Toward Sustainable Ubiquitous Computing and Interaction

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- Research Focus to Date
  - Self-sustainable smart things
  - Interaction techniques for resource-constrained things
  - Wearable computer mediated pervasive interaction
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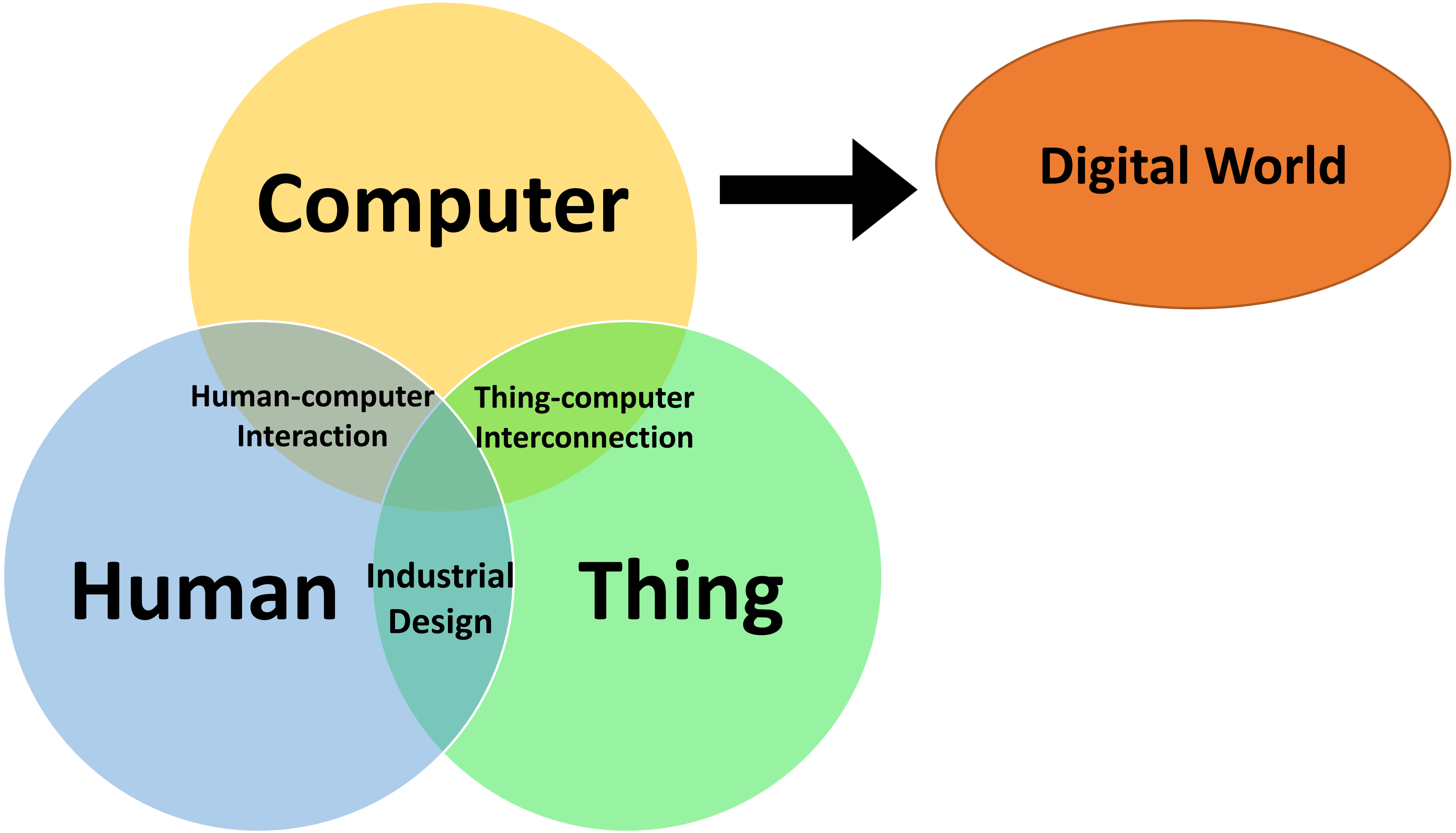
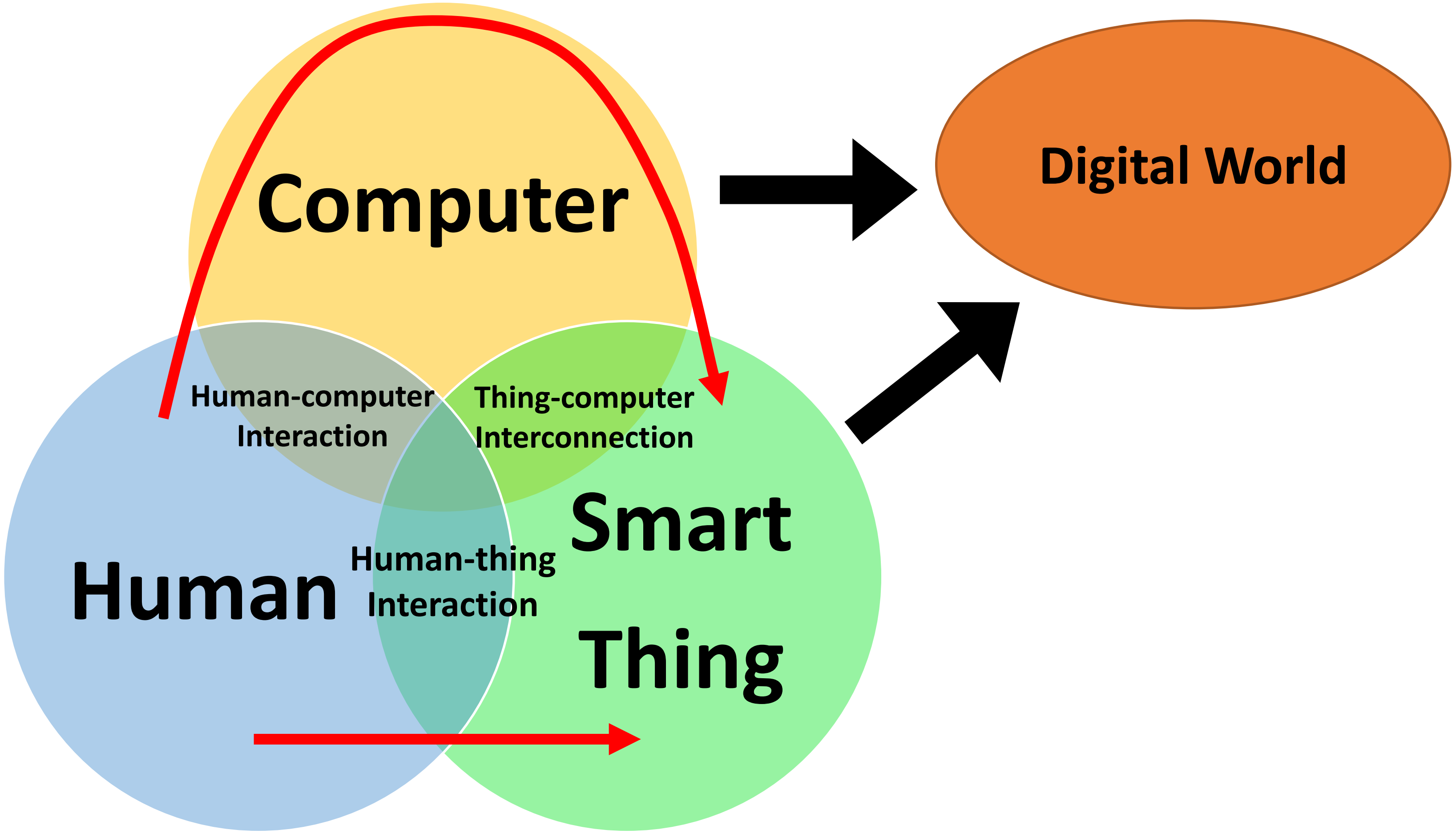
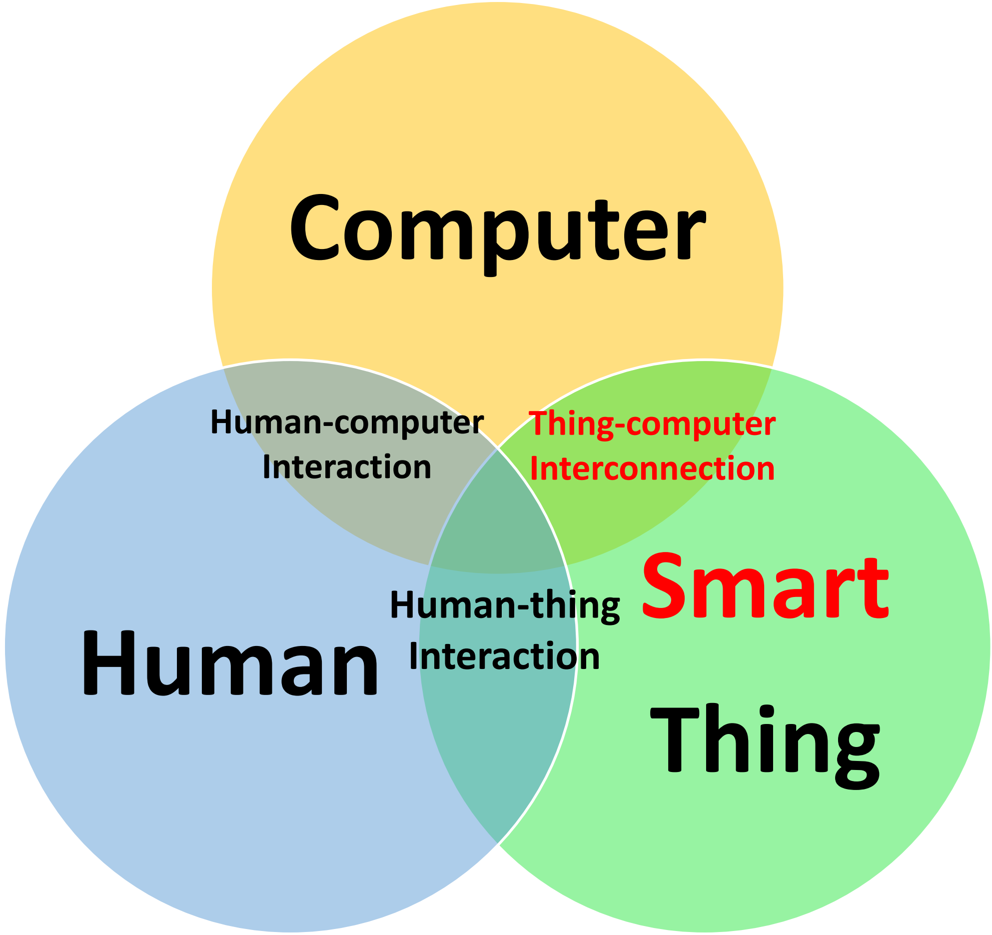
Human-computer-thing Triad



