Toward
Sustainable Ubiquitous Computing and Interaction

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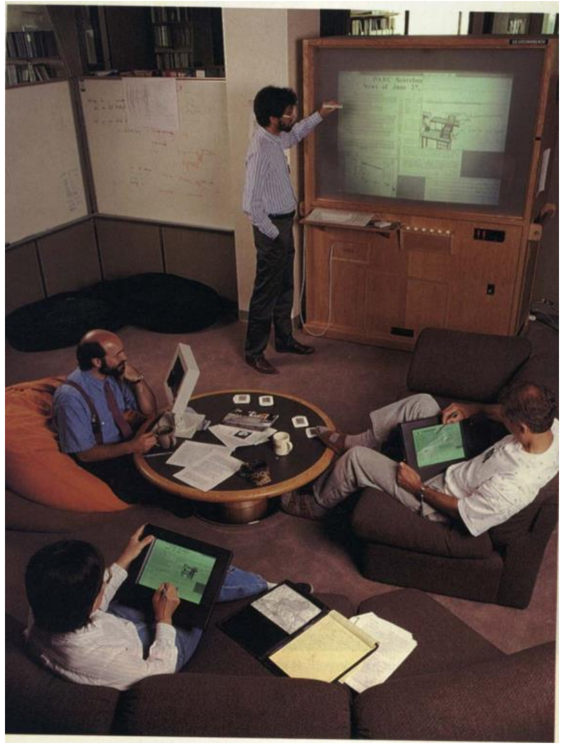
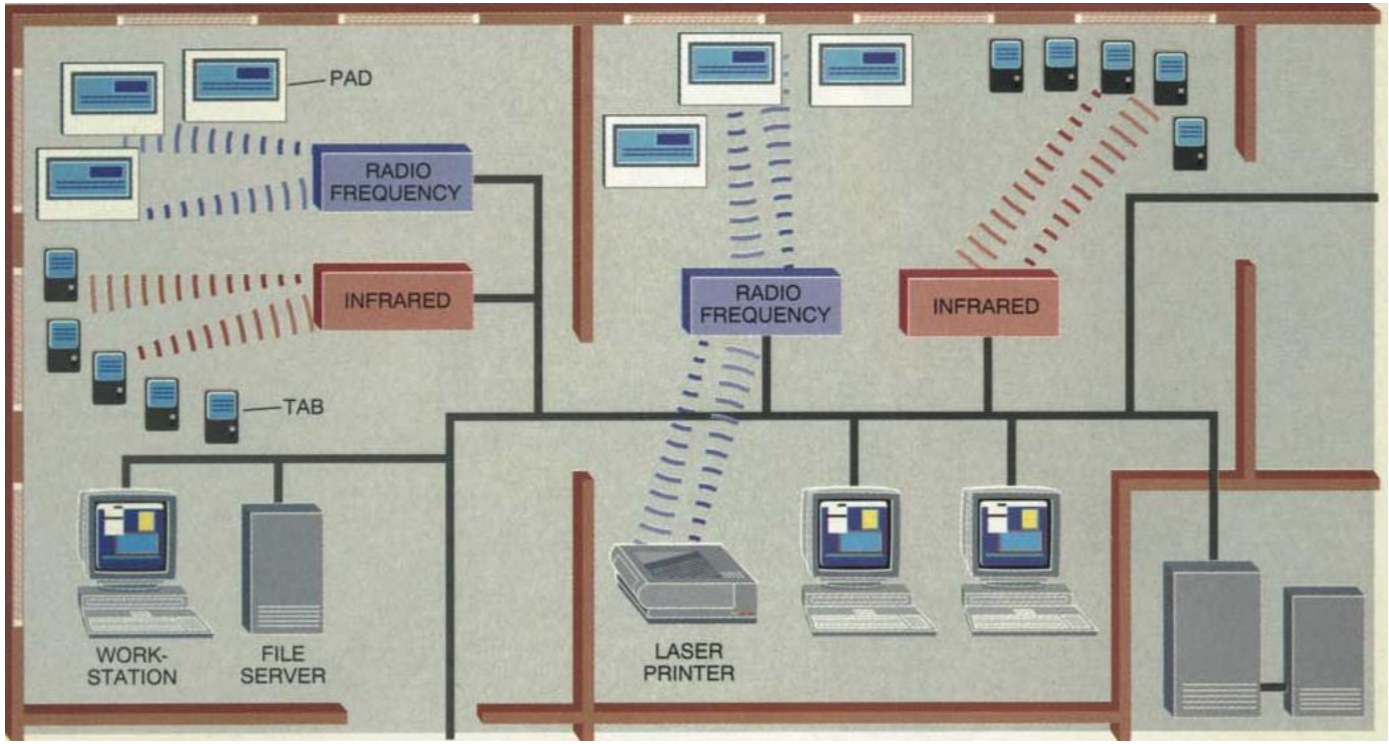
Contents

Mark Weiser's Vision of Ubiquitous Computing

Tab
Inch-size ~2.5cm
Pad
Foot-size ~30cm
Board
Yard-size ~1m





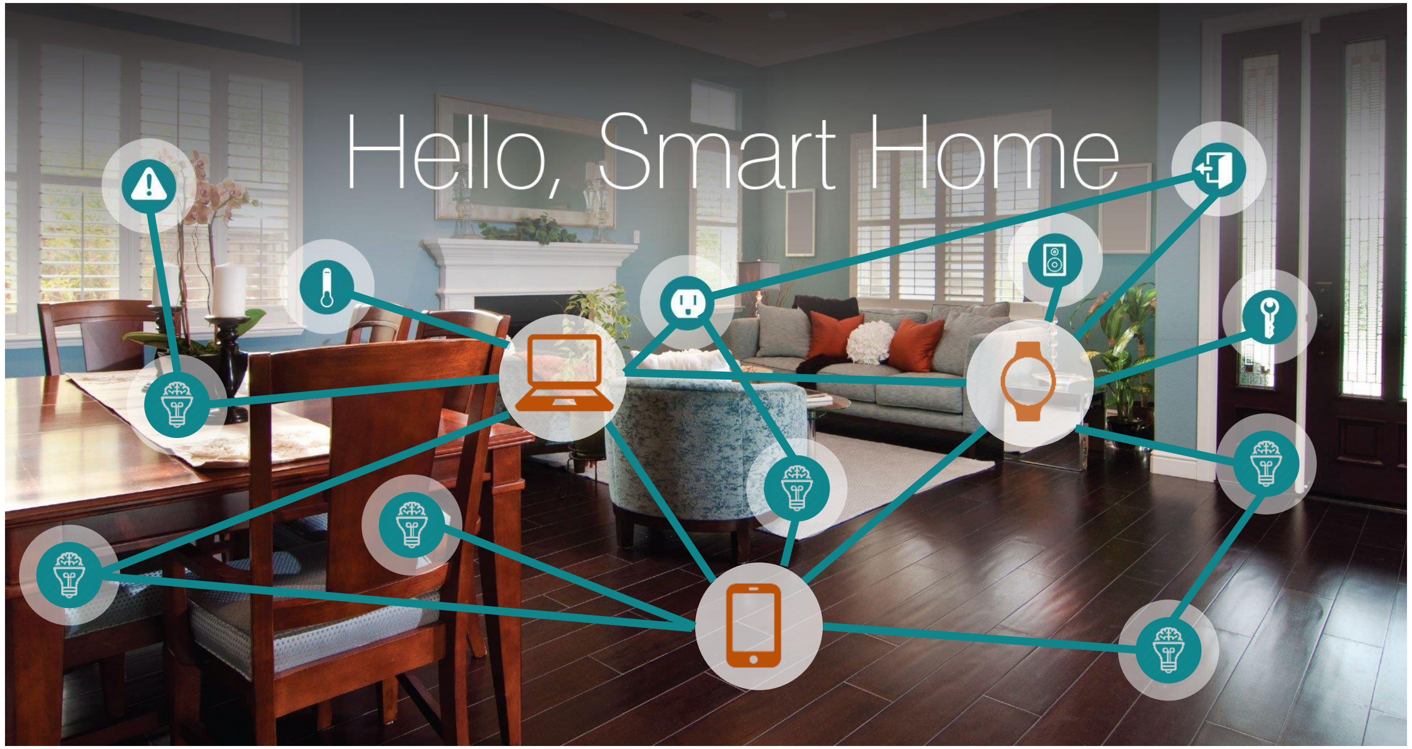
[Weiser, 1991]

"you may see more than 100 tabs, 10 or 20 pads and one or two boards. This leads to … hundreds of computers per room."

Mark Weiser. 1991. The Computer for the 21st Century. Scientific American 265, 3.

Ubiquitous Computing in the IoT era

Tab : Smartphone, smartwatch
Pad : Tablets and laptops
Board: TVs

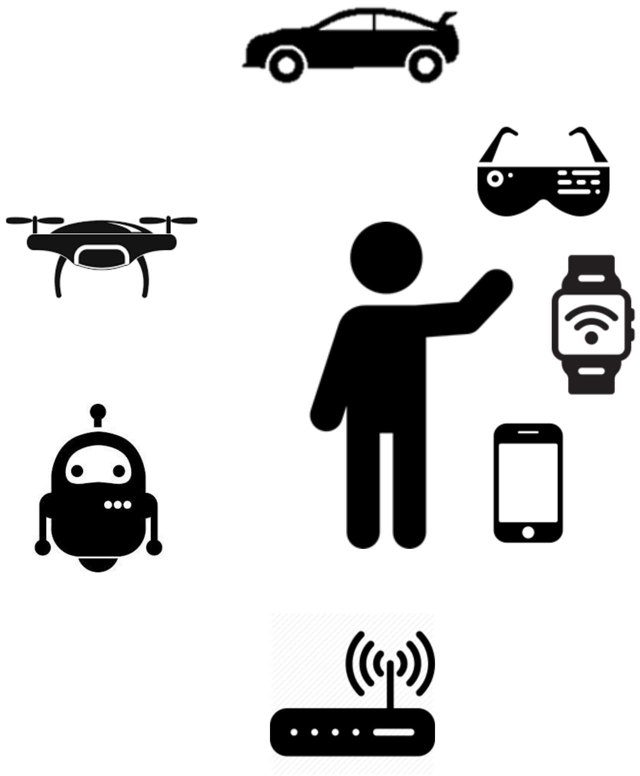


Internet of Things

World of Batteries

A Paradigm for Sustainable Ubiquitous Computing

Computer
Resource-abundant

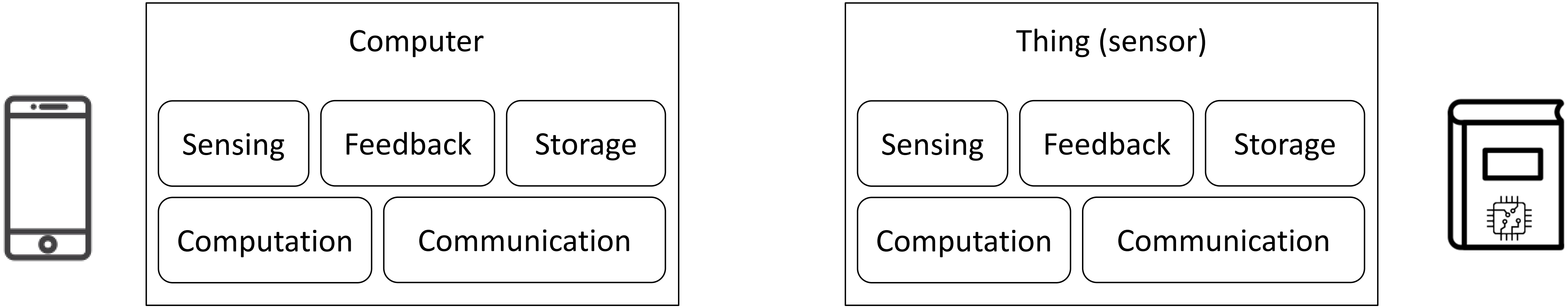


Interconnection

Power
Information

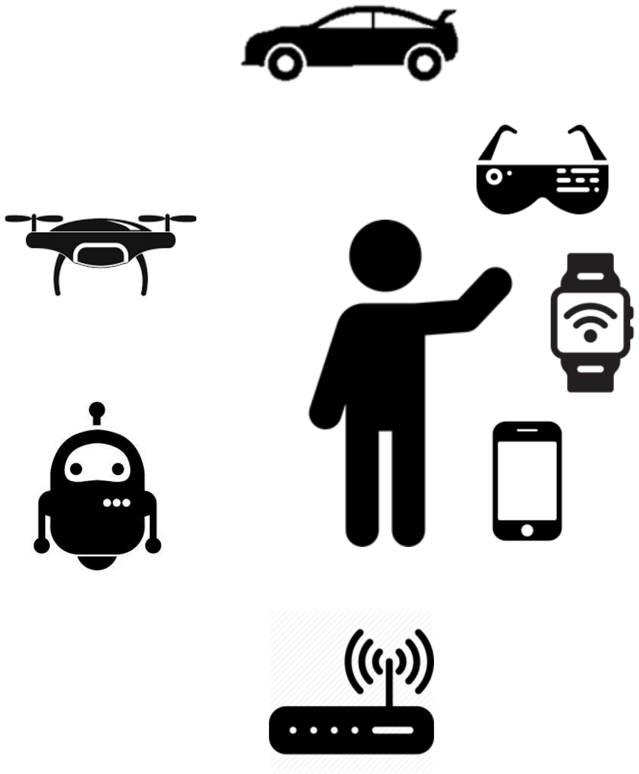
Thing
Resource-constrained

Necessary Functions for Computers and Things



Augmented Things

Computer
Resource-abundant



Interconnection

Power
Information

Thing
Resource-constrained

Research Taxonomy

Thing

1. Self-sustainable Backscatter Sensor

Computer

2. Finger Wearables

Interconnection

3. Power and Information Transfer Techniques

Research Taxonomy

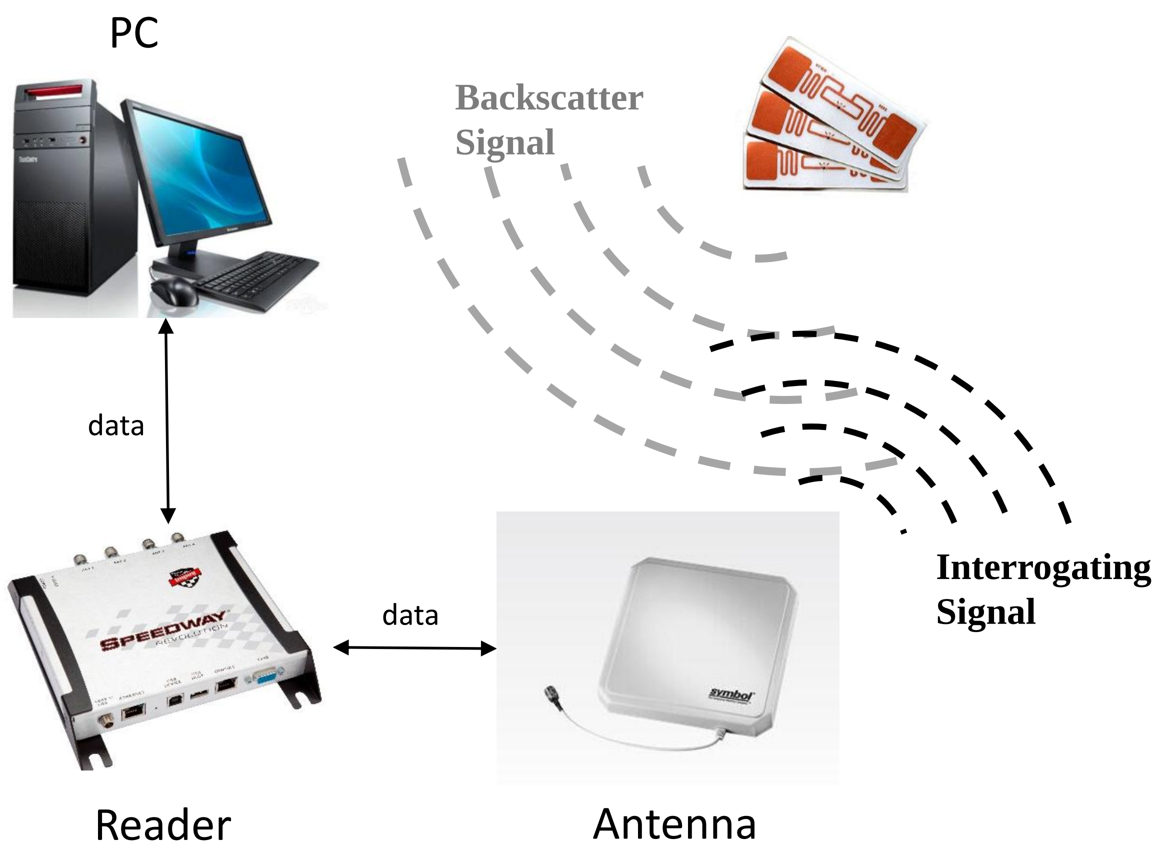
Thing

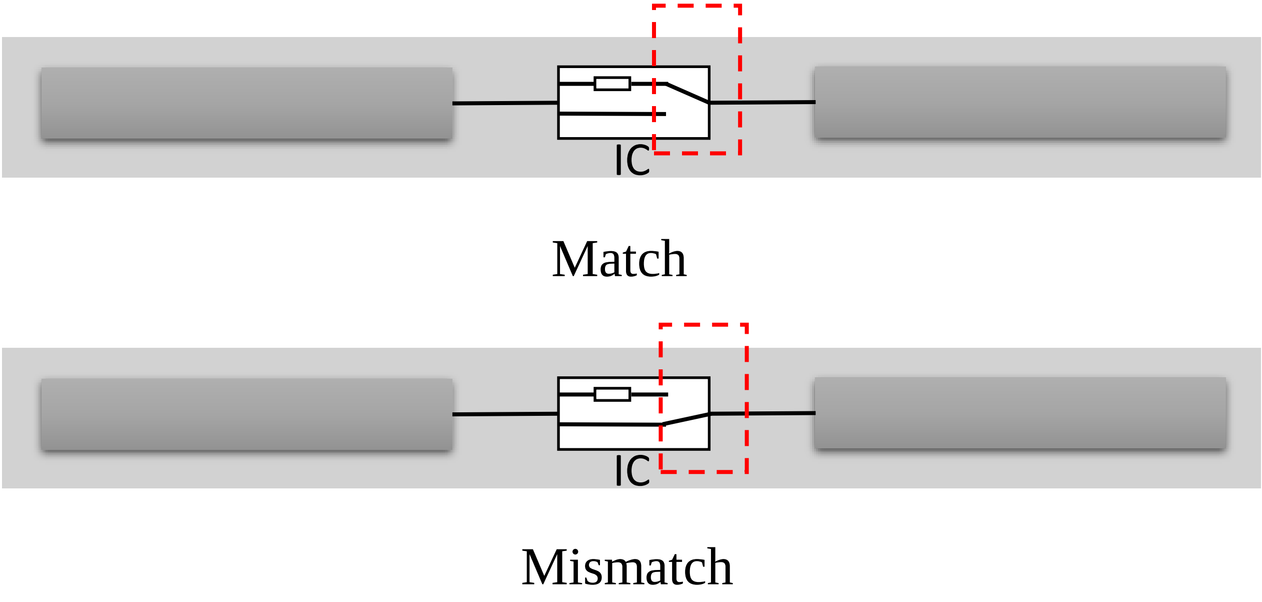
1. Self-sustainable Backscatter Sensor

- Easily deployed
  - Thin, flexible form factor
- Ultra-low-power
  - Passive sensing
  - Analog backscatter communication

