



# Toward Sustainable Ubiquitous Computing and Interaction

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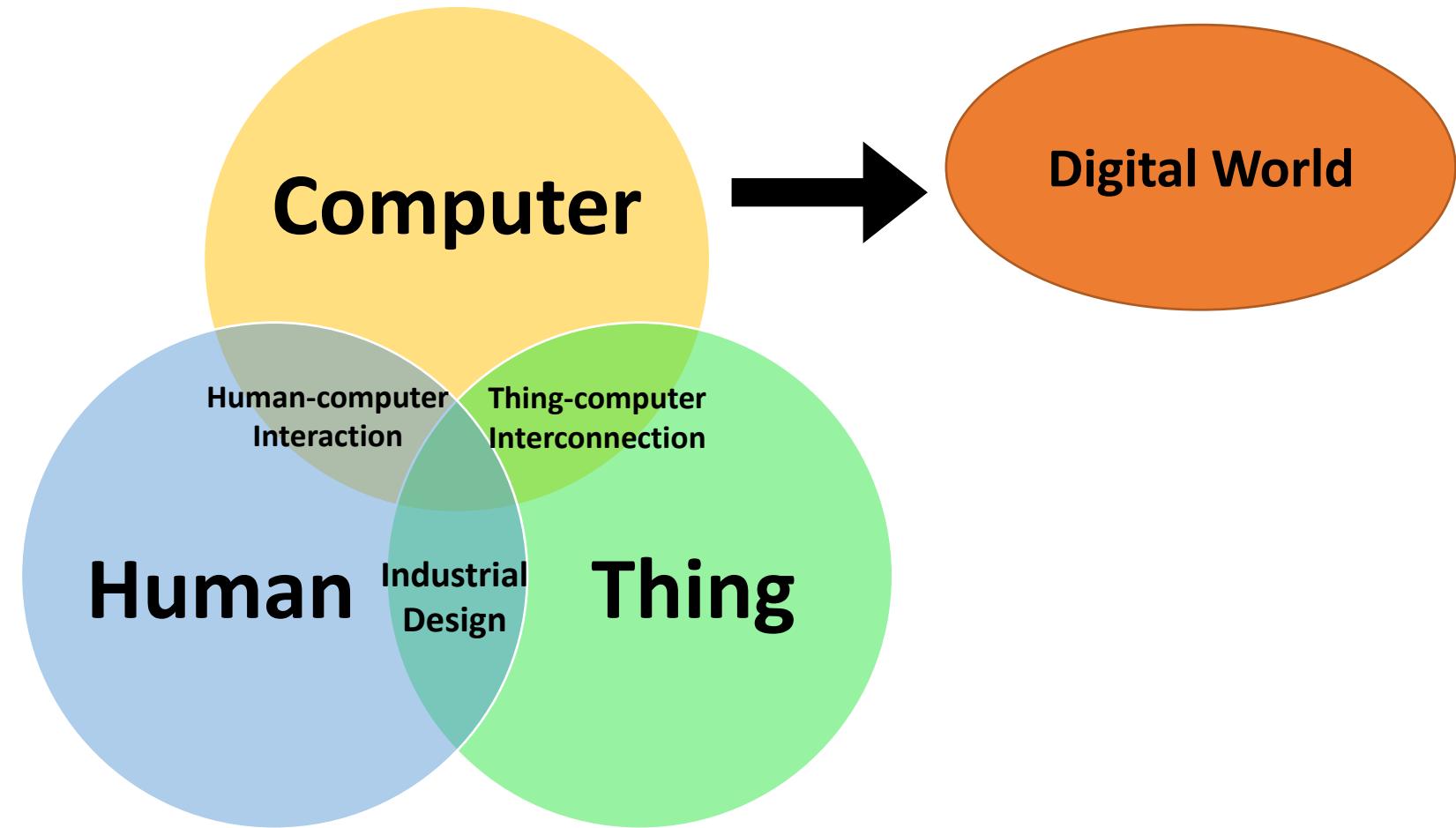
Chinese Academy of Sciences



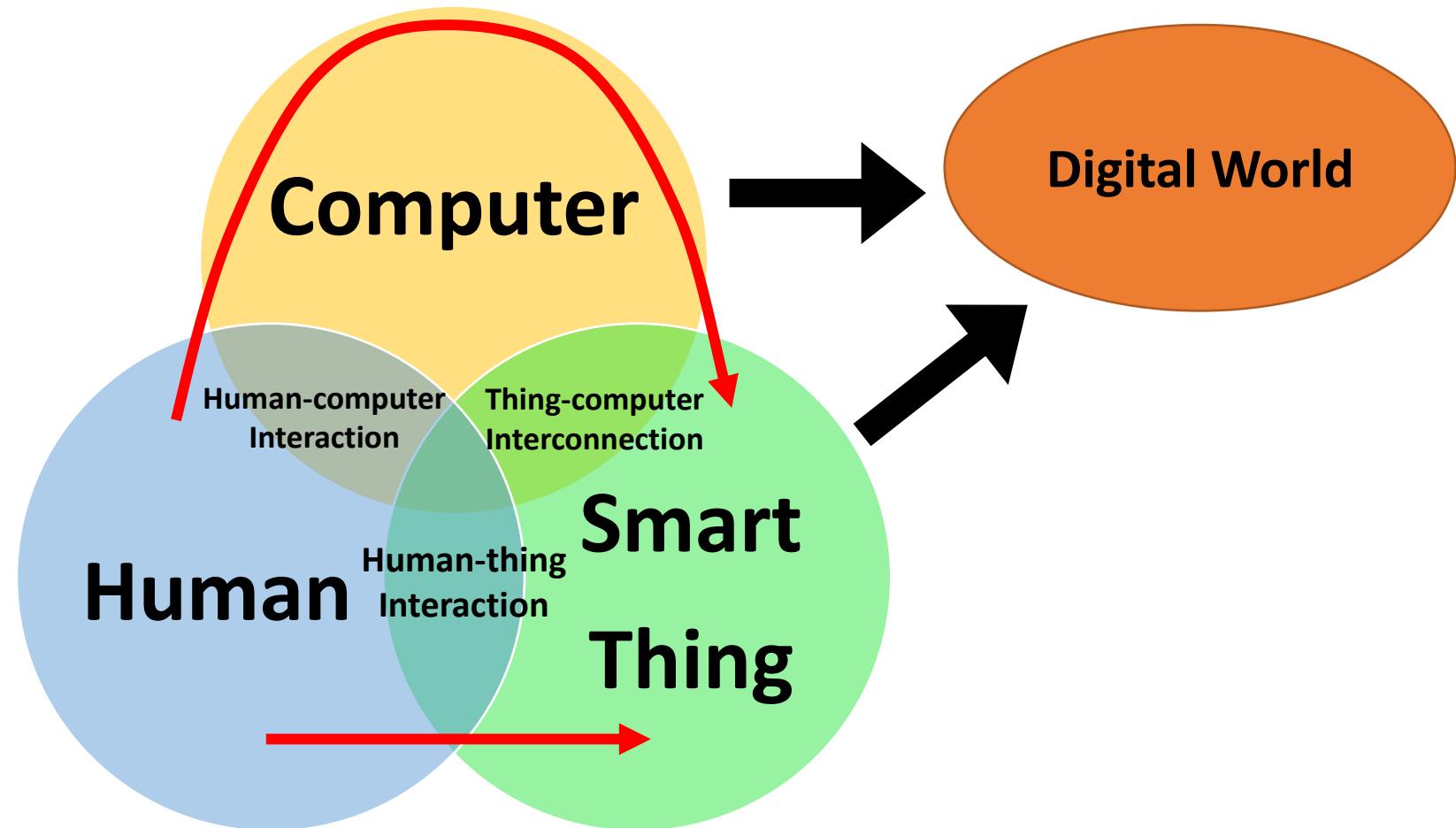
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  - Self-sustainable smart things
  - Interaction techniques for resource-constrained things
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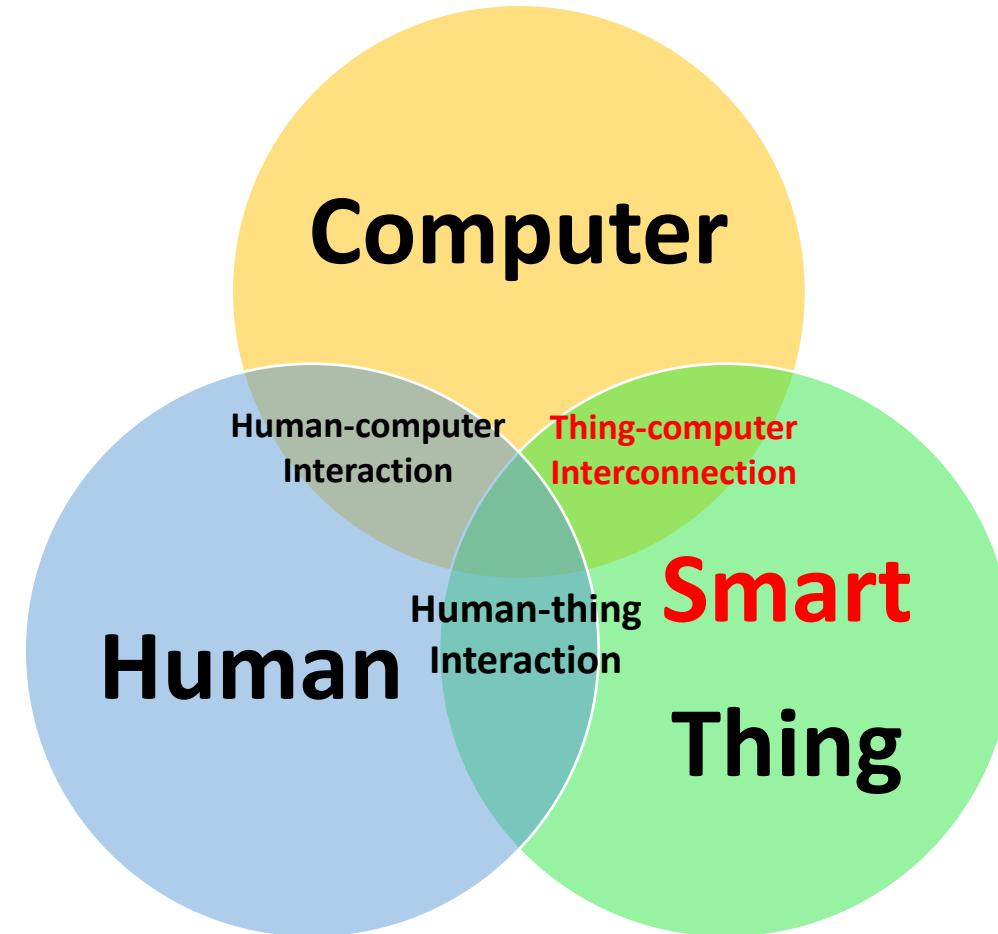
# Human-computer-thing Triad



# Human-computer-thing Triad

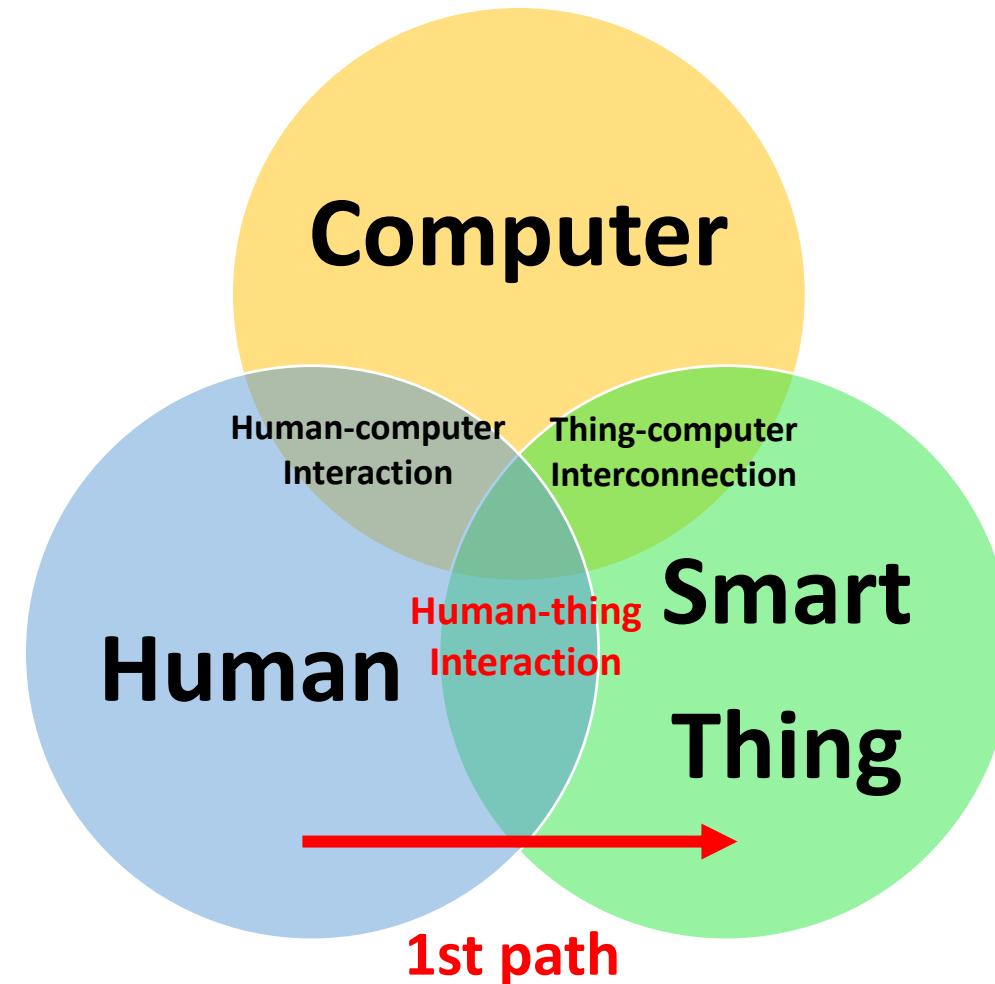


# Self-sustainable Smart Things



1. Self-sustainable smart things  
**Leverage computers**

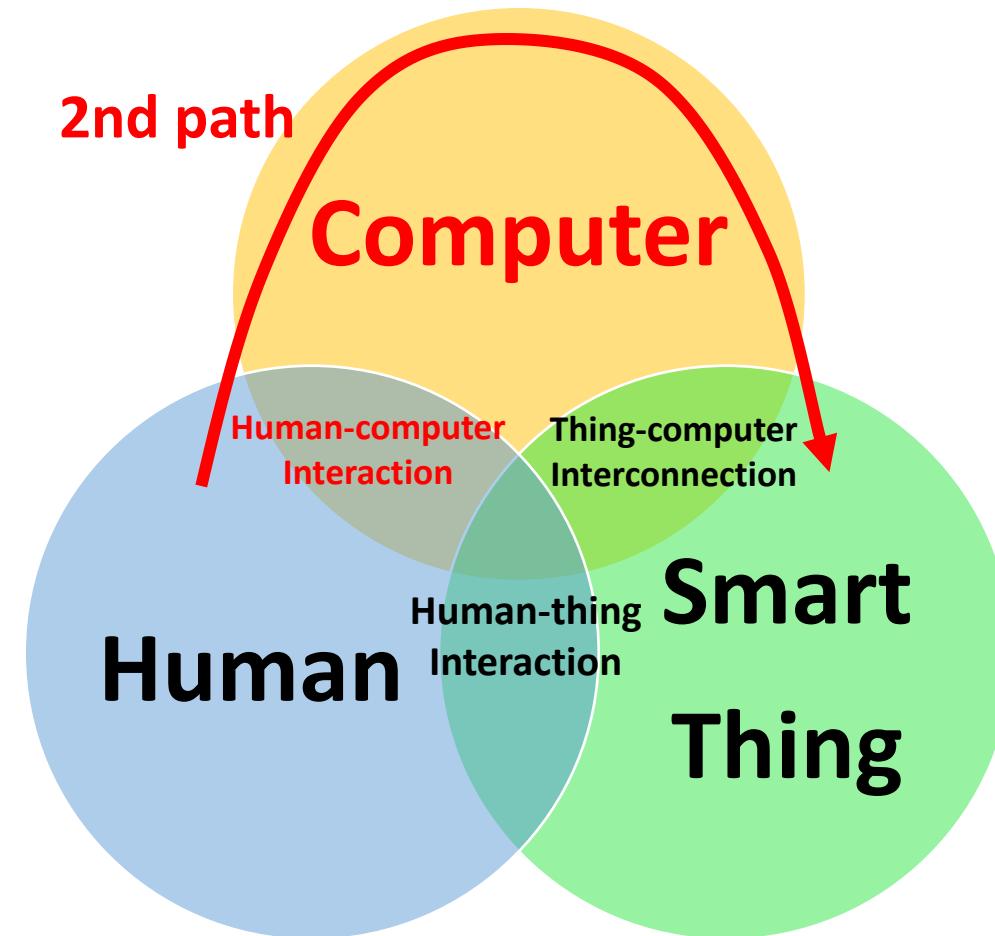
# Direct Human-thing Interaction



1. Self-sustainable smart things  
Leverage computers

2. Interaction techniques for resource-constrained things  
From spatial to temporal

# Wearable Computer Mediated Pervasive Interaction



1. **Self-sustainable smart things**  
**Leverage computers**
2. **Interaction techniques for resource-constrained things**  
**From spatial to temporal**
3. **Wearable computer mediated pervasive interaction**  
**Ring, AR**

# Research Focus



**1. Self-sustainable smart things**



**2. Interaction techniques for resource-constrained things**



**3. Wearable computer mediated pervasive interaction**

# Self-sustainable smart things



1. Why self-sustainability is important and how to achieve that
2. Brief intro to backscatter sensing  
*(accepted at Self-sustainableCHI20 Workshop  
Full version submitted to IEEE Pervasive Computing)*
3. BitID: RFID-based Binary Sensor  
*(SmartCom'17, Best-paper Runner-up)*
4. BLETouch: Bluetooth compatible touch sensor  
*(In-progress)*
5. TouchPower: On-body to off-body energy transfer  
*(IMWUT 2017, Discussion Paper)*

