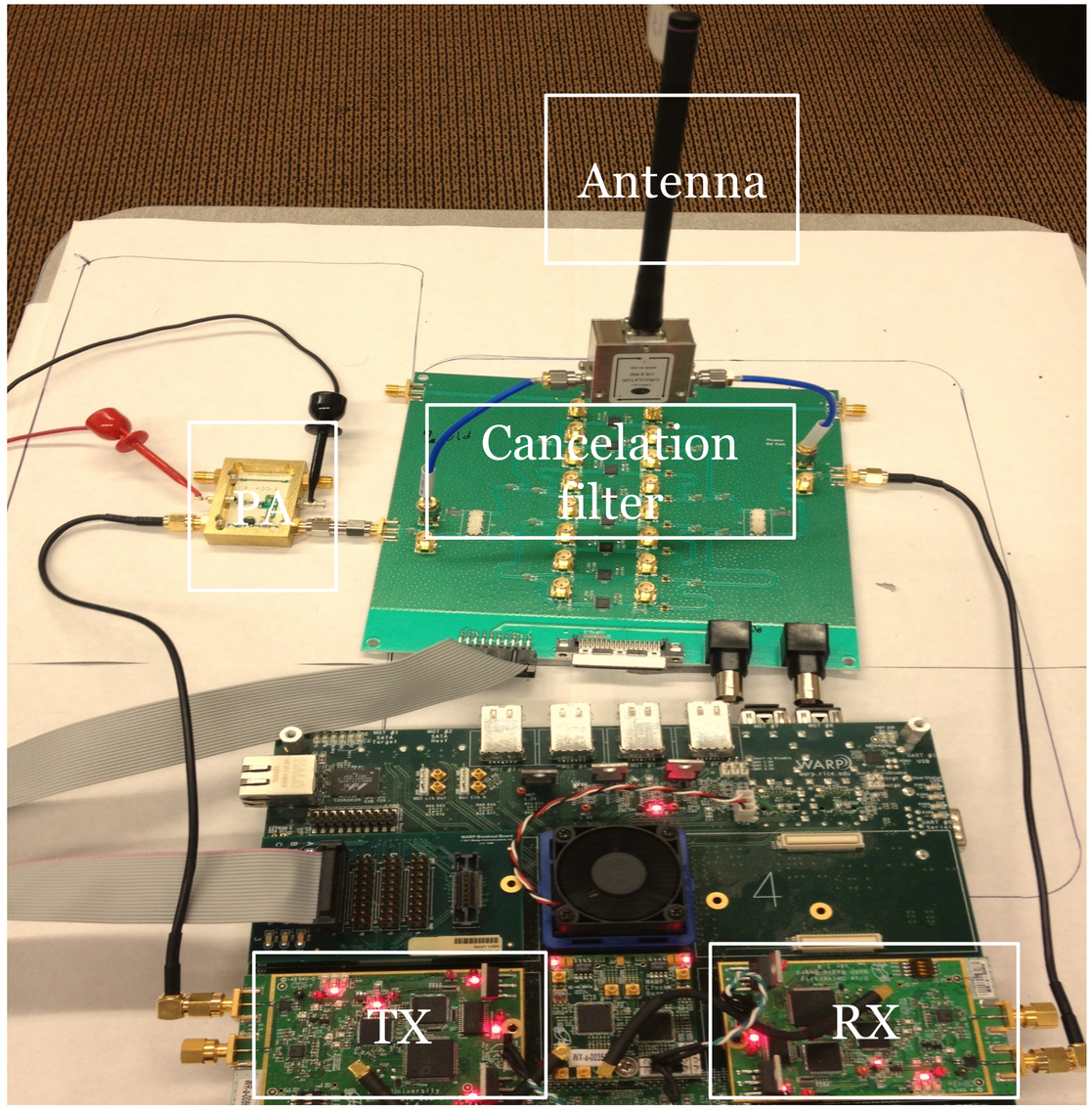
BackFi Prototype

Antenna

Modulator

Digital control board





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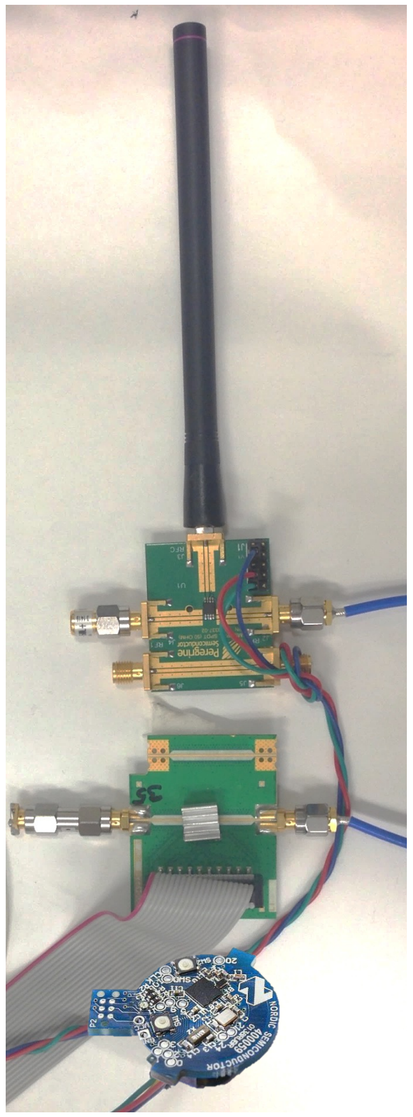
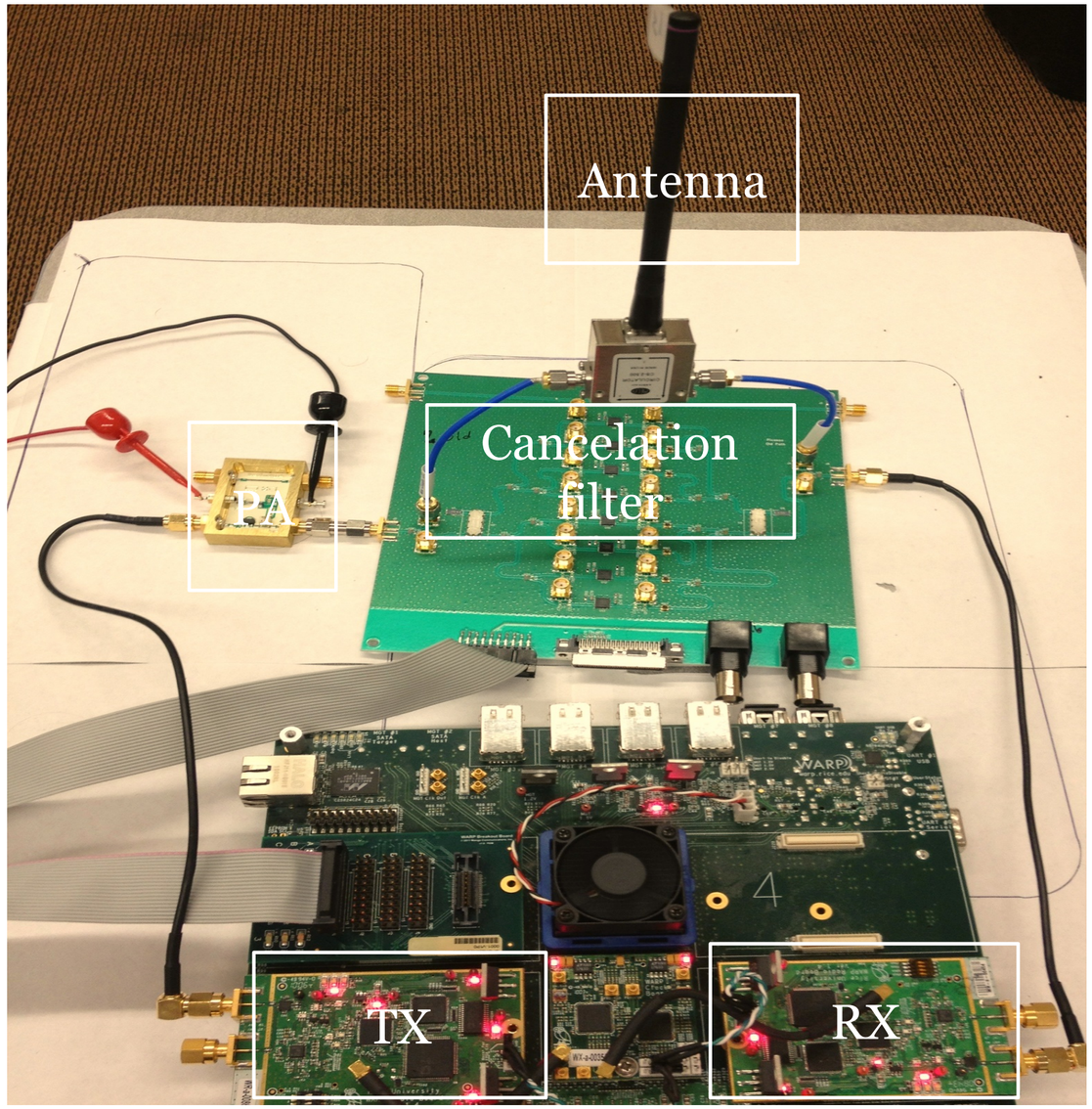