Human-computer-thing Triad

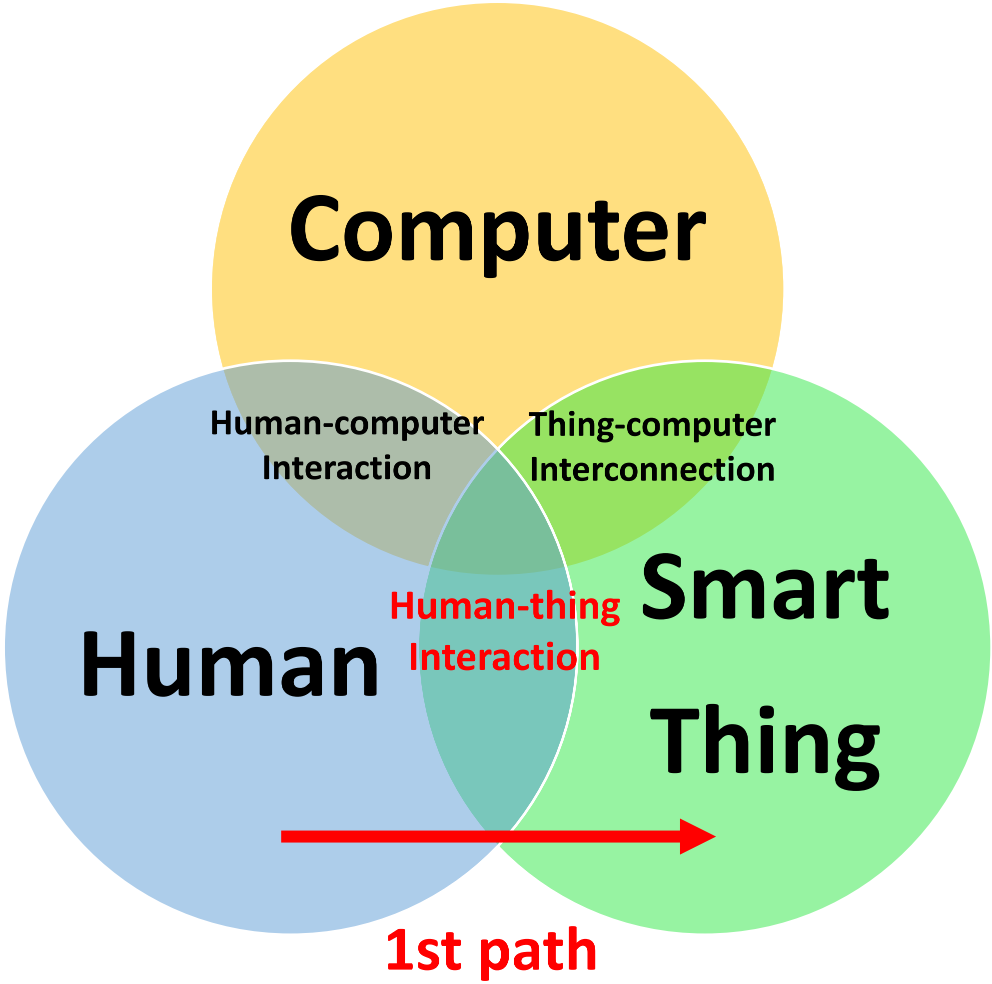


Self-sustainable Smart Things



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

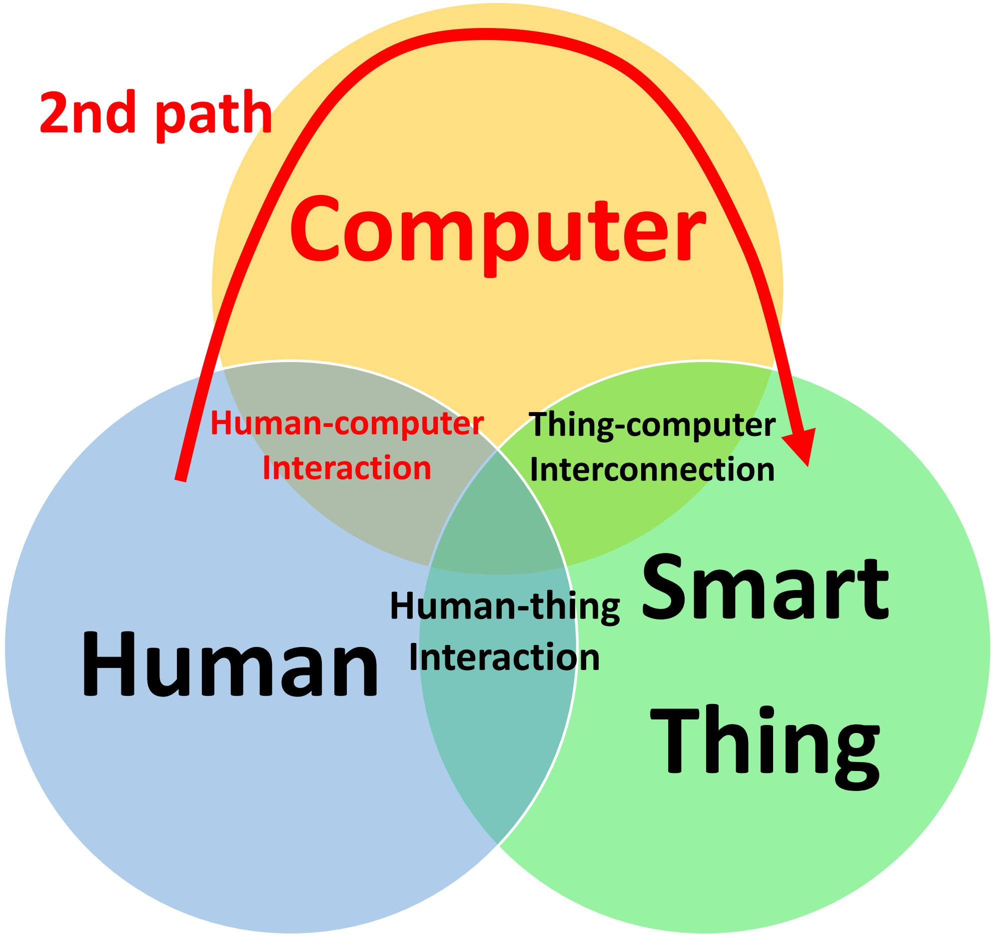
Direct Human-thing Interaction



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

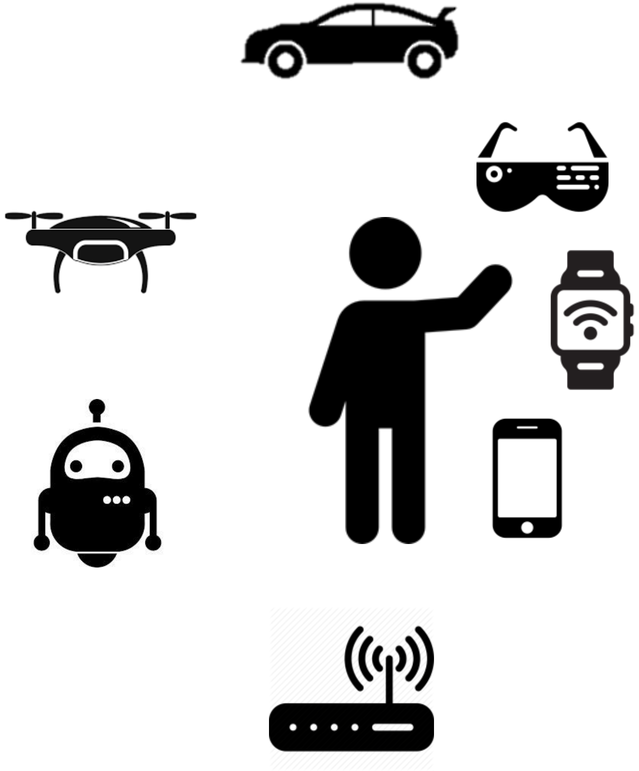
1. **Why self-sustainability is important and how to achieve that**
2. **Brief intro to backscatter sensing**
   (accepted at Self-sustainableCHI20 Workshop
   Full version submitted to IEEE Pervasive Computing)
3. **BitID: RFID-based Binary Sensor**
   (SmartCom'17, Best-paper Runner-up)
4. **BLETouch: 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

Computer
Resource-abundant

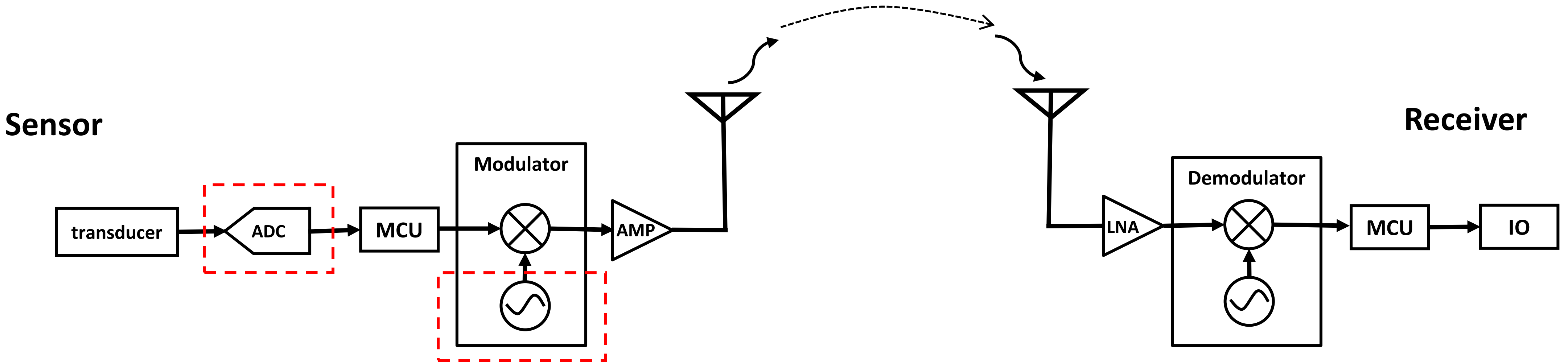


Interconnection Technique

Backscatter Wireless Sensing Technique

Thing
Resource-constrained

Conventional Wireless Sensing System

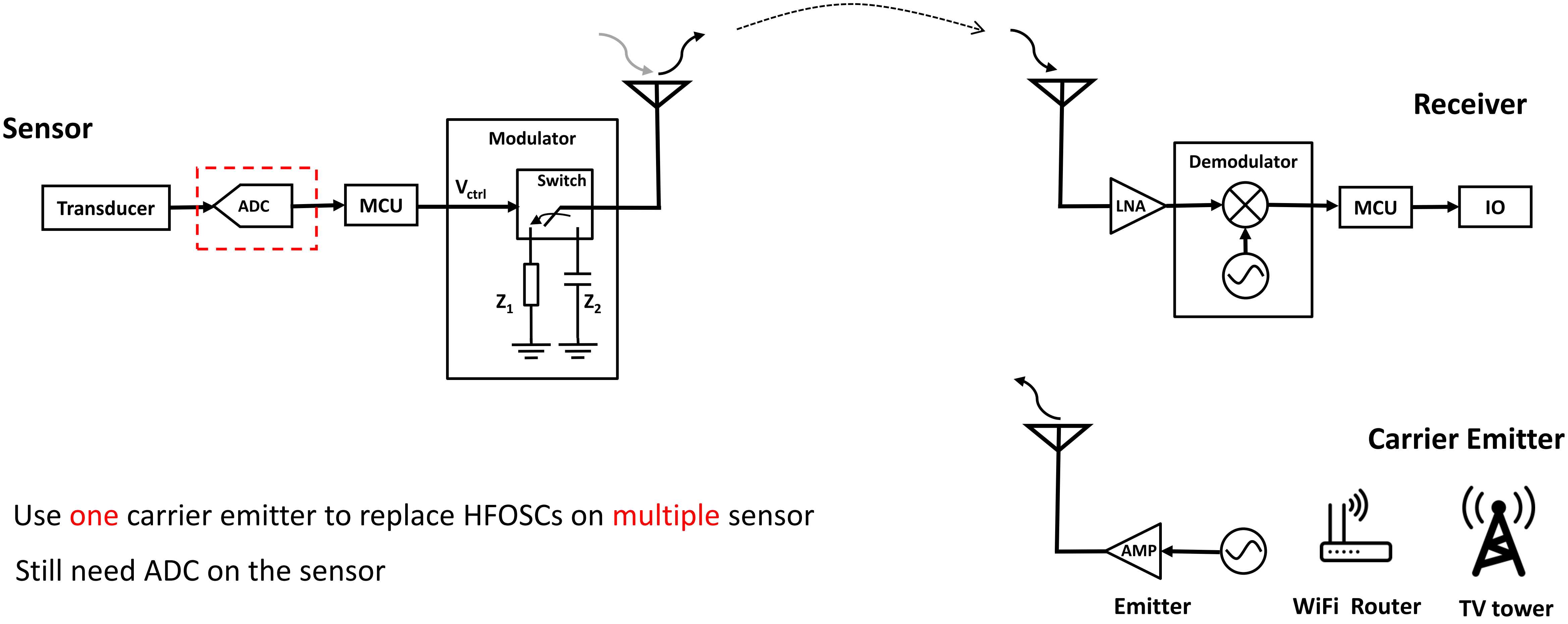


High power consumption parts:

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

Typical Power Consumption	zigbee	Bluetooth	WiFi
	10-15mW	10-15mW	30-150mW

Digital Backscatter Sensing System



Use one carrier emitter to replace HFOSCs on multiple sensor

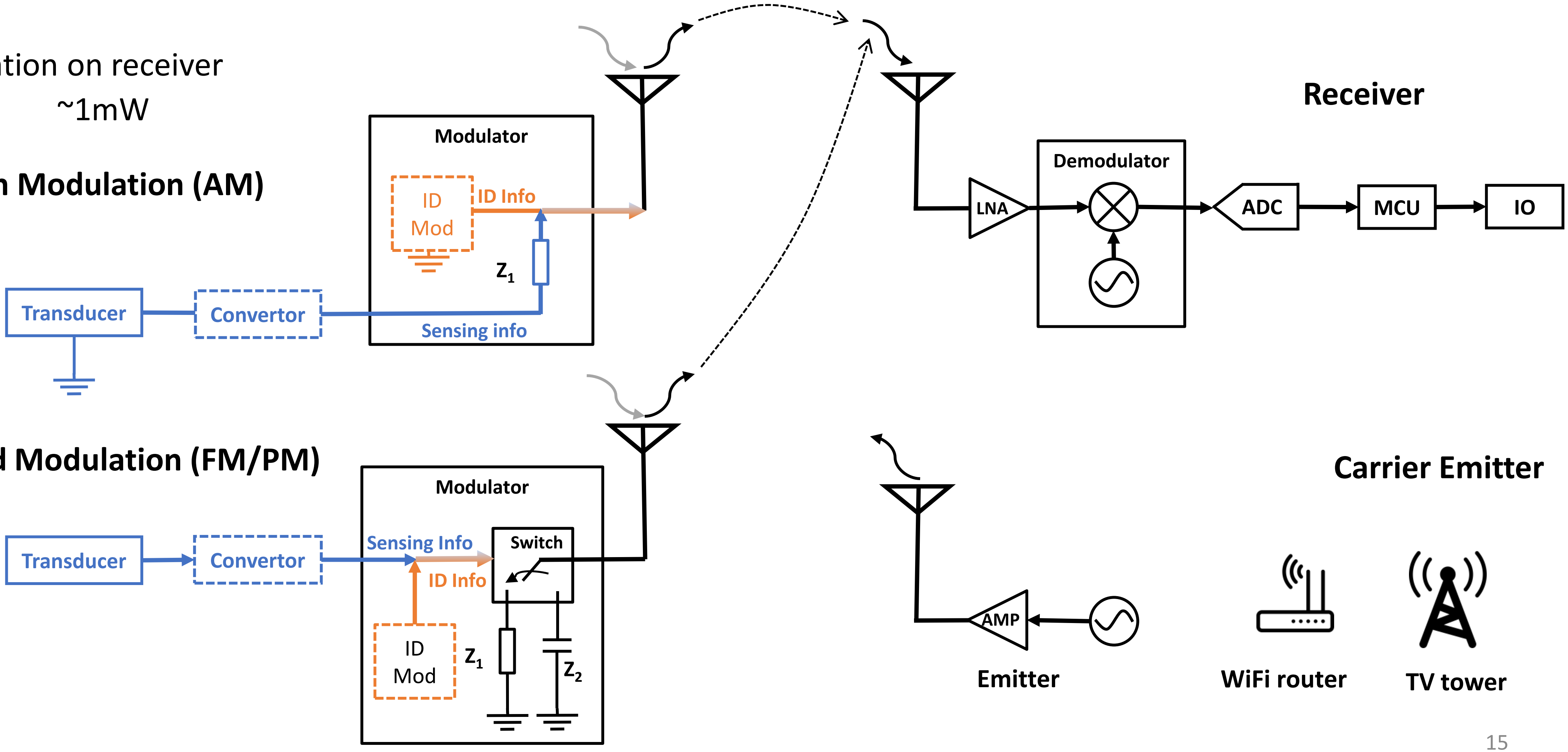
Still need ADC on the sensor

Analog(hybrid) Backscatter Sensing System

Digitalization on receiver
~1mW

1. Direction Modulation (AM)

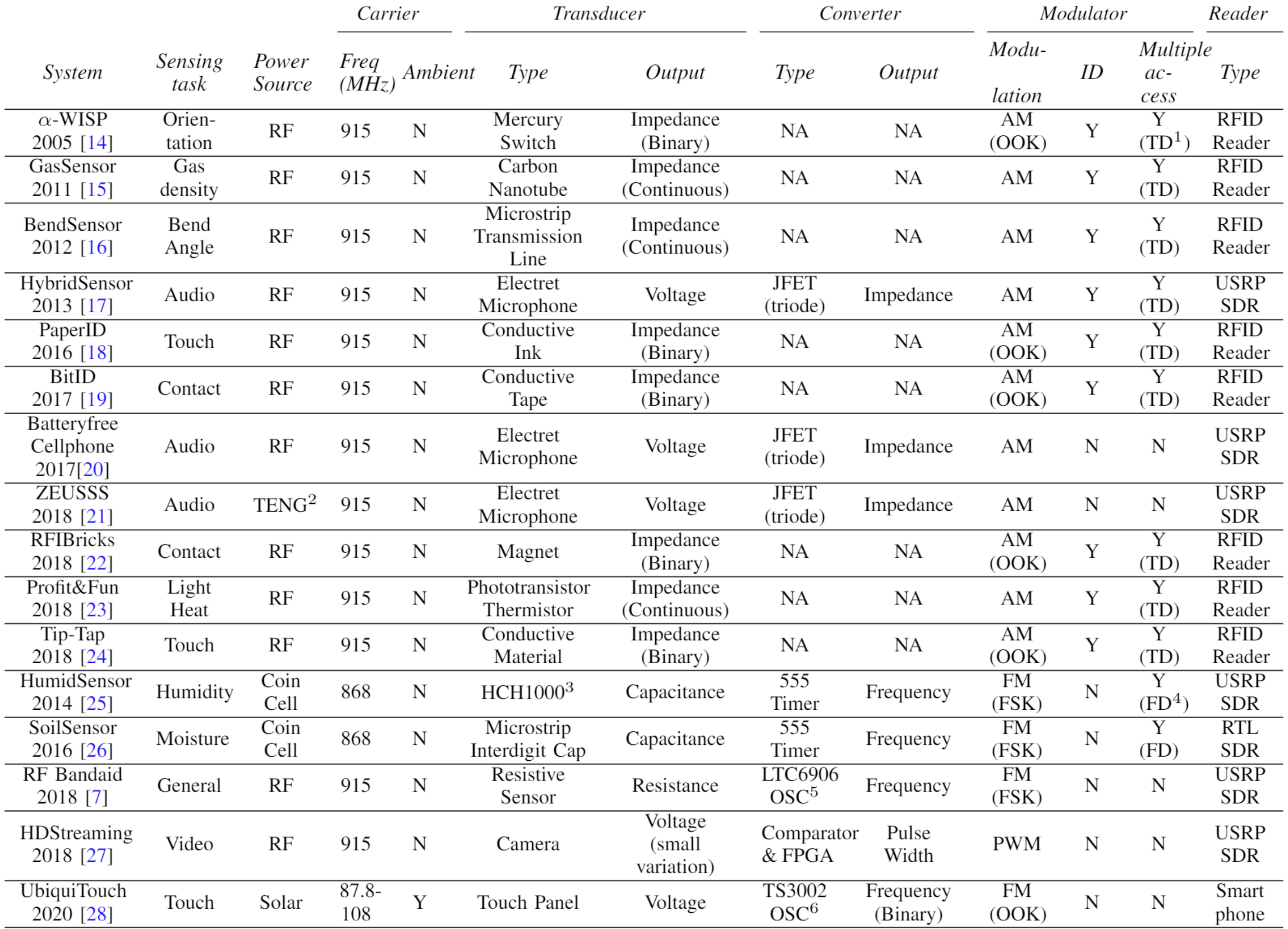
2. Sideband Modulation (FM/PM)



Receiver

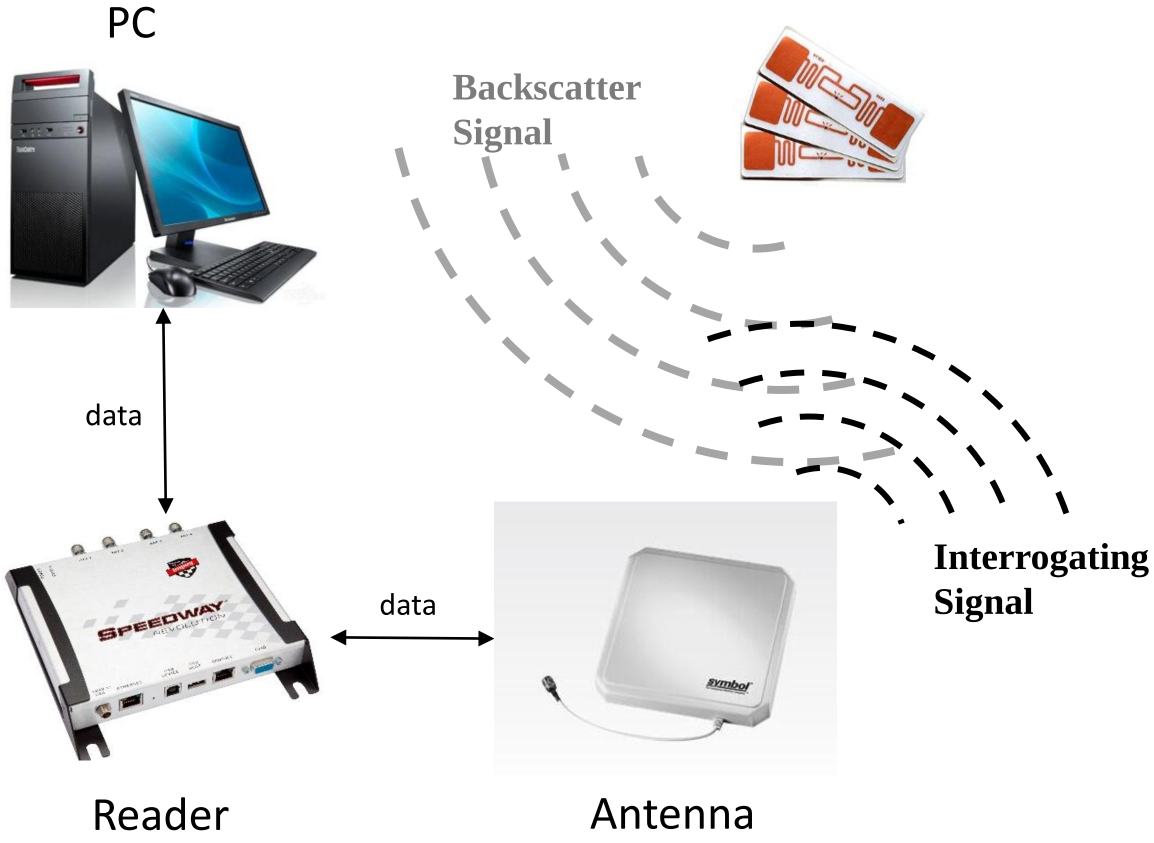
Carrier Emitter

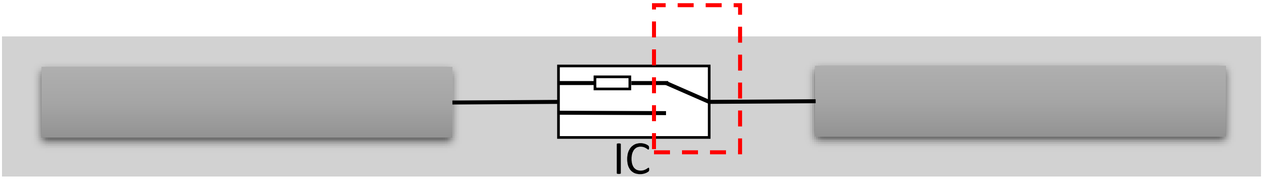
Analog Backscatter Sensing: An Emerging Solution for Pervasive Data Collection and Interaction



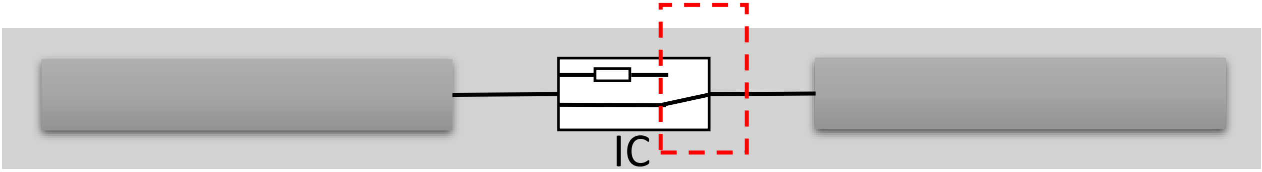
			Carrier		*Transducer*		*Converter*		*Modulator*			*Reader*
System	*Sensing task*	*Power Source*	*Freq (MHz)*	*Ambient*	*Type*	*Output*	*Type*	*Output*	*Modulation*	*ID*	*Multiple access*	*Type*
α-WISP 2005 [14]	Orientation	RF	915	N	Mercury Switch	Impedance (Binary)	NA	NA	AM (OOK)	Y	Y (TD^1)	RFID Reader
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^2	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	HCH1000^3	Capacitance	555 Timer	Frequency	FM (FSK)	N	Y (FD^4)	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^5	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
UbiquiTouch 2020 [28]	Touch	Solar	87.8-108	Y	Touch Panel	Voltage	TS3002 OSC^6	Frequency (Binary)	FM (OOK)	N	N	Smart phone

RFID Working Principle





Match



Mismatch

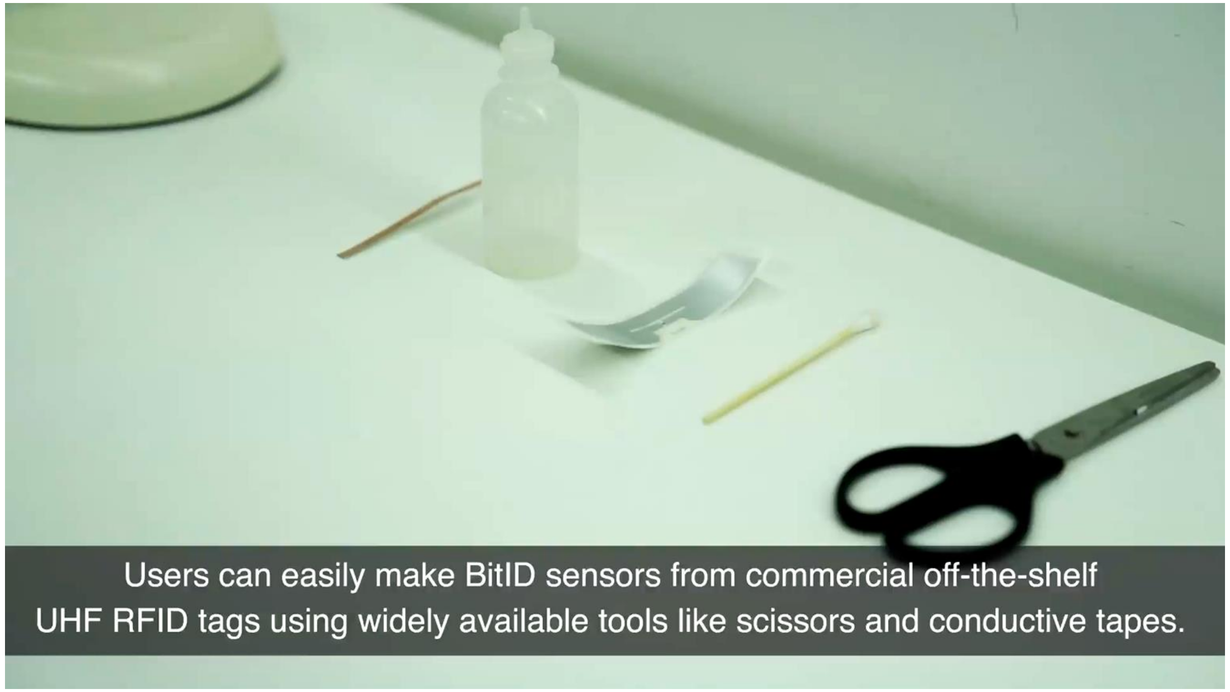
Differential Radar Cross Section

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

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

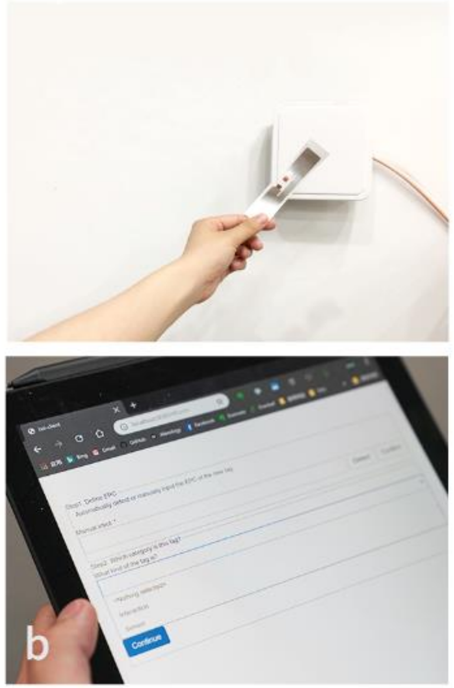
BitID is an RFID-based low-cost, unobtrusive, training-free sensing technique that enables users to augment everyday objects with sensing and interaction abilities in an easy and scalable way.