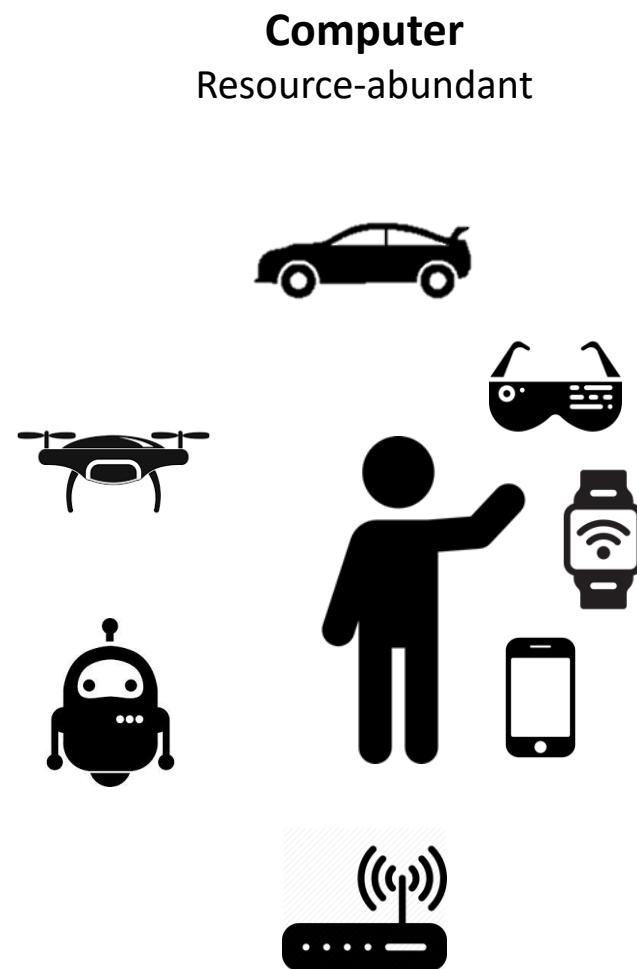
# Internet of Things



# World of Batteries



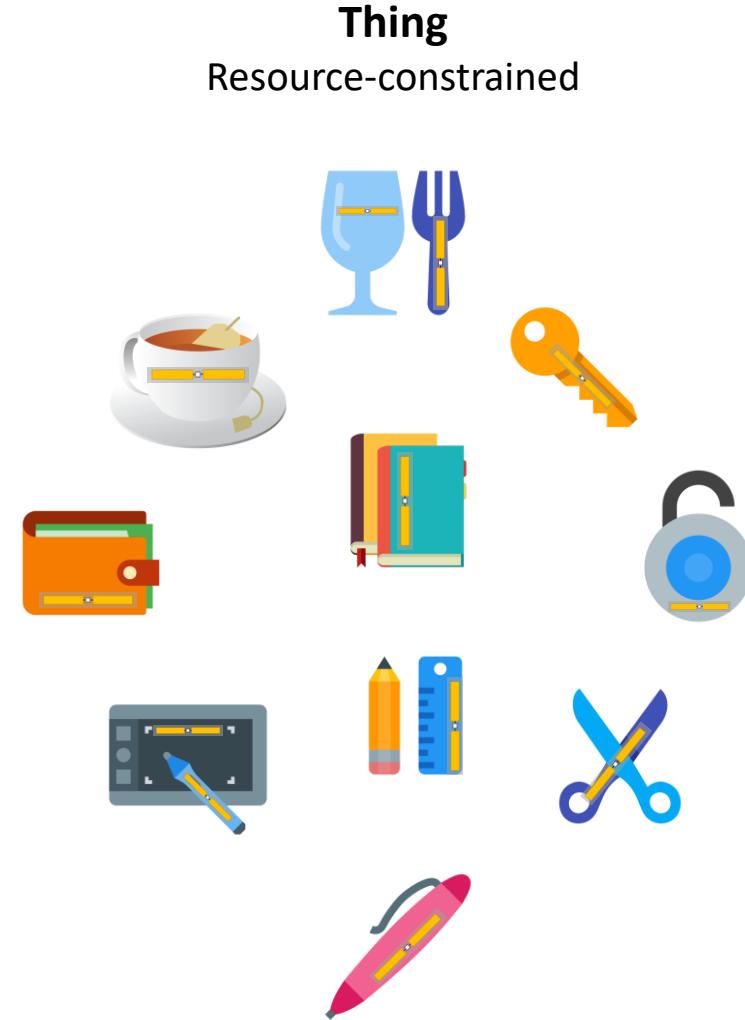
# Thing-computer interconnection



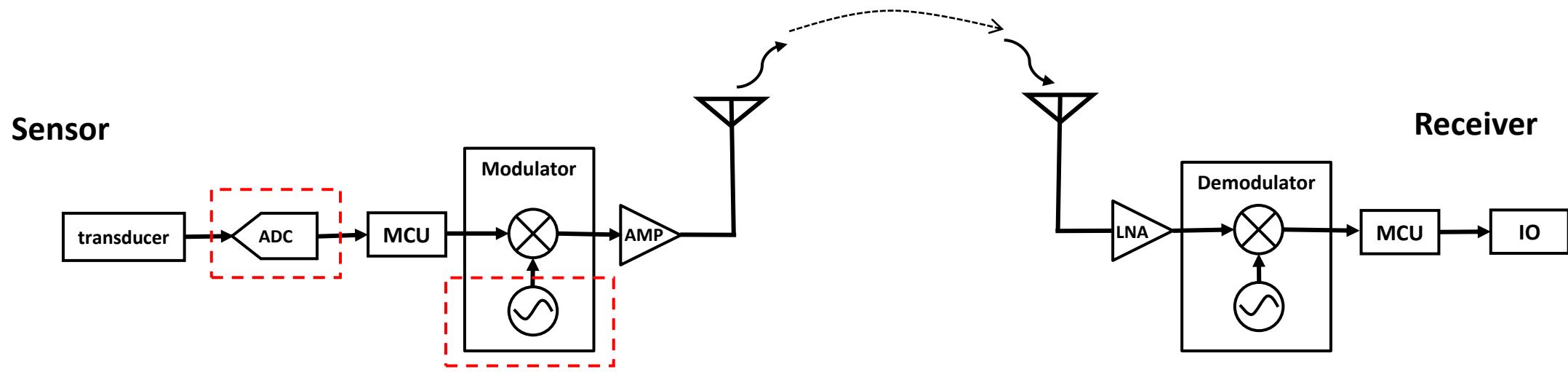
**Interconnection Technique**

A central icon consisting of three concentric arcs in yellow, with a lightning bolt symbol in the center, representing the backscatter wireless sensing technique.

**Backscatter Wireless Sensing Technique**



# Conventional Wireless Sensing System



High power consumption parts:

1. ADC  
Sensing: Digitize analog signals
2. High Frequency Oscillator (HFOSC)  
Transmission: Generate carrier frequency

Typical Power Consumption



10-15mW



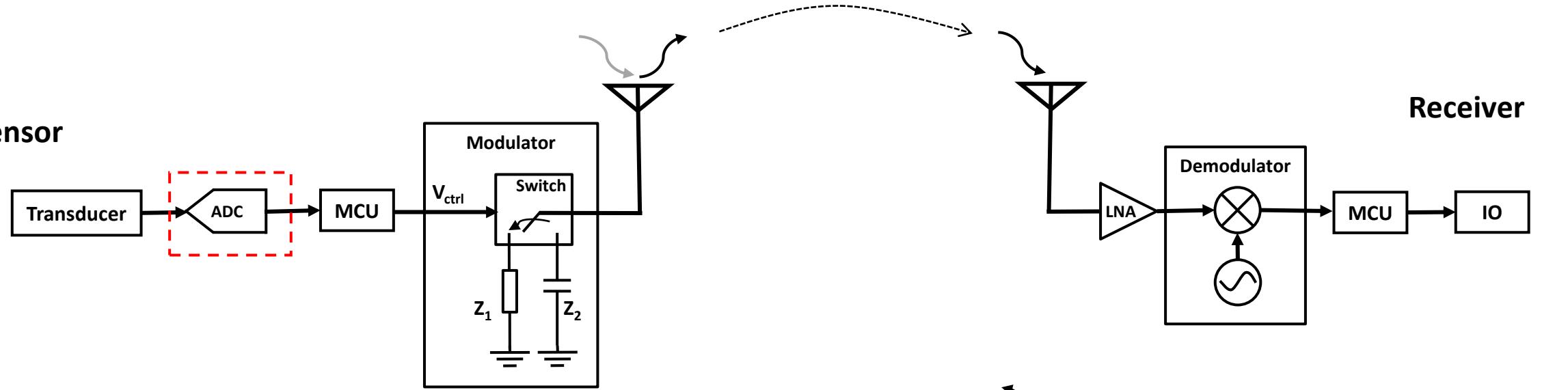
10-15mW



30-150mW

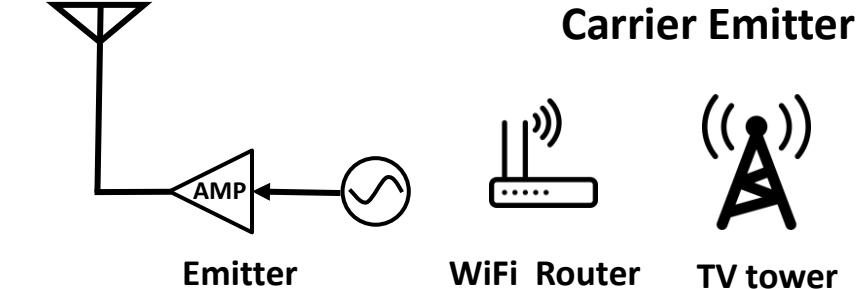
# Digital Backscatter Sensing System

Sensor



Use **one** carrier emitter to replace HFOSCs on **multiple** sensor

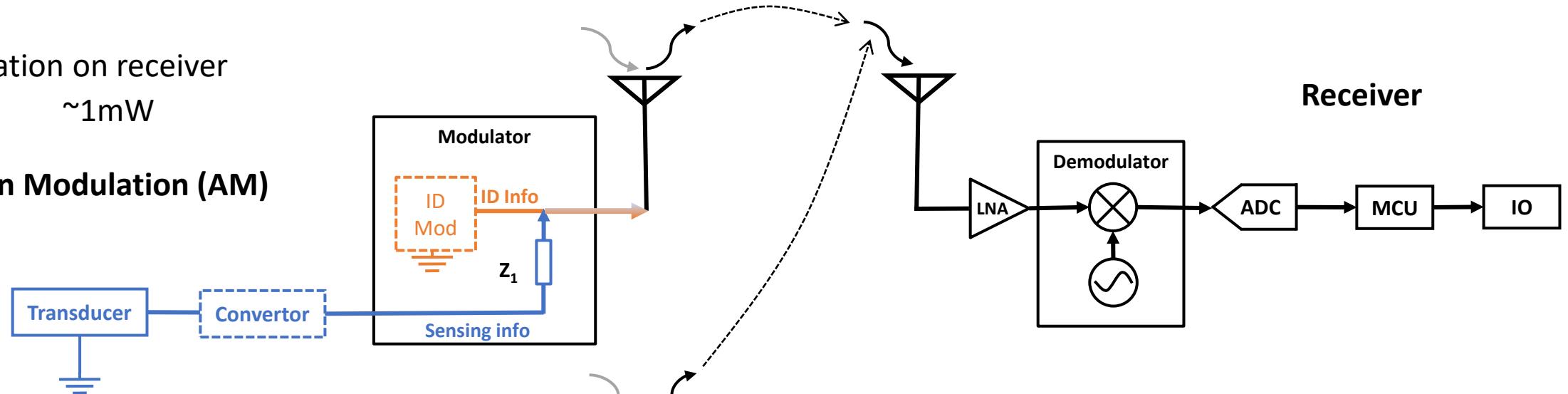
Still need ADC on the sensor



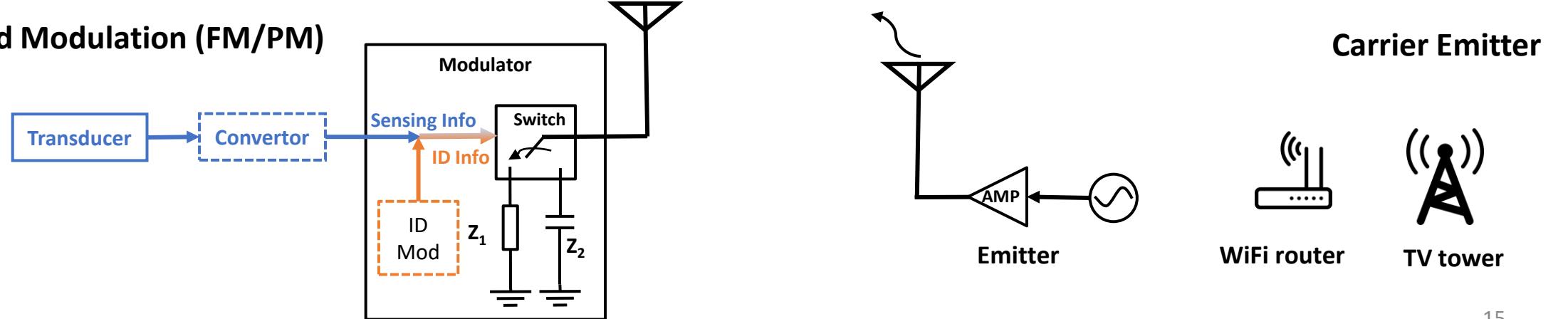
# Analog(hybrid) Backscatter Sensing System

Digitalization on receiver  
~1mW

## 1. Direction Modulation (AM)



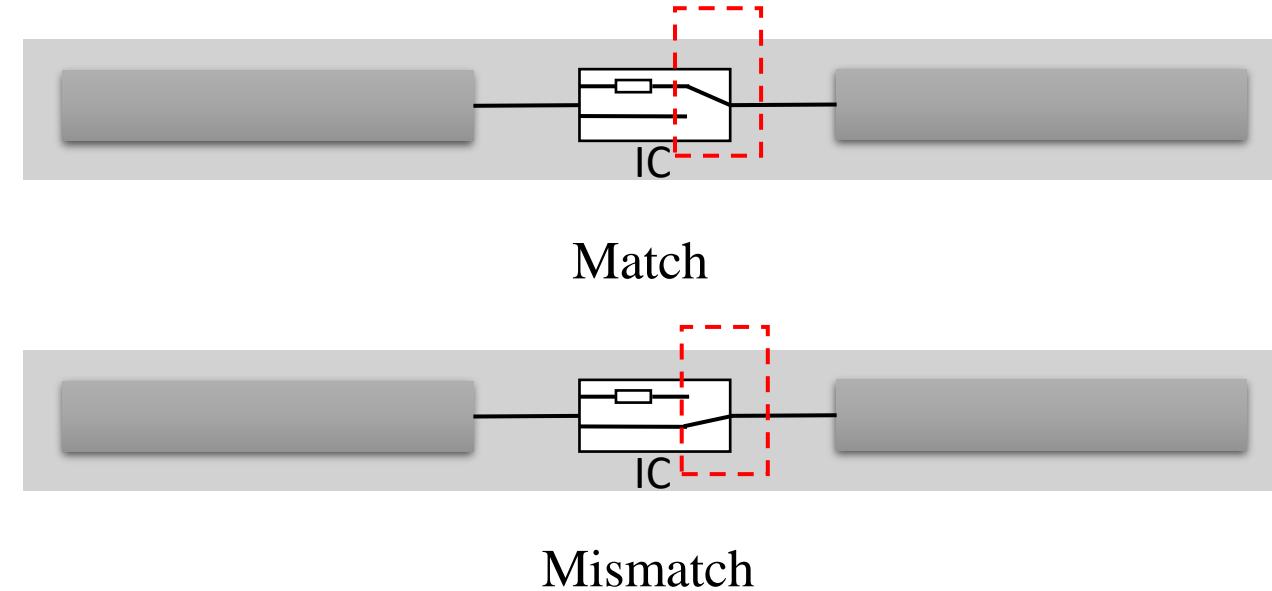
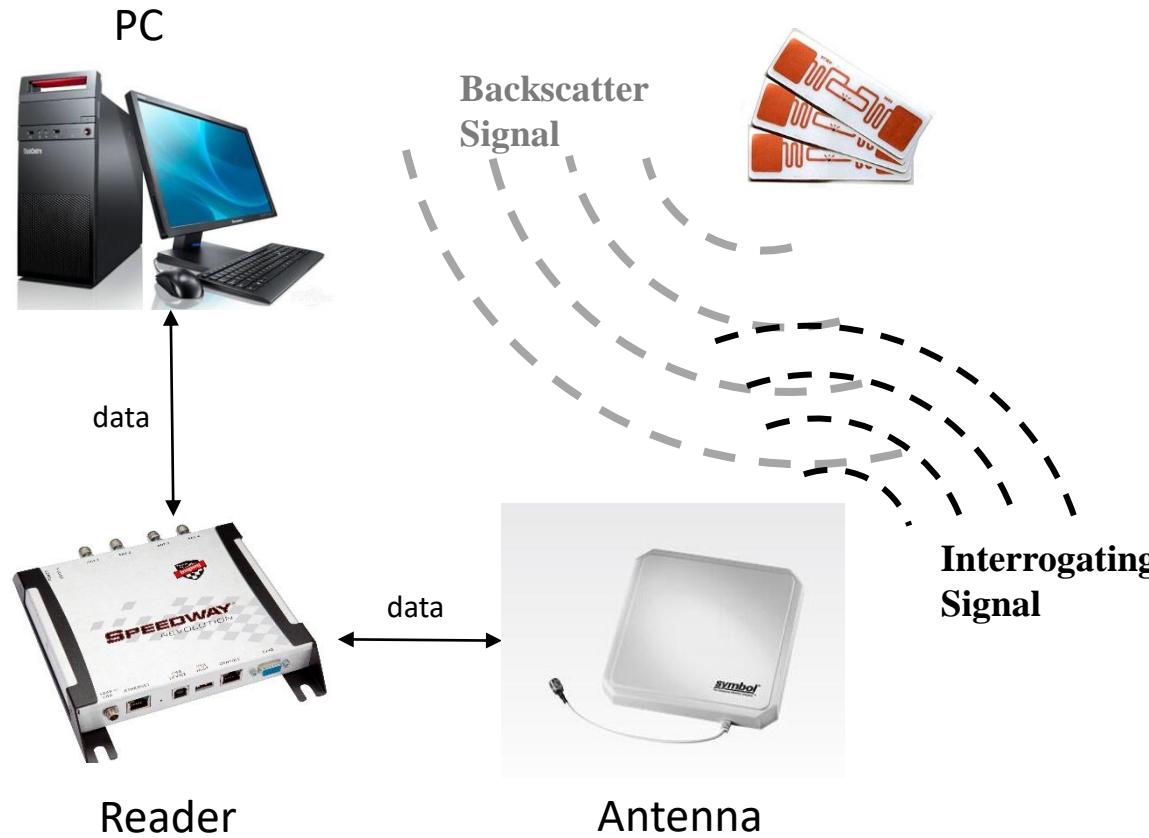
## 2. Sideband Modulation (FM/PM)