BackFi Prototype

Antenna

Modulator

Digital control board





WiFi Backscatter radio with BPSK, QPSK & 16 PSK

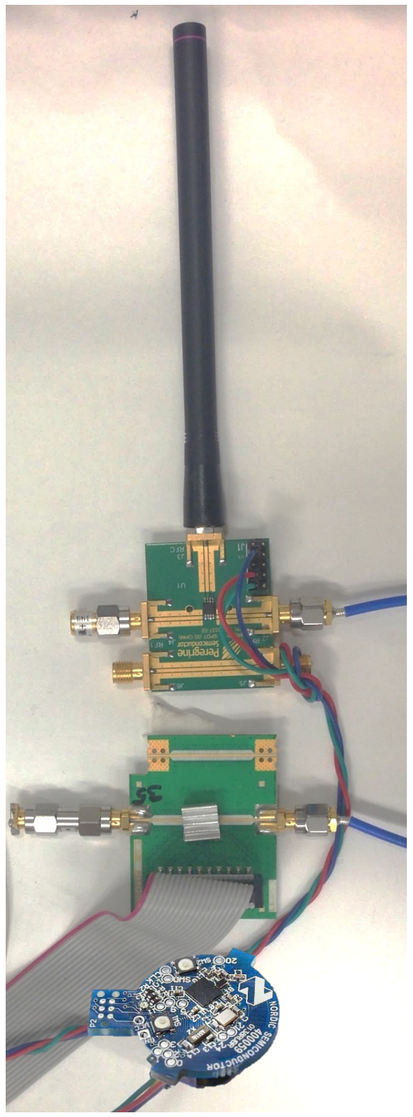
Built using WARP SDR platform, designed for 802.11, BW 20MHz, 20dBm TX power