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

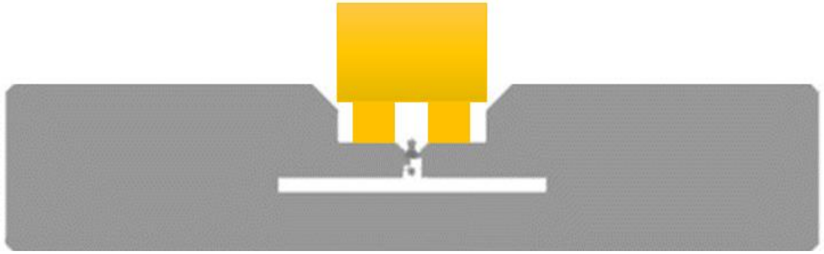
Deployment

BitID Short Sensor

Part A

Part B

A+B



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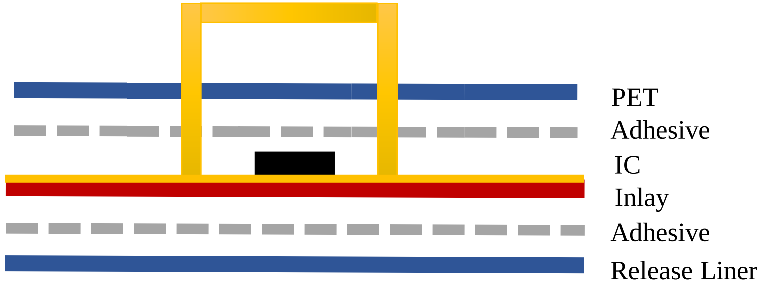
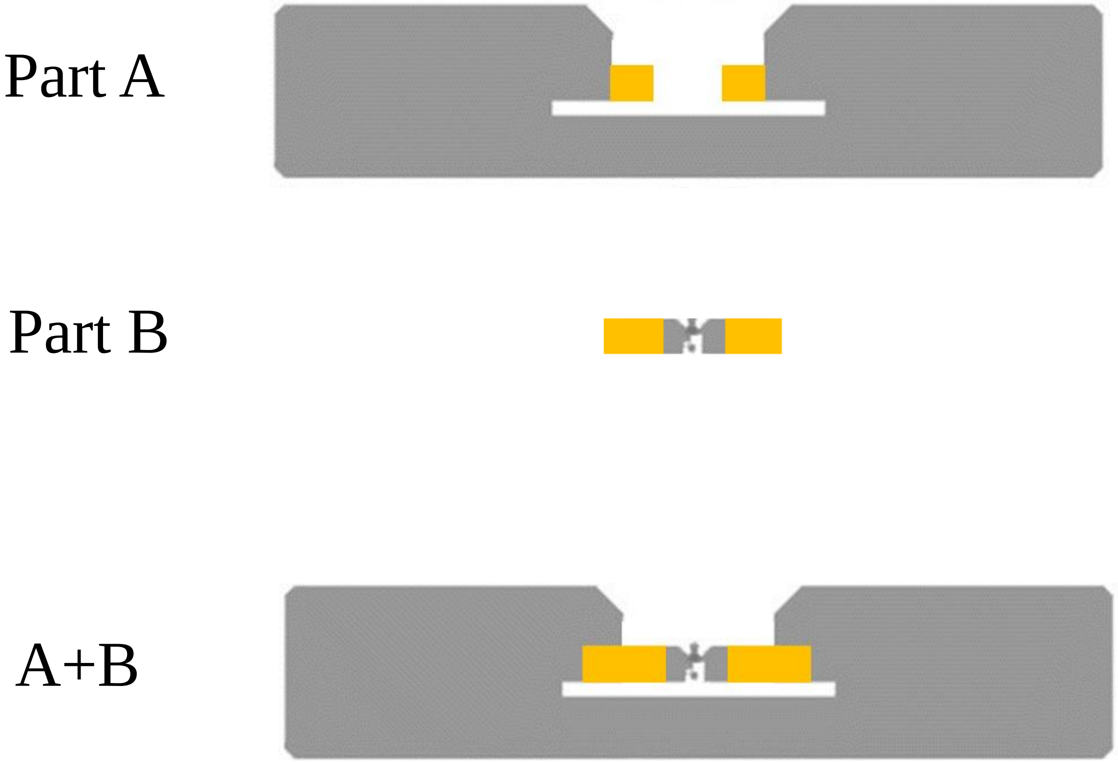
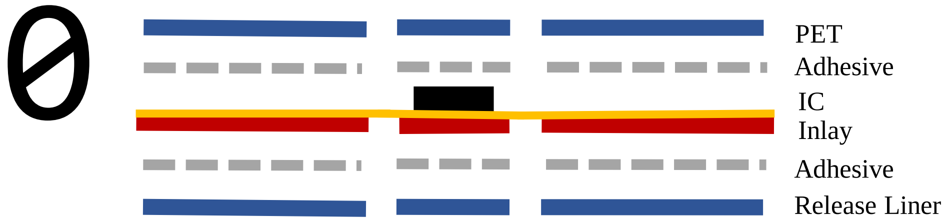


$$\Gamma_1 \approx \Gamma_2 \rightarrow \Delta\sigma \approx 0$$

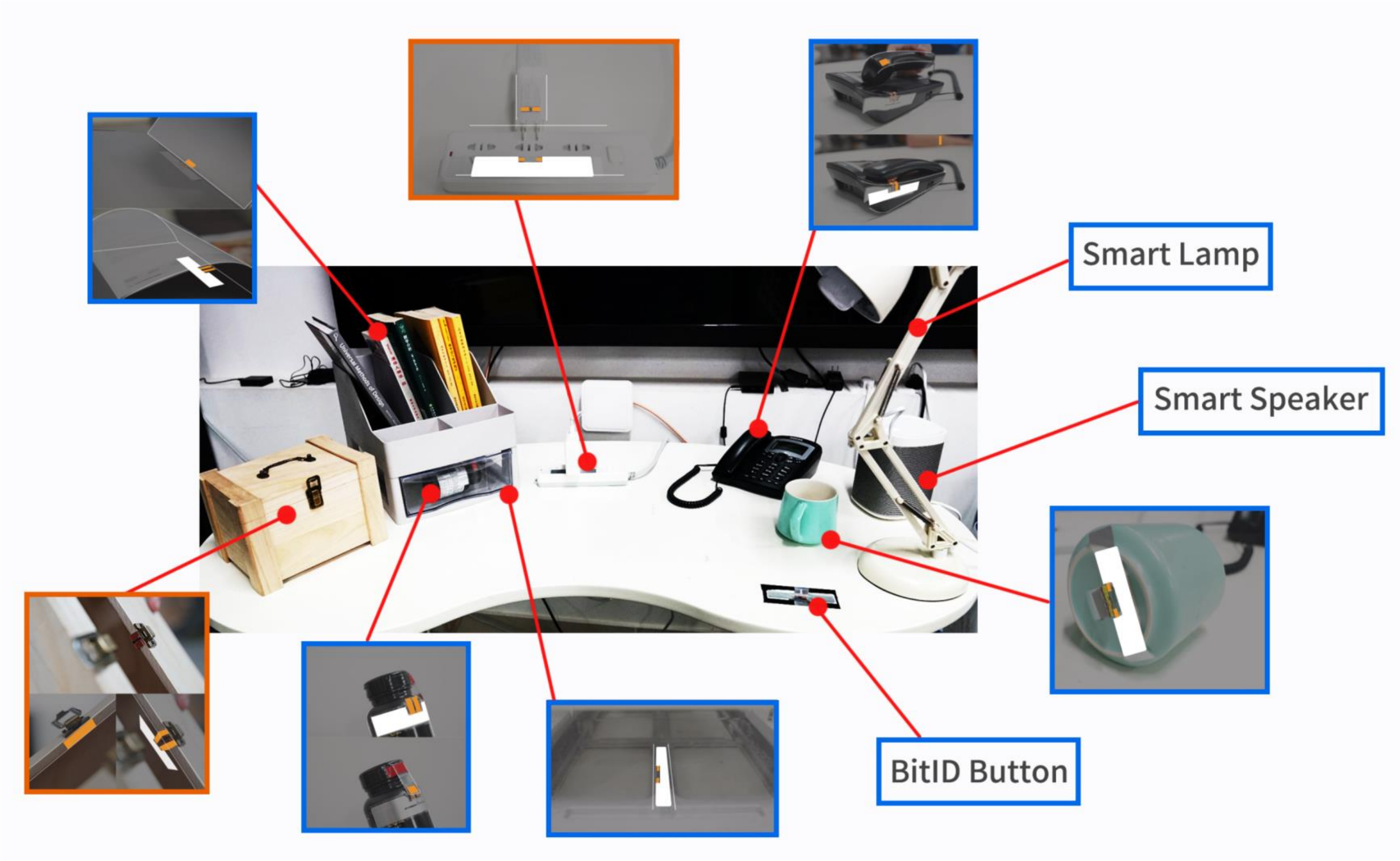
BitID Open Sensor





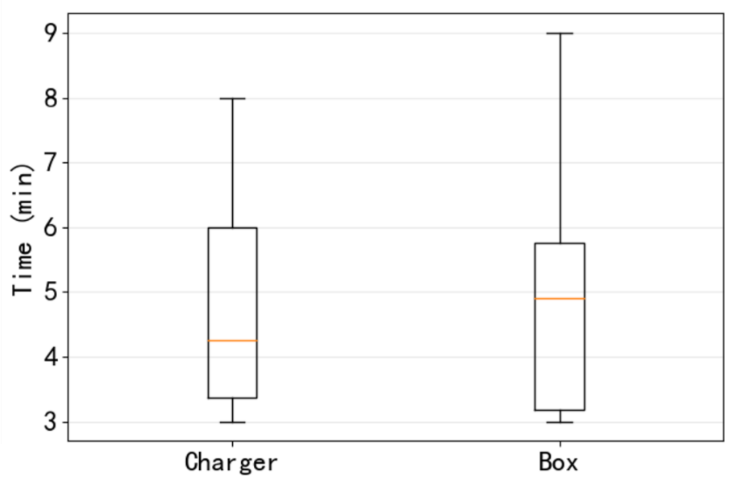
$$\begin{cases}\Gamma_1 \approx \Gamma_2 \\ G \approx 0\end{cases} \rightarrow \Delta\sigma \approx 0$$