RFID-based Sensing Technique

RFID Working Principle

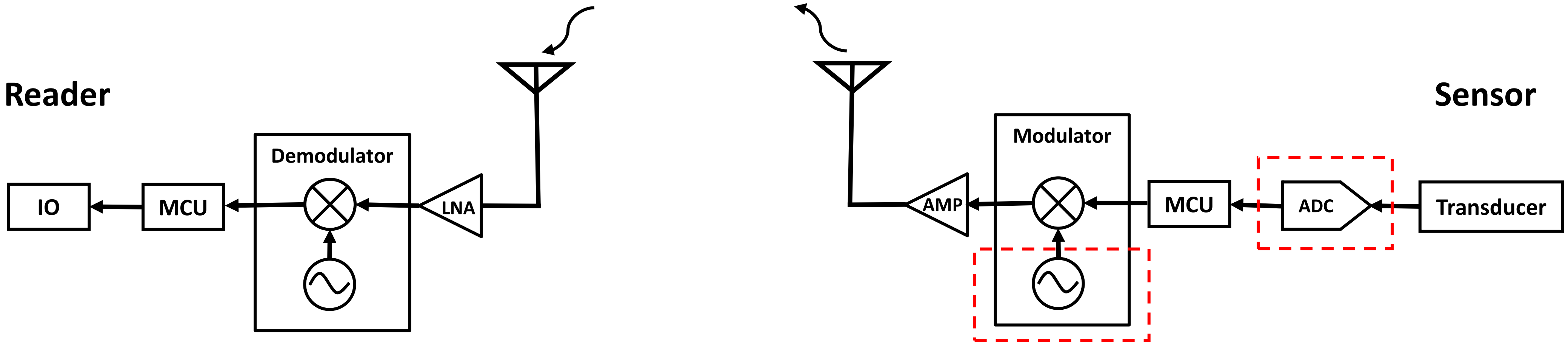




Differential Radar Cross Section

$$\Delta\sigma = \frac{\lambda^2 G^2}{4\pi} |\Gamma_1^2 - \Gamma_2^2|$$

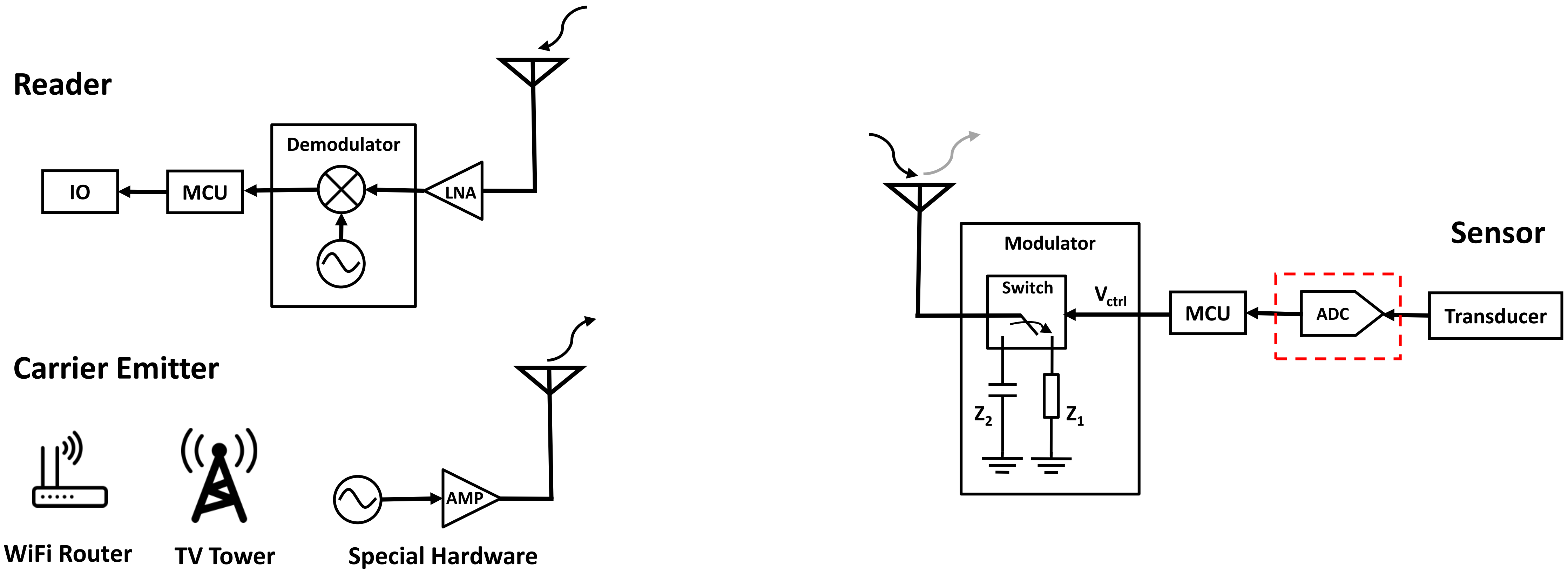
Conventional Wireless Sensing Systems



Bluetooth
zigbee
Wi Fi

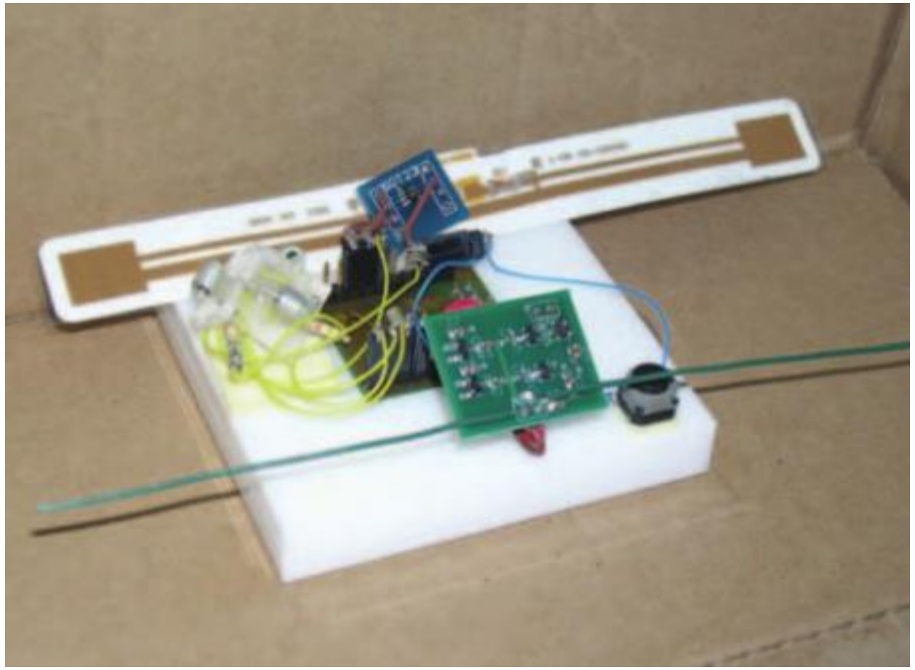
Bluetooth LE	10-15mW
Zigbee	10-15mW
WiFi	30-150mW

Backscatter Sensing Systems without HFOSC

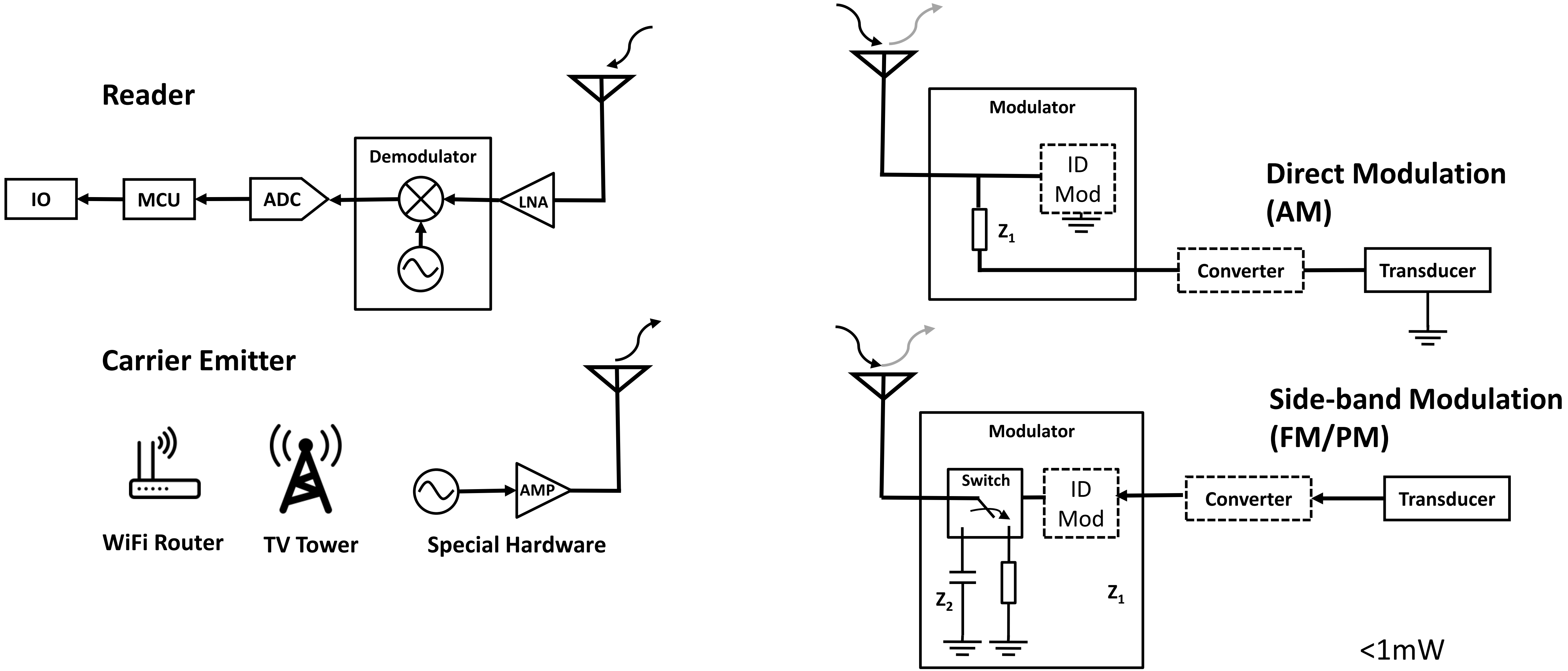


Wireless Identification Sensing Platform (WISP)

Power: RFID ~1mW
Communication: RFID
Computing/Storage: Low Power MCU
Sensing: IMU/Touch Panel/Camera…

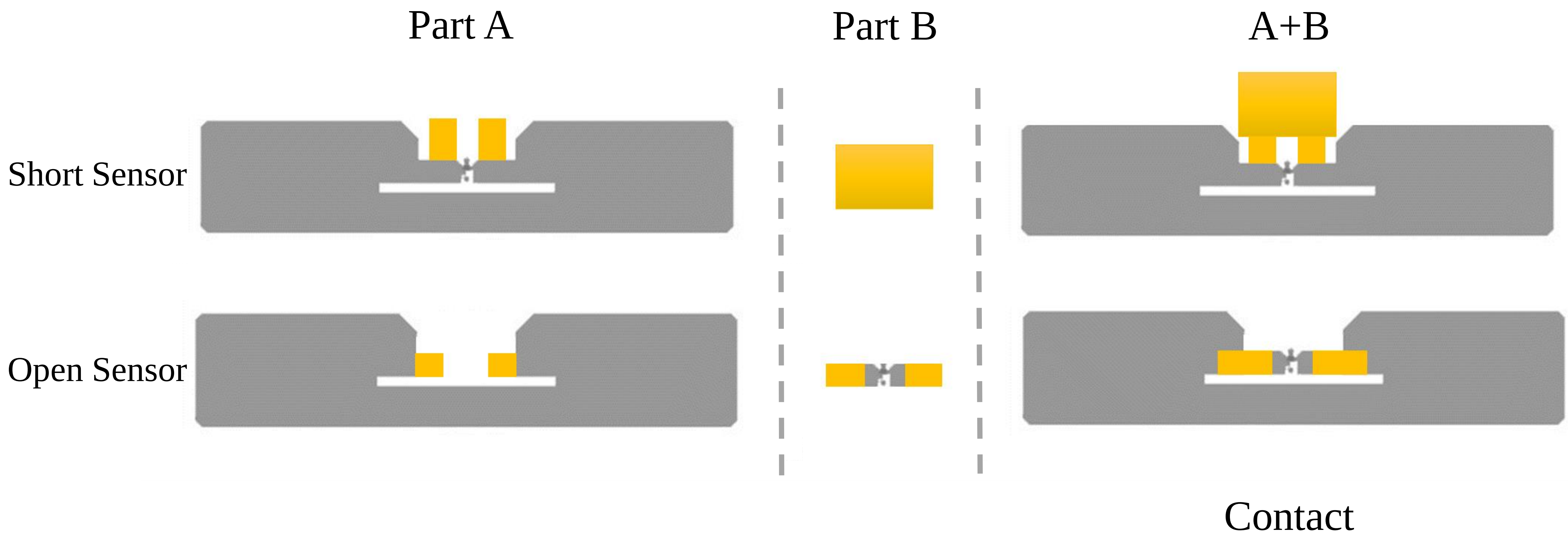


Backscatter Sensing Systems without HFOSC and ADC

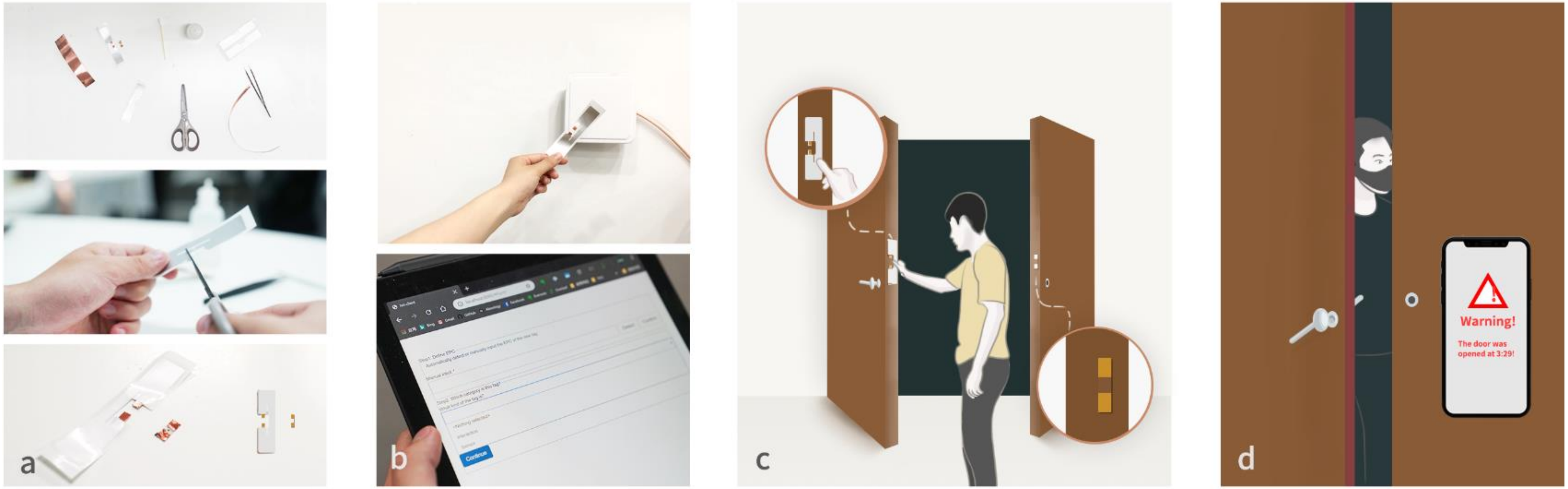


User DIYed Backscatter Sensor: BitID

BitID Sensor



BitID



Manufacture

Registration and Definition

Deployment

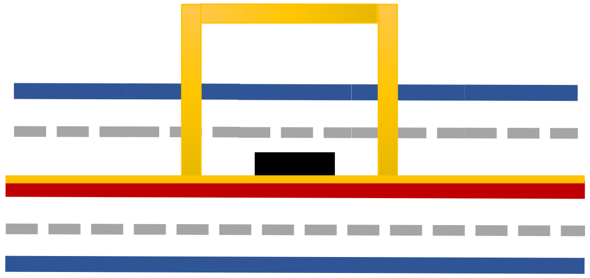
Feedback

Sensing Principle

Differential Radar Cross Section $\Delta\sigma = \dfrac{\lambda^2 G^2}{4\pi} |\Gamma_1^2 - \Gamma_2^2|$