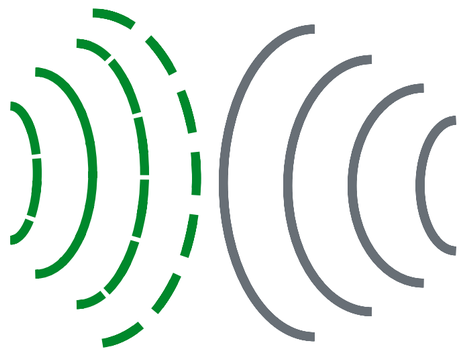
BackFi Prototype

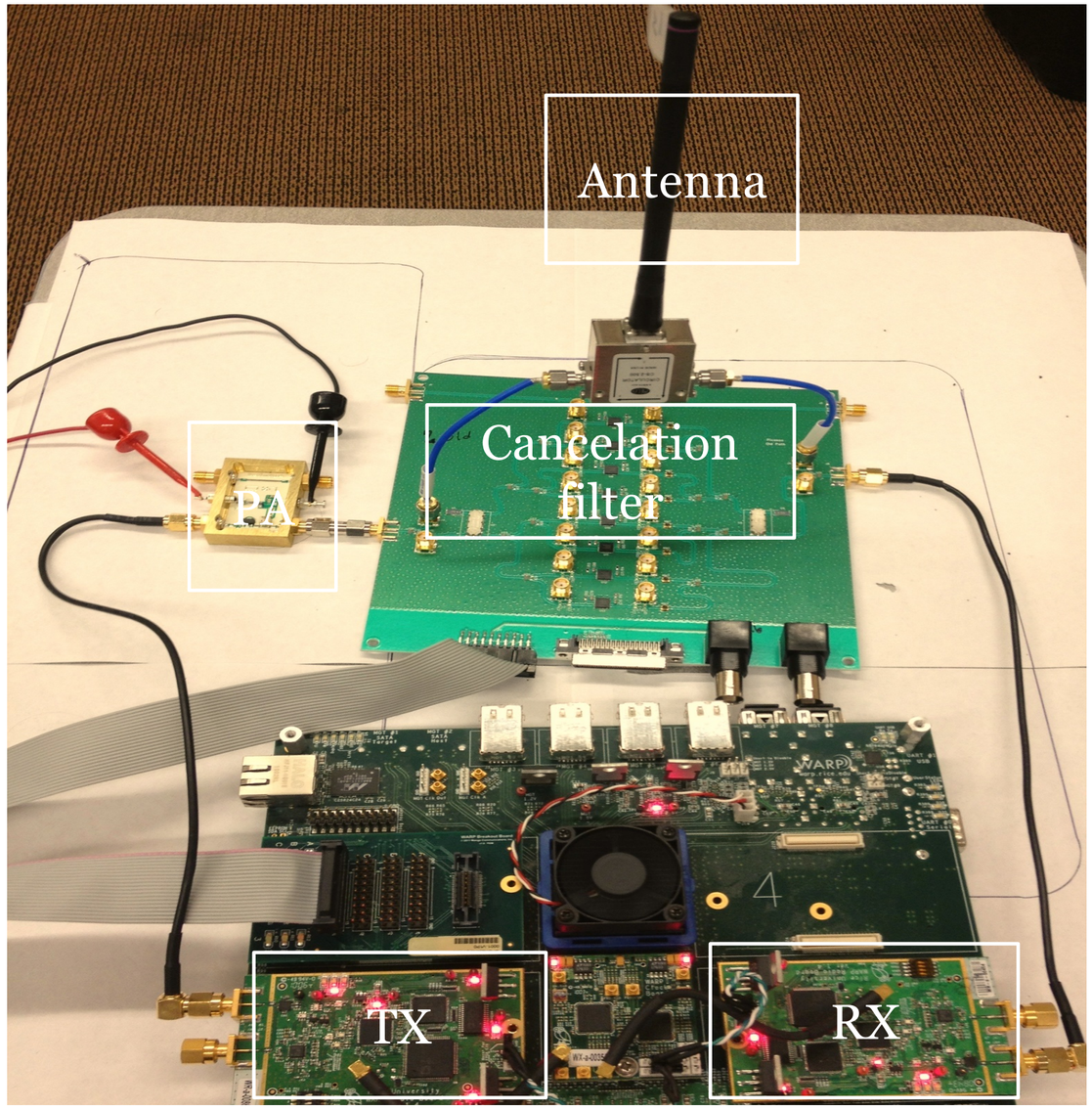
Antenna

Modulator

Digital control board





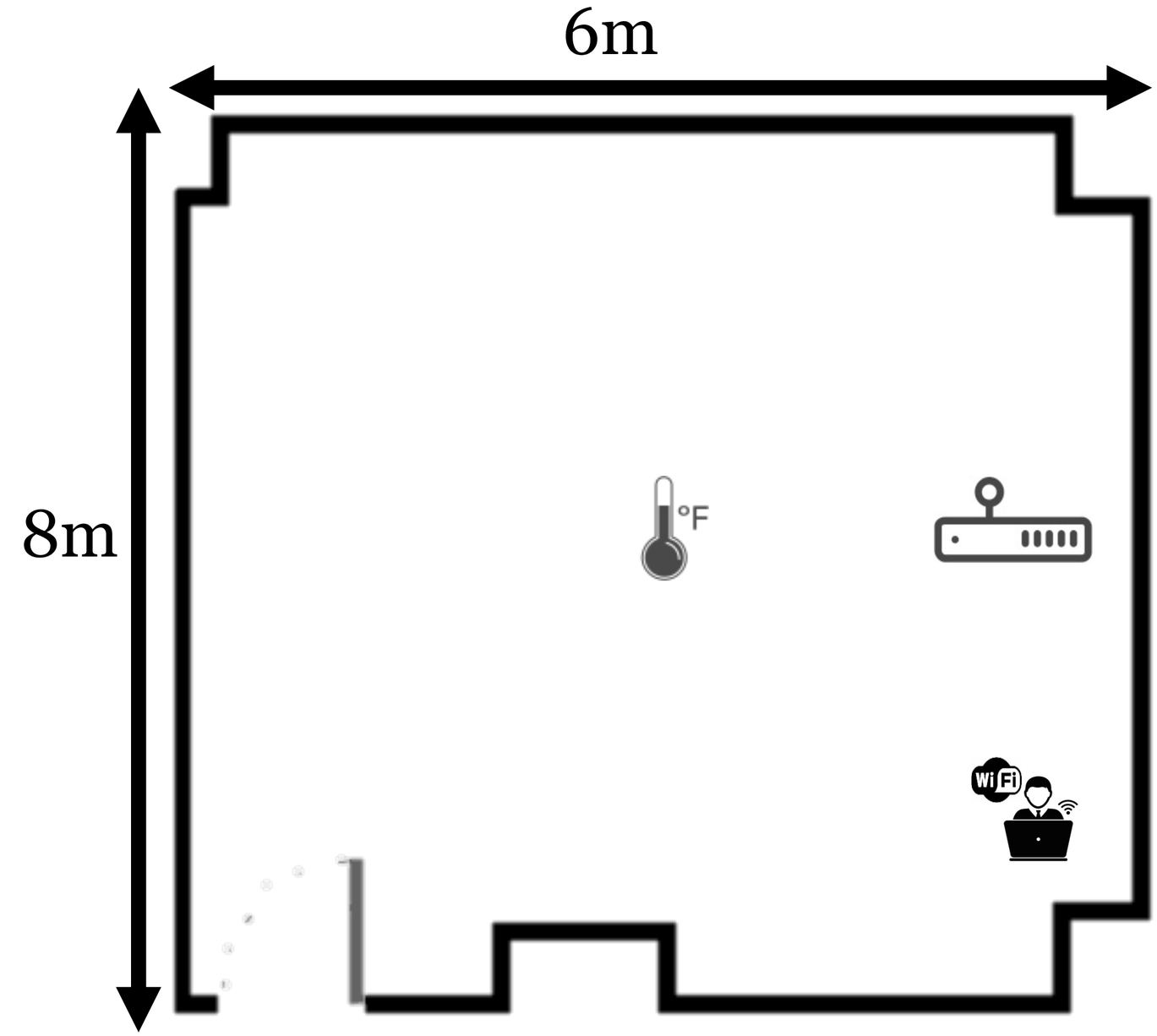


WiFi Backscatter radio with BPSK, QPSK & 16 PSK