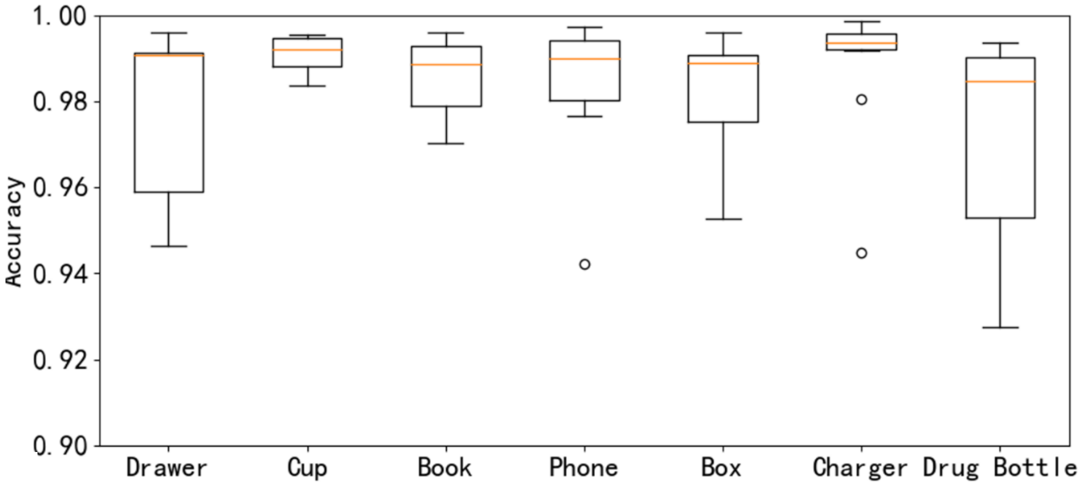
User Study: Deployment Evaluation



- 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

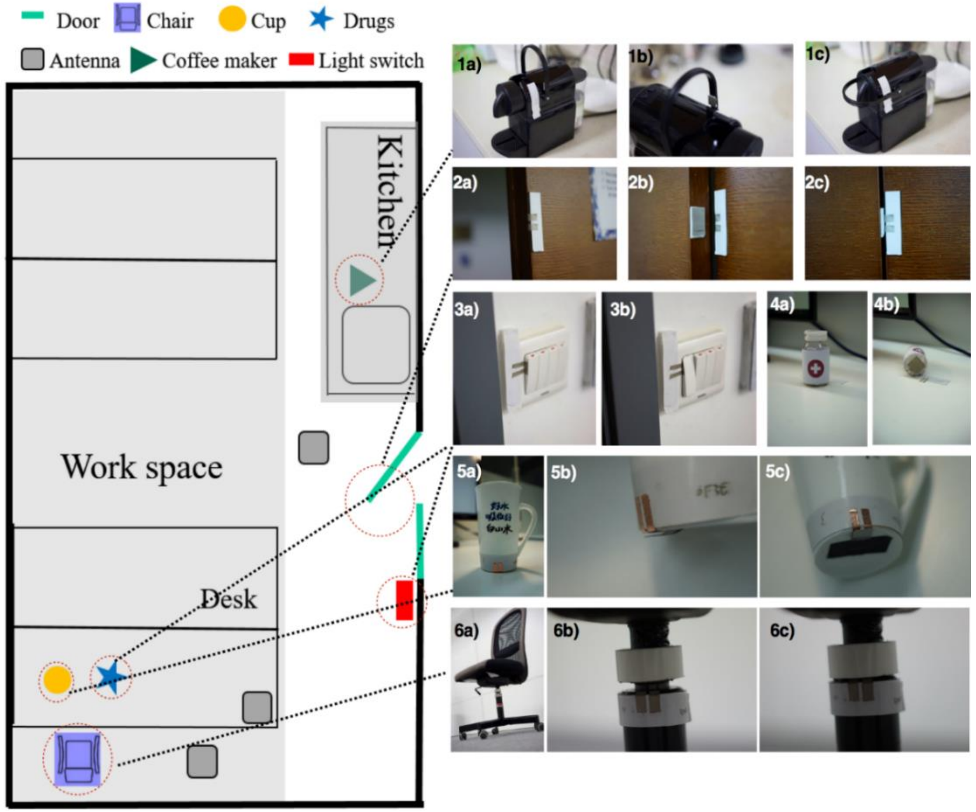




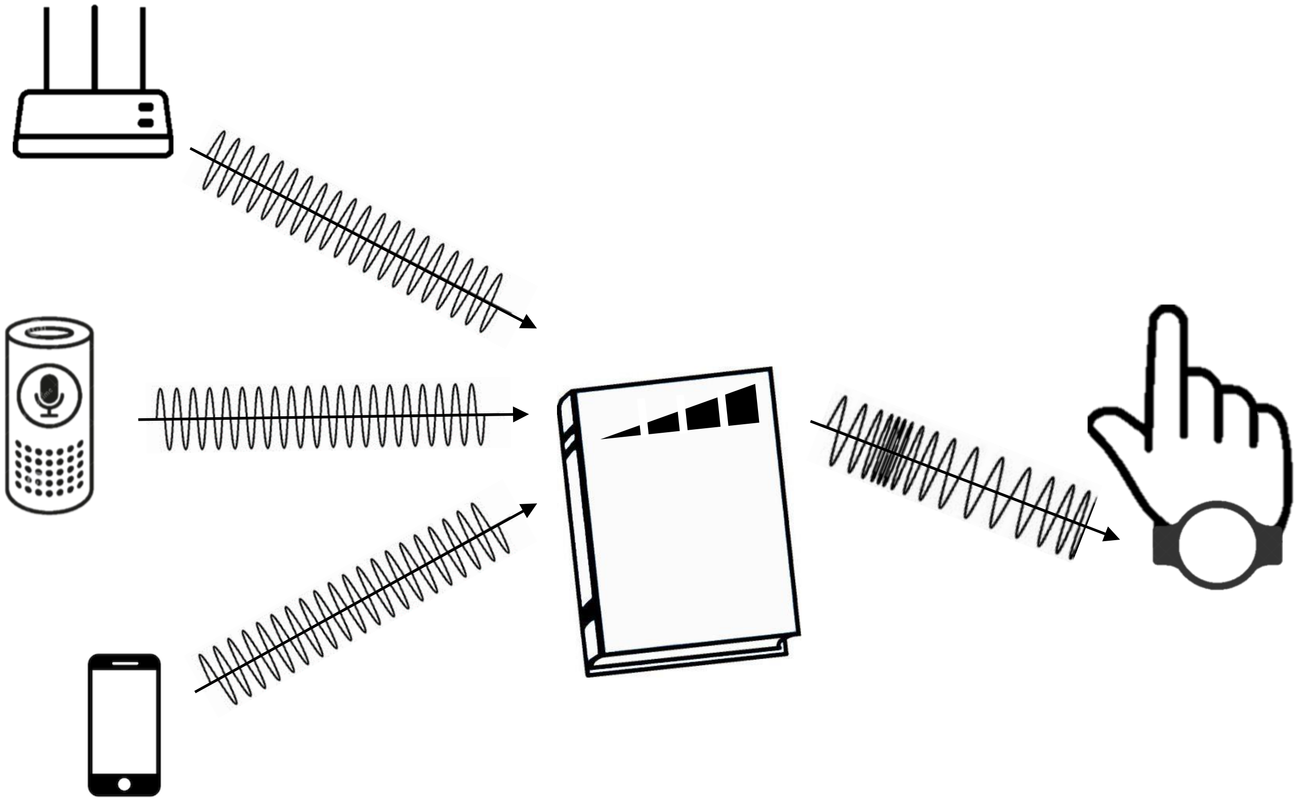
- Charger task completed in MEAN = 4.8min (SD=1.8)
- Box task completed in MEAN = 5.1min (SD=2.0)
- 23/24 deployment trials are successfully completed and evaluated robust

- 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)

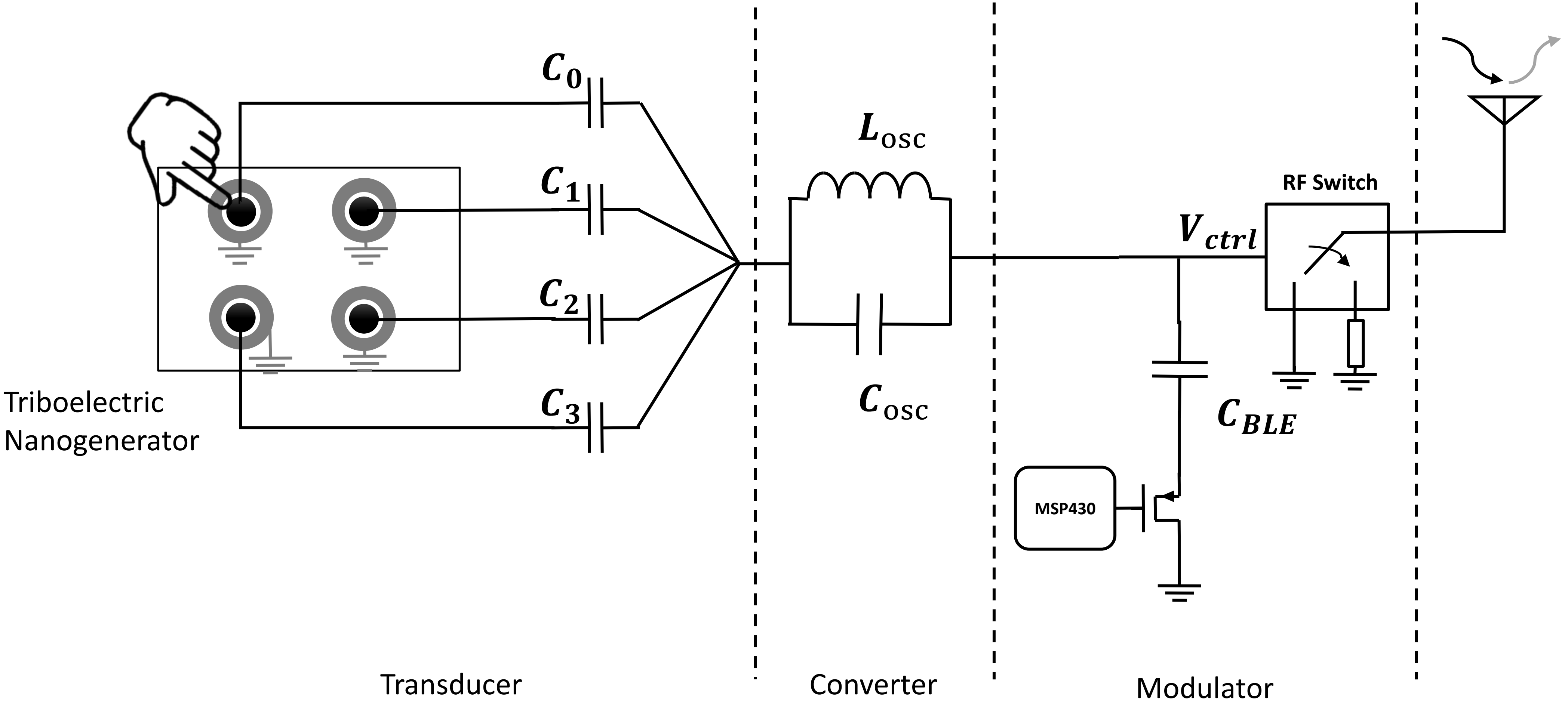
Room Scale Applications



BLETouch: Bluetooth Compatible Backscatter Touch Sensing System



FM Backscatter Touch Sensor with BLE ID Modulation

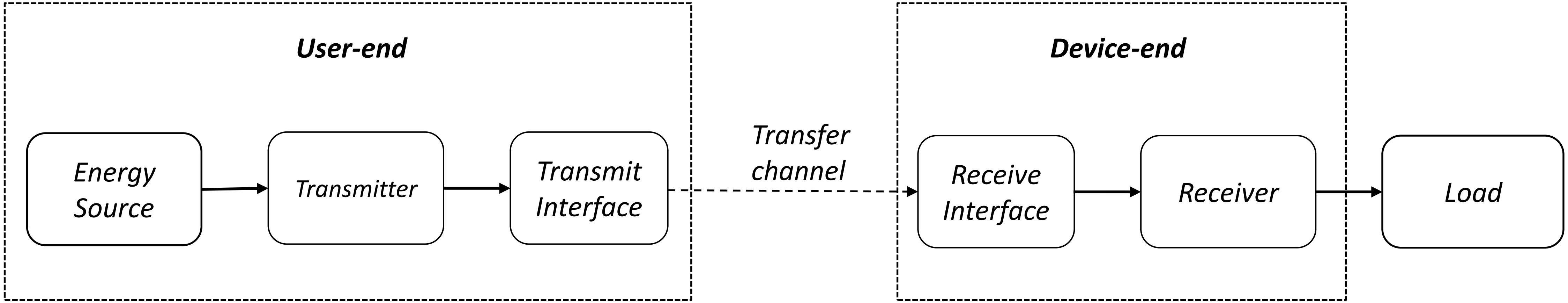


Interaction-based Power Transfer (IPT)

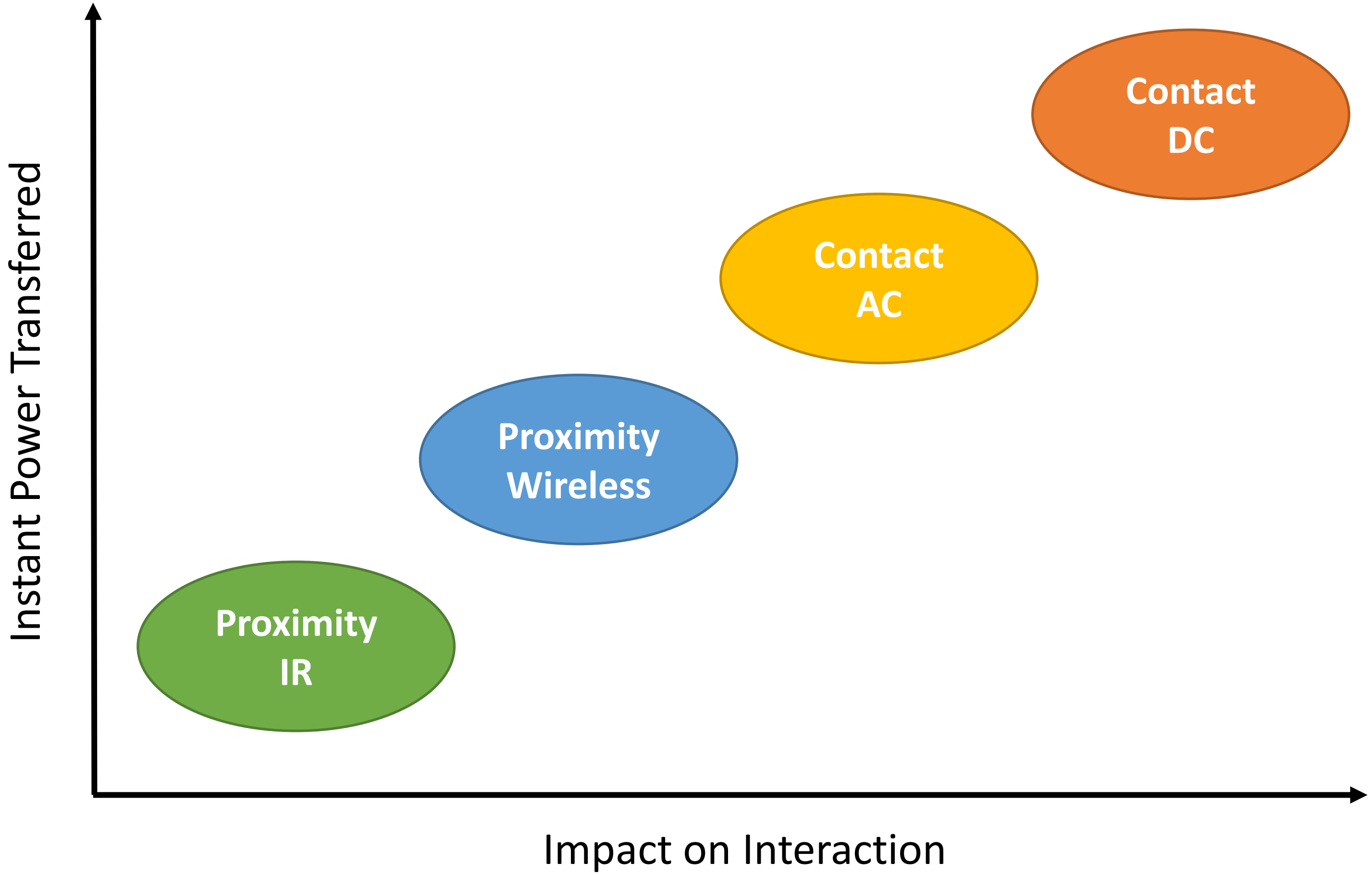
Transfer power from on-body energy sources to off-body power-as-needed devices only during interaction