Short

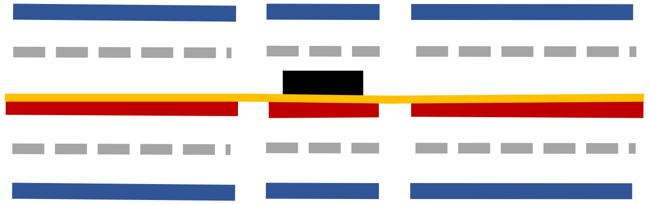
0



$$\Gamma_1 \approx \Gamma_2 \rightarrow \Delta\sigma \approx 0$$

Open

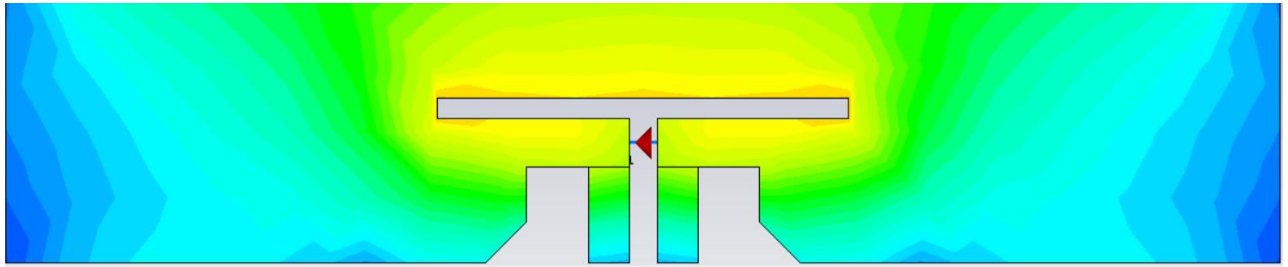
0



$$\begin{cases} \Gamma_1 \approx \Gamma_2 \\ G \approx 0 \end{cases} \rightarrow \Delta\sigma \approx 0$$

Full-wave Electromagnetic Simulation (short)

Matching State



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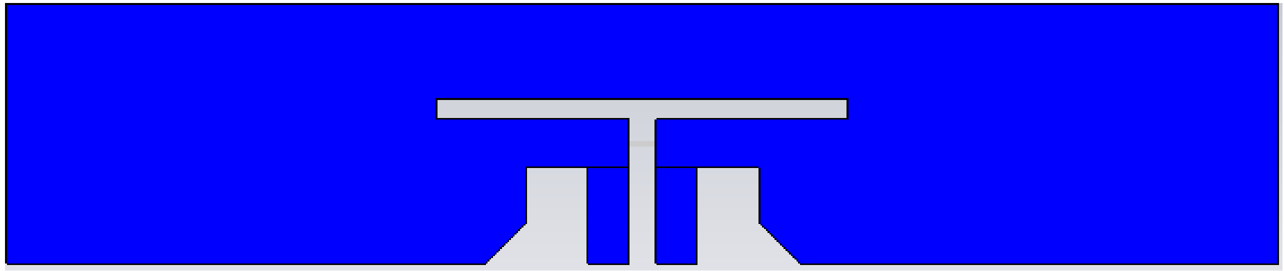
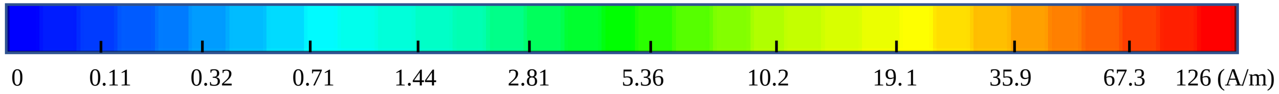
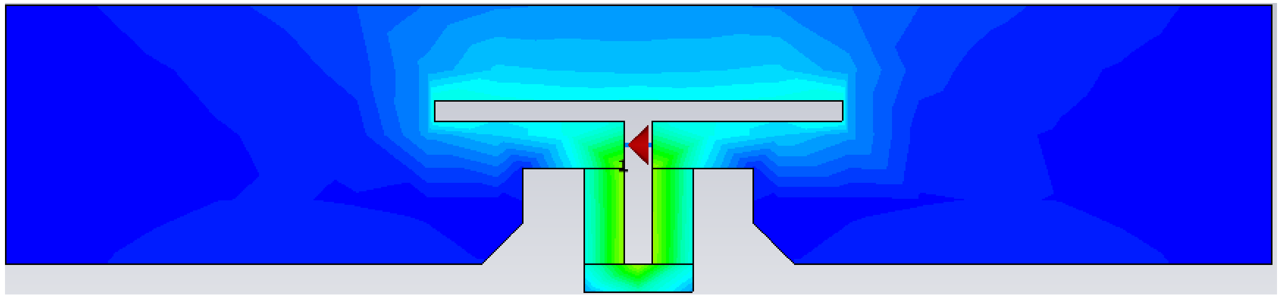
Mismatching Sate





Full-wave Electromagnetic Simulation (short)

Matching State



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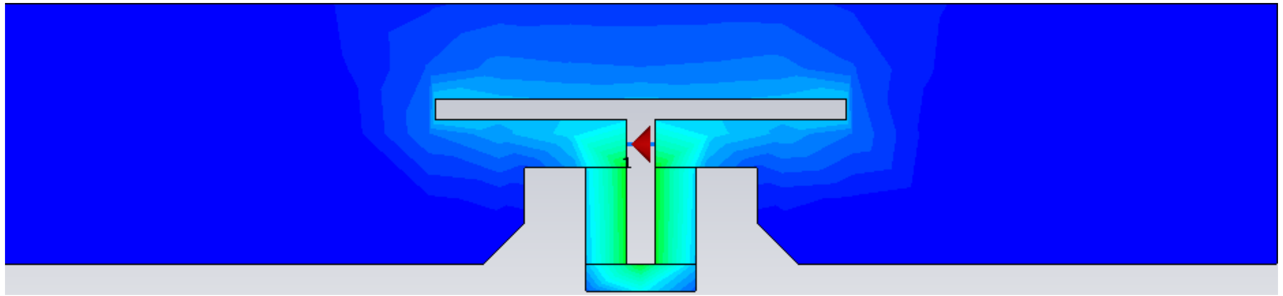
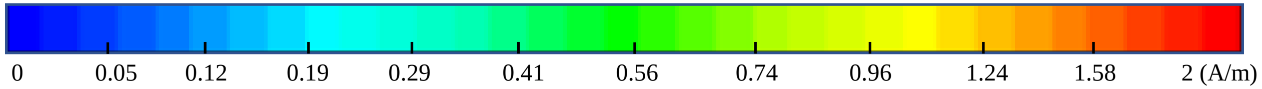
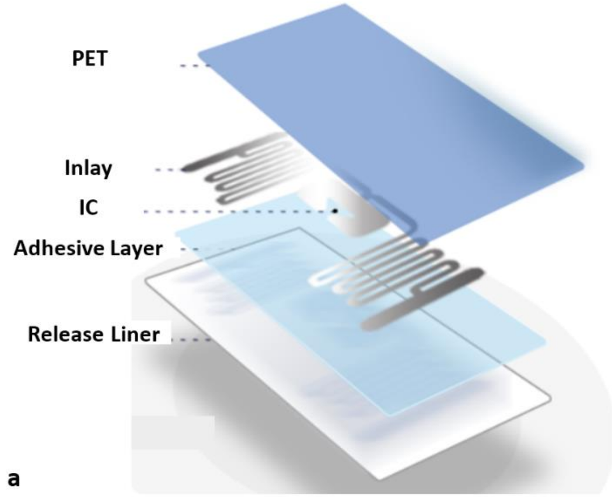
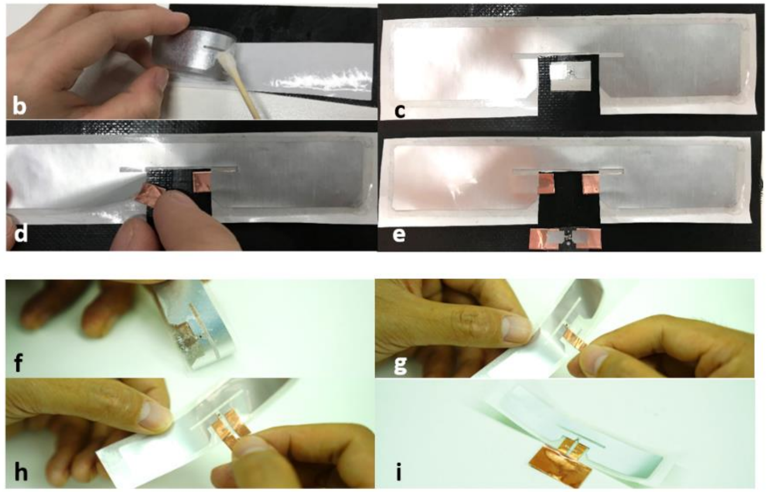
Mismatching State

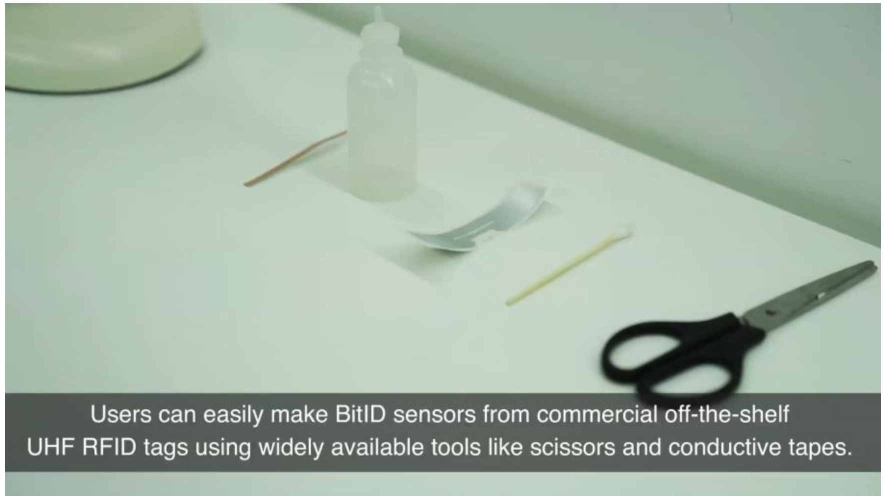




Manufacture Procedure

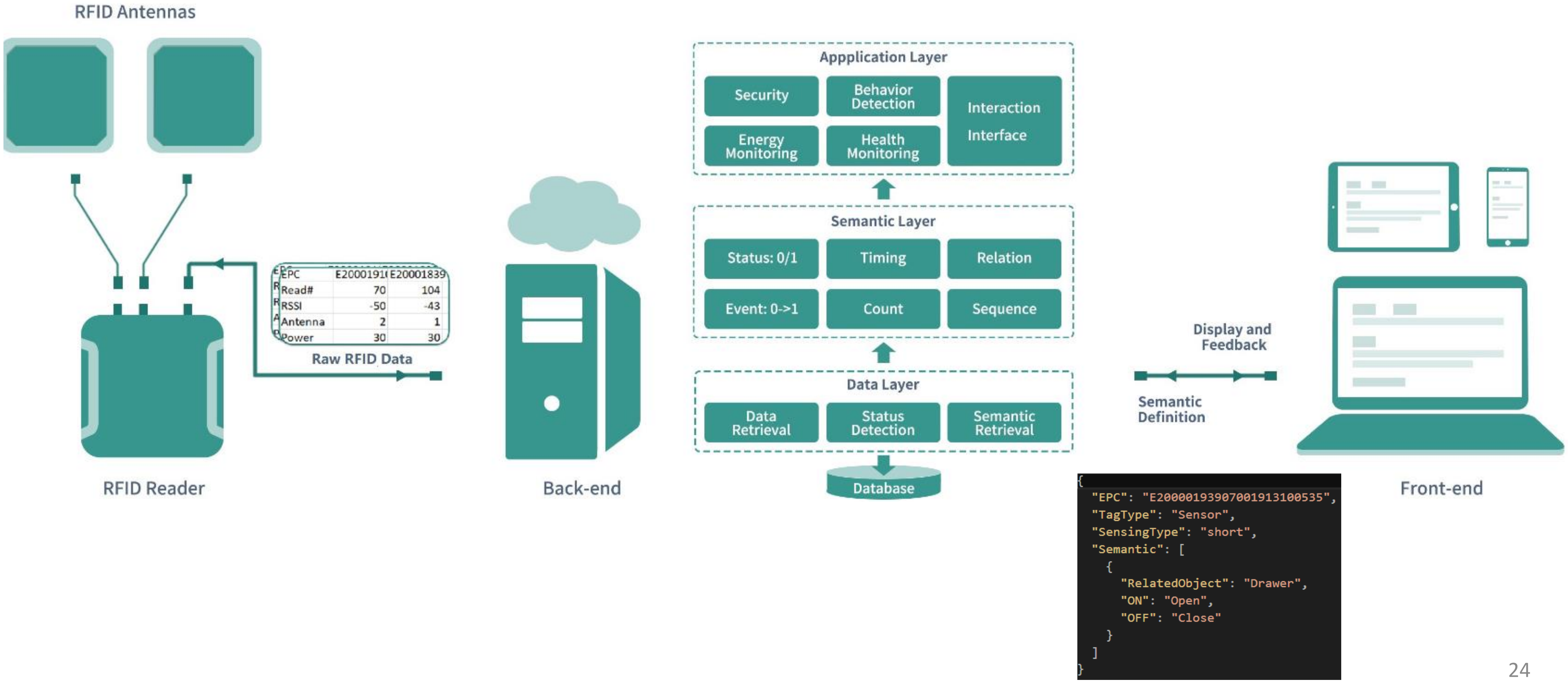




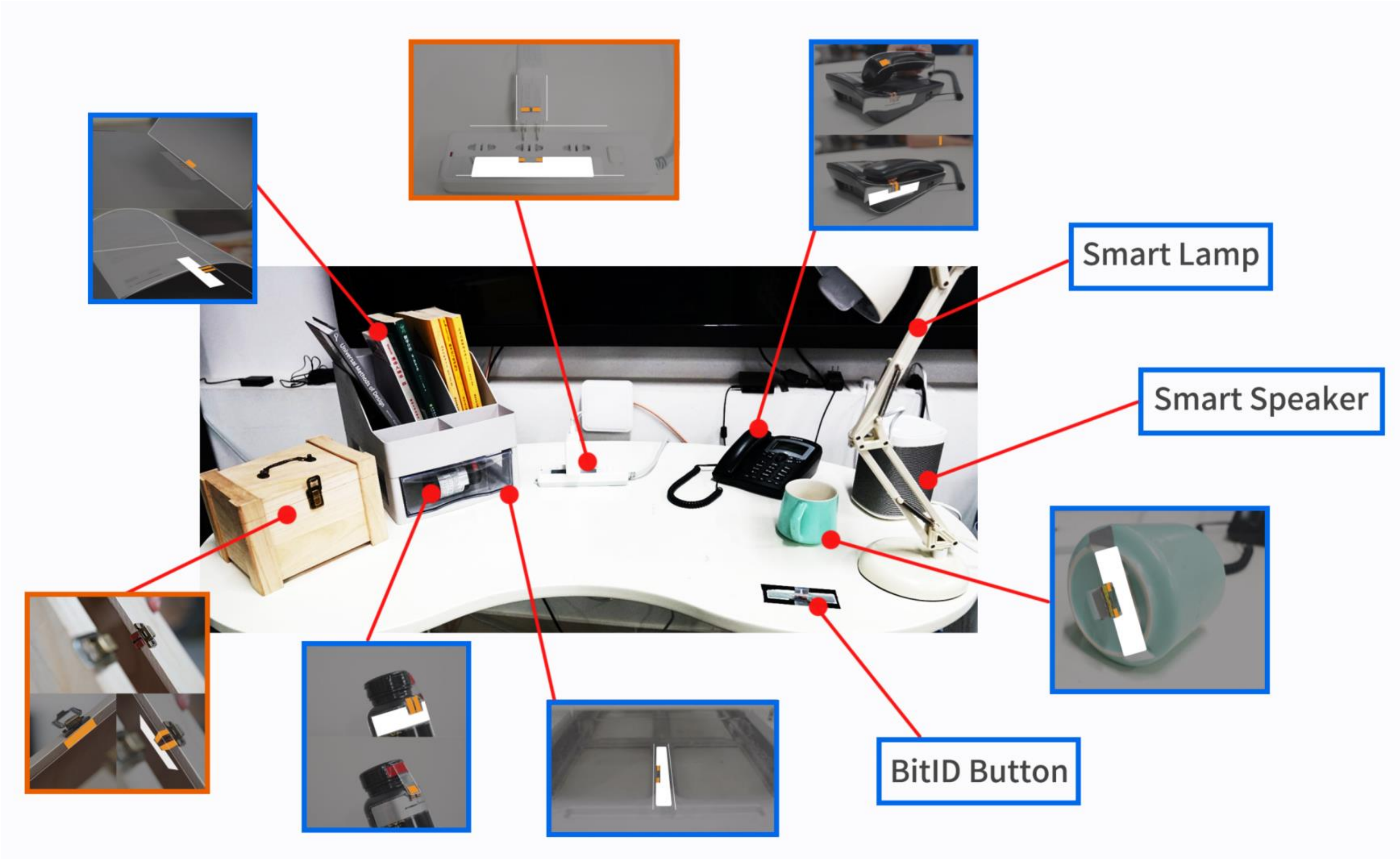


1. COTS UHF RFID Tag
2. Scissor
3. Alcohol
4. Conductive Tag

System Implementation

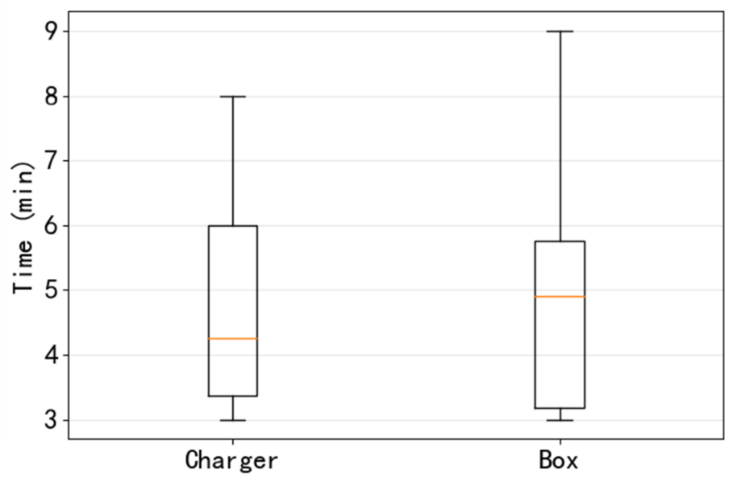


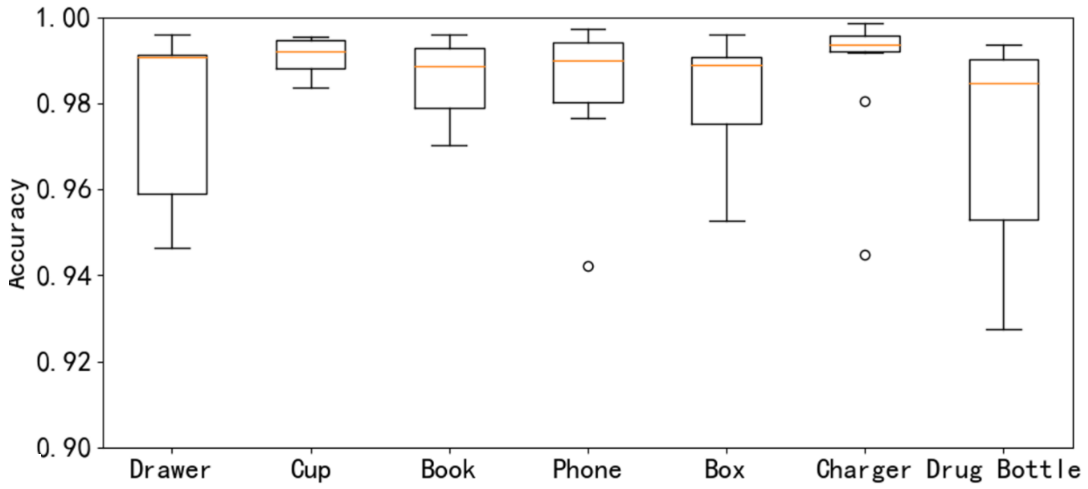
User Study: Evaluating Desktop Applications