# Analog Backscatter Sensing: An Emerging Solution for Pervasive Data Collection and Interaction

System	Sensing task	Power Source	Carrier		Transducer		Converter		Modulator		Reader	
			Freq (MHz)	Ambient	Type	Output	Type	Output	Modulation	ID	Multiple access	Type
$\alpha$ -WISP 2005 [14]	Oriente- nation	RF	915	N	Mercury Switch	Impedance (Binary)	NA	NA	AM (OOK)	Y	Y (TD <sup>1</sup> )	RFID Reader
GasSensor 2011 [15]	Gas density	RF	915	N	Carbon Nanotube	Impedance (Continuous)	NA	NA	AM	Y	Y (TD)	RFID Reader
BendSensor 2012 [16]	Bend Angle	RF	915	N	Microstrip Transmission Line	Impedance (Continuous)	NA	NA	AM	Y	Y (TD)	RFID Reader
HybridSensor 2013 [17]	Audio	RF	915	N	Electret Microphone	Voltage	JFET (triode)	Impedance	AM	Y	Y (TD)	USRP SDR
PaperID 2016 [18]	Touch	RF	915	N	Conductive Ink	Impedance (Binary)	NA	NA	AM (OOK)	Y	Y (TD)	RFID Reader
BitID 2017 [19]	Contact	RF	915	N	Conductive Tape	Impedance (Binary)	NA	NA	AM (OOK)	Y	Y (TD)	RFID Reader
Batteryfree Cellphone 2017[20]	Audio	RF	915	N	Electret Microphone	Voltage	JFET (triode)	Impedance	AM	N	N	USRP SDR
ZEUSSS 2018 [21]	Audio	TENG <sup>2</sup>	915	N	Electret Microphone	Voltage	JFET (triode)	Impedance	AM	N	N	USRP SDR
RFIBricks 2018 [22]	Contact	RF	915	N	Magnet	Impedance (Binary)	NA	NA	AM (OOK)	Y	Y (TD)	RFID Reader
Profit&Fun 2018 [23]	Light Heat	RF	915	N	Phototransistor Thermistor	Impedance (Continuous)	NA	NA	AM	Y	Y (TD)	RFID Reader
Tip-Tap 2018 [24]	Touch	RF	915	N	Conductive Material	Impedance (Binary)	NA	NA	AM (OOK)	Y	Y (TD)	RFID Reader
HumidSensor 2014 [25]	Humidity	Coin Cell	868	N	HCH1000 <sup>3</sup>	Capacitance	555 Timer	Frequency	FM (FSK)	N	Y (FD <sup>4</sup> )	USRP SDR
SoilSensor 2016 [26]	Moisture	Coin Cell	868	N	Microstrip Interdigit Cap	Capacitance	555 Timer	Frequency	FM (FSK)	N	Y (FD)	RTL SDR
RF Bandaid 2018 [7]	General	RF	915	N	Resistive Sensor	Resistance	LTC6906 OSC <sup>5</sup>	Frequency	FM (FSK)	N	N	USRP SDR
HDStreaming 2018 [27]	Video	RF	915	N	Camera	Voltage (small variation)	Comparator & FPGA	Pulse Width	PWM	N	N	USRP SDR
UbiquiTouc 2020 [28]	Touch	Solar	87.8- 108	Y	Touch Panel	Voltage	TS3002 OSC <sup>6</sup>	Frequency (Binary)	FM (OOK)	N	N	Smart phone

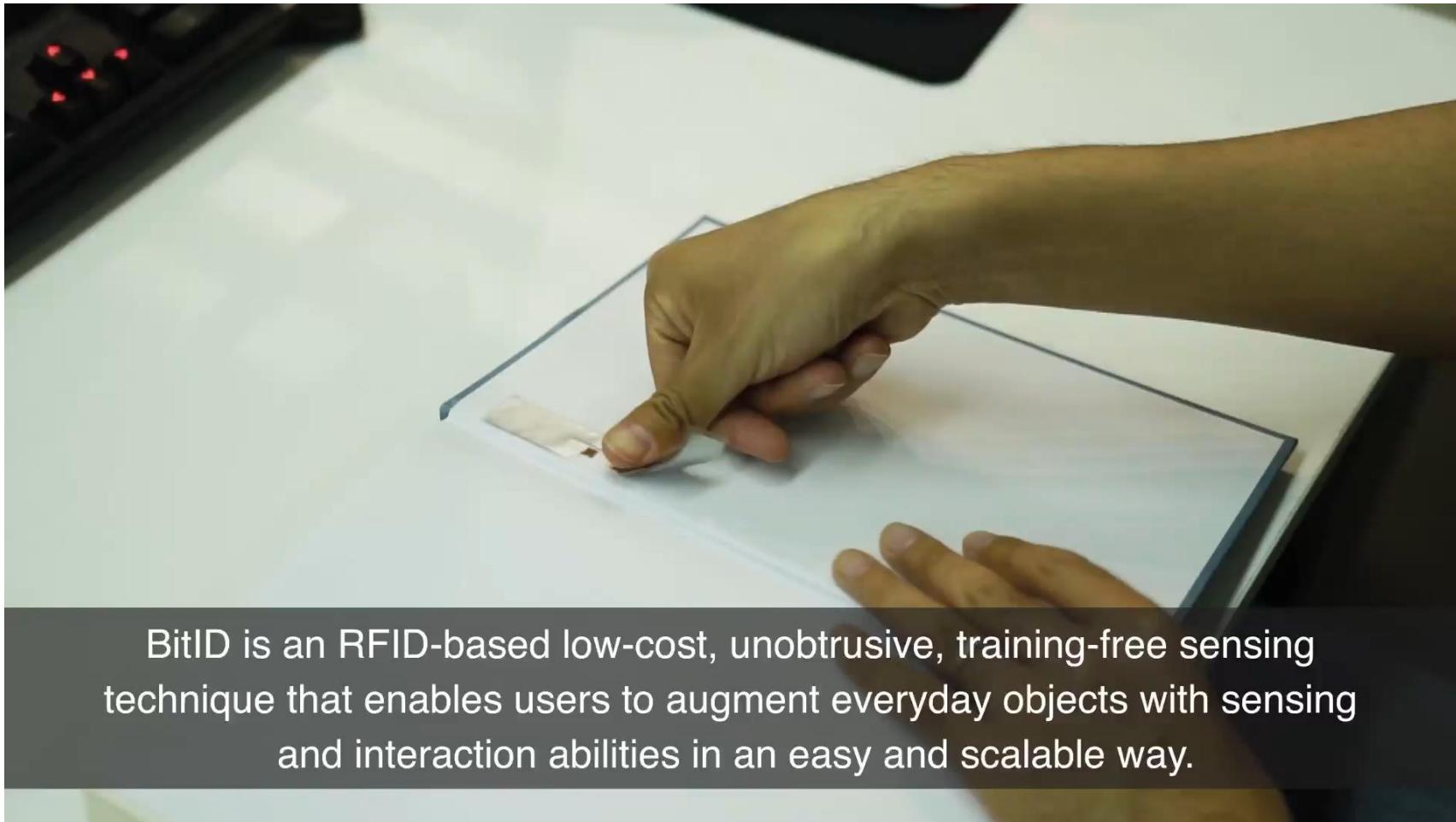
# RFID Working Principle



**Differential Radar Cross Section**

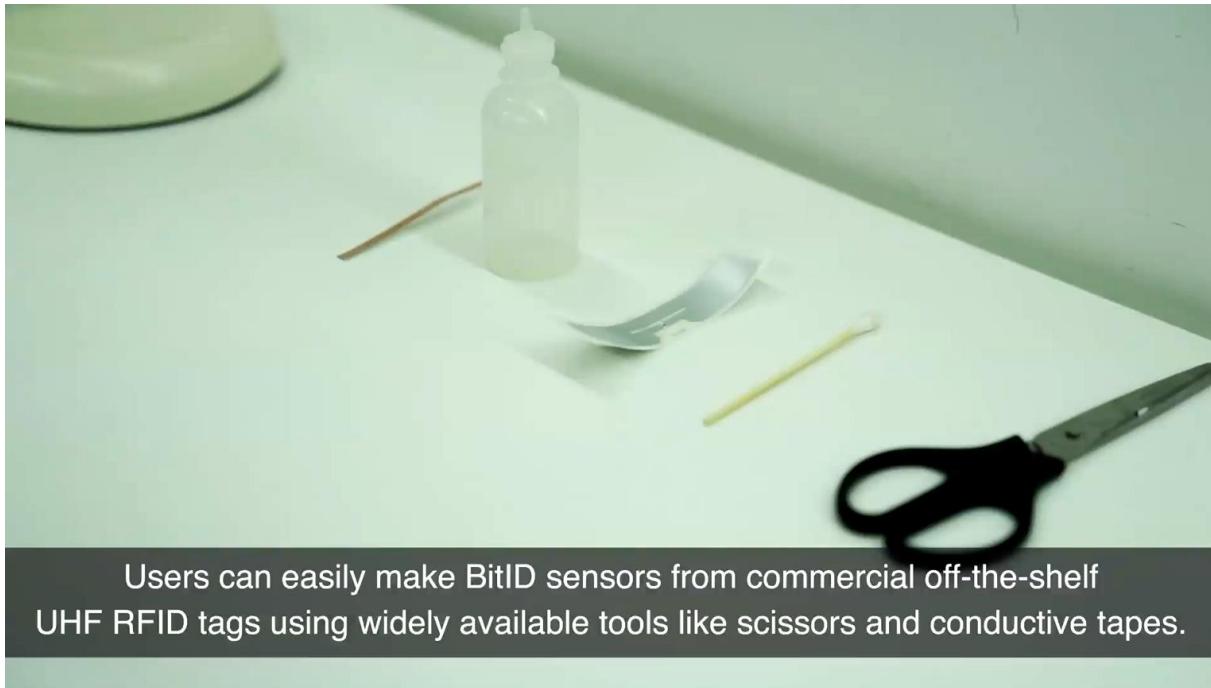
$$\Delta\sigma = \frac{\lambda^2 G^2}{4\pi} |\Gamma_1^2 - \Gamma_2^2|$$

# BitID: RFID-based Easily Add Battery-free Wireless Sensors



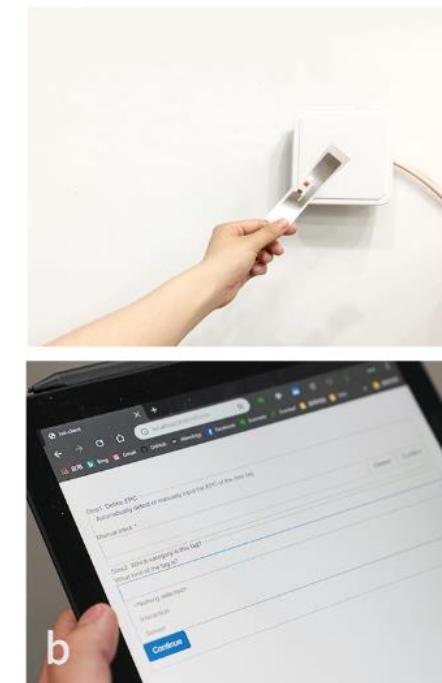
BitID is an RFID-based low-cost, unobtrusive, training-free sensing technique that enables users to augment everyday objects with sensing and interaction abilities in an easy and scalable way.

# Manufacturing and Usage of BitID



Users can easily make BitID sensors from commercial off-the-shelf UHF RFID tags using widely available tools like scissors and conductive tapes.

Build



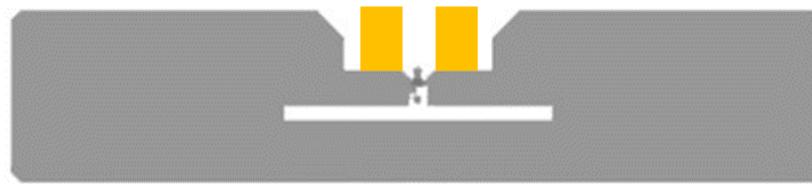
Registration  
and Definition



Deployment

# BitID Short Sensor

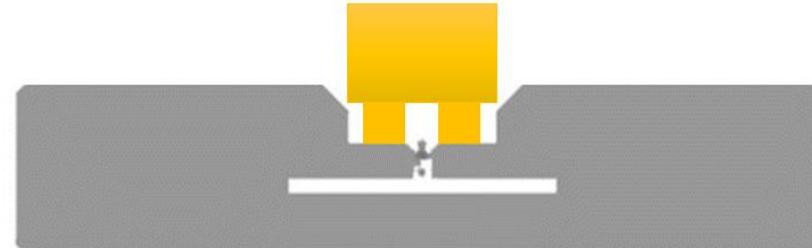
Part A



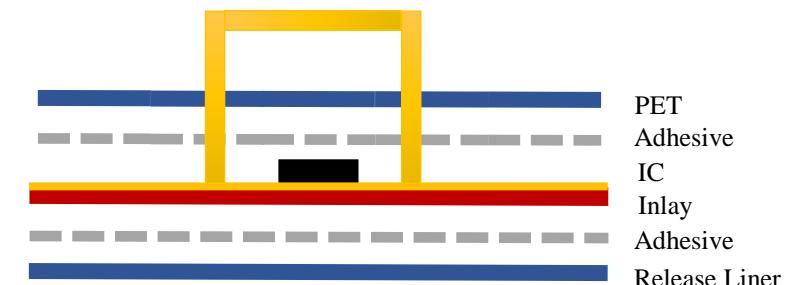
Part B



A+B



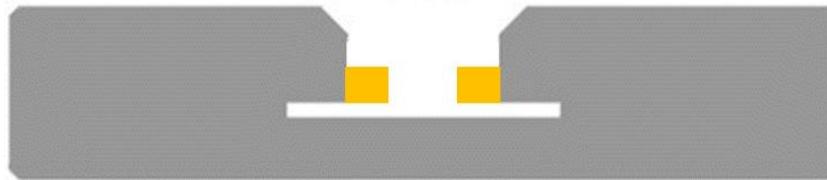
∅



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

# BitID Open Sensor

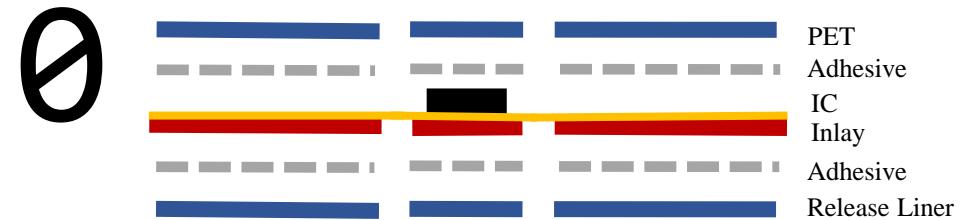
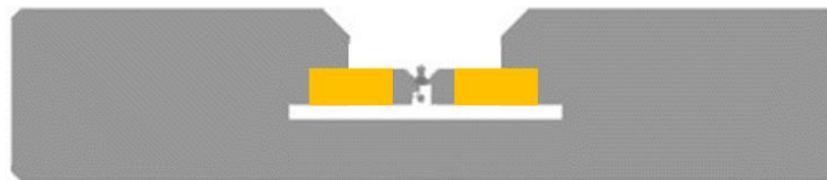
Part A



Part B

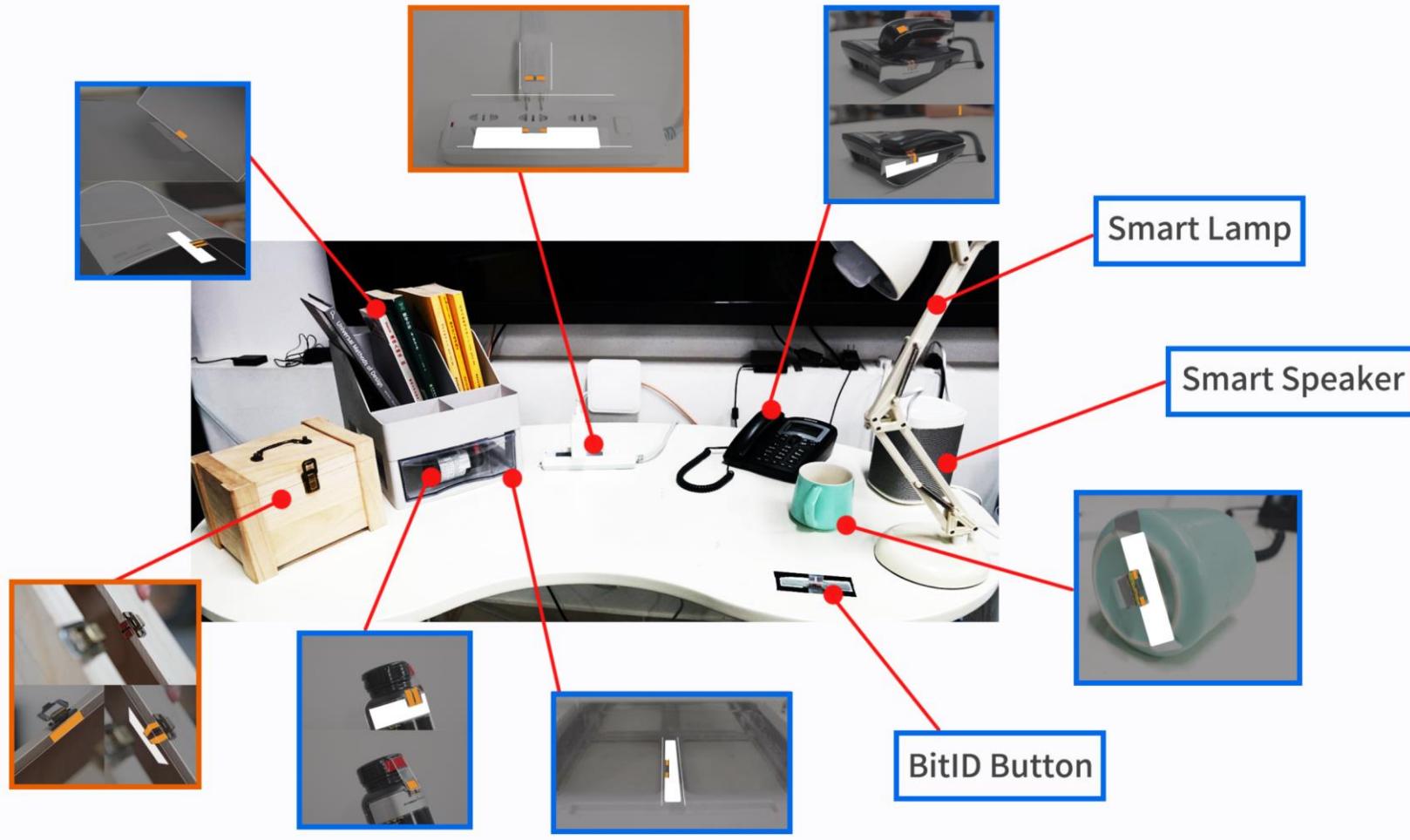


A+B



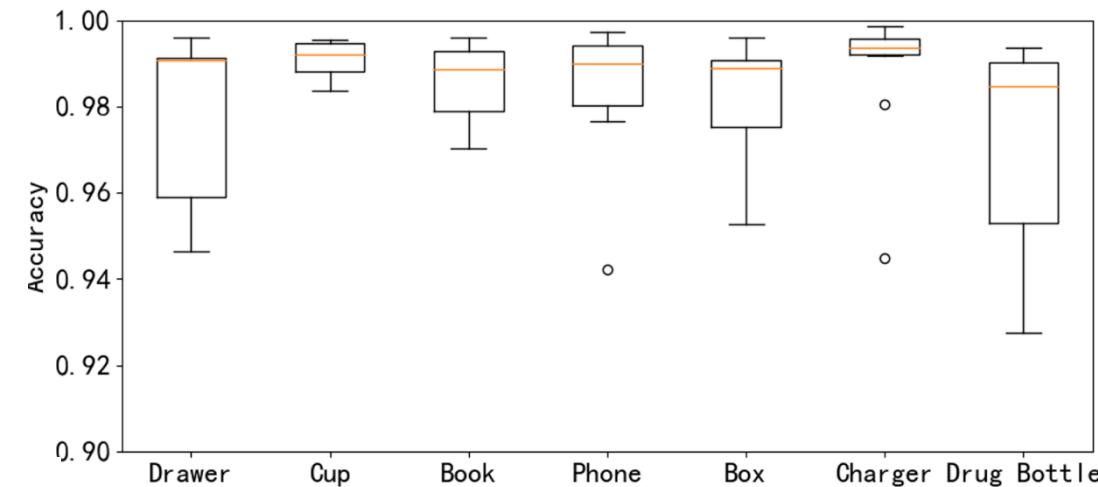
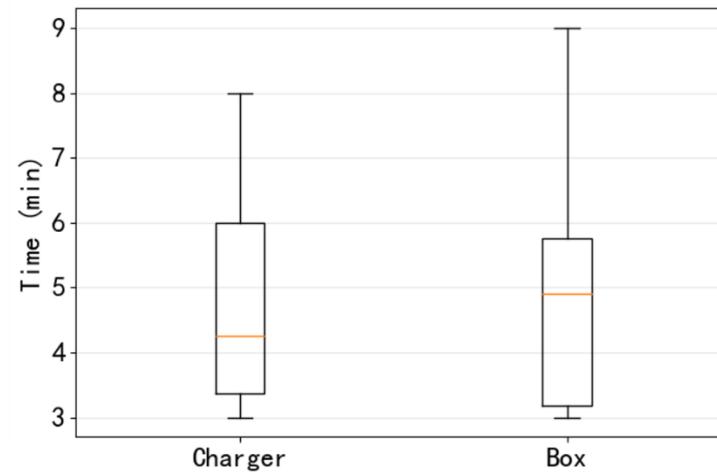
$$\begin{cases} \Gamma_1 \approx \Gamma_2 \\ G \approx 0 \end{cases} \rightarrow \Delta\sigma \approx 0$$