Interaction → Proactive Object Tracking + Adaptive Contact

System Architecture



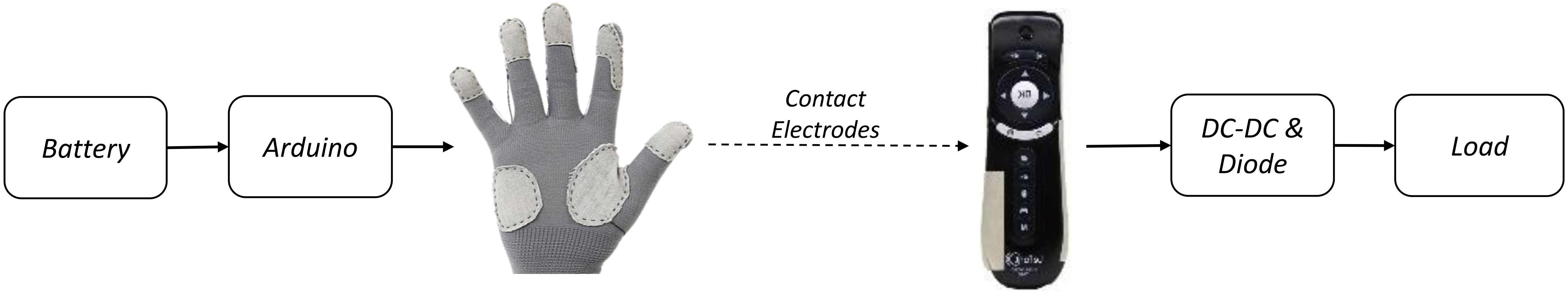
Interaction Impact vs Power Transfer



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

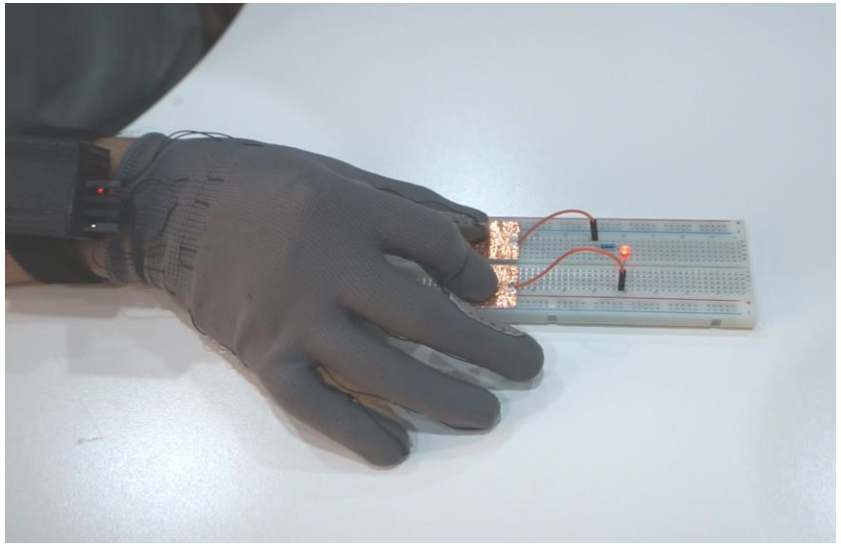
[1] E. R. Post, M. Reynolds, M. Gray, J. Paradiso, and N. Gershenfeld, “Intrabody buses for data and power,” in *Digest of Papers. First International Symposium on Wearable Computers*, 1997, pp. 52–55.

Contact-based DC IPT Prototype: TouchPower

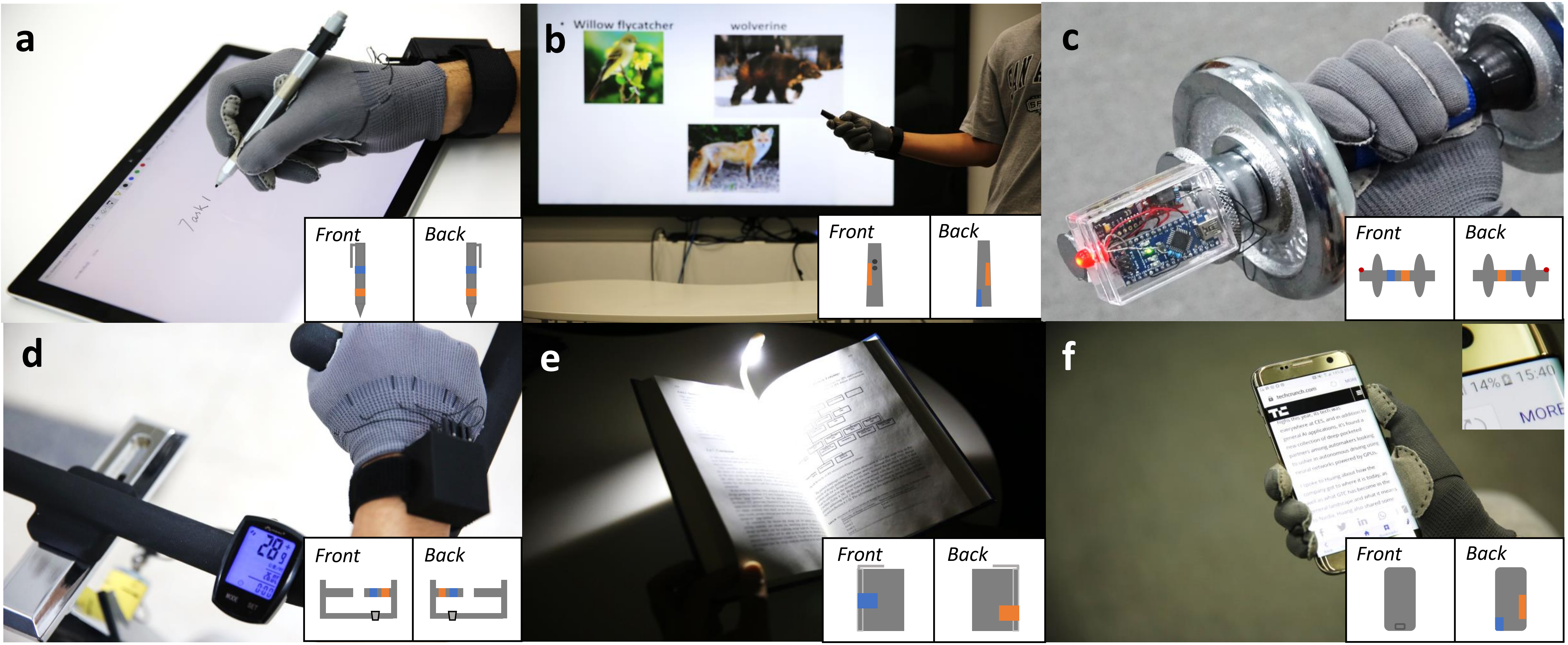

Battery → *Arduino* →

Contact Electrodes

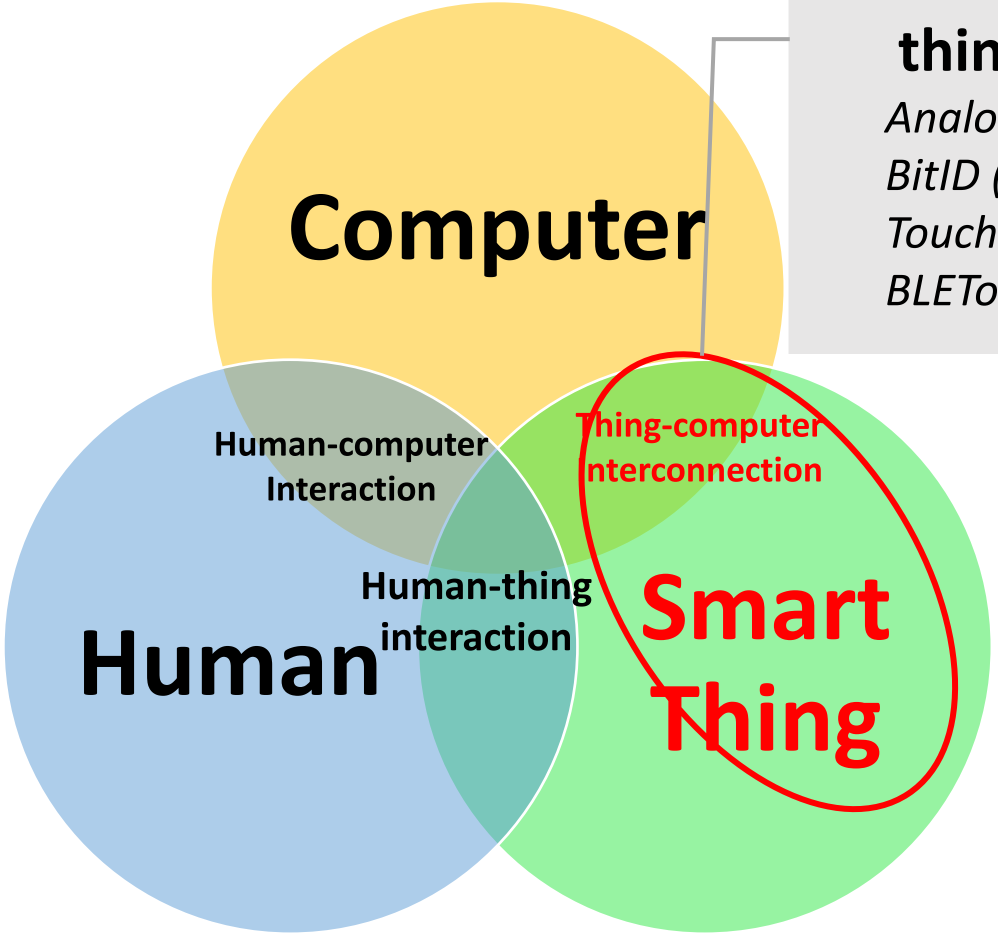
→ *DC-DC & Diode* → *Load*



Implemented Applications



Research Summary



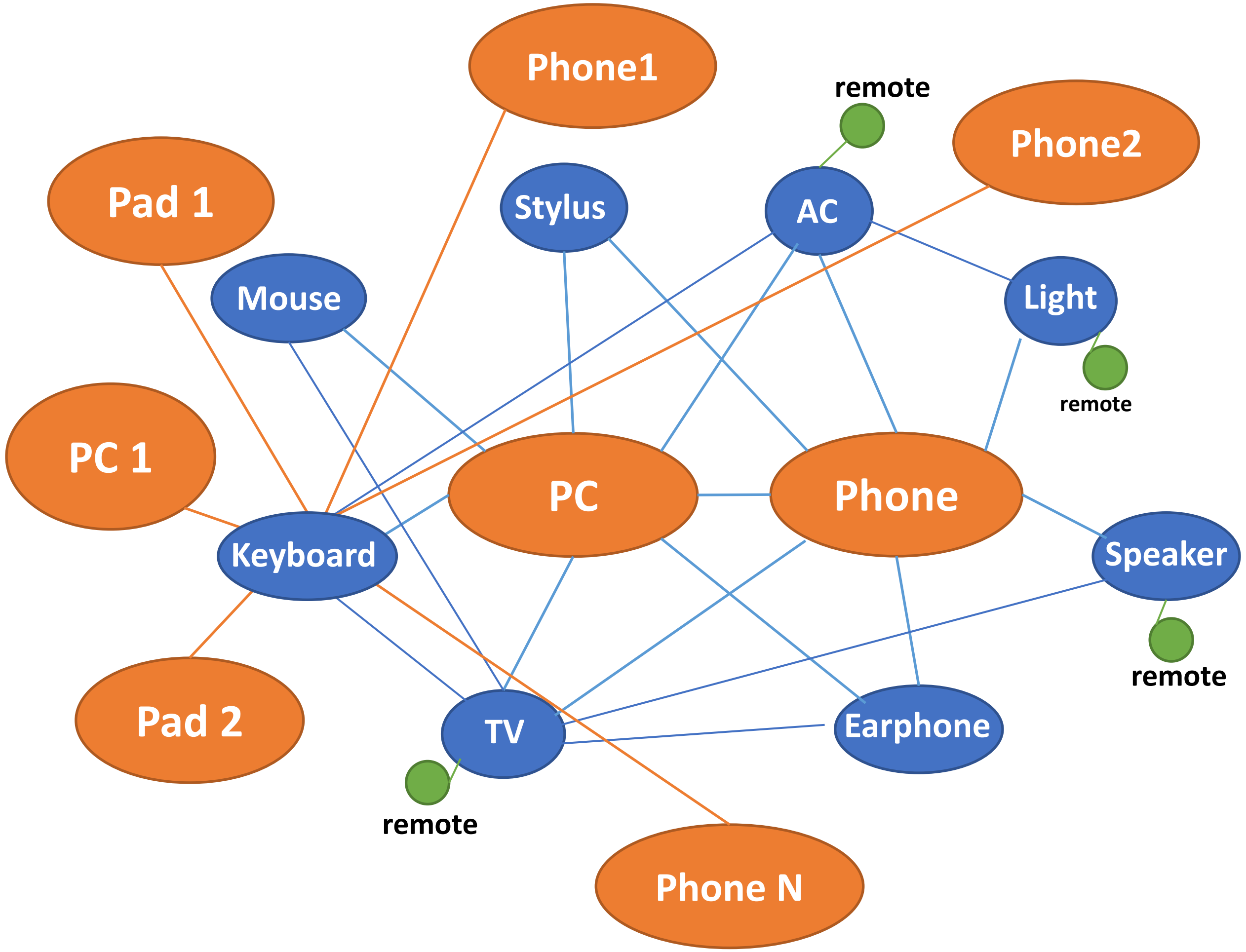
Self-sustainable smart things through thing-computer interconnection

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)
3. **BoldMove: Semantic-based IoT Device Control**
   (in progress)