- 12 participants (9M3F), Mean Age = 22.1
- 7 Sensing tags, 1 interactive tag
- Watch Video to learn the registration and definition procedure
- 2 deployment tasks (Orange)
  - Charger
  - Box
- 4 behavior tasks (blue)

Results Analysis

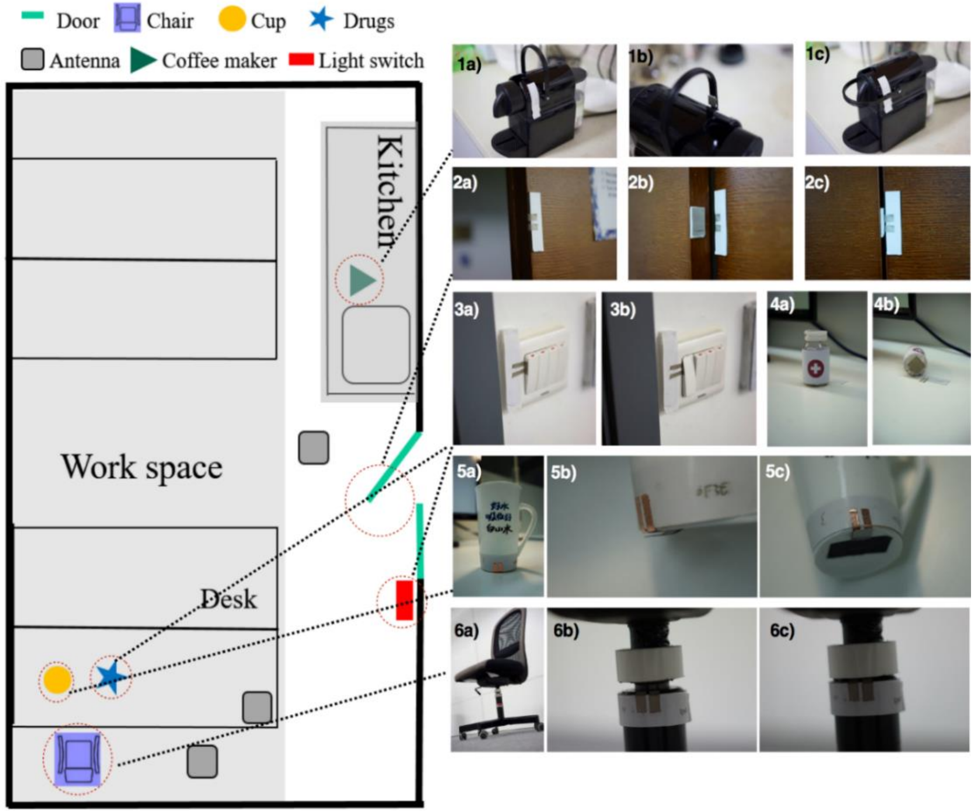


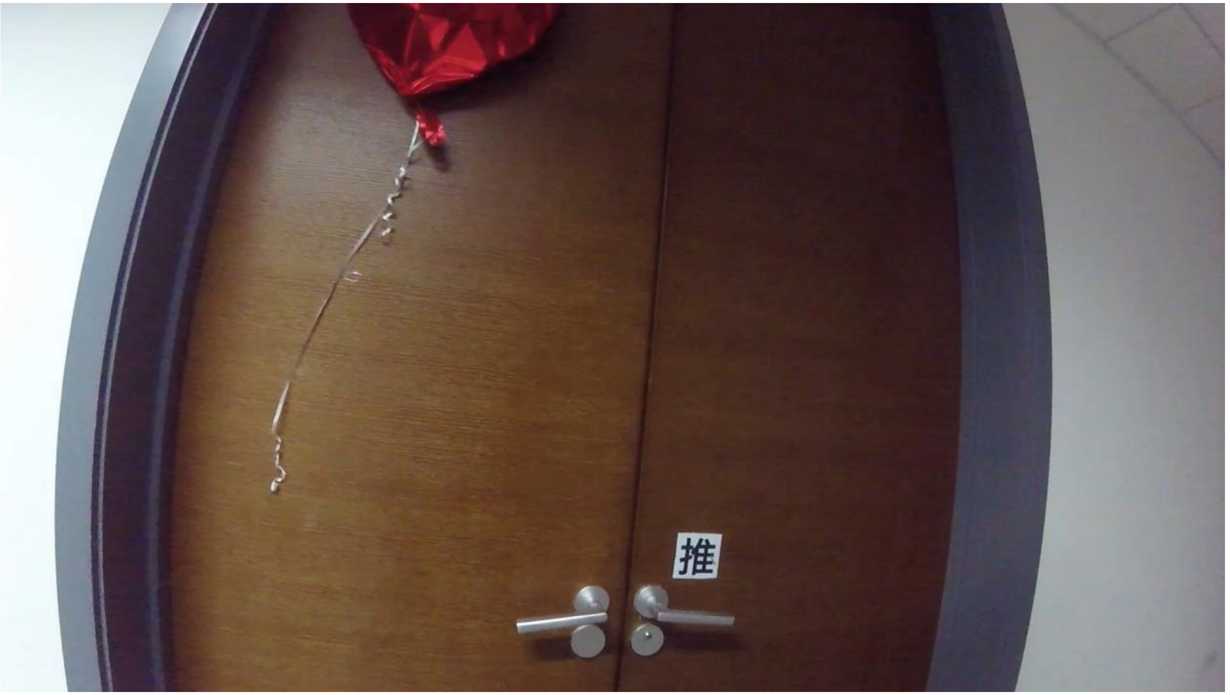


- Charger task completed in MEAN = 4.8min (std1.8)
- Box task completed in MEAN = 5.1min (std2.0)
- 23/24 deployment trials are successfully completed and evaluated robust

- 7 Sensing Tags Accuracy 98.3%
- 11/12 participants feels BitID is easy to use (>4， MEDIAN=7)
- Short sensor (MEDIAN=6) is easier to deploy than open sensor (MEDIAN=5)

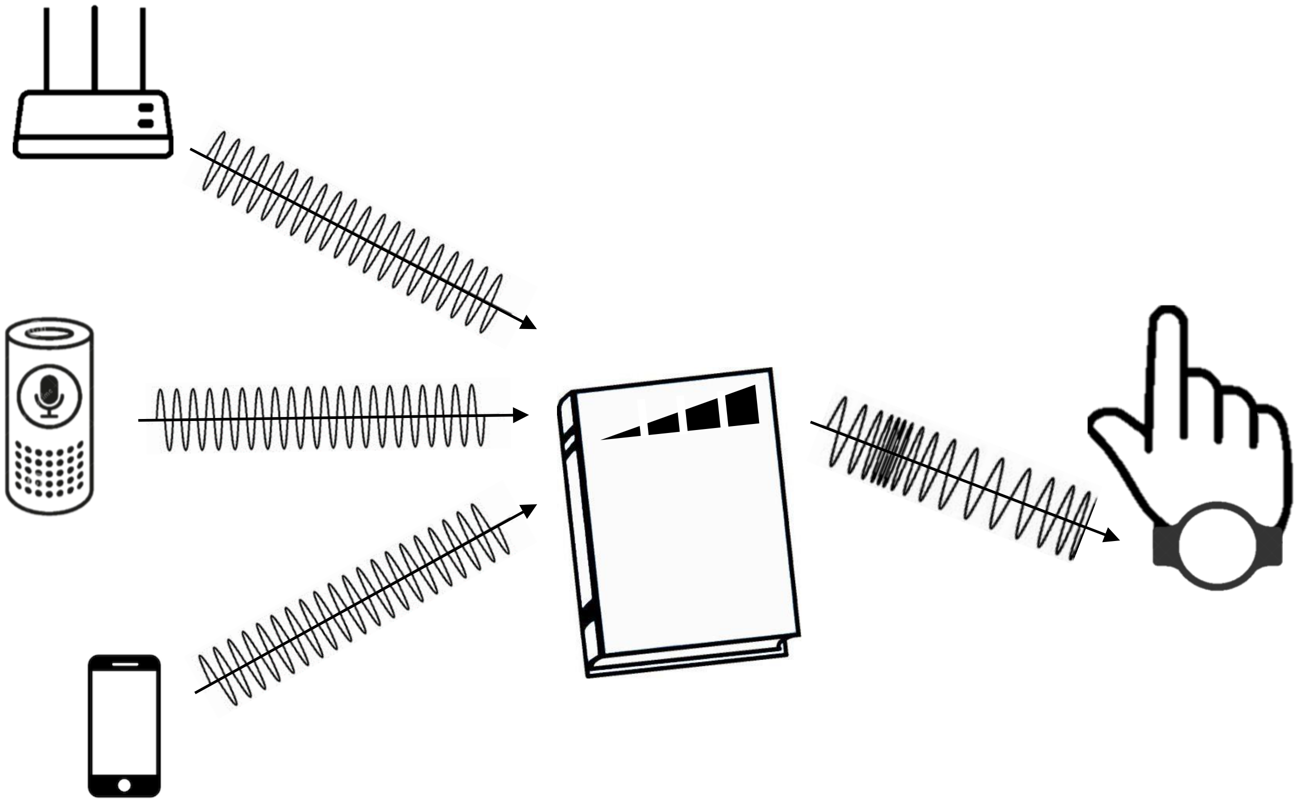
Room Scale Applications





- Drug
- Coffee maker
- Light Switch
- Door
- Chair
- Cup

BLE Transceiver Compatible Backscatter Touch Sensing System



Research Taxonomy

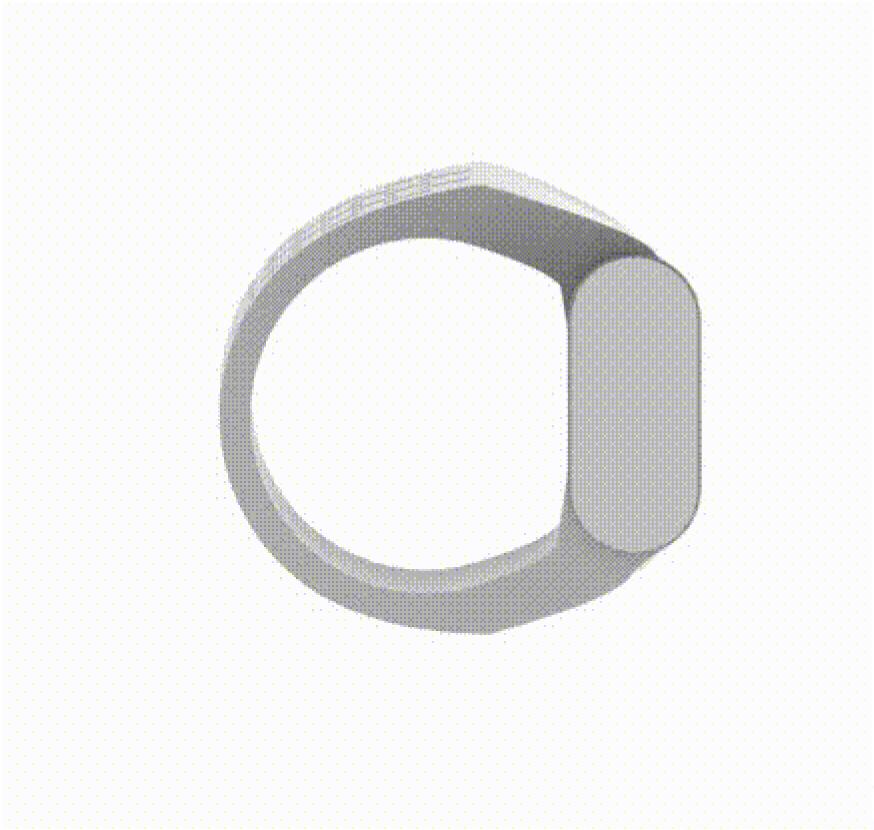
Computer

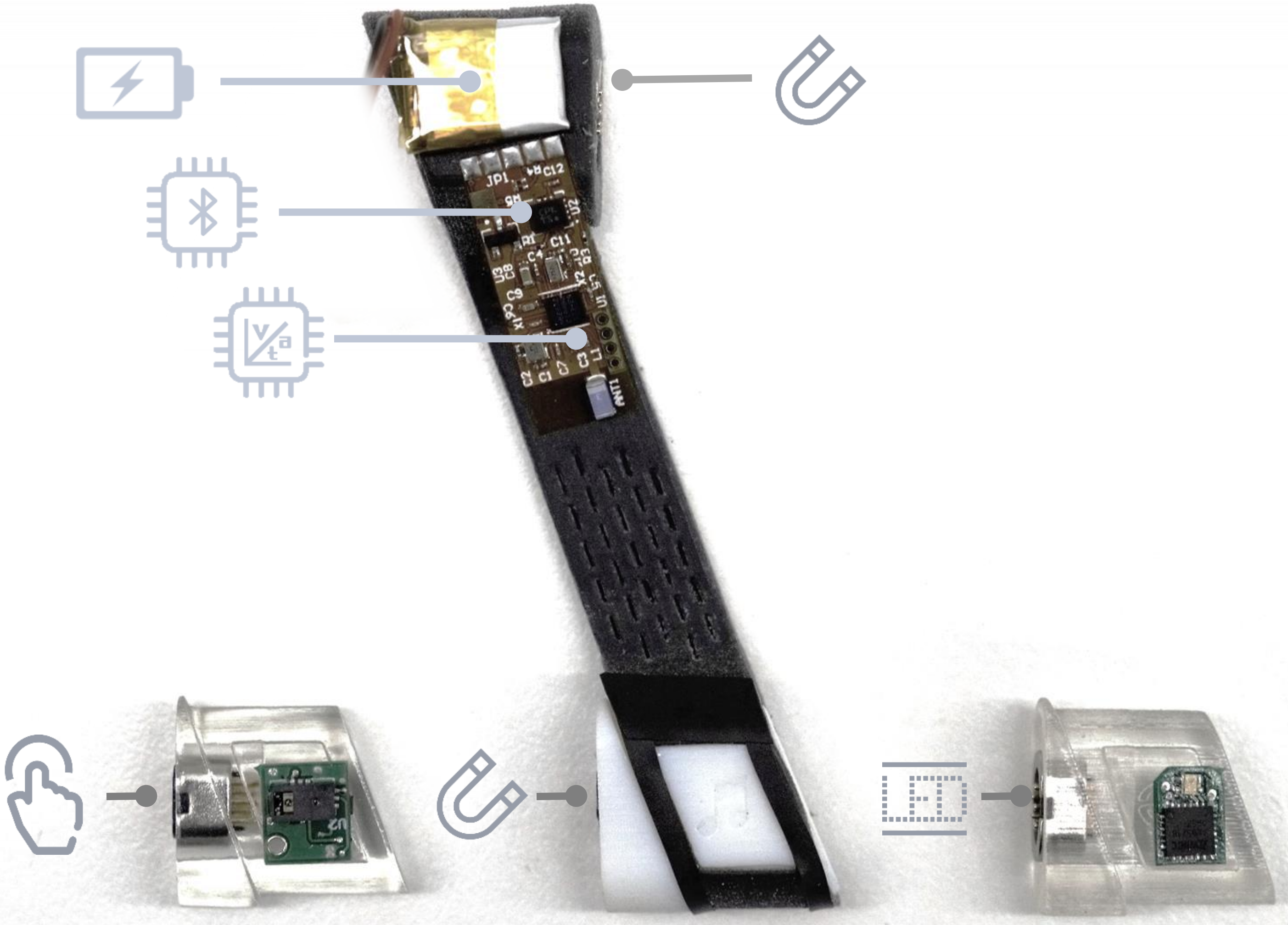
2. Finger Wearables

+ Close to the interacting object
+ Dexterity of human hand
+ Spontaneous, accurate, efficient, and subtle