# User Study: Deployment Evaluation



- 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)

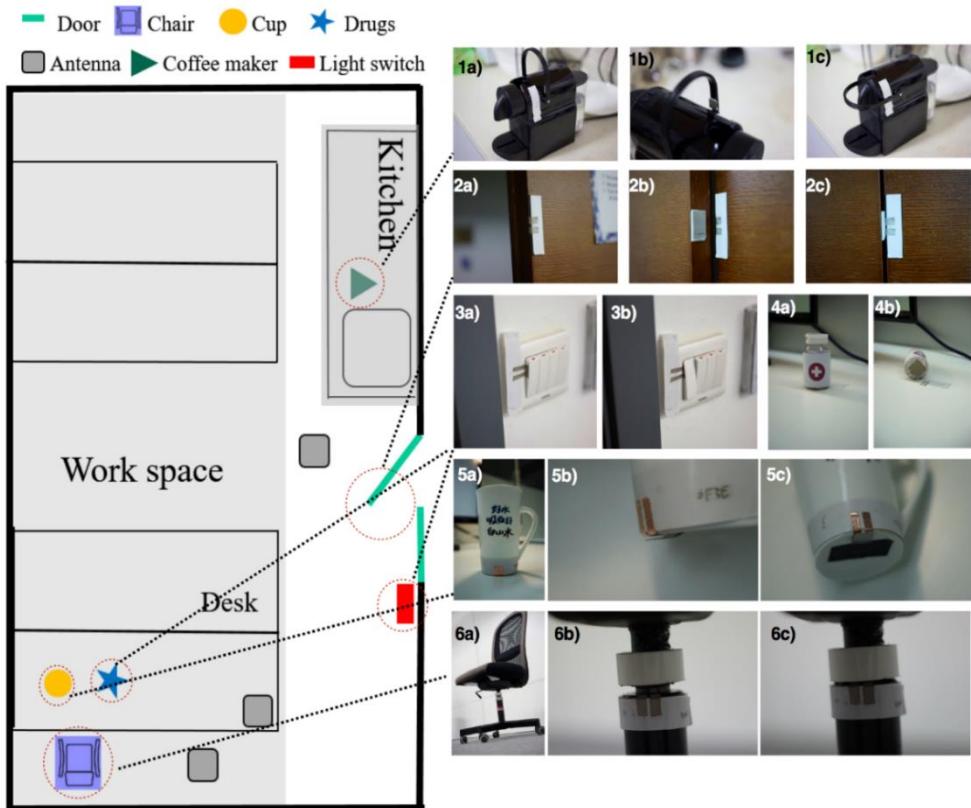
# Results Analysis



- Charger task completed in MEAN = **4.8min** (SD=1.8)
- Box task completed in MEAN = **5.1min** (SD=2.0)
- 23/24 deployment trials are successfully completed and evaluated robust

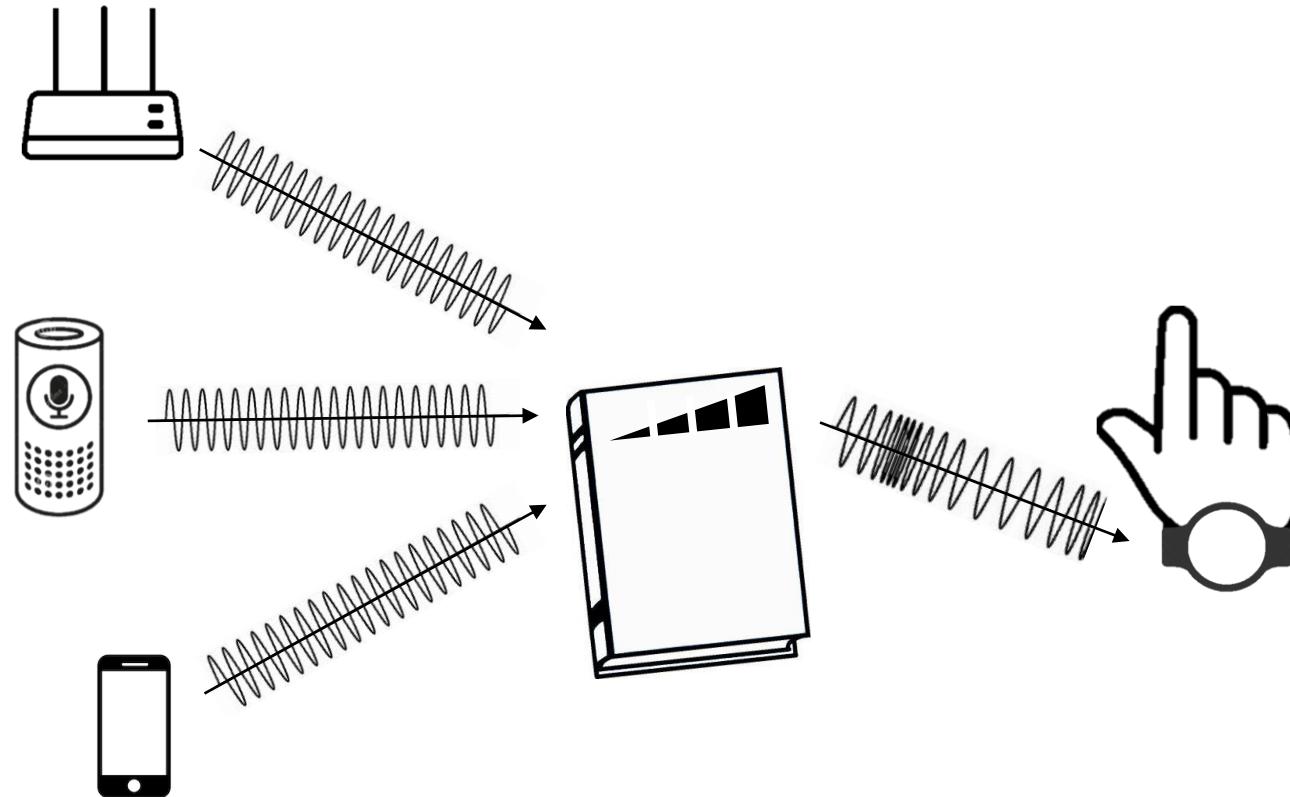
- 7 Sensing Tags Accuracy **98.3%**
- 11/12 participants feels BitID is easy to use (>4, MEDIAN=7)
- Short sensor (MEDIAN=6) is easier to deploy than open sensor (MEDIAN=5)

# Room Scale Applications

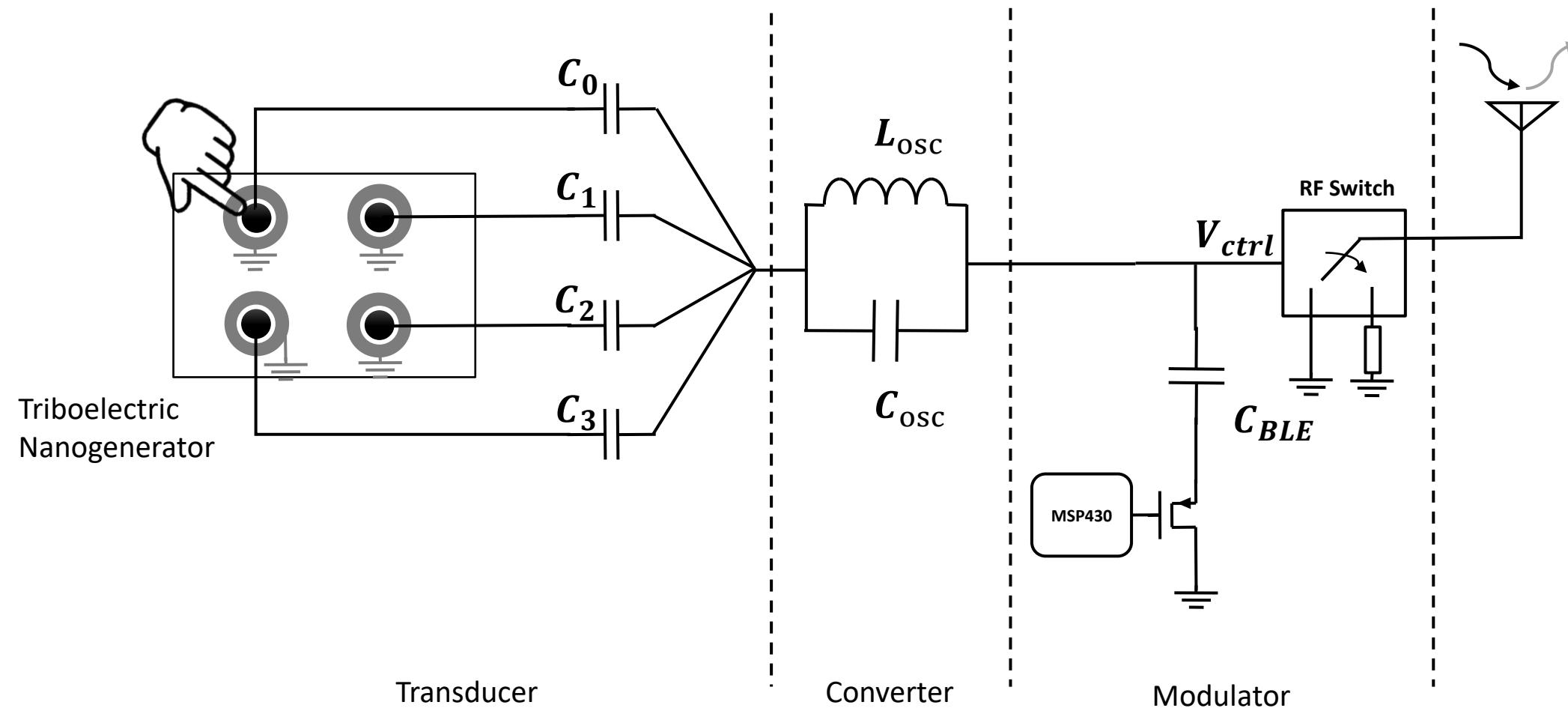


- Drug
- Coffee maker
- Light Switch
- Door
- Chair
- Cup

# BLETouch: Bluetooth Compatible Backscatter Touch Sensing System



# FM Backscatter Touch Sensor with BLE ID Modulation



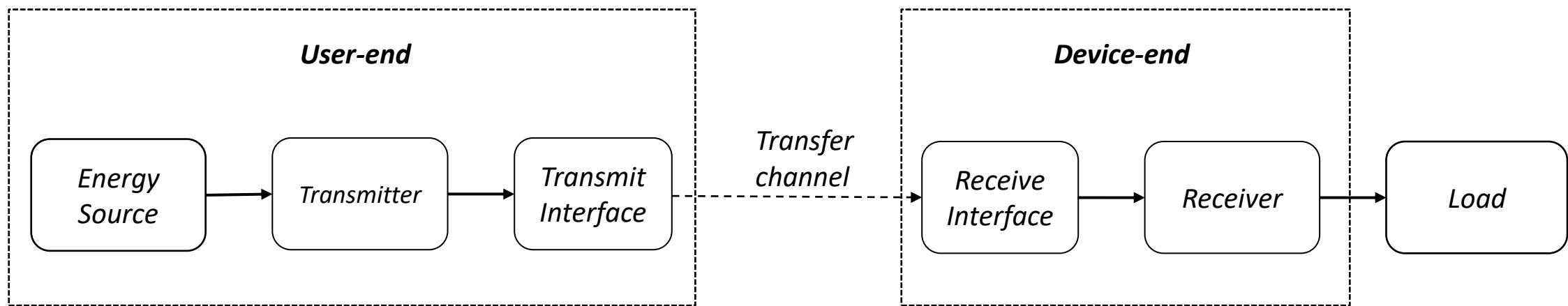
# Interaction-based Power Transfer (IPT)



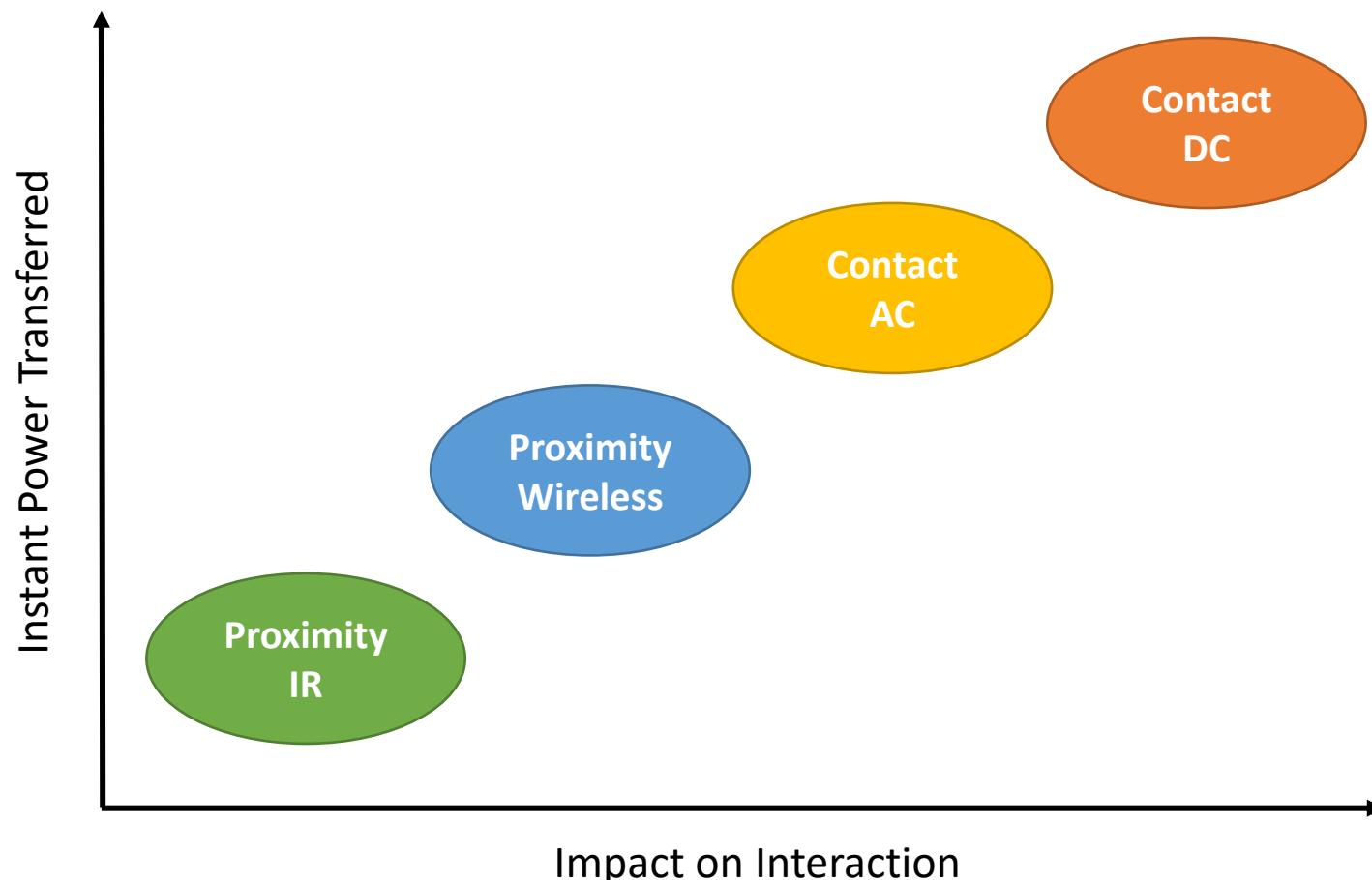
Transfer power from **on-body energy sources** to **off-body power-as-needed devices** only during interaction