Built using WARP SDR platform, designed for 802.11, BW 20MHz, 20dBm TX power

BackFi Prototype

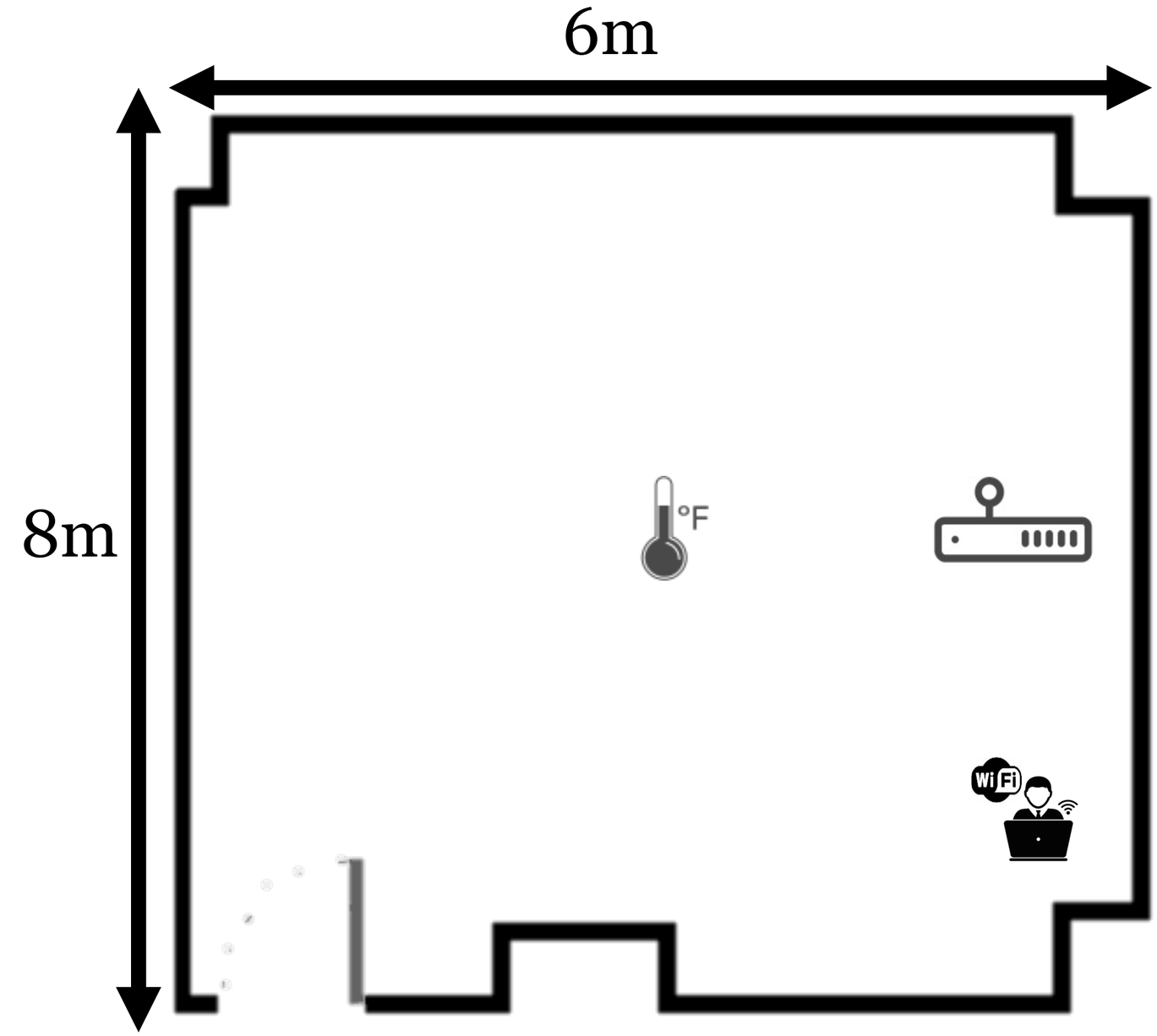
Testbed & Performance Metrics



Testbed & Performance Metrics

Indoor office environment:

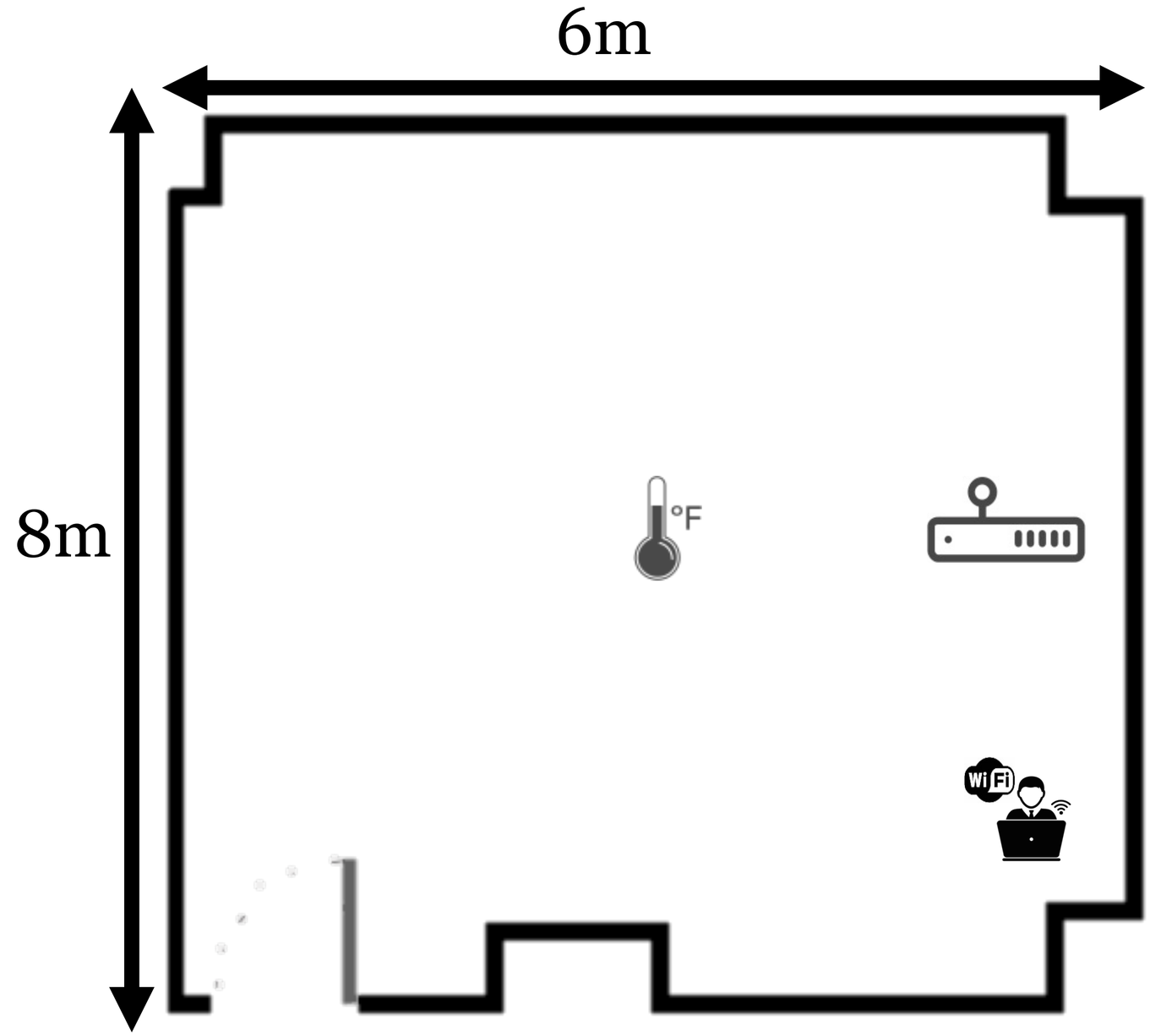
- AP and IoT sensor are placed in LOS



Testbed & Performance Metrics

Indoor office environment:

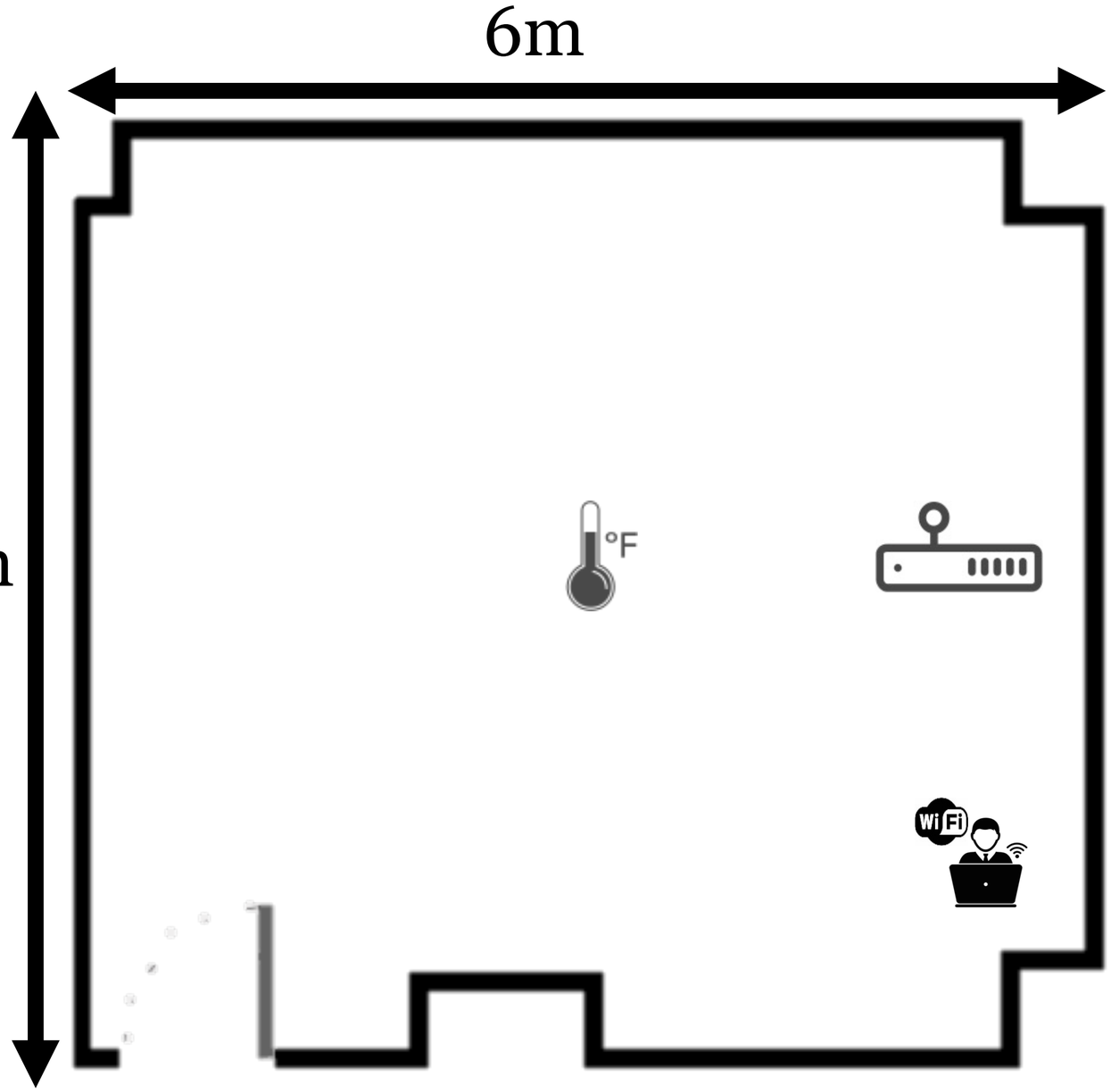
- AP and IoT sensor are placed in LOS
- WiFi clients are placed nearby