- Does not fit with different finger sizes
- Space-constrained

ModularRing



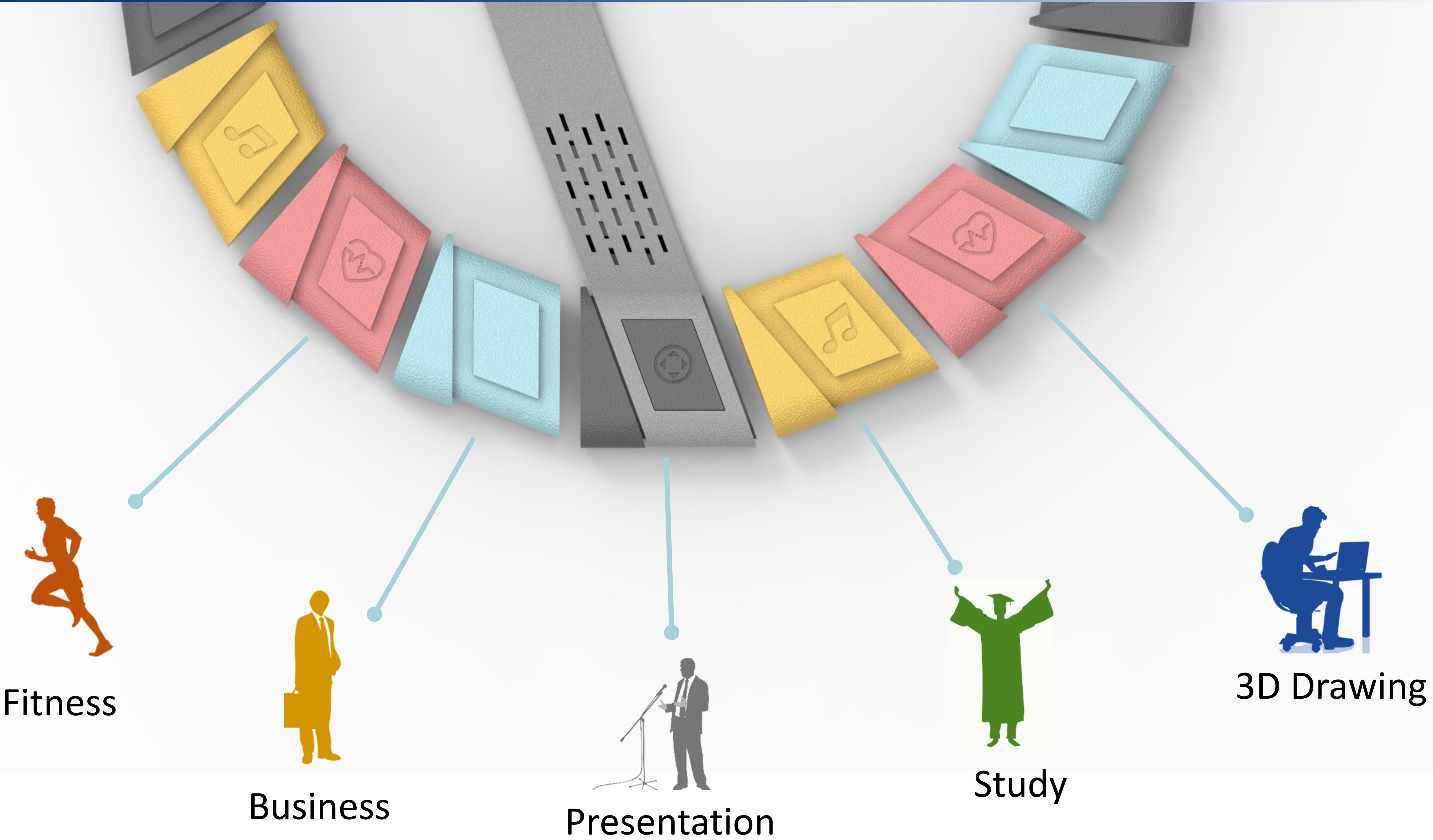


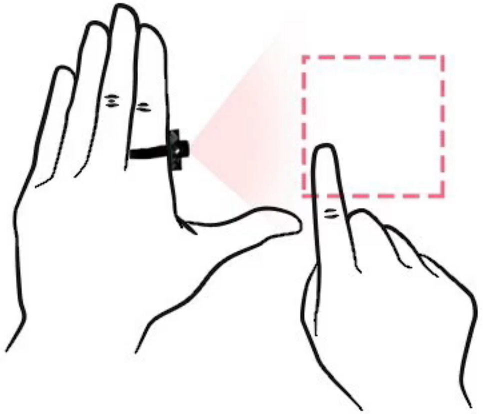
Wearing Mechanism

1

2

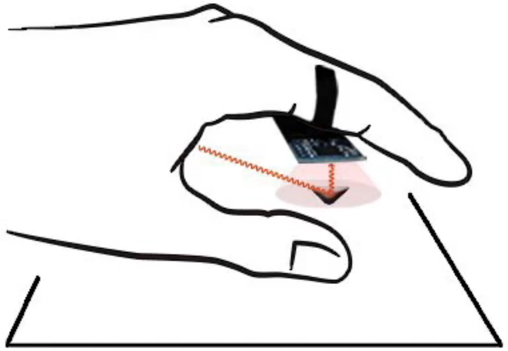
3


Fitness
Business
Presentation
Study
3D Drawing



ThermalRing

Gesture and Tag Inputs Enabled by a Thermal Imaging Smart Ring



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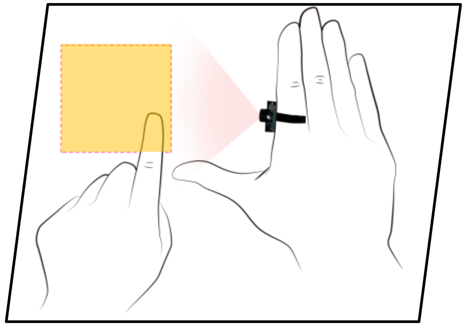
Lenovo

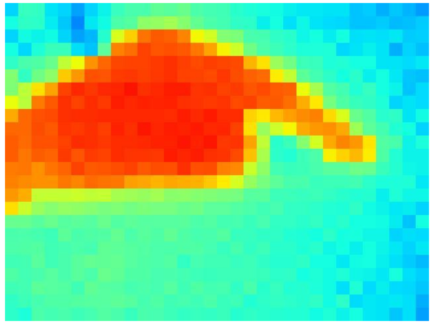
HUAWEI

清華大學 Tsinghua University

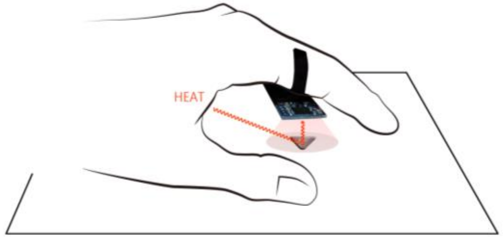
ThermalRing

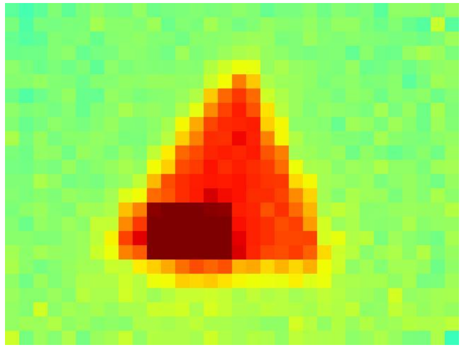
Drawing Gesture Recognition





Thermal Tag Identification





Identity-anonymous, illumination-invariant, power-efficient
Finger-worn Vision-based Input Technique

Versatile, Spontaneous, Subtle, Private

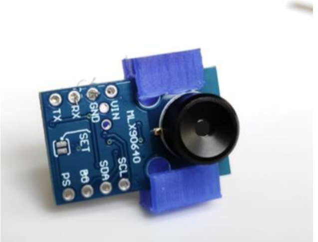
Related Work

- RGB Camera vs Near Infrared (NIR) Camera vs Long-wavelength Infrared (LWIR) Camera

	Wave Length	Imaging signal	Illumination Robustness	Privacy Preserving	Transmitter	Power Consumption
RGB	400nm-700nm	Reflection	Low	Low	No	Medium
NIR	750nm-1.4um	Reflection	Medium	High	Yes	High
LWIR	8um-15um	Emission	High	High	No	Low

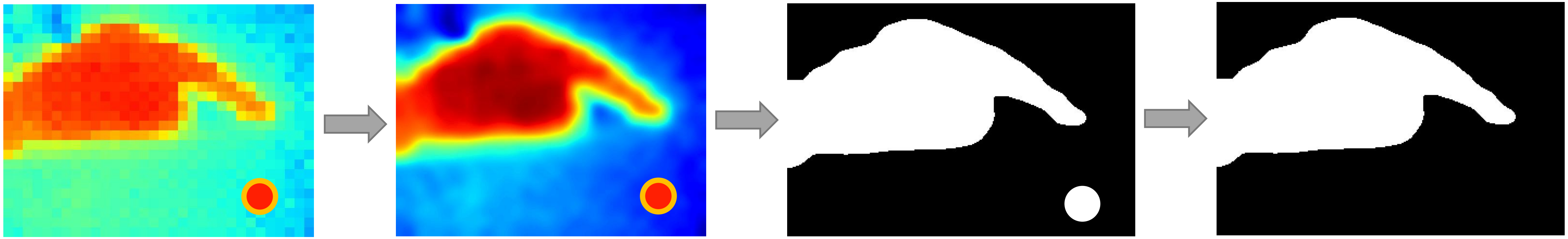
ThermalRing

Hardware Implementation



MLX90640 FoV: 110°× 75° Res: 32x24 Size: Φ8mm, H6mm;
Cost: ~40 USD Power: 20mA@3V
Communicate with PC via cabled serial port
*Bluetooth version firmware open sourced at https://github.com/saintnever/thermalring

Thermal Image Preprocessing Flow



Raw Temperature Data → Scale and Filter → Otsu Thresholding → Contour Filter

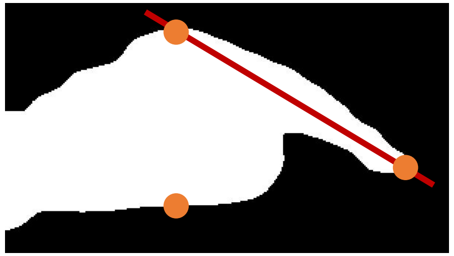
Example Domain 1: Drawing Gesture Sensing

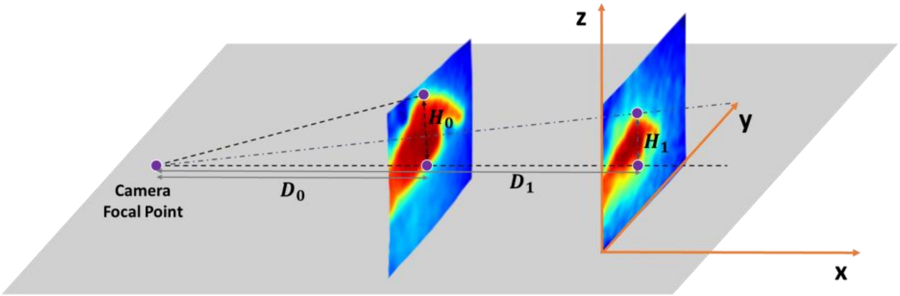
- Asymmetrical Bimanual Interaction: Natural, Easy, Affordant
- 6 step sensing flow

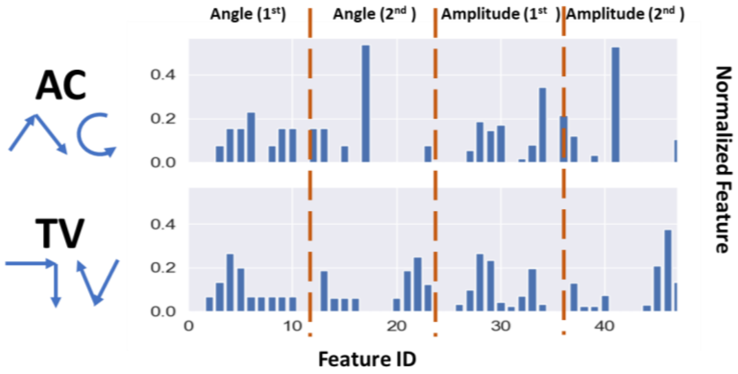
1. Fingertip Extraction
2. Finger Lift Detection

3. X/Y Coordinates Estimation
4. Kalman Filtering

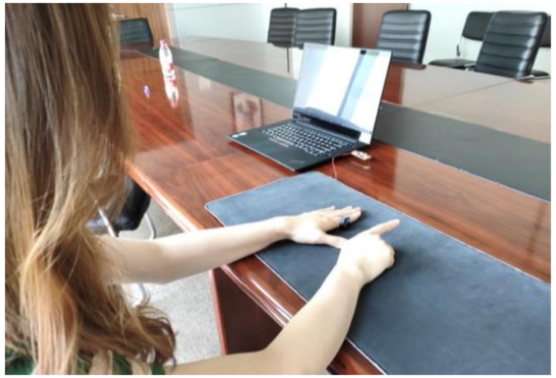
5. Bag of Words Feature Extraction
6. SVM Prediction



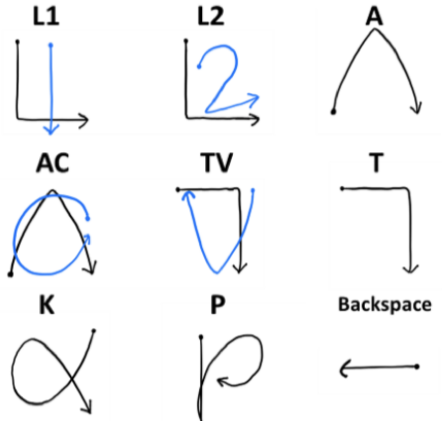




Example Domain 1: User Study



Experiment Setup



Graffiti Gesture Set

Task: Smart Device Pairing

Demographic: 6 participants (4 males) with ages 23-30

Procedure: 3 sessions (ring taken down during rest)
20 trials of each gesture per session

Data: 3240 trials, 360 for each gesture

Accuracy: Average Within-user 89.2% (SD=0.04)
Average Between-user 85.7% (SD=0.06)

Subjective: 5-point Likert Scale (the higher the better)

Comfort	MEDIAN=4, MODE=4
Convenience	MEDIAN=4.5, MODE=4
Ring Rotation	MEDIAN=5, MODE=5
Input Speed	MEDIAN=3, MODE=3

	AC	TV	L1	L2	K	P	A	T	←
AC	94.8	0.0	0.0	4.2	0.0	0.0	1.0	0.0	0.0
TV	2.0	89.2	2.8	2.1	0.0	1.3	0.0	2.6	0.0
L1	4.6	2.6	81.9	6.5	0.0	3.1	0.7	0.7	0.0
L2	5.3	0.6	5.6	85.1	2.0	0.7	0.0	0.6	0.0
K	0.7	0.0	0.0	0.7	91.2	0.7	5.3	0.7	0.7
P	2.6	1.5	2.6	0.7	1.5	91.1	0.0	0.0	0.0
A	6.8	1.1	0.0	1.1	6.8	0.6	80.7	2.3	0.6
T	0.0	0.0	2.3	0.0	0.8	0.8	0.8	95.4	0.0
←	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	99.3

Within-user Confusion Matrix

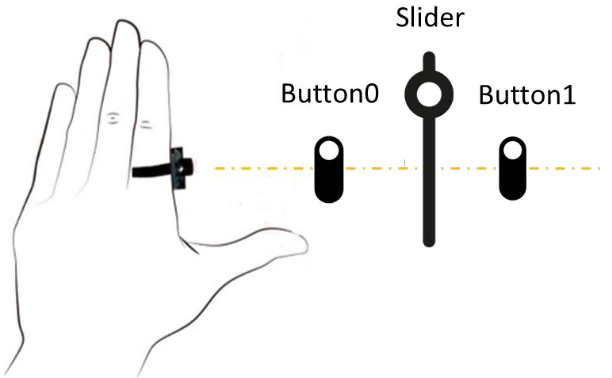
	AC	TV	L1	L2	K	P	A	T	←
AC	84.6	1.9	2.1	3.8	2.5	2.5	2.5	0.2	0.0
TV	1.0	86.2	2.3	0.8	1.0	4.6	1.2	1.9	0.8
L1	1.7	3.8	79.6	6.9	0.0	5.8	0.0	1.7	0.6
L2	5.2	1.0	7.5	72.3	5.0	6.5	0.8	1.5	0.2
K	1.5	0.0	0.0	2.7	89.8	1.0	3.3	1.2	0.4
P	3.1	4.6	3.1	2.9	1.7	82.9	0.6	0.4	0.6
A	2.7	0.8	0.0	0.2	4.8	0.4	87.9	2.9	0.2
T	0.8	0.0	1.0	1.5	0.8	0.2	6.2	89.4	0.0
←	0.0	0.6	0.0	0.0	0.2	0.2	0.0	0.0	99.0

Between-user Confusion Matrix

Camera with a higher frame rate for faster drawing

Example Domain 2: Click and Slide Gesture Sensing

Experiment Setup



2 virtual buttons and 1 virtual slider

Task: Smart Device Click and Slide (5 scales) **Control**

Demographic: 8 participants (4 males) with ages 23-30

Procedure: 3 sessions (ring taken down during rest)
16 clicks and 8 slides per session

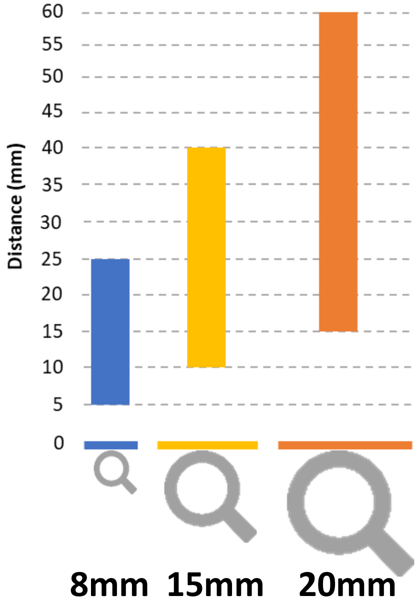
Data: 768 click gestures, 192 slide gesture