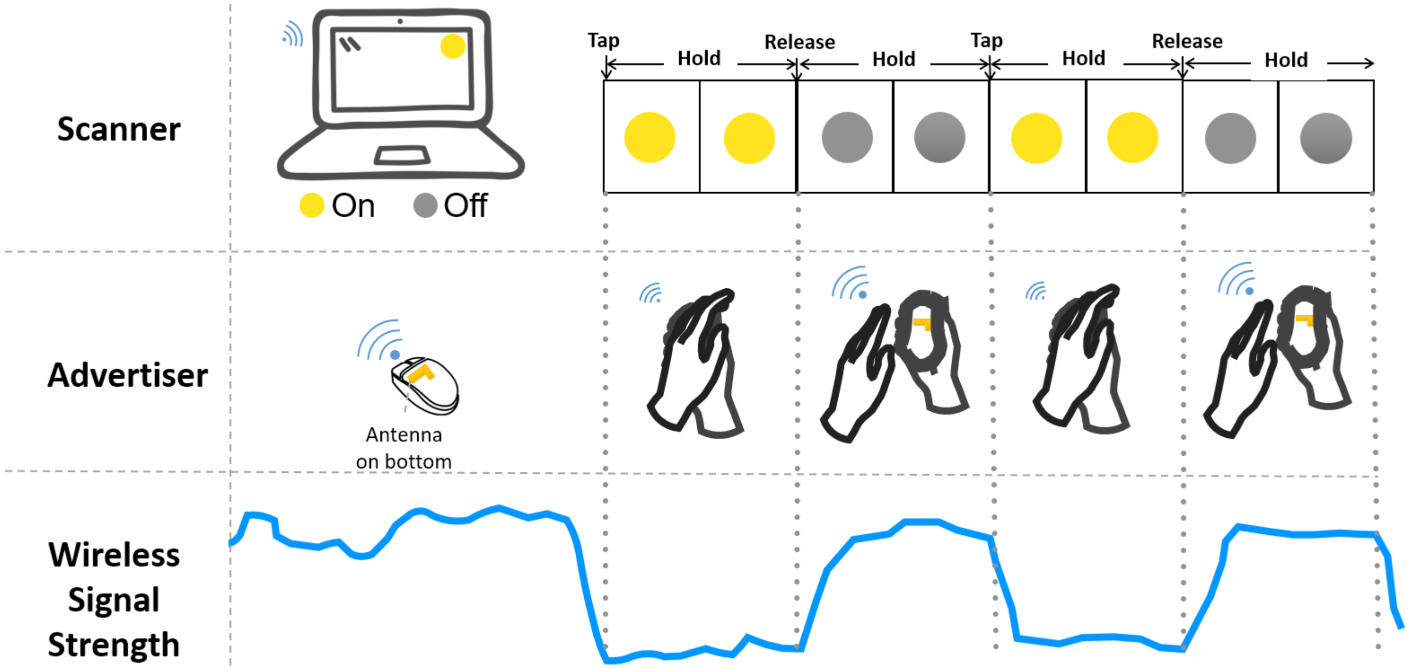
Device Association Demands

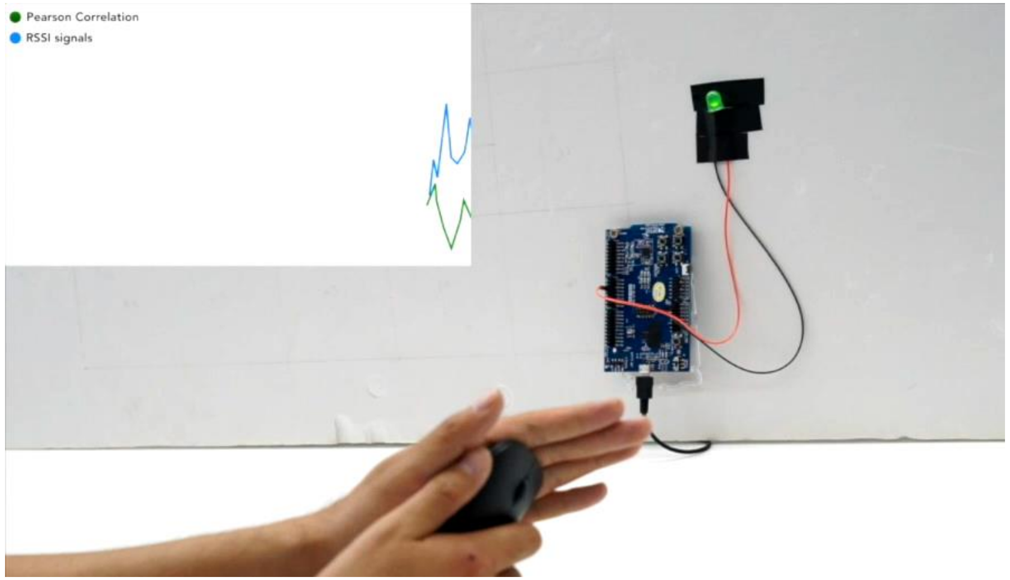


What is closest to the user?
The input and feedback device!

Computers	Association Demands
	Low
	Medium
	High

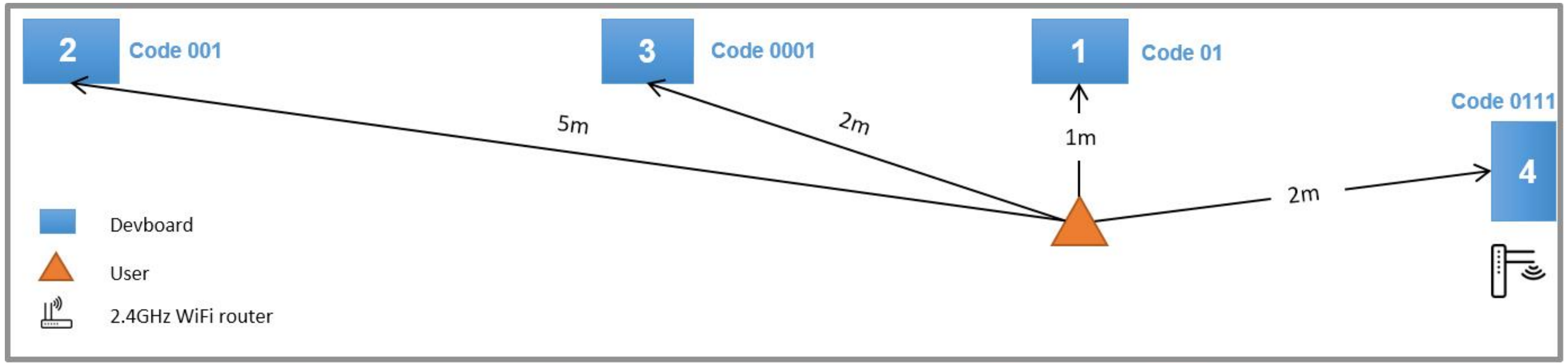
Tap-to-Pair: Wireless Device Association from Things

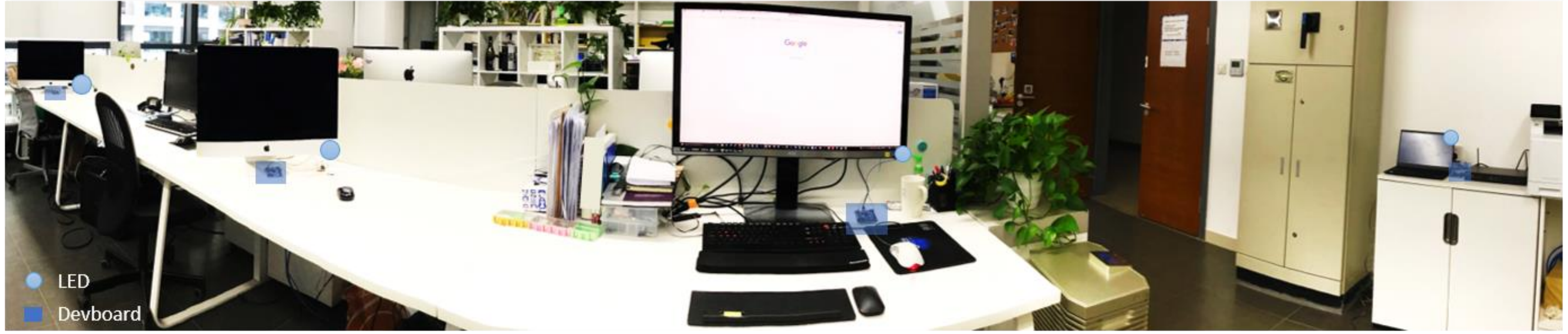




- **”Hand effect”**: signal strength reduction due to hands near an antenna
- **Synchronized taps**: correlated wireless signal strength with a blinking pattern

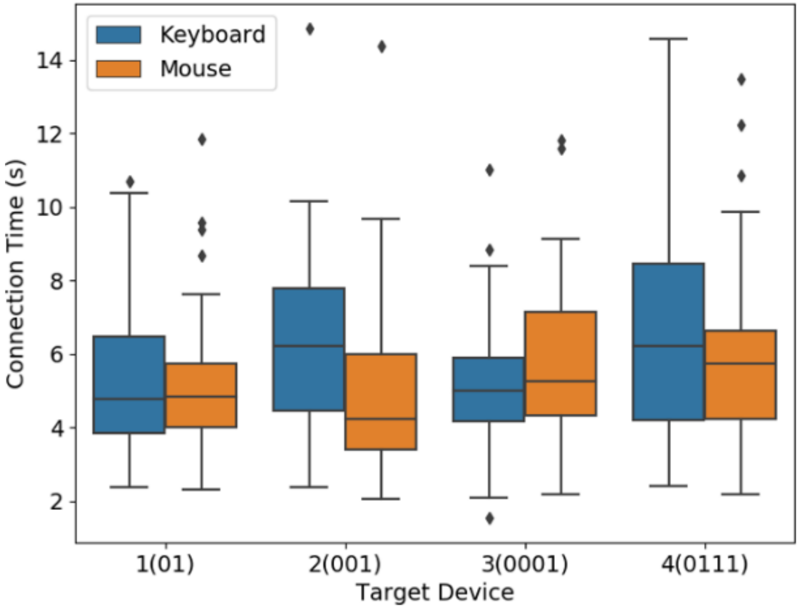
Evaluation

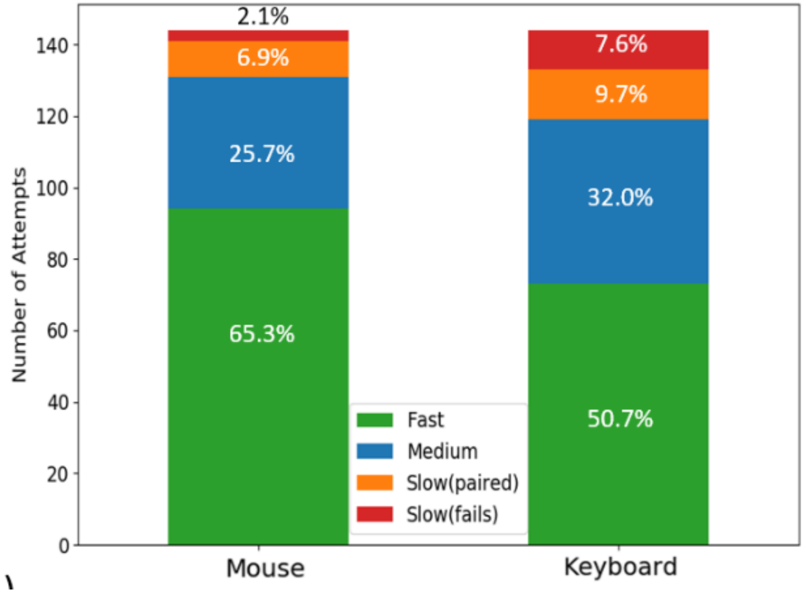


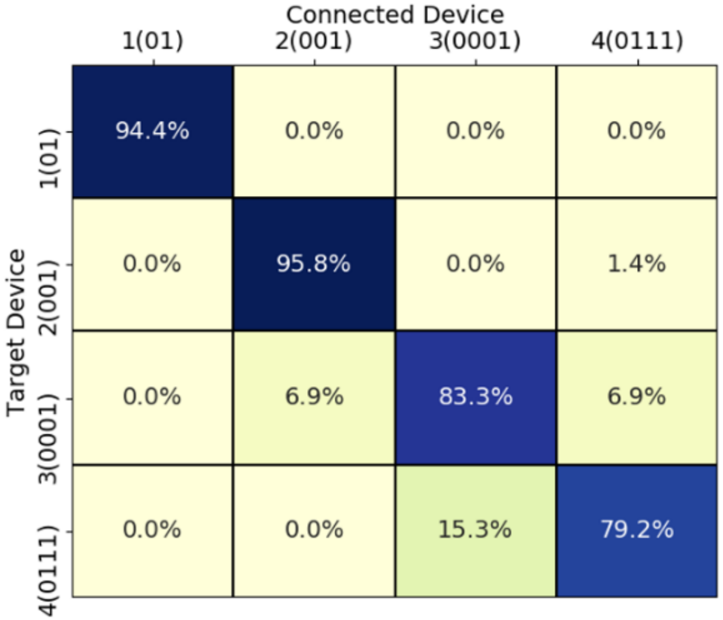


- Goals: Validate **on-chip** association performance
- 12 participants (10 males)
- 4 devices at different **distances** with different **blinking patterns**
- Typical office wireless environment

Results Analysis





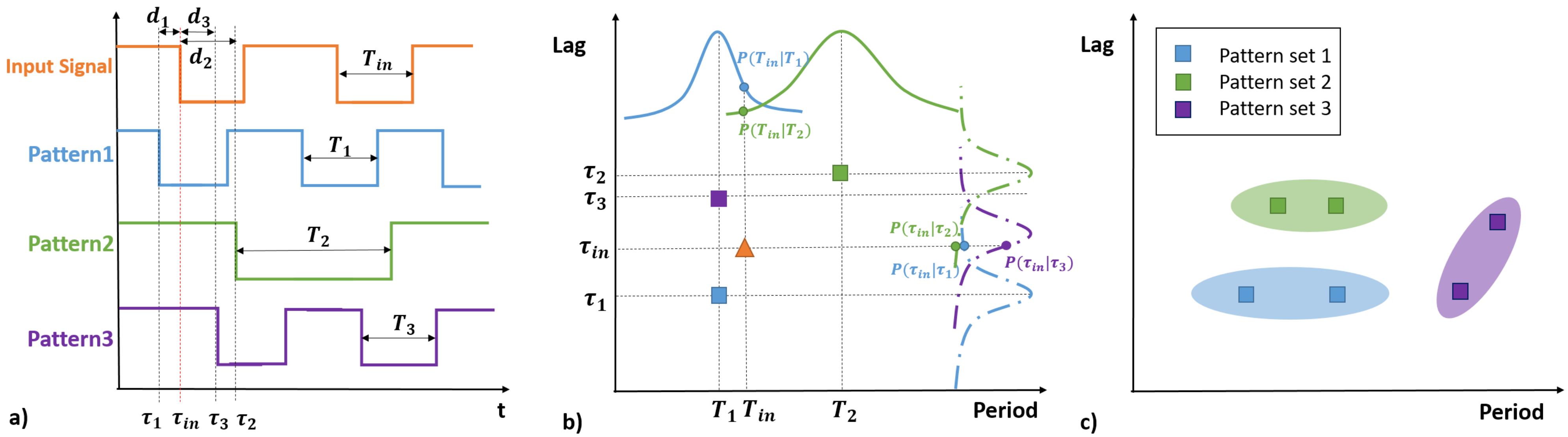


	1(01)	2(001)	3(0001)	4(0111)
1(01)	94.4%	0.0%	0.0%	0.0%
2(001)	0.0%	95.8%	0.0%	1.4%
3(0001)	0.0%	6.9%	83.3%	6.9%
4(0111)	0.0%	0.0%	15.3%	79.2%