Testbed & Performance Metrics

Indoor office environment:

- AP and IoT sensor are placed in LOS
- WiFi clients are placed nearby
- Varied the placement of IoT device, client and WiFi AP.



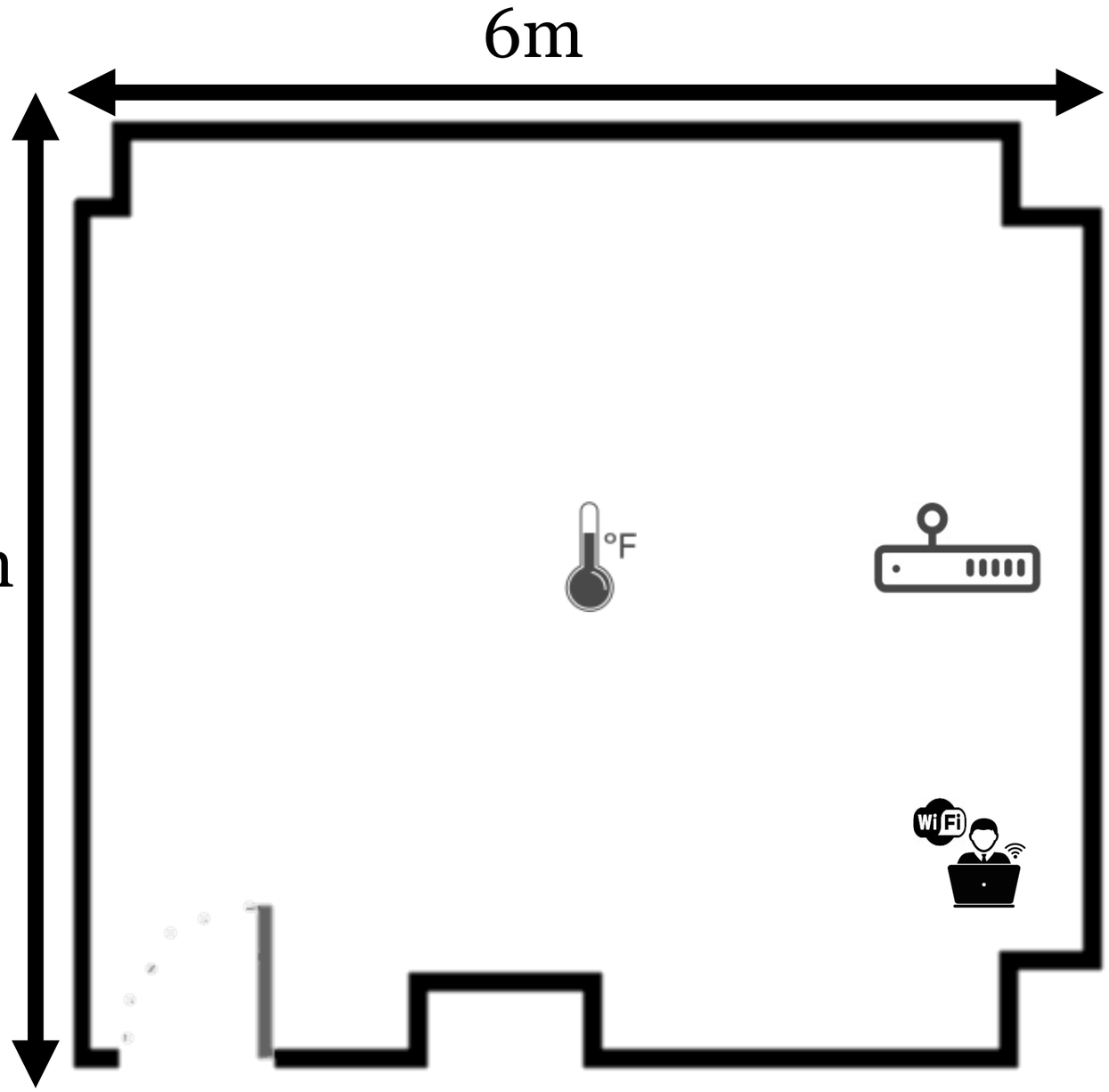
Testbed & Performance Metrics

Indoor office environment:

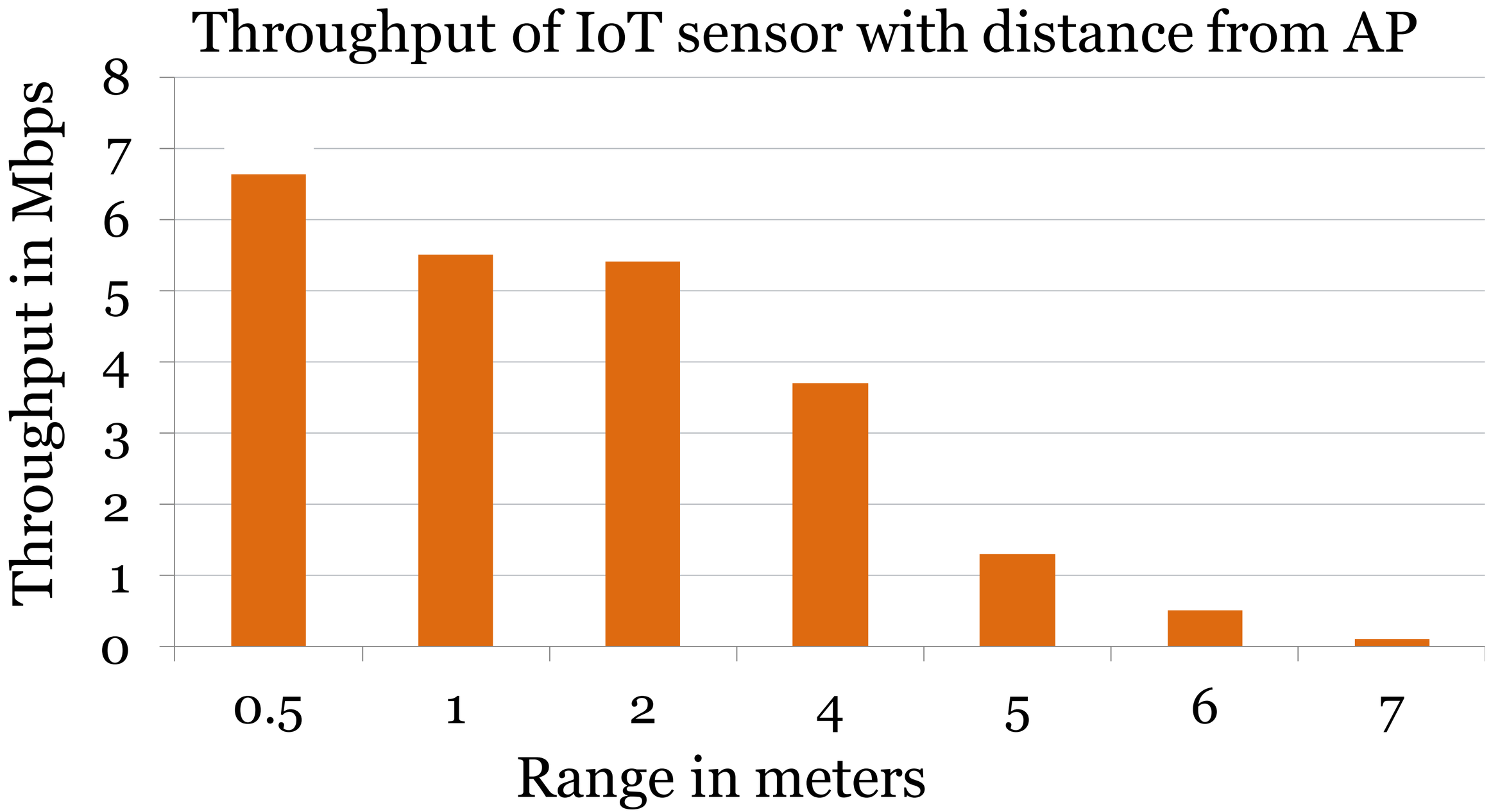
- AP and IoT sensor are placed in LOS
- WiFi clients are placed nearby
- Varied the placement of IoT device, client and WiFi AP.

Performance metrics

- Throughput
- Energy per bit



What is the range and throughput ?



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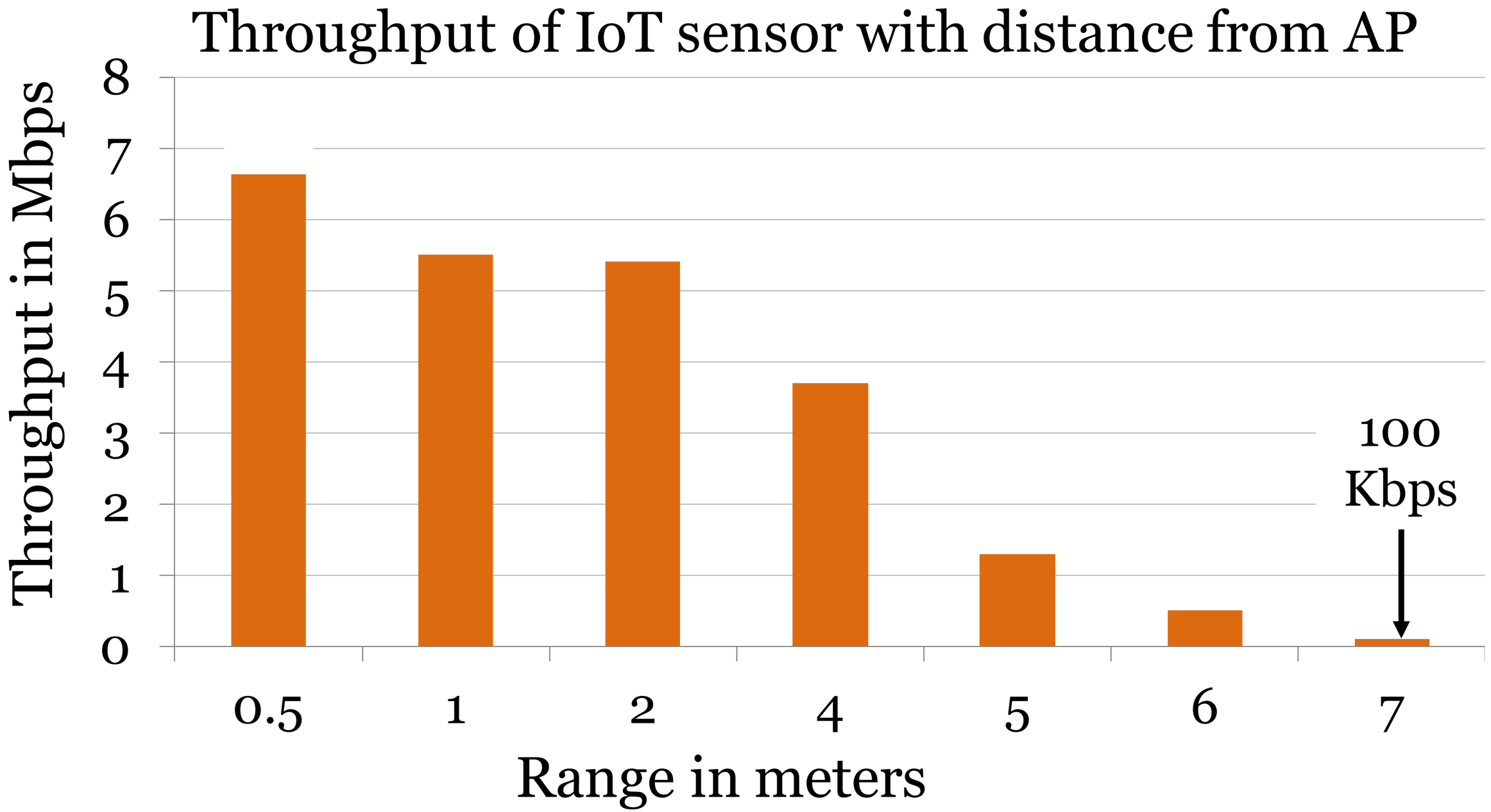