Result: Overall Accuracy 94.9% (SD=0.02)
191 of 192 slides successfully completed

Subjective: 1. Users feel they can locate 4 buttons (SD=1) and 2 sliders (SD=0.71) referring to the auxiliary hand
2. 5-point Likert Scale (the higher the better)

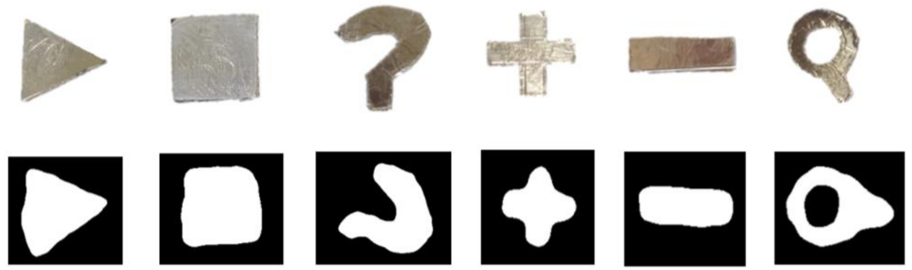
UI Locating	MEDIAN=4, MODE=4
Precision	MEDIAN=5, MODE=5
Fatigue	MEDIAN=5, MODE=5

Example Domain 3: ThermalTag Identification



- ThermalTag: Thin and Passive Tags made of high heat reflection materials in DIY manner
- Imaging Principle: ThermalTag reflects heat from the hand
- Interaction: Touch-Lift-Hold
- Tag size: 20mm Square

Example Domain 3: User Study



Play Stop Help Up Down Search

	Up	Down	Play	Stop	Search	Help
Up	93.1	0.0	1.6	3.8	0.8	0.7
Down	0.0	95.5	4.5	0.0	0.0	0.0
Play	1.2	0.0	97.9	0.8	0.0	0.0
Stop	0.0	0.0	0.0	100.0	0.0	0.0
Search	0.0	0.0	0.0	0.0	98.2	1.8
Help	0.8	0.0	0.0	0.0	4.7	94.5

Within-user Confusion Matrix

	Up	Down	Play	Stop	Search	Help
Up	93.2	0.0	0.3	0.9	1.5	4.1
Down	0.9	95.0	3.1	0.3	0.3	0.3
Play	2.2	0.0	96.6	0.9	0.3	0.0
Stop	4.7	5.0	1.2	89.1	0.0	0.0
Search	1.2	0.0	0.9	0.6	87.3	9.9
Help	2.8	1.6	0.6	0.0	15.4	79.6

Between-user Confusion Matrix

Task: Scanning 6 different ThermalTags

Demographic: 8 participants (4 males) with ages 23-30

Procedure: 2 sessions (ring taken down during rest)
6 blocks per session and 20 trials per block

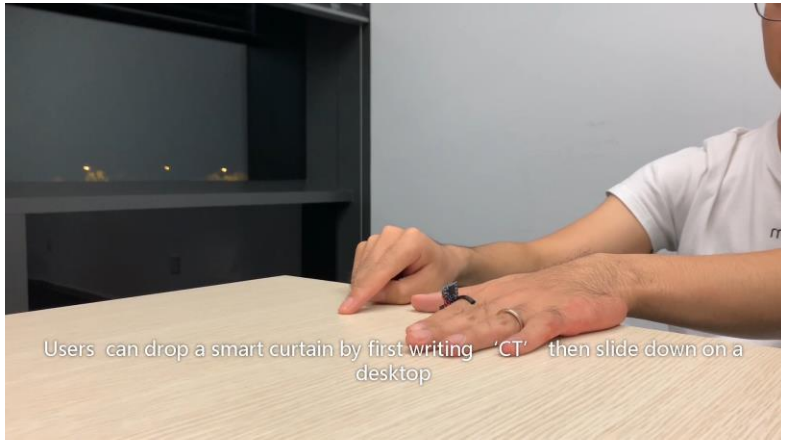
Data: 1920 scans, 320 for each tag

Result: Average Within-user 95% (SD=0.04)
Average Between-user 90.1% (SD=0.08)
Average scan complete time 3.5 seconds

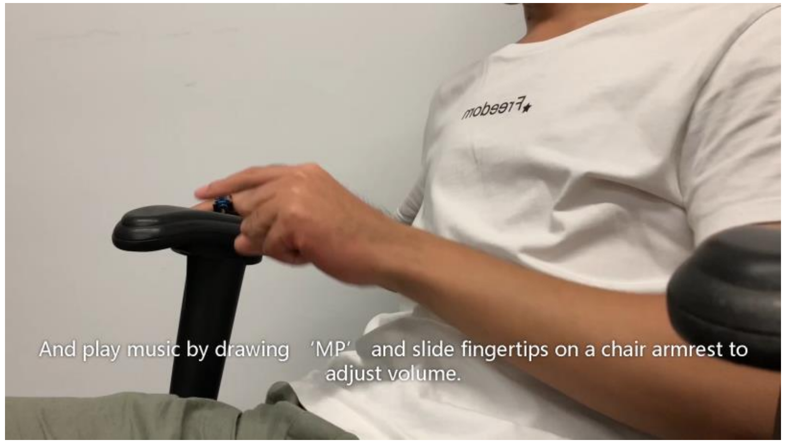
Subjective: 5-point Likert Scale (the higher the better)

Physical efforts	MEDIAN=4, MODE=4
Mental efforts	MEDIAN=4, MODE=4
Scan speed	MEDIAN=4, MODE=4

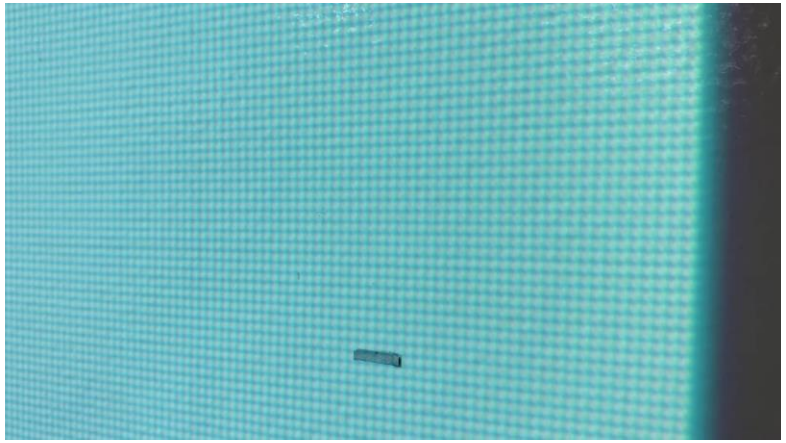
Application Scenarios



Smart Curtain Control on a Table



Smart Speaker Control on a Chair



Slides Navigation on Whiteboard

Smart Light Control on a Door

Research Taxonomy

Interconnection

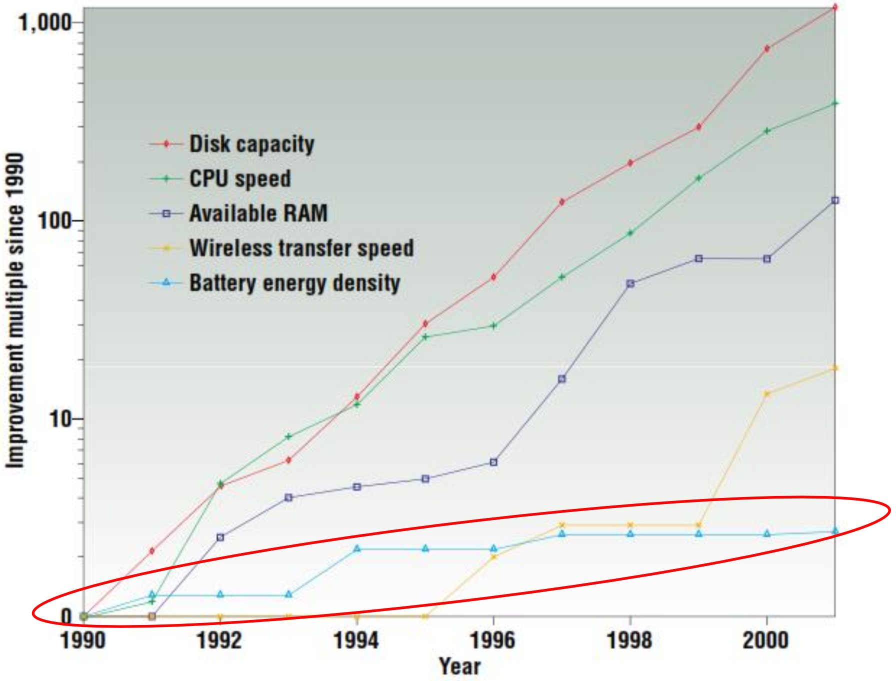
3. Power and Information Transfer Techniques

Always-on vs On-demand Power Supply

Computer-centered vs Thing-centered Assocaition

Issues of Battery

Require Maintenance

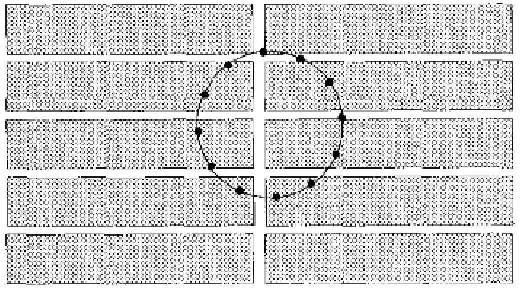


Linear Evolution

Big size
Fixed form factor

[1] T. E. Starner, "Powerful Change Part 1: Batteries and Possible Alternatives for the Mobile Market," *IEEE Pervasive Computing*, vol. 2, no. 4, pp. 86–88, Oct. 2003.

Related Work

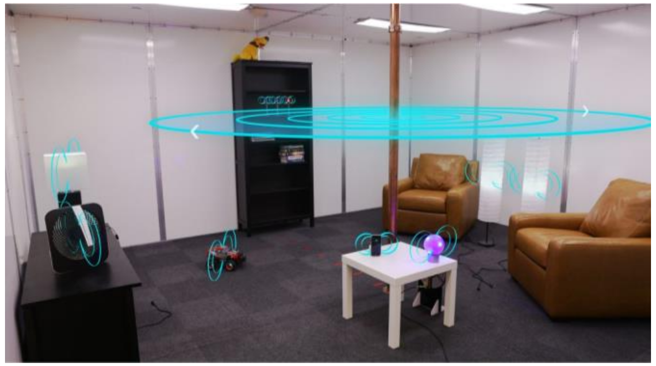


Network Surfaces

Hardware modification
Flat surface only

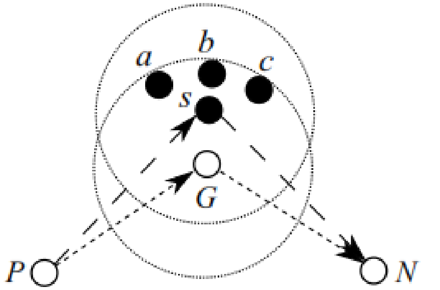
Inductive Charging

1-2cm Range



Wireless Power Transfer

Low Power, Low Efficiency



Qi-ferry

Robot consumes Power
Limited Access

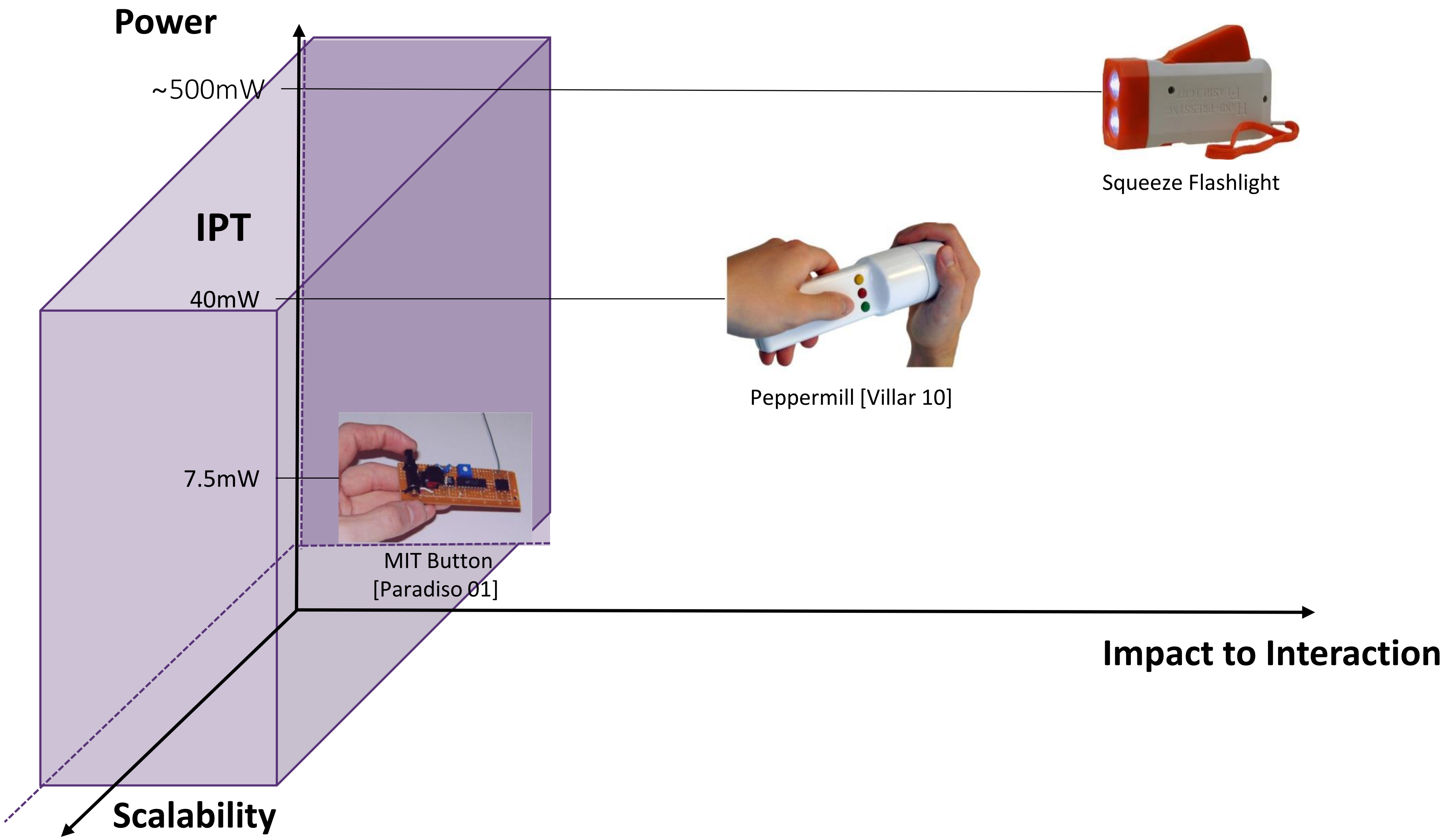
[1]T. Sasatani, A. P. Sample, and Y. Kawahara, “3-D Wireless Charging for Indoor Electronics Using Multimode Quasistatic Cavity Resonators,” presented at the Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers, 2018, pp. 444–447.
[2]K. Li, H. Luan, and C. C. Shen, “Qi-ferry: Energy-constrained wireless charging in wireless sensor networks,” in *2012 IEEE Wireless Communications and Networking Conference (WCNC)*, 2012, pp. 2515–2520.
[3]J. Scott, F. Hoffmann, M. Addlesee, G. Mapp, and A. Hopper, “Networked surfaces: a new concept in mobile networking,” in Proceedings Third IEEE Workshop on Mobile Computing Systems and Applications, 2000, pp. 11–18.