**Interaction → Proactive Object Tracking + Adaptive Contact**

# System Architecture

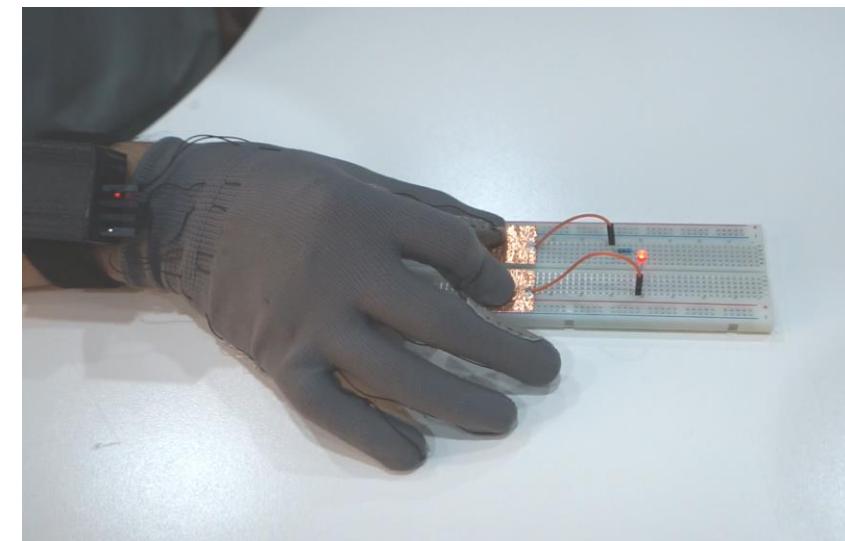
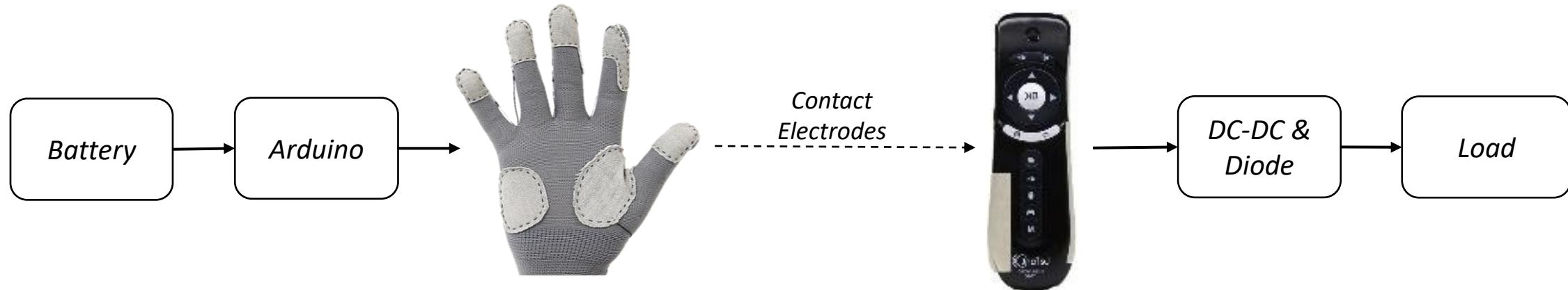


# Interaction Impact vs Power Transfer

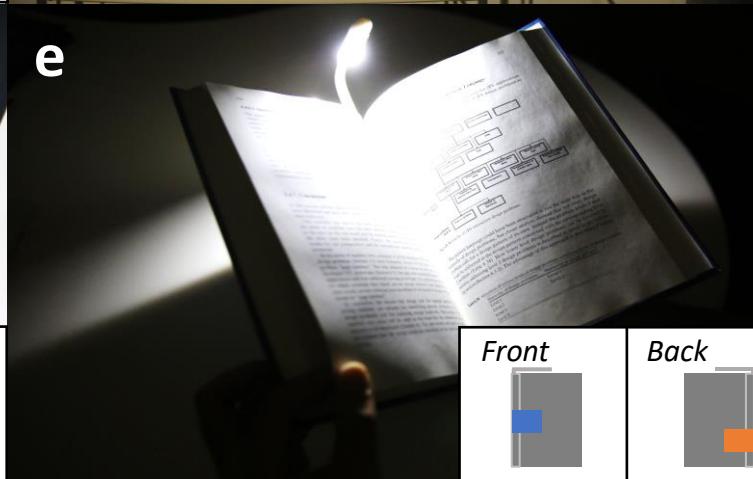
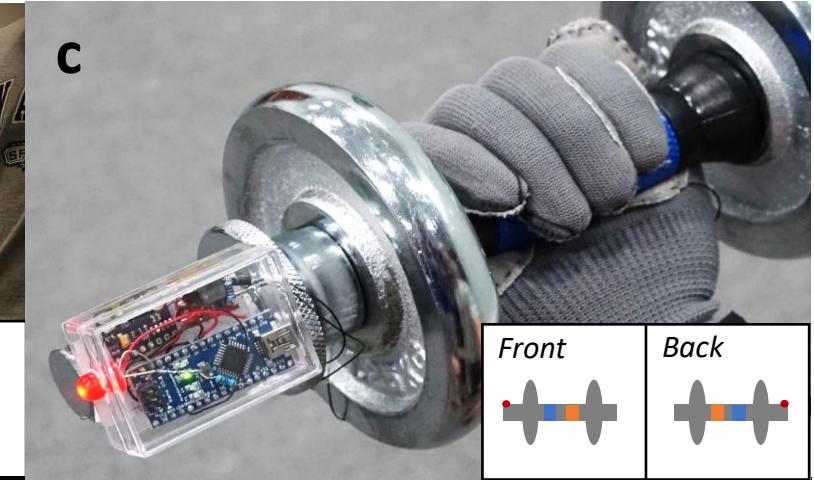
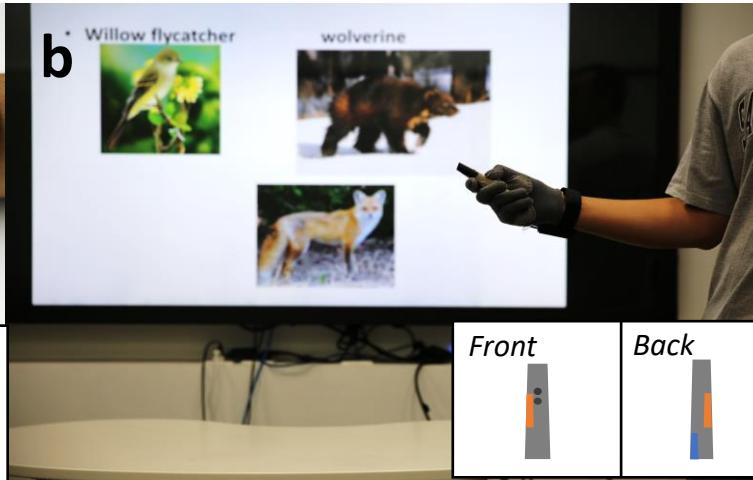
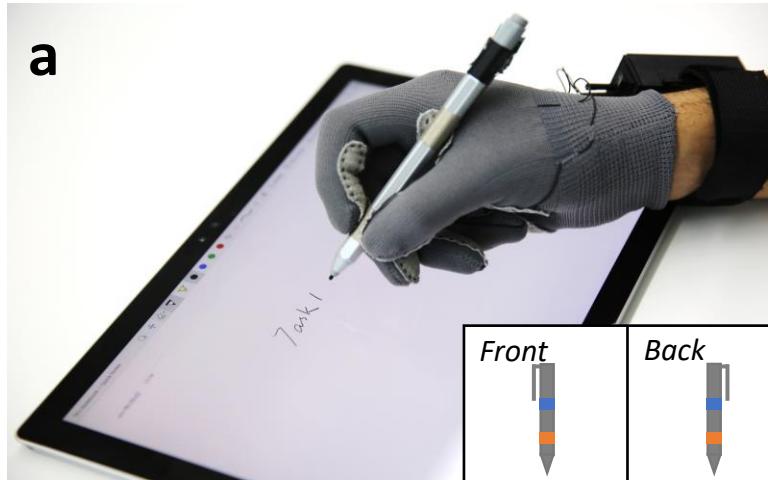


A tradeoff between *Impact on interaction* and *Power transferred*

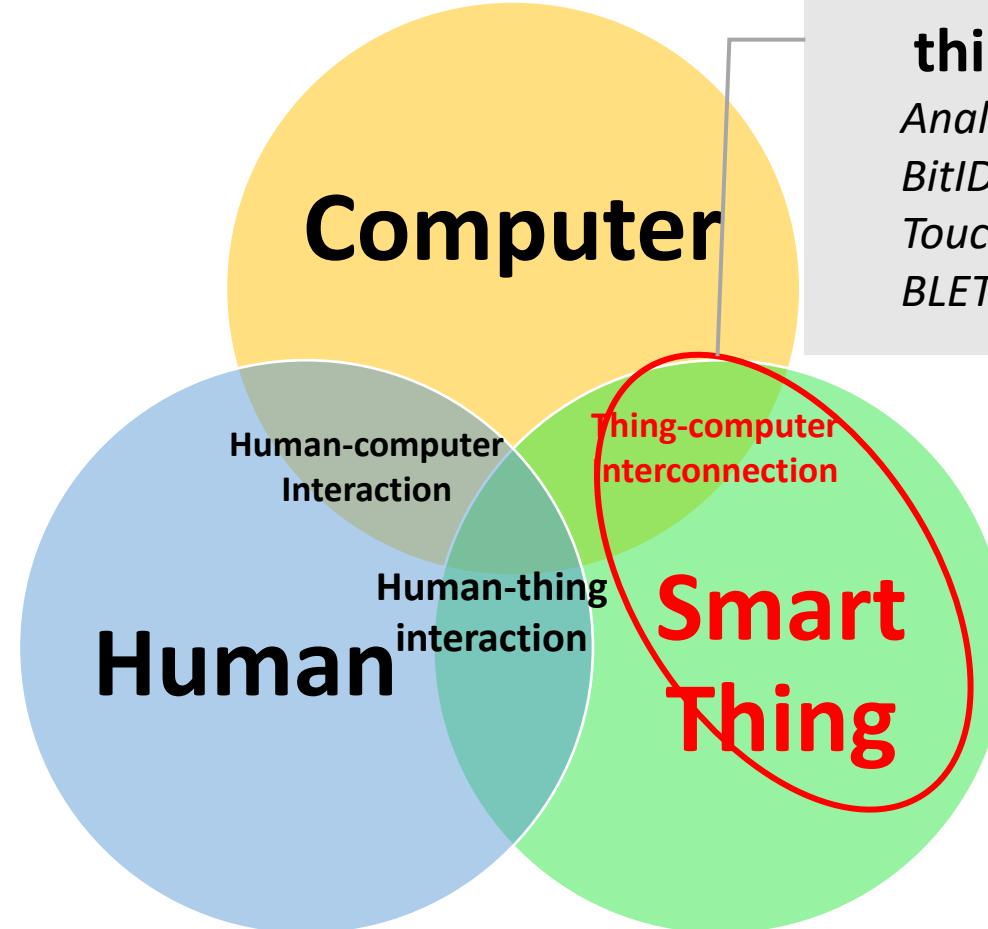
# Contact-based DC IPT Prototype: TouchPower



# Implemented Applications



# Research Summary



**Self-sustainable smart things through thing-computer interconnection**

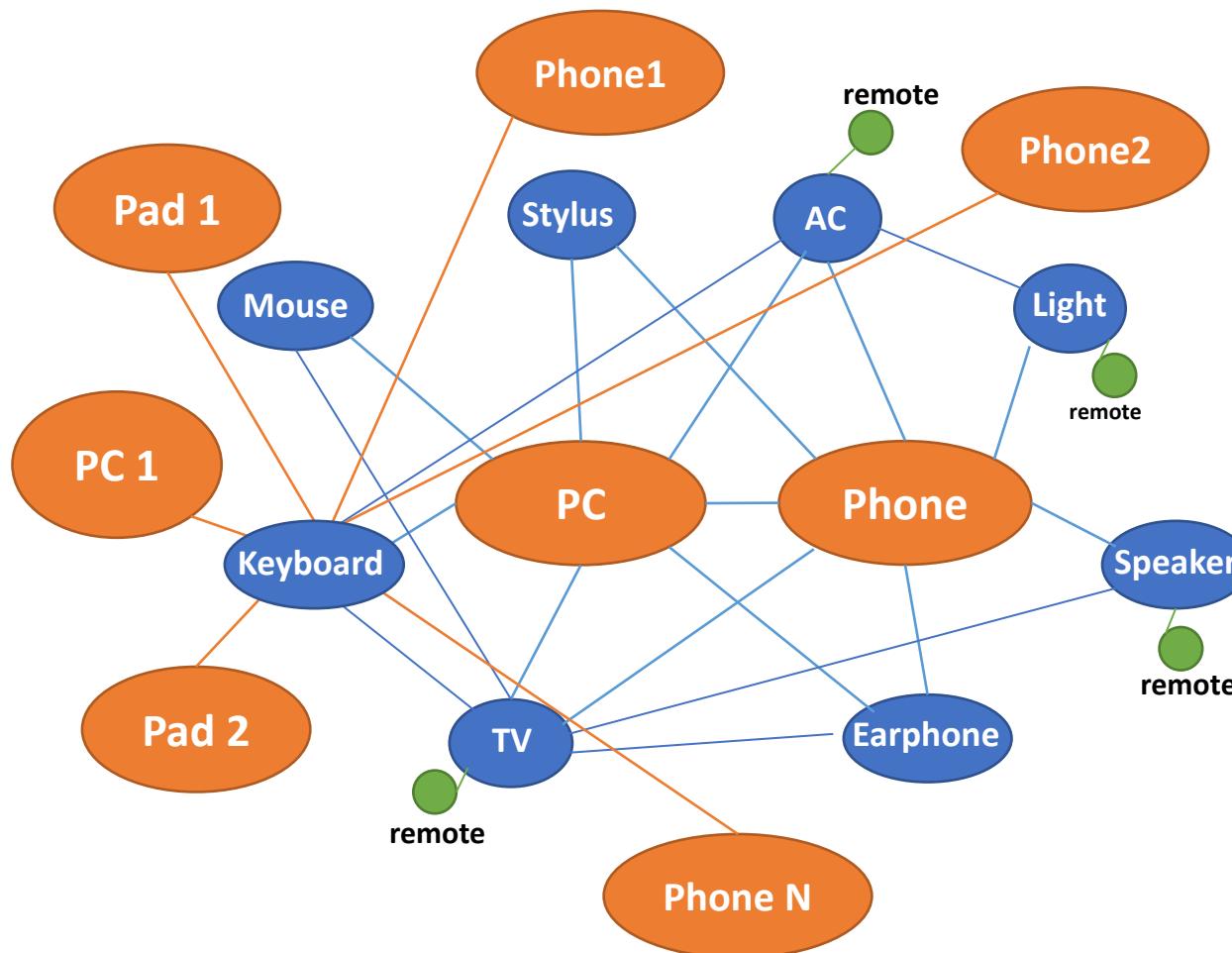
*Analog Backscatter Survey (submitted to PvC)  
BitID (SmartCom'17, Best paper Runner-up)  
TouchPower (IMWUT 17, Discussion Paper)  
BLETouch (in progress)*

# Interaction Techniques for Resource-constrained Things

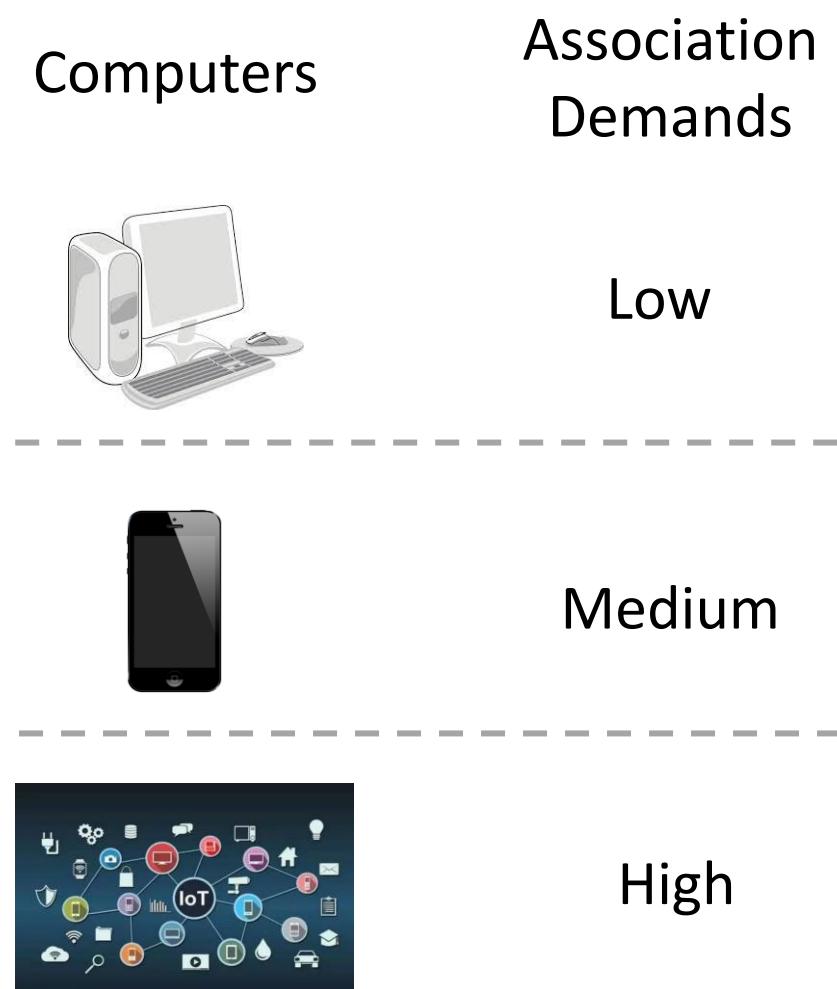


- 1. Tap-to-Pair: Synchronous association initiation from things  
*(IMWUT 2018)***
- 2. Synchronous pattern design by user behavior modeling  
*(IMWUT 2019)***