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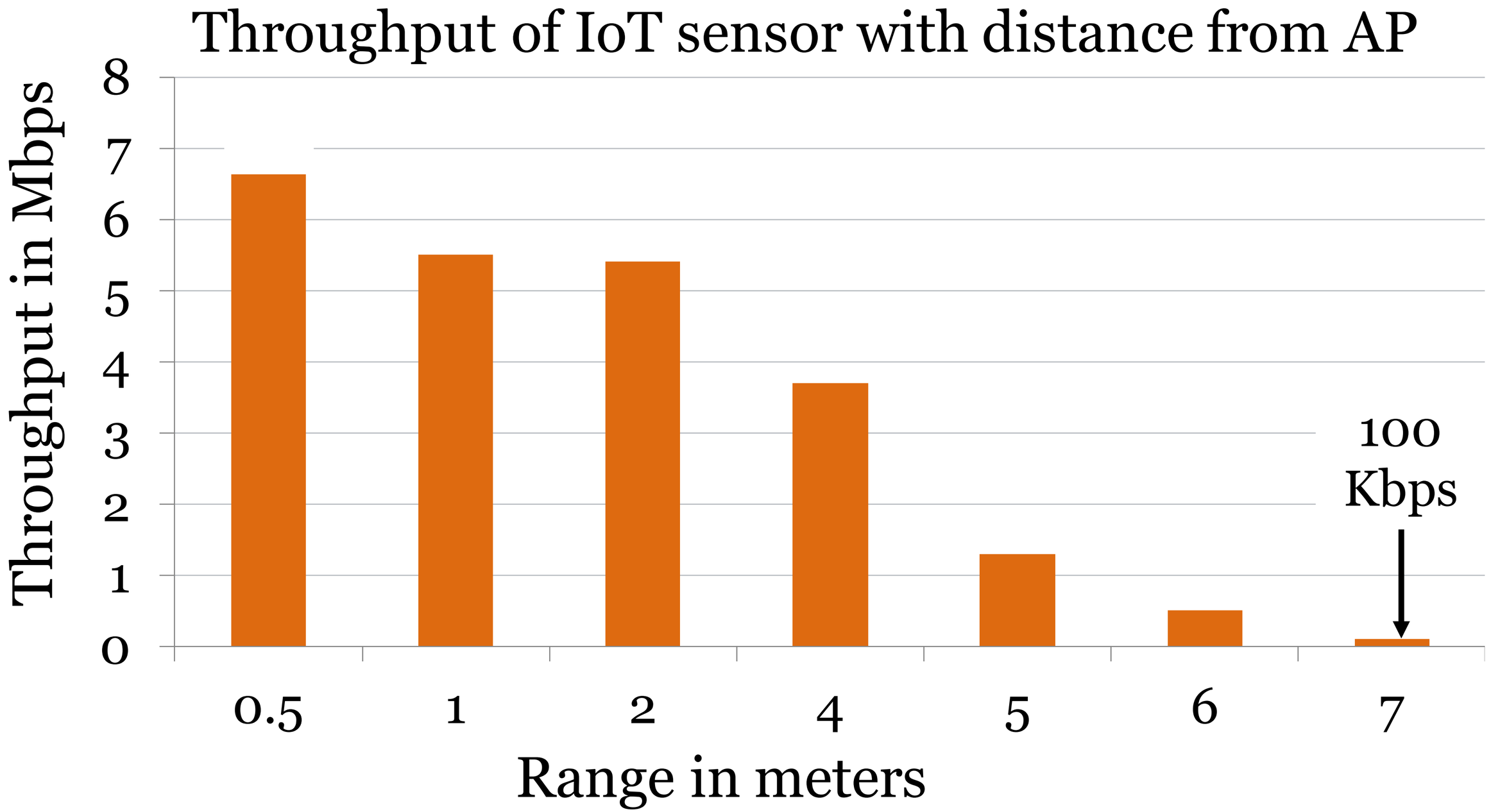

Three order of magnitude better throughput than prior WiFi backscatter

What is the power consumption of BackFi?

Throughput in Mbps	EPB in pJ/bit	Total Power Consumption in uW for continuous mode
.1	12.66	1.27
.5	5.04	2.52
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What is the power consumption of BackFi?

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Two order magnitude better EPB than prior work

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- Vision: Build a pervading layer of connectivity over all amb ient communication signals
- Next step: go from a link to a network