Interaction-based Power Transfer (IPT)

Transfer power from on-body energy sources to off-body power-as-needed devices only during interaction

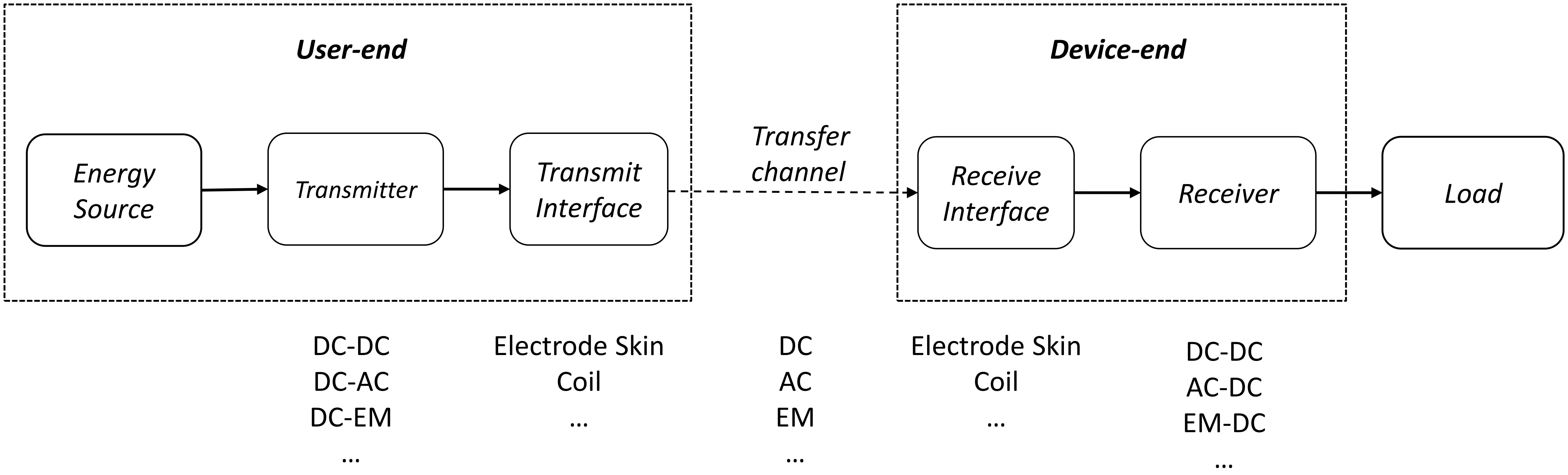
Interaction ⟶ Proactive Object Tracking + Adaptive Contact

Related Work

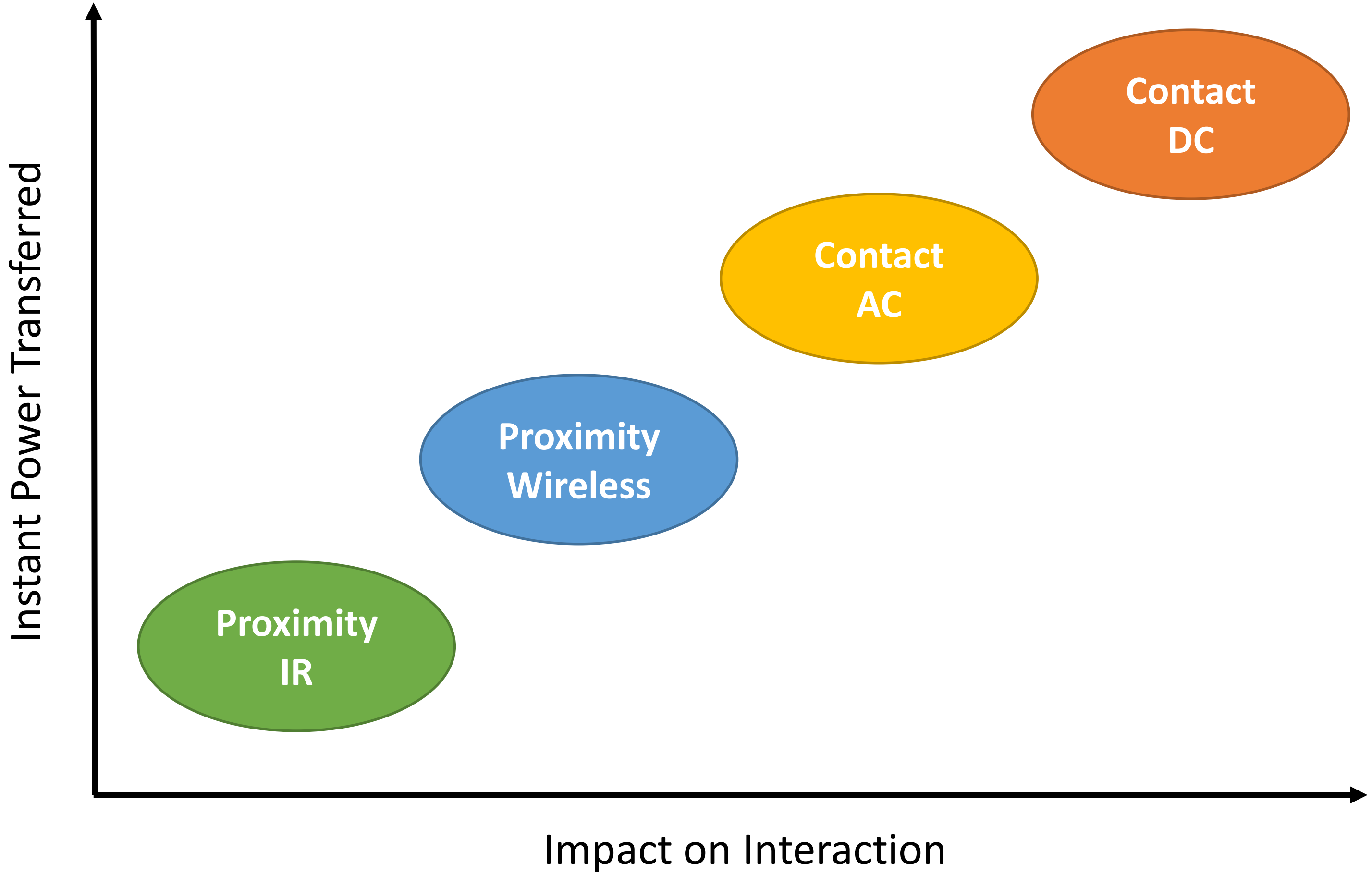


[1] J. A. Paradiso and M. Feldmeier, “A Compact, Wireless, Self-Powered Pushbutton Controller,” in Proceedings of the 3rd International Conference on Ubiquitous Computing, London, UK, UK, 2001, pp. 299–304.
[2] N. Villar and S. Hodges, “The Peppermill: A Human-powered User Interface Device,” in Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction, New York, NY, USA, 2010, pp. 29–32.

System Architecture



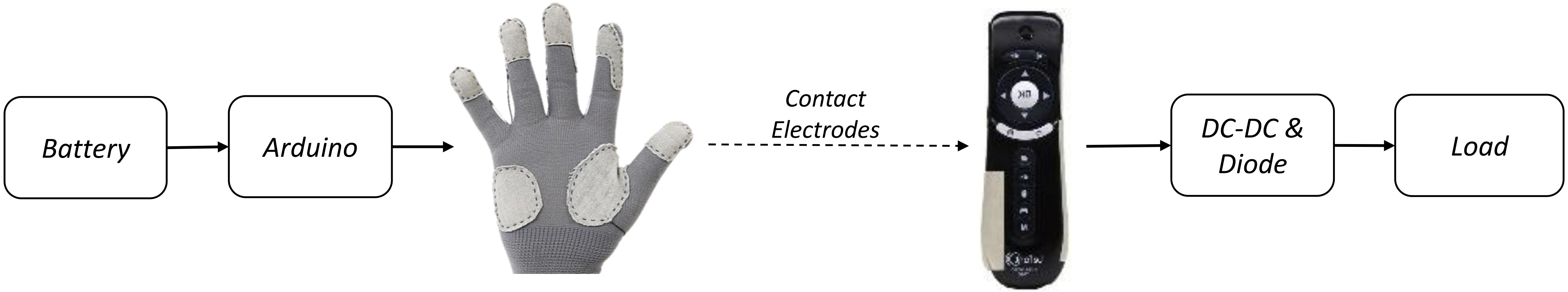
Different IPT Systems

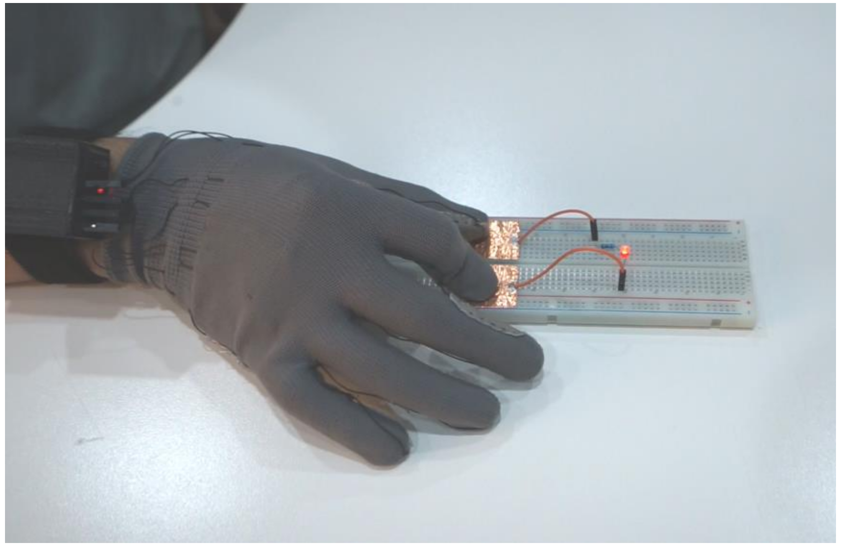


A tradeoff between *Impact on interaction* and *Power transferred*

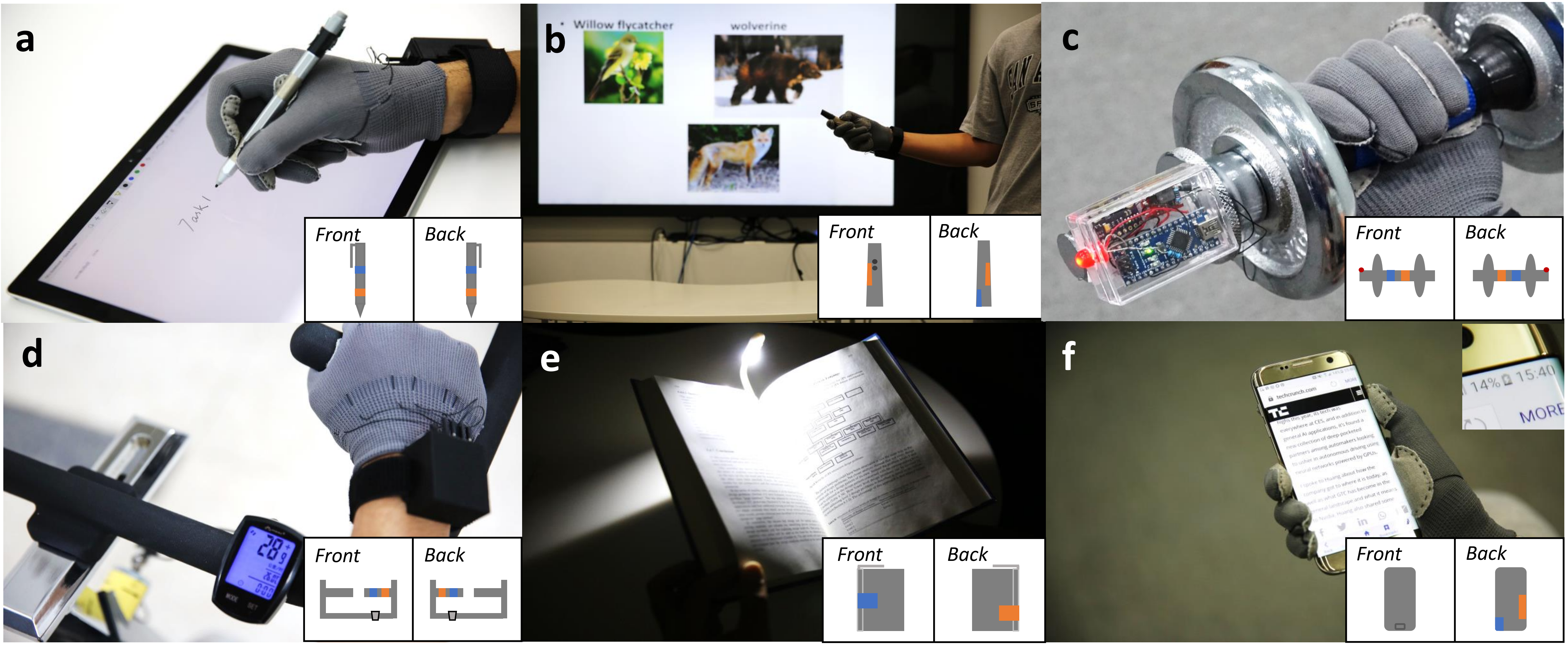
[1] E. R. Post, M. Reynolds, M. Gray, J. Paradiso, and N. Gershenfeld, "Intrabody buses for data and power," in *Digest of Papers. First International Symposium on Wearable Computers*, 1997, pp. 52–55.

Contact-based DC IPT Prototype: TouchPower

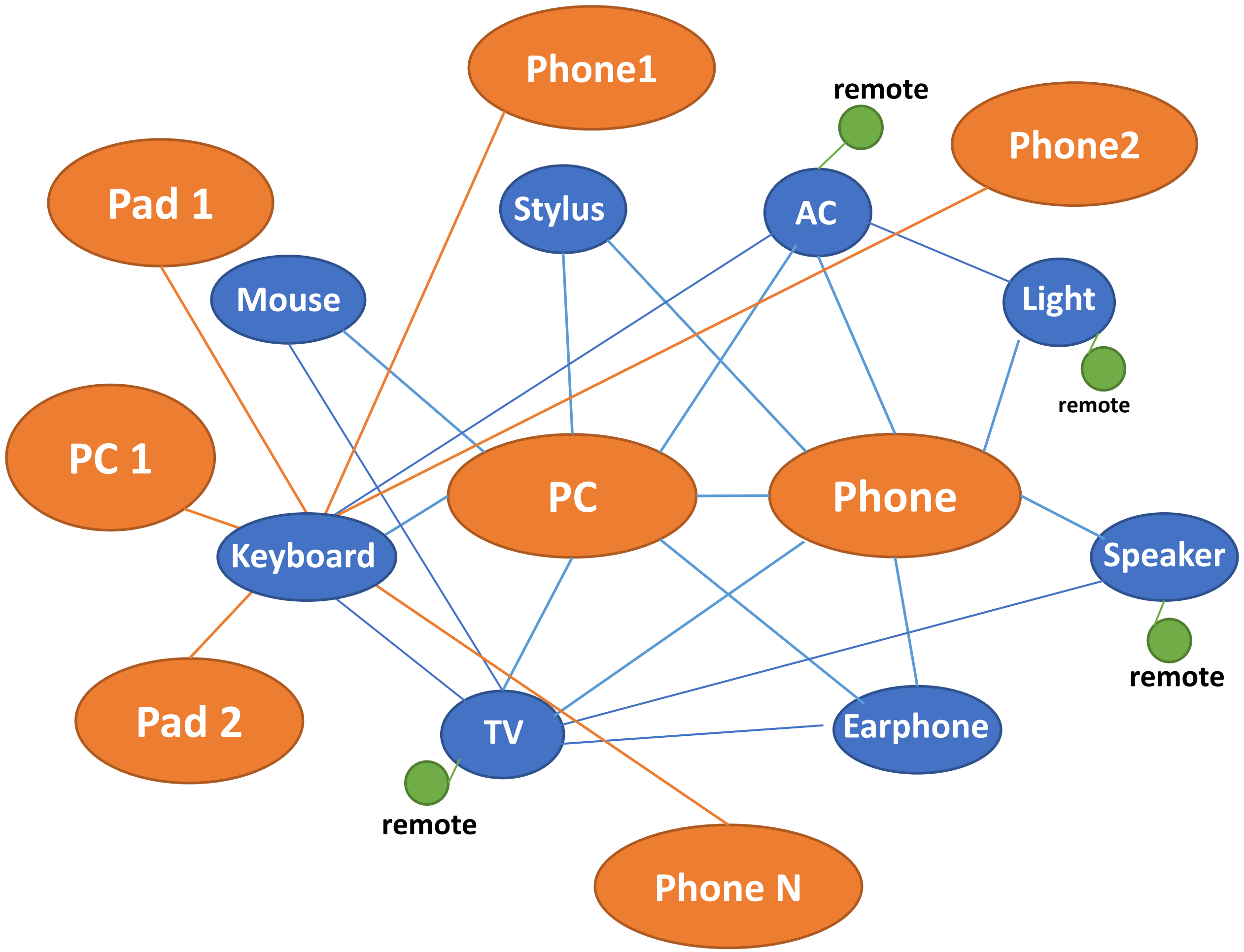




Applications



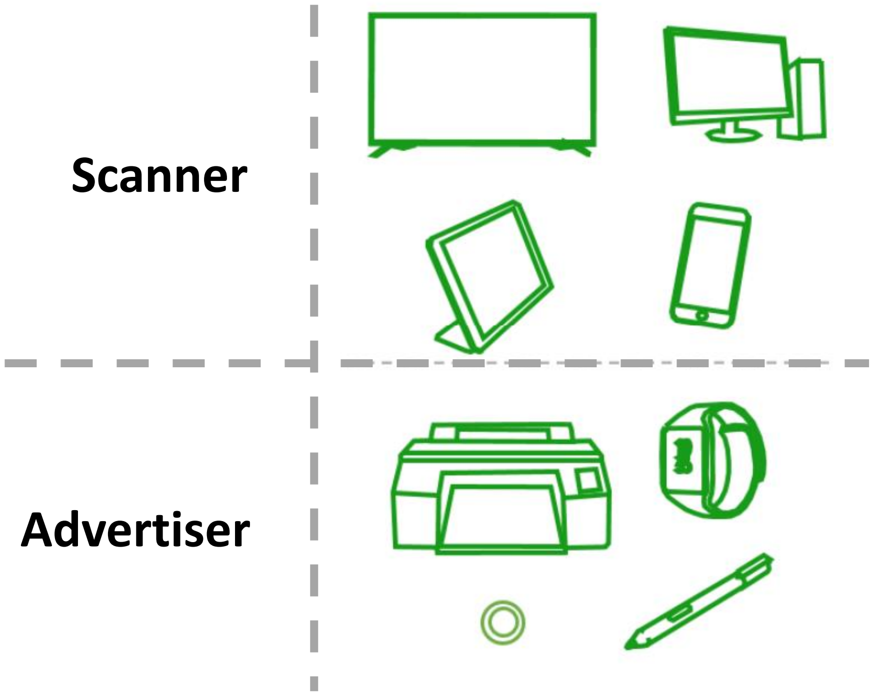
Device Association Demands



What is closest to the user?
The input and feedback device!