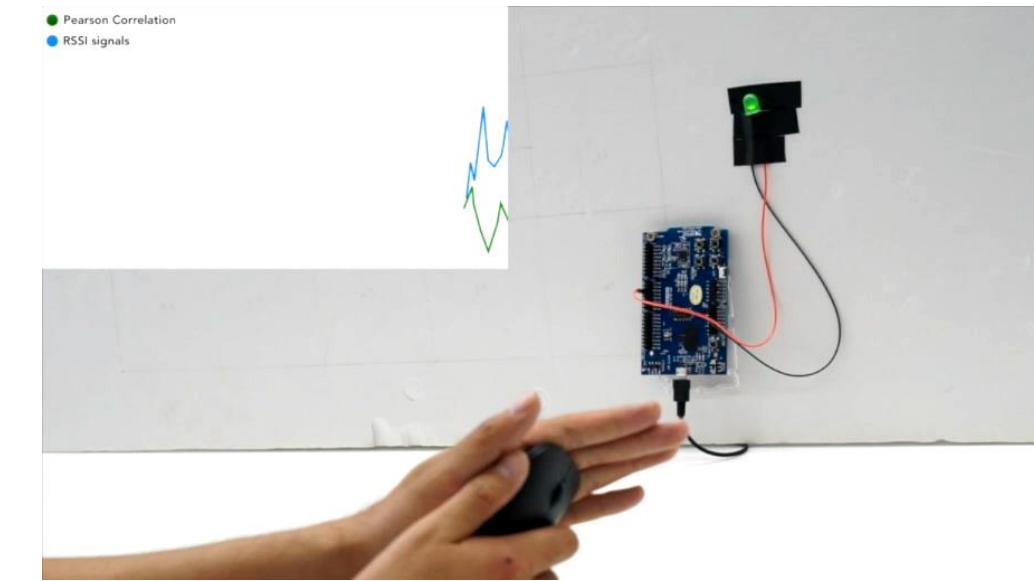
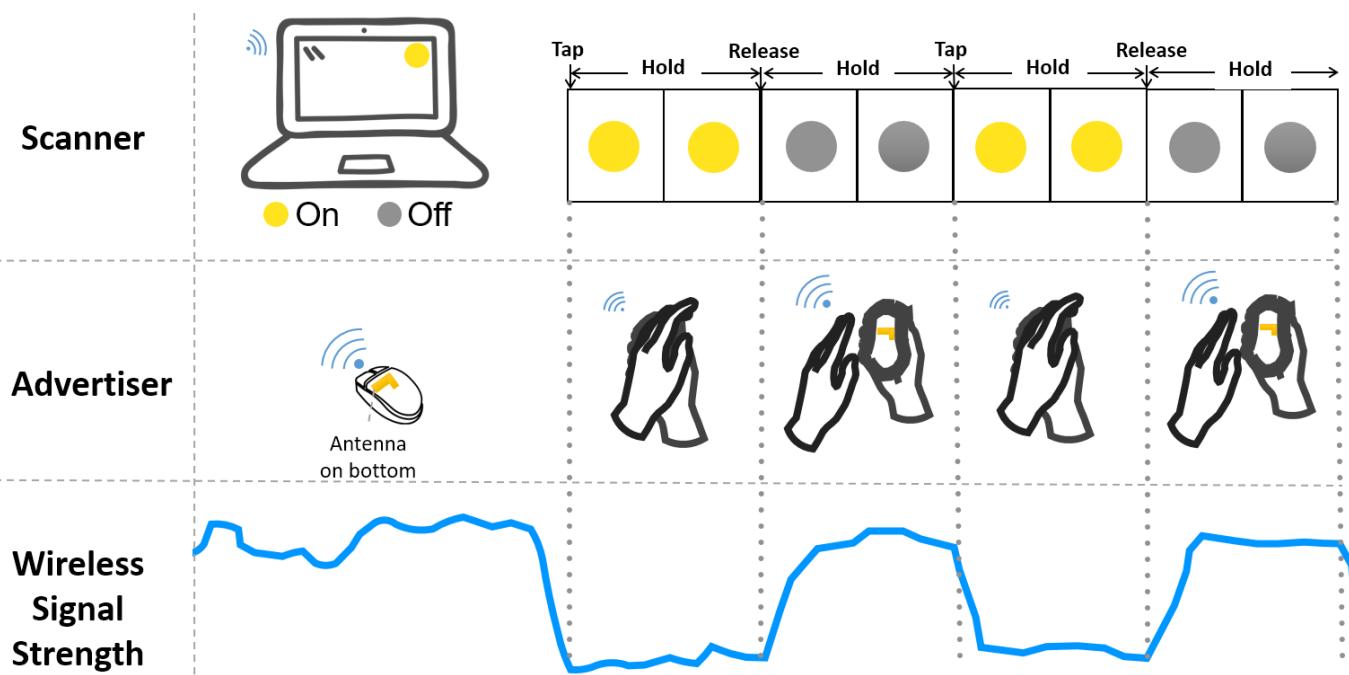
# Device Association Demands



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

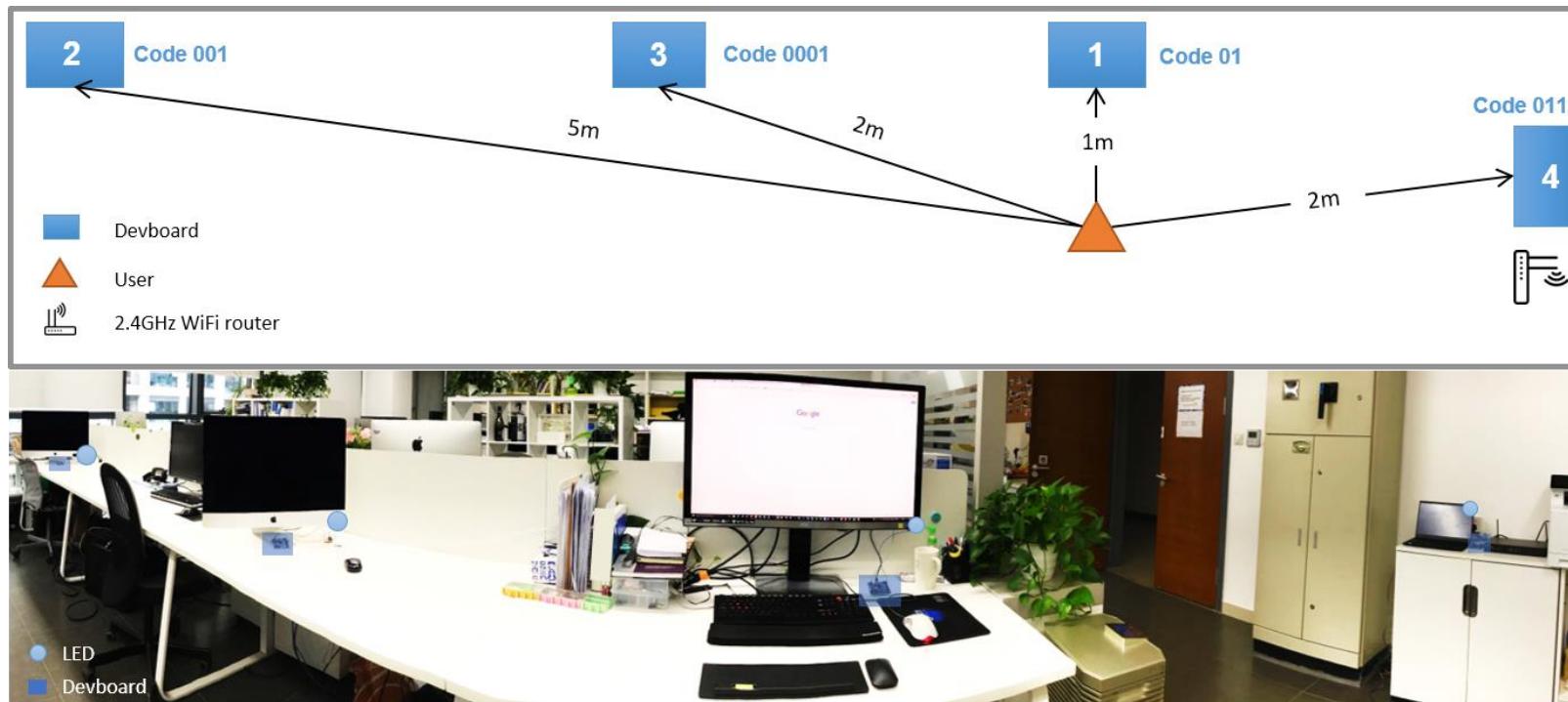


# Tap-to-Pair: Wireless Device Association from Things



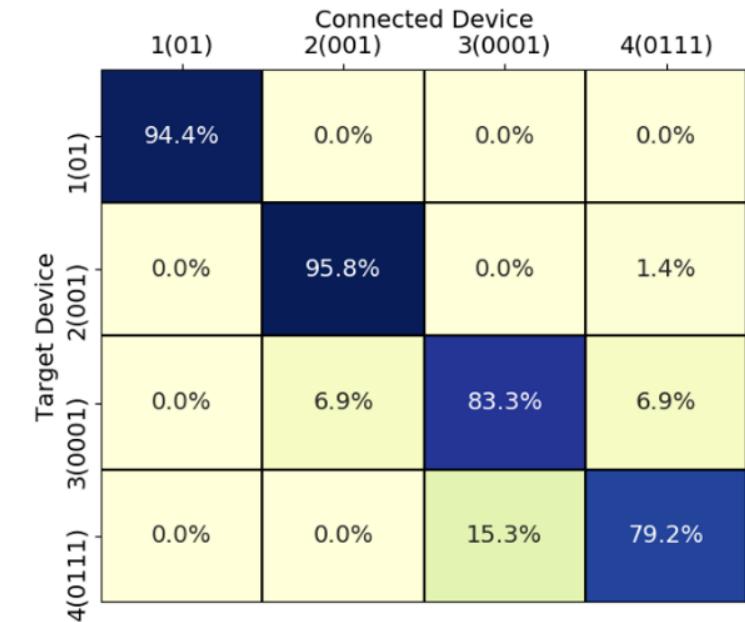
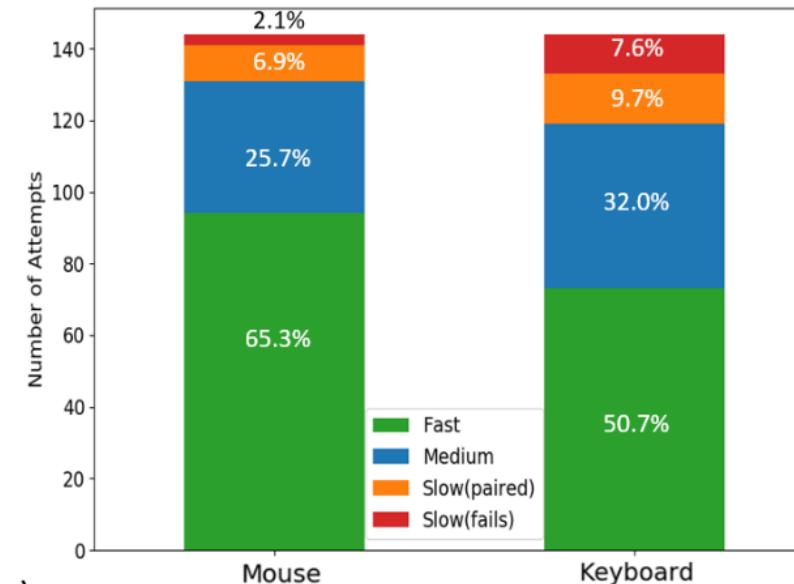
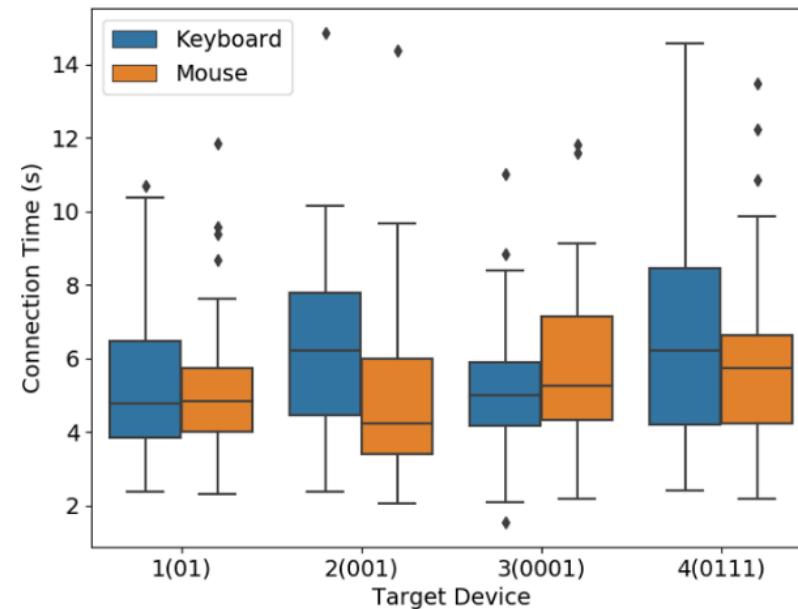
- **"Hand effect":** signal strength reduction due to hands near an antenna
- **Synchronized taps:** correlated wireless signal strength with a blinking pattern

# Evaluation



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

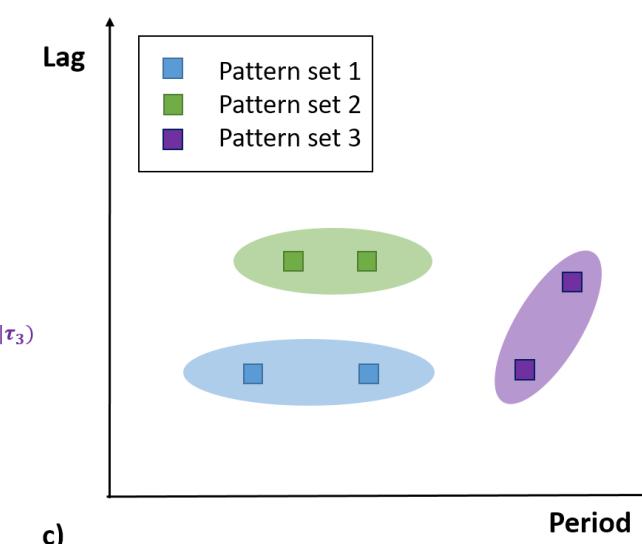
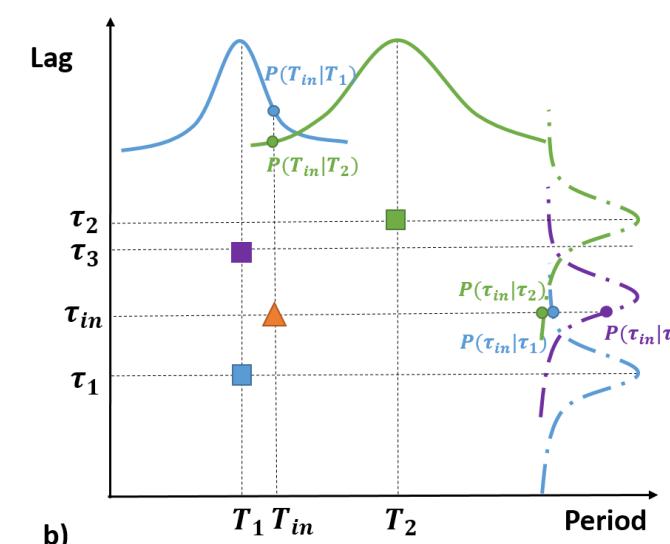
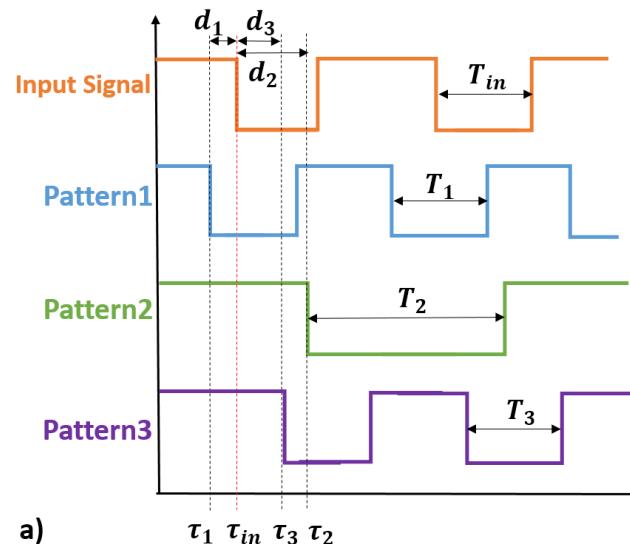
# Results Analysis



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

# Blinking Pattern Design

- Goal:
  - Design pattern set quantitatively
  - Reduce the impact of imprecise inputs
- Fixed Duty Cycle(50%) without coding
- Design space: Period ( $T$ ), Initial Lag ( $\tau$ )



# Optimization Goal

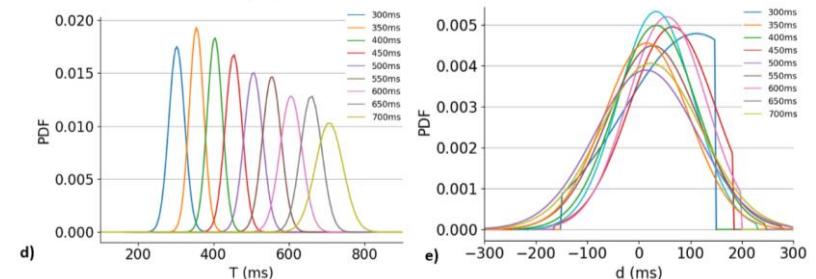
$i, j$ : two blinking patterns,

The probability the input  $i$  is recognized as pattern  $j$

$$\begin{aligned}
 P(i|input = j) &= P(T_i, \tau_i | T_{input}, \tau_{input}) \\
 &= P(T_i | T_{input}) \times P(\tau_i | \tau_{input}) \\
 &= \frac{P(T_{input} | T_i) P(T_i)}{P(T_{input})} \times \frac{P(\tau_{input} | \tau_i) P(\tau_i)}{P(\tau_{input})} \\
 &= \frac{P(T_{input} | T_i) P(T_i)}{\sum_{k=1}^n P(T_{input} | T_k) P(T_k)} \times \frac{P(\tau_{input} | \tau_i) P(\tau_i)}{\sum_{k=1}^n P(\tau_{input} | \tau_k) P(\tau_k)}
 \end{aligned}$$

$$\bar{\eta} = \frac{1}{n} \sum_{i=1}^n P(i|input = i)$$

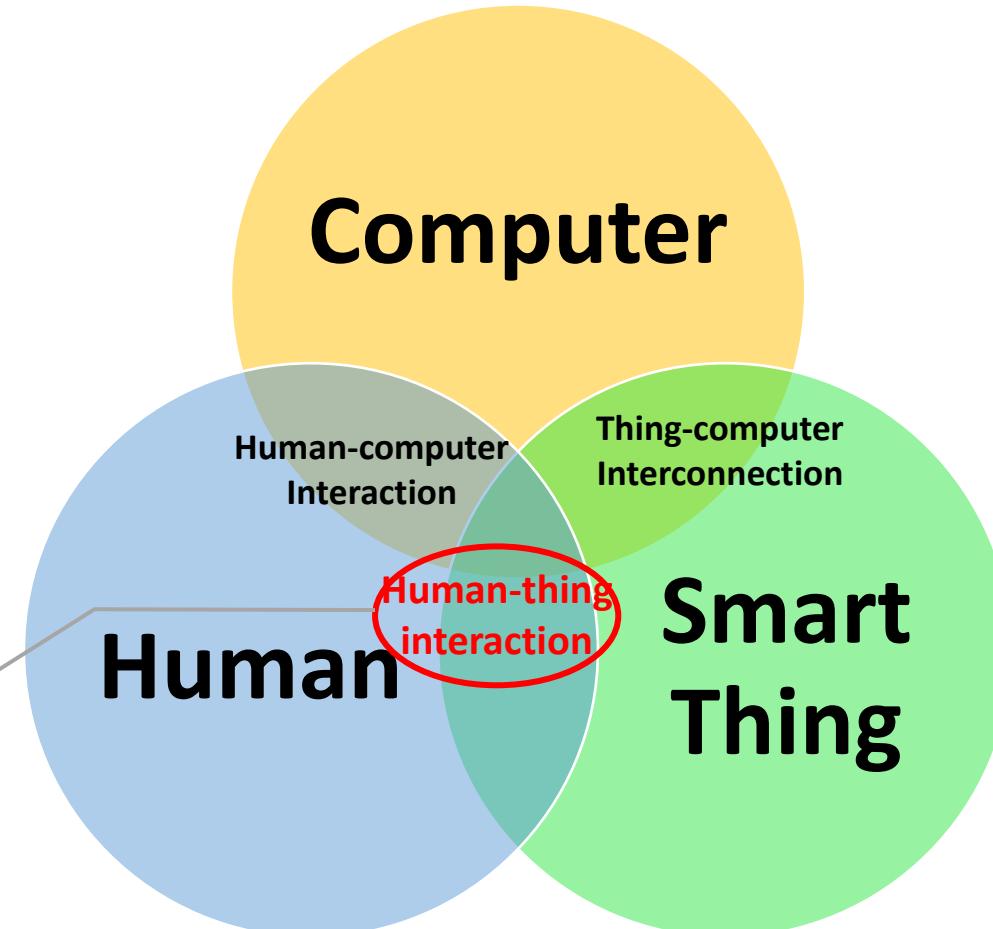
Find the pattern set that maximize  $\bar{\eta}$