Computers	Association Demands
	Low
	Medium
	High

Current Wireless Device Association Methods



Scanner Initiated

Bluetooth, WiFi…

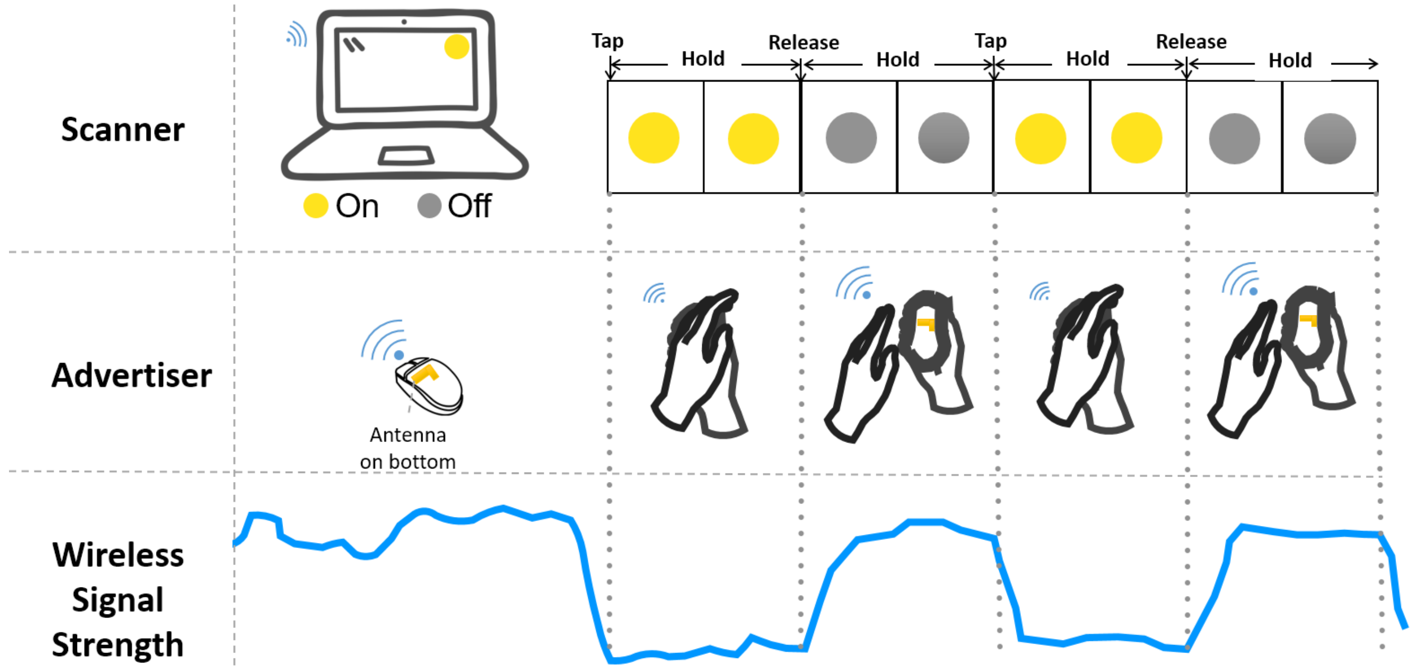
- Need a screen
- Hidden settings

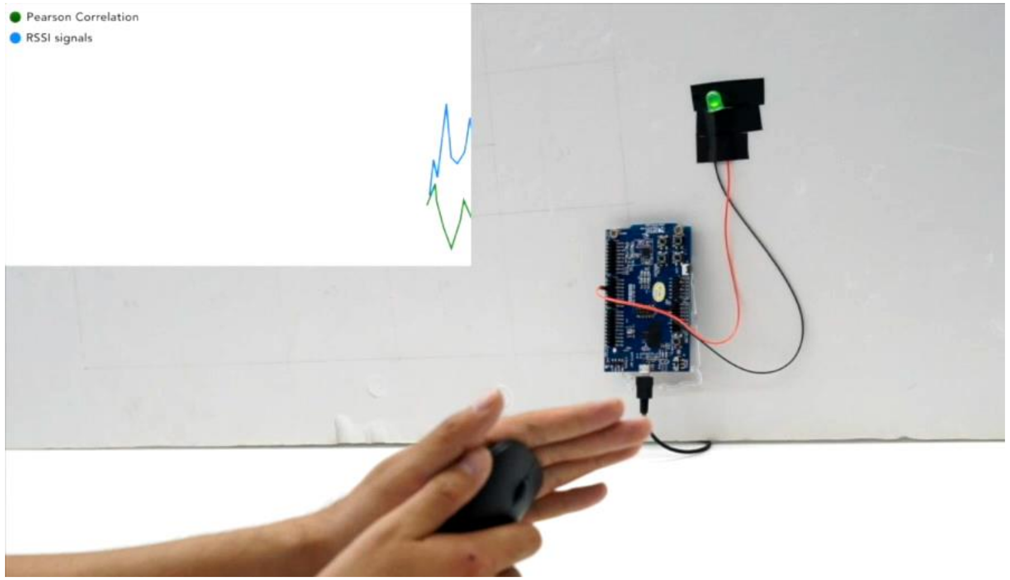
Advertiser Initiated

IR controller…

- Extra hardware on both ends
- Clean line-of-sight for alignment

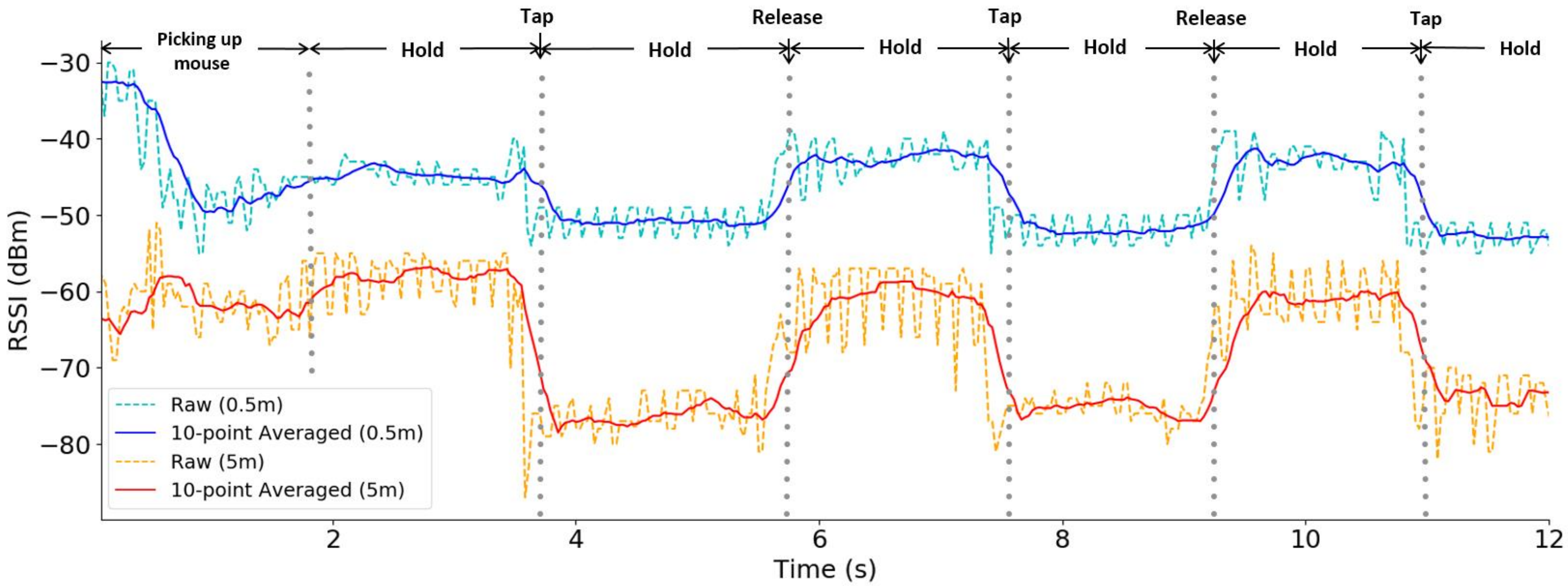
Tap-to-Pair: Thing-centered Association





- **"Hand effect"**: signal strength reduction due to hands near an antenna
- **Synchronized taps**: correlated wireless signal strength with a blinking pattern

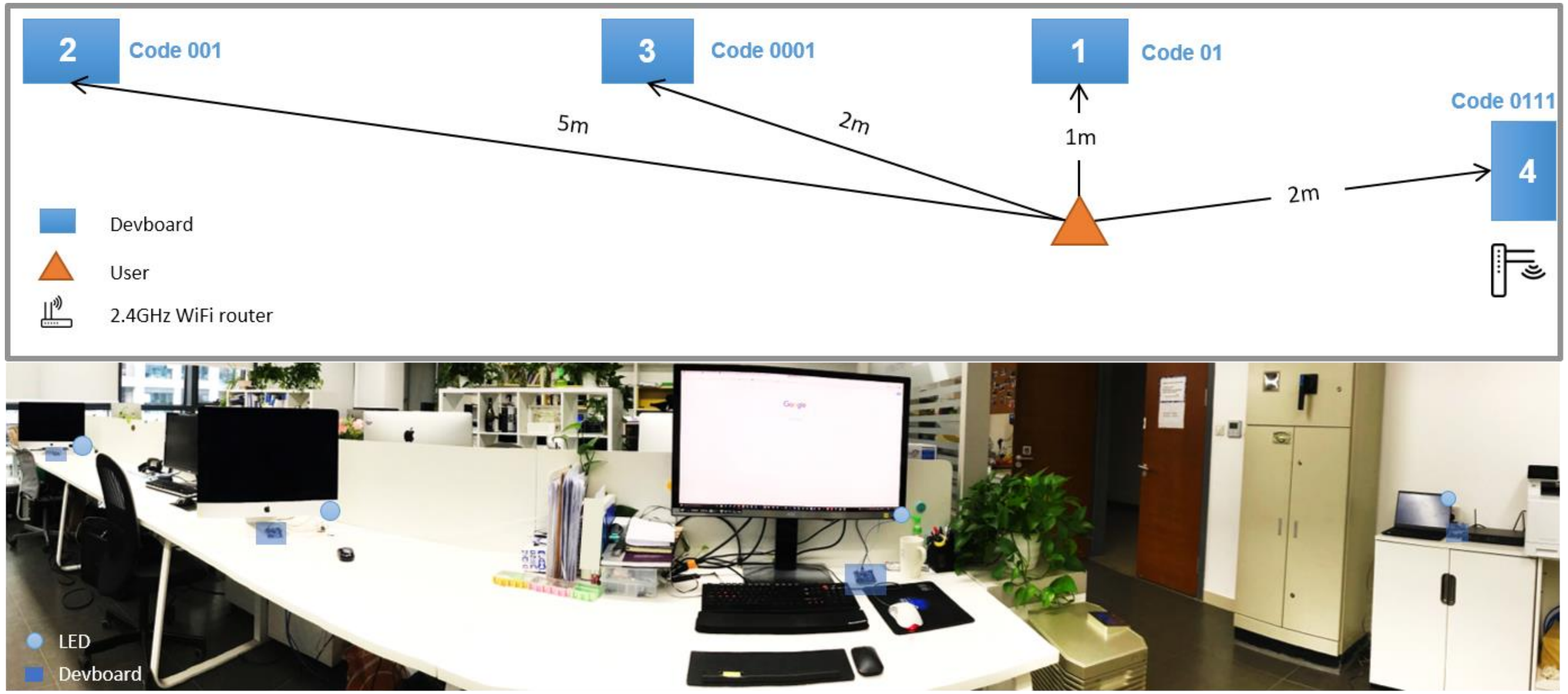
RSSI Changes



Proposed Association Mechanisms

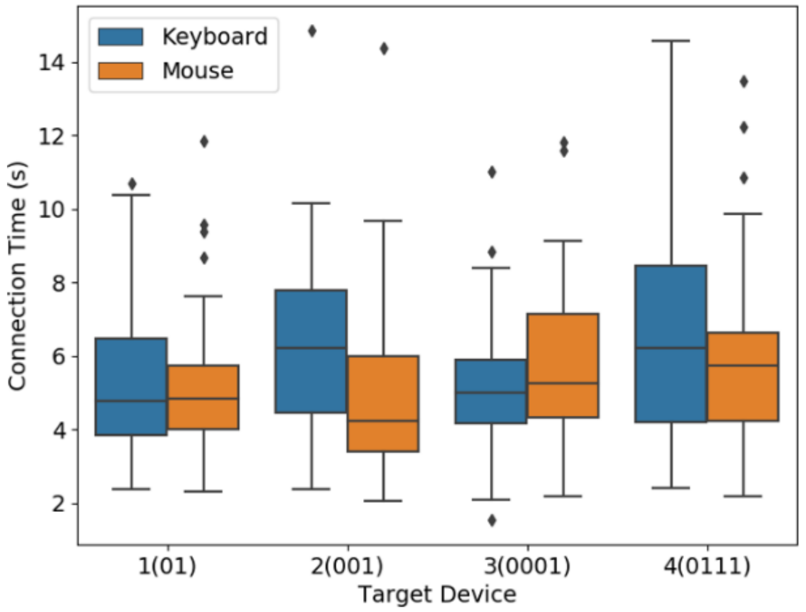
	Initiating Device	*Target Device*	*Other requirements*
IR/Laser [2, 14, 25, 35]	IR/laser transmitter	IR/laser receiver	None
Acoustic Gesture [1, 27, 32]	Speaker	Microphone	None
Vision Gesture [4, 12]	None	None	Kinect and cloud services
Synchronous Gestures [16, 22]	IMU	IMU	None
Tagging system [23, 28]	Camera	Tags	None
Snapping pictures[6, 10]	Camera	None	Cloud services
Rhythmic Taps [18, 39]	Binary Sensor	Binary Sensor	None
Tap-to-Pair	None	Binary display	None

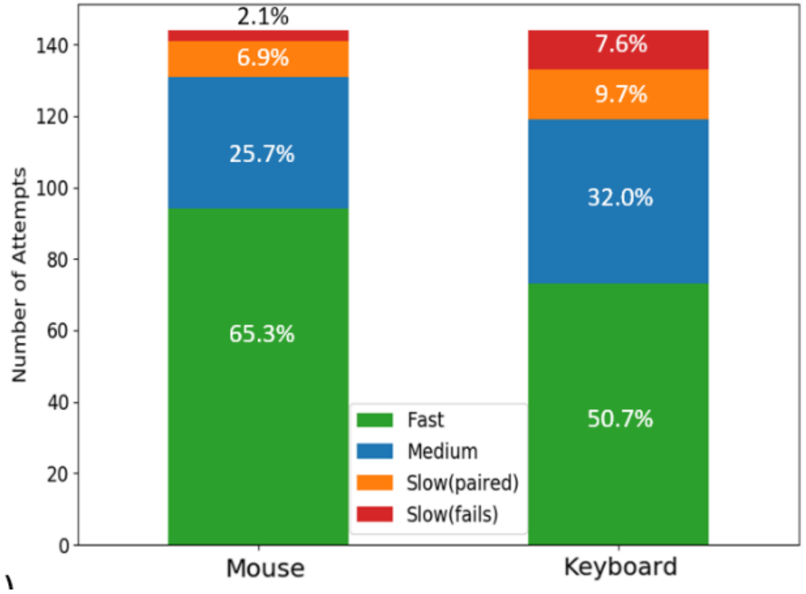
Evaluation

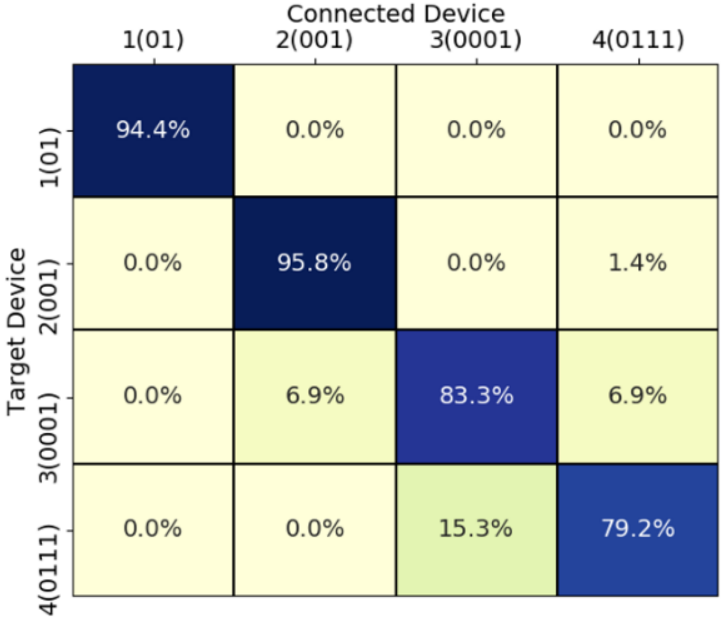


- Goals: Validate **on-chip** association performance
- 12 **new** participants (10 males)
- 4 devices at different **distances** with different **blinking patterns**
- Typical office wireless environment

Results Analysis



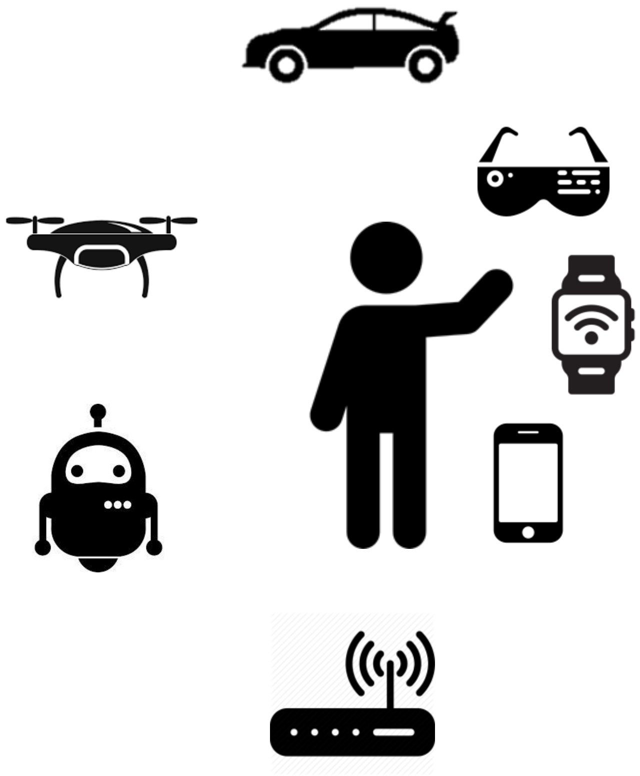




- Averaged pairing time **5.7s** (SD = 2.5s)
- **The association is faster or close to users' expectation** in 88% trials
- Accuracy： 94% (3 devices, follow the design guideline)
  88% (4 devices, against the design guideline)

A Paradigm for Sustainable Ubiquitous Computing

Computer
Resource-abundant



Interconnection

Power
Information

Thing
Resource-constrained

Research Summary

Thing

Computer

Interconnection

1. **Self-sustainable Backscatter Sensor**
   - **BitID**: RFID-based Binary Sensor
   - **TouchTag**: Backscatter Bluetooth Touch Interface

2. **Finger Wearables**
   - **ModularRing**: Modular Designed Smart Ring
   - **ThermalRing**: Thermal Imaging Smart Ring

3. **Power and Information Transfer Techniques**
   - **TouchPower**: Interaction-based On-demand Power Transfer
   - **Tap-to-Pair**: Correlation-based Thing-centered Device Association

Thanks!

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