User Behavior Model

n	Pattern set $(T, \tau)$	win <sub>baye</sub>	TH <sub>baye</sub>	win <sub>R</sub>	TH <sub>R</sub>
2	(300,0),(550,0)	2s	0.1	2s	0.3
3	(300,0),(450,0),(650,0)	2s	0.6	2s	0.4
4	(300,0),(400,0),(550,0),(700,0)	2s	0.6	2s	0.6
5	(300,0),(400,0),(500,0),(600,0),(700,0)	3s	0.3	2s	0.7
6	Pset5,(350,0)	2s	0.7	5s	0.2
7	Pset6,(450,0)	4s	0.4	5s	0.2
8	Pset7,(550,0)	4s	0.5	5s	0.2
9	Pset8,(650,0)	5s	0.4	5s	0.2
10	Pset9,(700,467)	5s	0.4	5s	0.3
11	Pset10,(650,433)	5s	0.4	6s	0.2
12	Pset11,(600,400)	6s	0.3	6s	0.3
13	Pset12,(700,233)	6s	0.3	6s	0.3
14	Pset13,(550,367)	7s	0.1	7s	0.2
15	Pset14,(650,216)	6s	0.3	7s	0.2
16	Pset14,(450,225),(500,333)	7s	0.1	7s	0.3
17	Pset15,(500,333),(600,200)	7s	0.2	7s	0.3
18	Pset17,(450,225)	7s	0.2	7s	0.3
19	Pset18,(550,183)	7s	0.2	7s	0.3
20	Pset19,(400,200)	7s	0.2	7s	0.3
21	Pset20,(500,167)	7s	0.2	7s	0.3
22	Pset21,(350,175)	7s	0.2	7s	0.3

# Research Summary

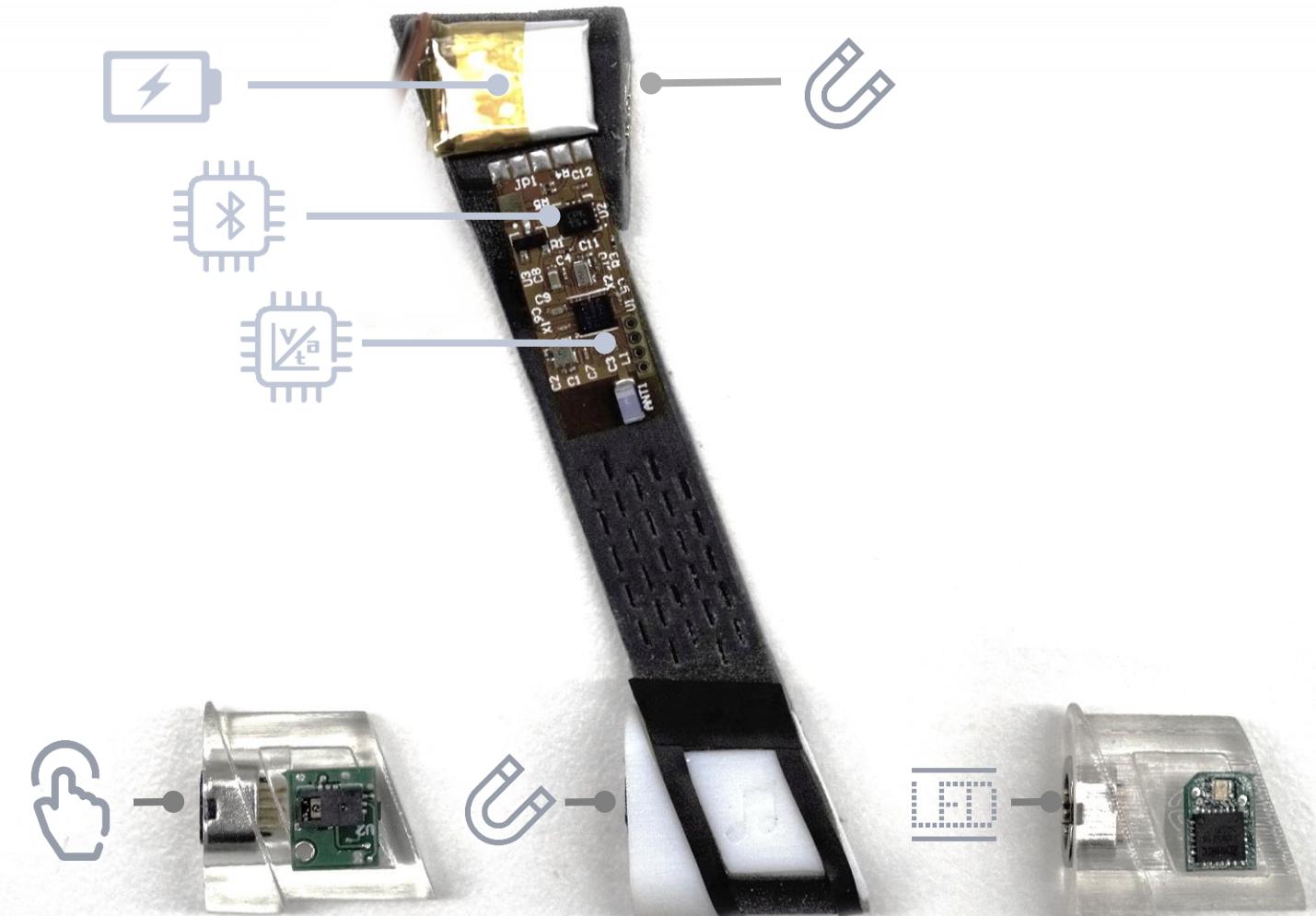
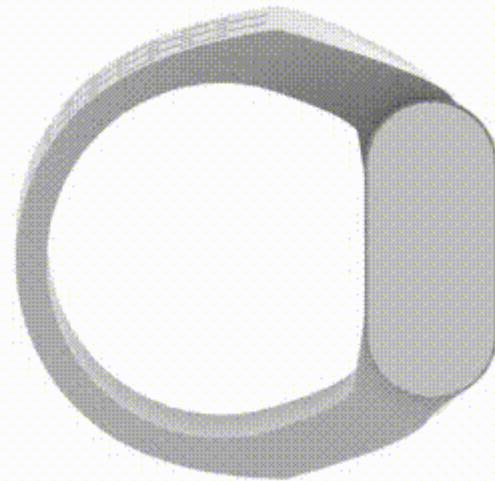


# Wearable computers for human-centered interaction



1. **ModularRing: Modular design for a smart ring**  
*(GIX Innovation Competition 2018 Finalist)*
2. **ThermalRing: Gesture and tag inputs by thermal imaging**  
*(CHI'20)*
3. **ScreenJump: AR-facilitated fine-grained resource manipulation across screens**  
*(CHI21 Workshop on UX4MDE)*

# ModularRing



# Wearing Mechanism



1

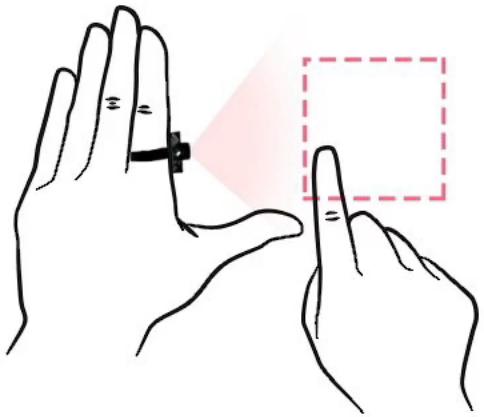


2



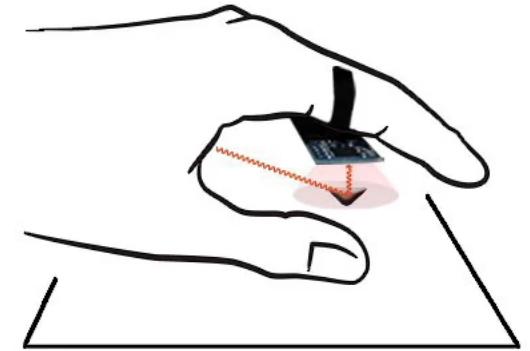
3

43



# ThermalRing

Gesture and Tag Inputs Enabled  
by a Thermal Imaging Smart Ring



Tengxiang Zhang (ztxseuthu@gmail.com), Xin Zeng, Yinshuai Zhang, Ke Sun, Yuntao Wang, Yiqiang Chen



**Lenovo**

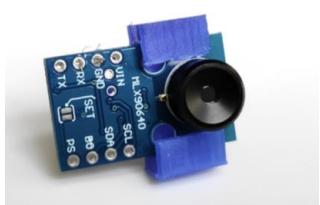
**HUAWEI**



**清华大学**  
Tsinghua University

# ThermalRing

## Hardware Implementation

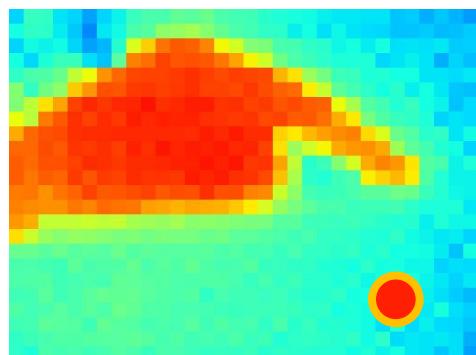


**MLX90640** FoV:  $110^\circ \times 75^\circ$  Res:  $32 \times 24$  Size:  $\Phi 8\text{mm}, H6\text{mm};$   
Cost: ~40 USD Power: 20mA@3V

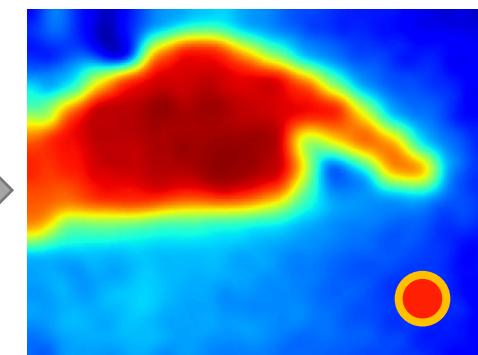
Communicate with PC via cabled serial port

\*Bluetooth version firmware open sourced at <https://github.com/saintnever/thermalring>

## Thermal Image Preprocessing Flow



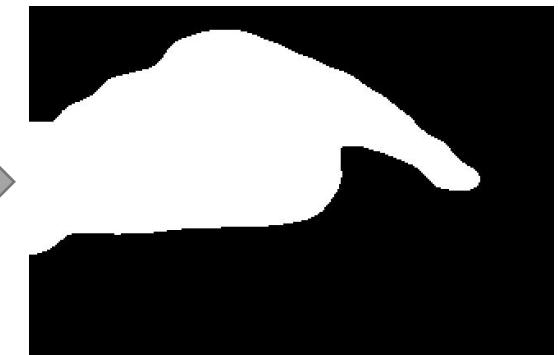
Raw Temperature Data



Scale and Filter



Otsu Thresholding

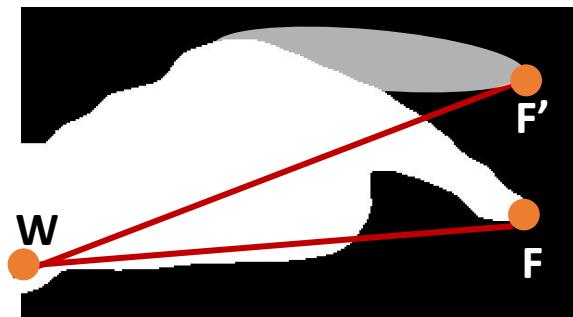


Contour Filter

# Drawing Gesture Sensing

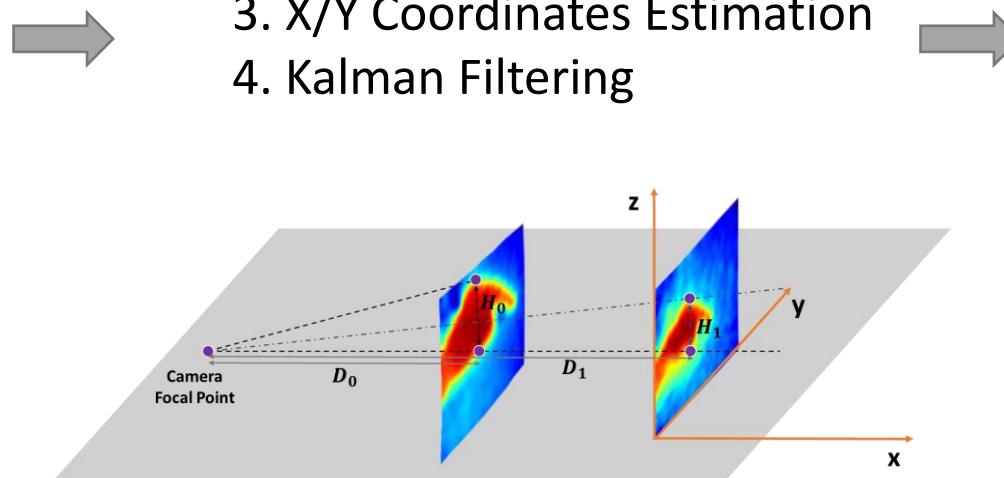
- 6 step sensing flow

1. Fingertip Extraction
2. Finger Lift Detection



Slope calculation

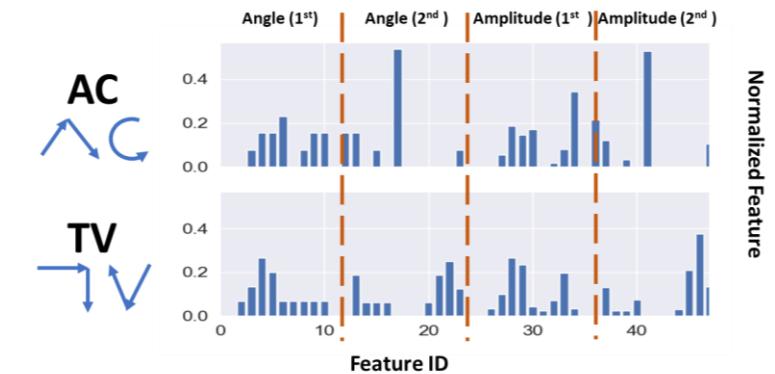
3. X/Y Coordinates Estimation
4. Kalman Filtering



Triangular similarity

$$FL = \frac{H_{real} \times D}{H}$$

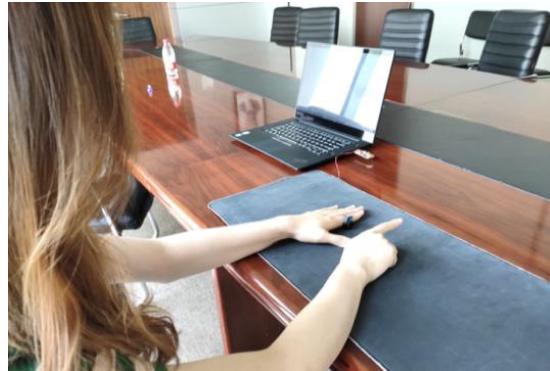
5. Bag of Words Feature Extraction
6. SVM Prediction



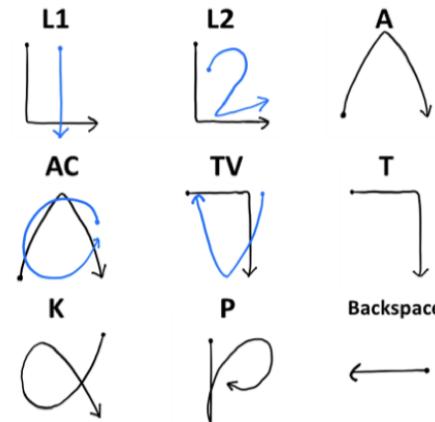
$$\theta = \arctan\left(\frac{\Delta y}{\Delta x}\right)$$

$$r = \sqrt{x^2 + y^2}$$

# User Study



Experiment Setup



Graffiti Gesture Set

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

Within-user Confusion Matrix

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

Between-user Confusion Matrix

**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

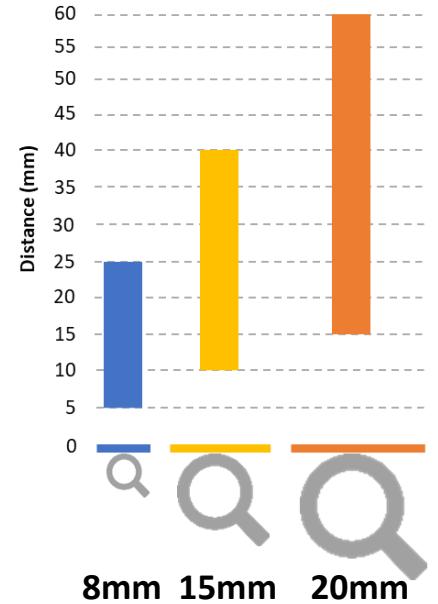
Convenience MEDIAN=4.5, MODE=4

Ring Rotation MEDIAN=5, MODE=5

Input Speed MEDIAN=3, MODE=3

Camera with a higher frame rate for faster drawing

# 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

# User Study



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
	Up	Down	Play	Stop	Search	Help

Within-user Confusion Matrix

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
	Up	Down	Play	Stop	Search	Help

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

**Feature:** Hu's Moments

**Result:** Average **Within-user 95%** (SD=0.04)

Average **Between-user 90.1%** (SD=0.08)

Average scan complete time **3.5 seconds**

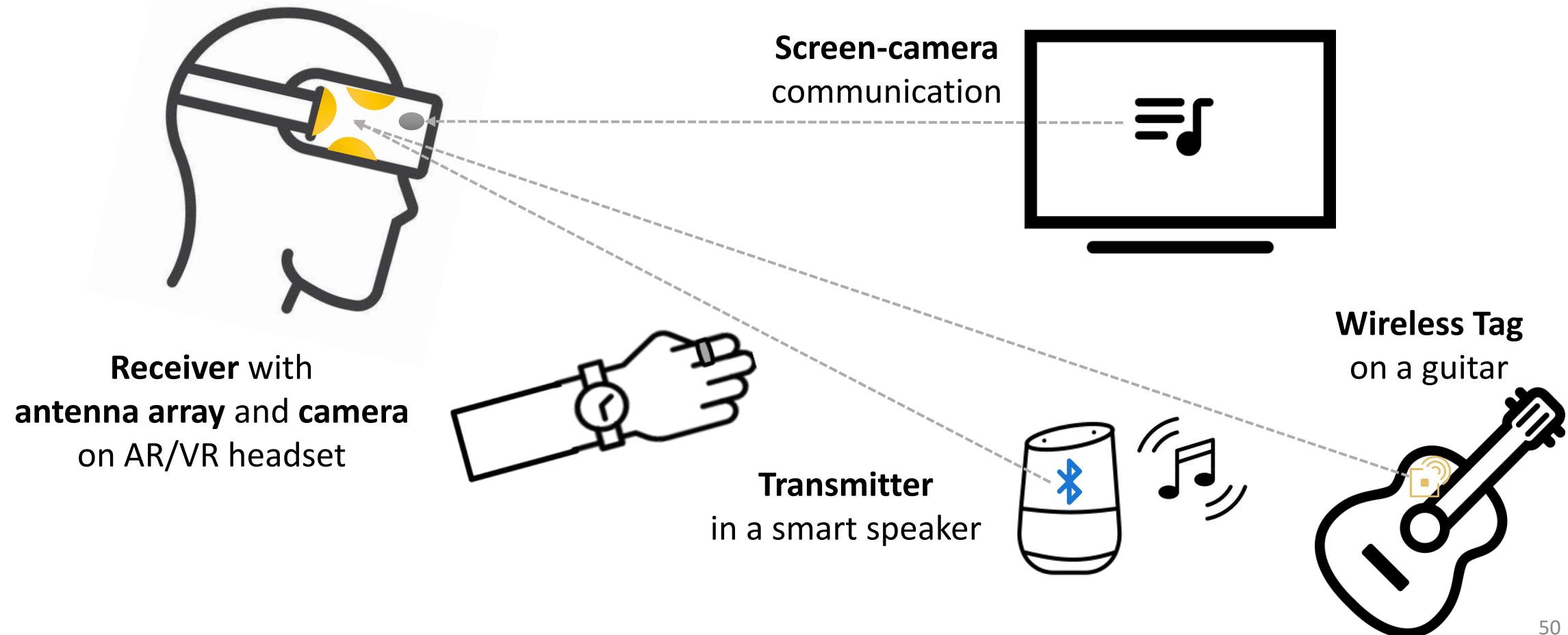
**Subjective:** 5-point Likert Scale (the higher the better)

Physical efforts    MEDIAN=4, MODE=4

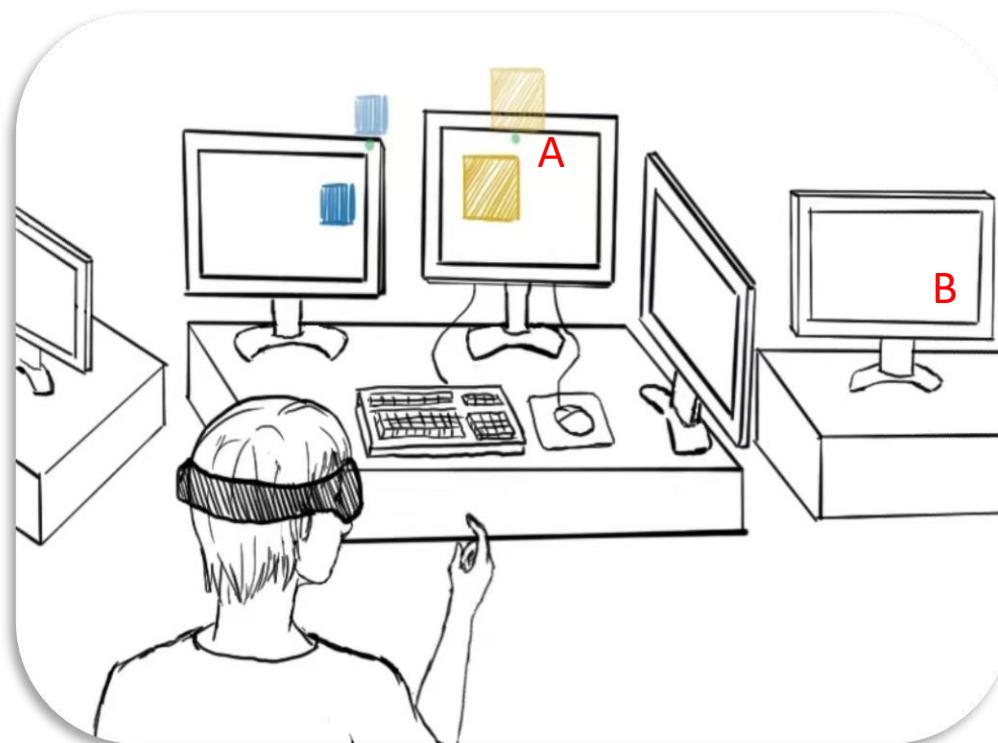
Mental efforts    MEDIAN=4, MODE=4

Scan speed    MEDIAN=4, MODE=4

# AR-facilitated Cross-device Resource Manipulation

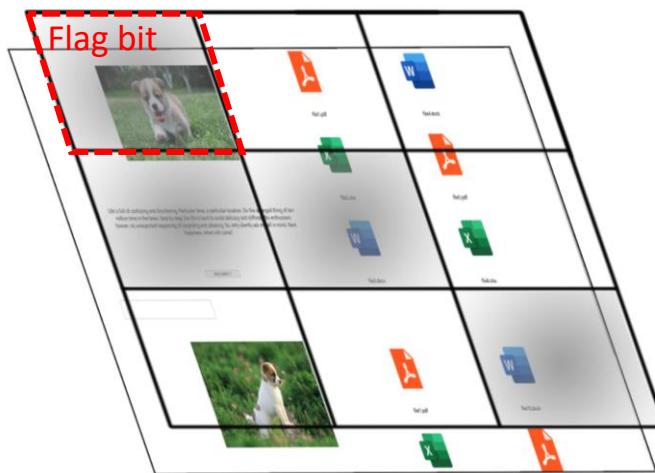


# ScreenJump: AR-facilitated Fine-grained Resource Manipulation Across Displays



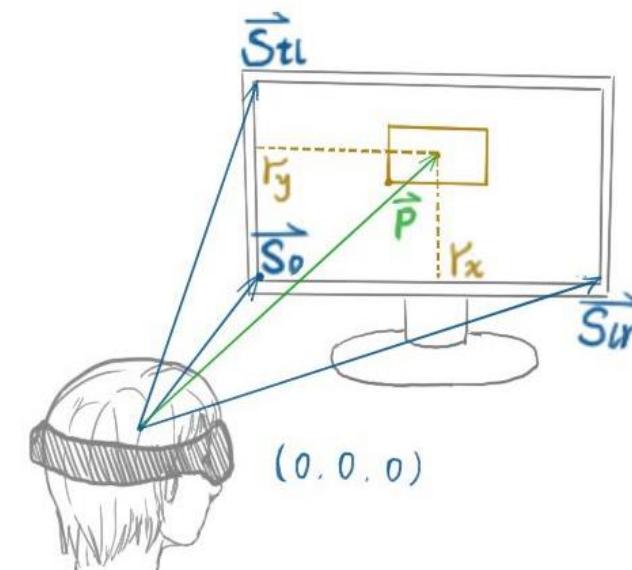
# System Functions

Unobtrusive and spontaneous  
**Screen-camera Communication**



FSK Modulation by  
changing grid transparency

On-screen digital resource  
**Localization in World Coordinates**



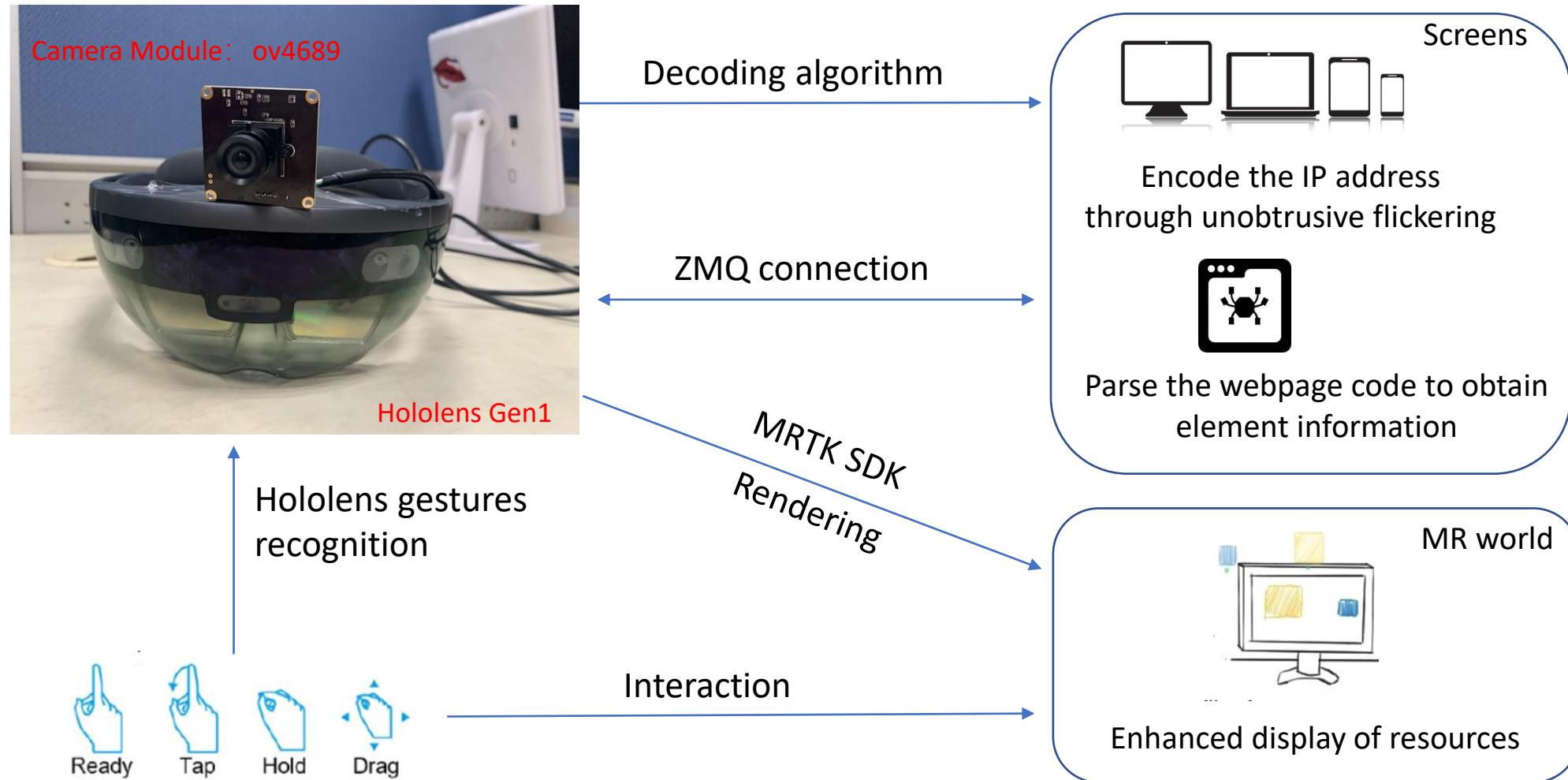
$$\vec{p} = \vec{s_0} + r_x \cdot (\vec{s_{lr}} - \vec{s_0}) + r_y \cdot (\vec{s_{tl}} - \vec{s_0})$$

UI Rendering and  
**Manipulation Gestures**



Gaze selection  
Hand manipulation<sup>52</sup>

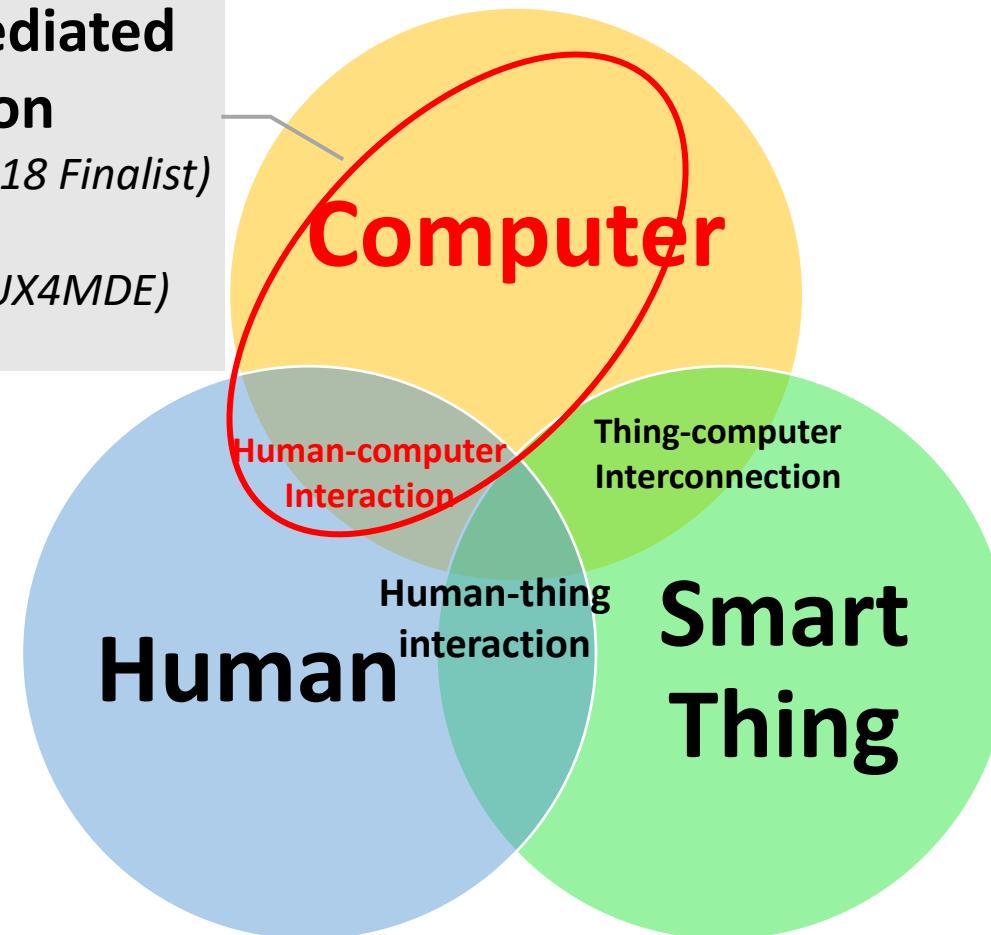
# System Implementation



# Research Summary

## Wearable computer-mediated pervasive interaction

*ModularRing (GIX Competition'18 Finalist)*  
*ThermalRing (CHI'20)*  
*ScreenJump (CHI21 Workshop UX4MDE)*  
*FlexTouch (IMWUT 19)*



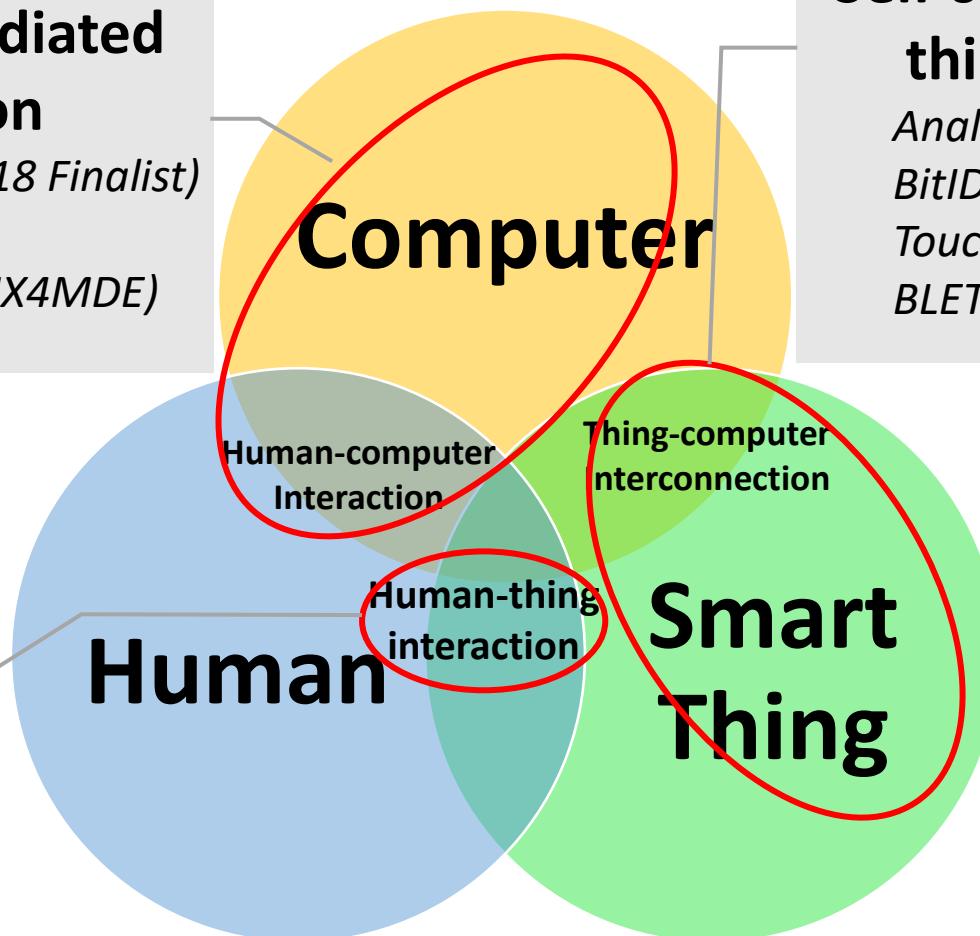
# Research Summary

## Wearable computer-mediated pervasive interaction

*ModularRing (GIX Competition'18 Finalist)  
ThermalRing (CHI'20)  
ScreenJump (CHI21 Workshop UX4MDE)  
FlexTouch (IMWUT 19)*

## Resource-constrained Interaction

*Tap-to-Pair (IMWUT 18)  
SyncSelect (IMWUT 19)*



## Self-sustainable smart things through thing-computer interconnection

*Analog Backscatter Survey (submitted to PvC)  
BitID (SmartCom'17, Best paper Runner-up)  
TouchPower (IMWUT 17, Discussion Paper)  
BLETouch (in progress)*

# Sustainable and Calm Pervasive Interface