- 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 (τ)



Optimization Goal

i, j: two blinking patterns,
The probability the input i is recognized as pattern j

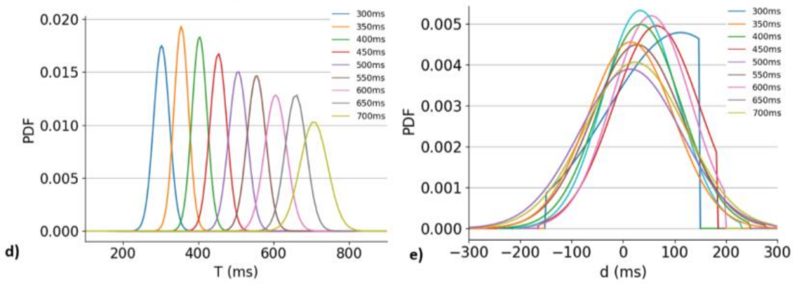
$$
\begin{aligned}
P(i|input = j) &= P(T_i, \tau_i | T_{input}, \tau_{input}) \\
&= P(T_i|T_{input}) \times P(\tau_i|\tau_{input}) \\
&= \frac{P(T_{input}|T_i)P(T_i)}{P(T_{input})} \times \frac{P(\tau_{input}|\tau_i)P(\tau_i)}{P(\tau_{input})} \\
&= \frac{P(T_{input}|T_i)P(T_i)}{\sum_{k=1}^{n} P(T_{input}|T_k)P(T_k)}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

User Behavior Model

Blinking Pattern

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

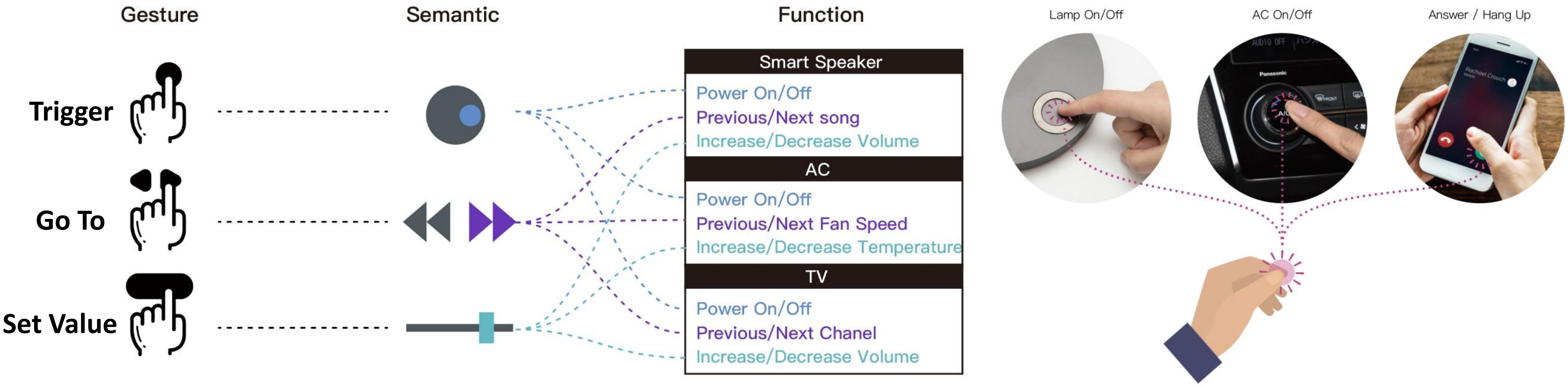
Find the pattern set that maximize $\bar{\eta}$



n	Pattern set (T, τ)	win_{baye}	TH_{baye}	win_R	TH_R
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

BoldMove: Semantic-based IoT Device Control

Semantic: Affordance of a function



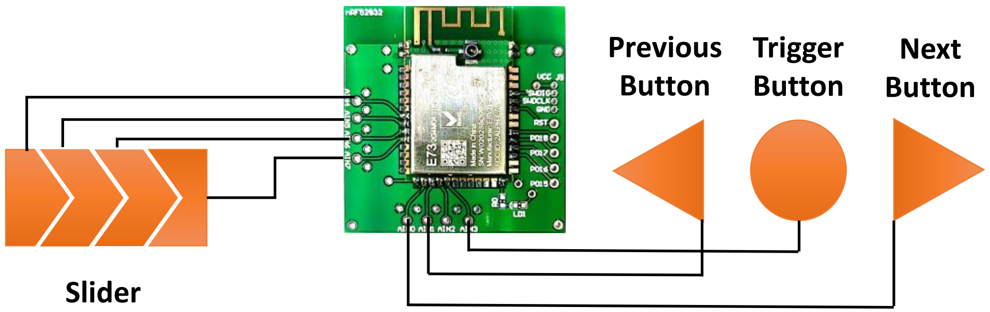
Simon Mayer, Andreas Tschofen, Anind K. Dey, and Friedemann Mattern. 2014. User interfaces for smart things -- A generative approach with semantic interaction descriptions. *ACM Transactions on Computer-Human Interaction* 21, 2: 1–25. https://doi.org/10/gfs78x

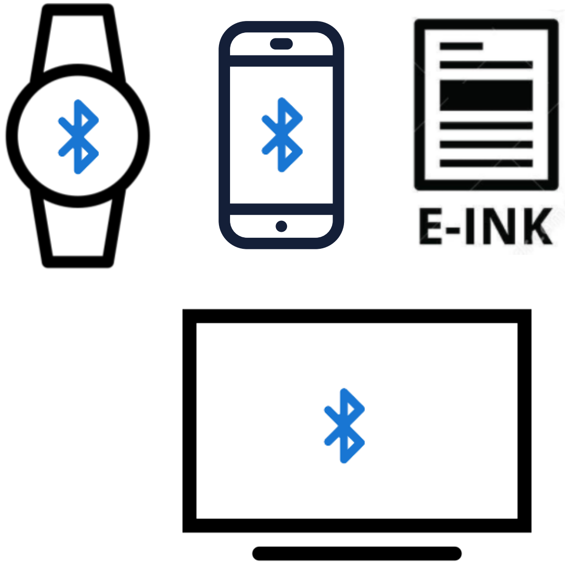
Ubiquitous Touch Interface Prototype

Input:
Low-power BLE Transceiver with Touch Sensing

Communication:
BLE Advertisement

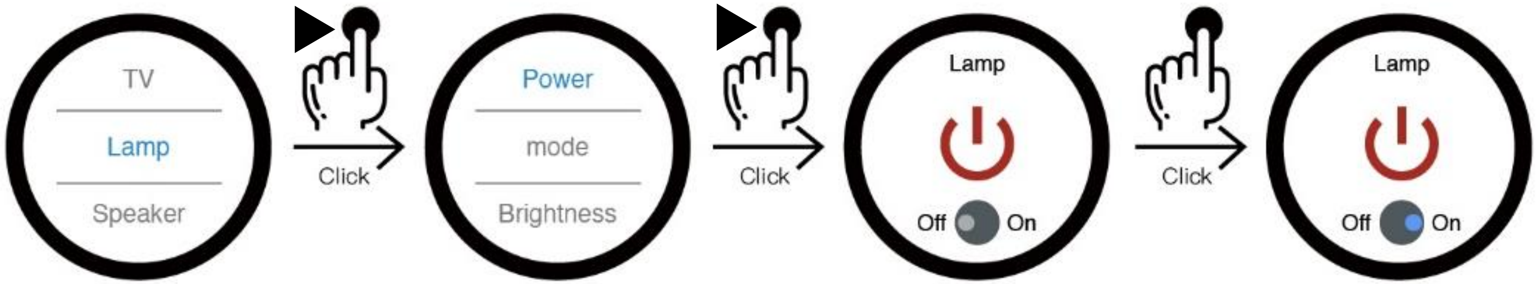
Display:
Smartwatch Screen



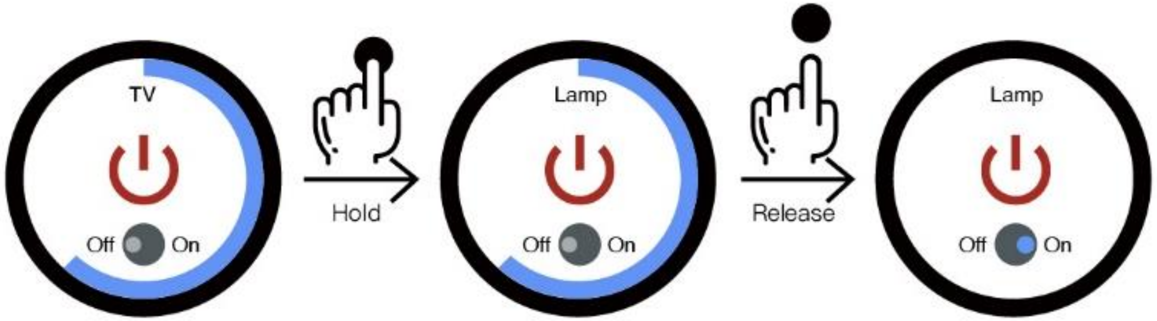


List Navigation vs Dwell Selection

Movement (spatial)
Multiple clicks on 2-3 buttons



Dwell (temporal)
One click on one button



User Study

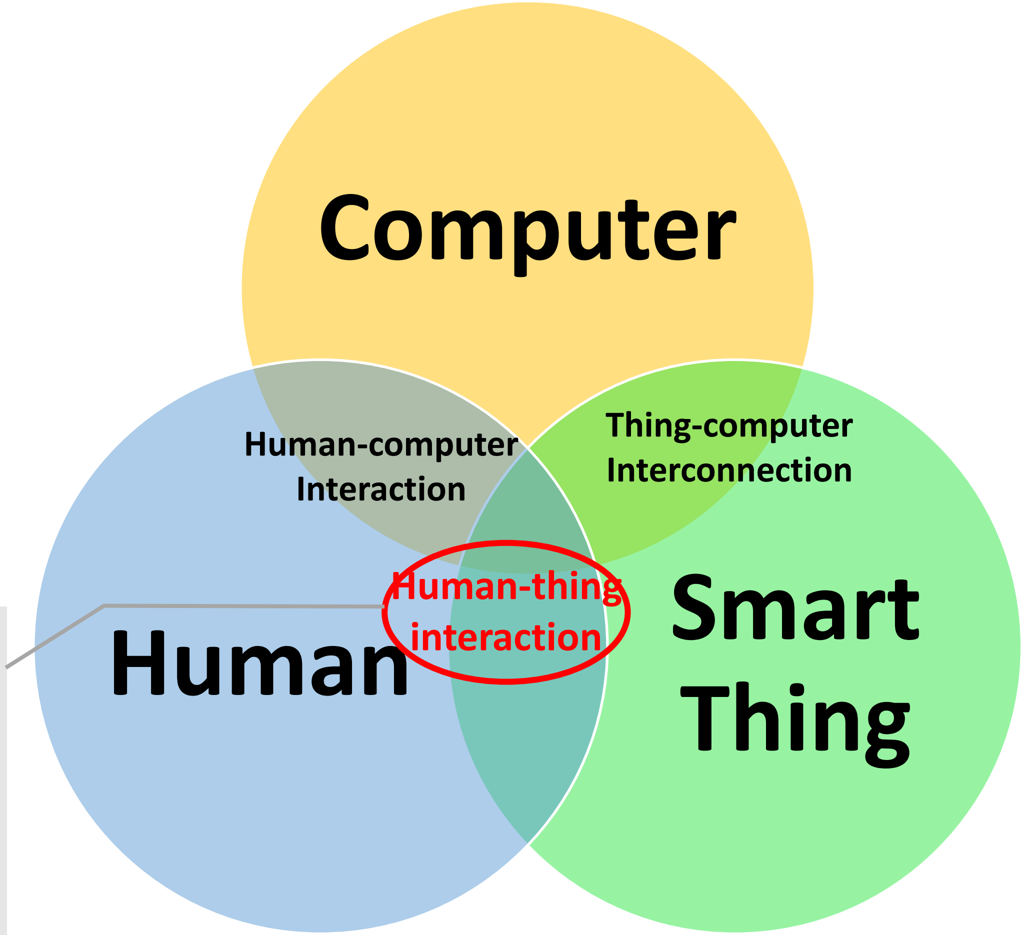
Procedure: 7 participant, 3 Scenarios, Each has 7 tasks

Selection Time: BoldMove Mean 3.25s (SD=2.34s)
Baseline Mean 10.22s (SD=5.66s)

User Preference: BoldMove is rated significantly better for
Mental $(F_{1,30} = 4.58, p < .05)$
Physical $(F_{1,30} = 34.7, p < .001)$
Overall $(F_{1,30} = 33.1, p < .001)$

*P4 said "The new method is intuitive and straight-forward.
The many clicks of the conventional method suddenly feel redundant."*

Research Summary



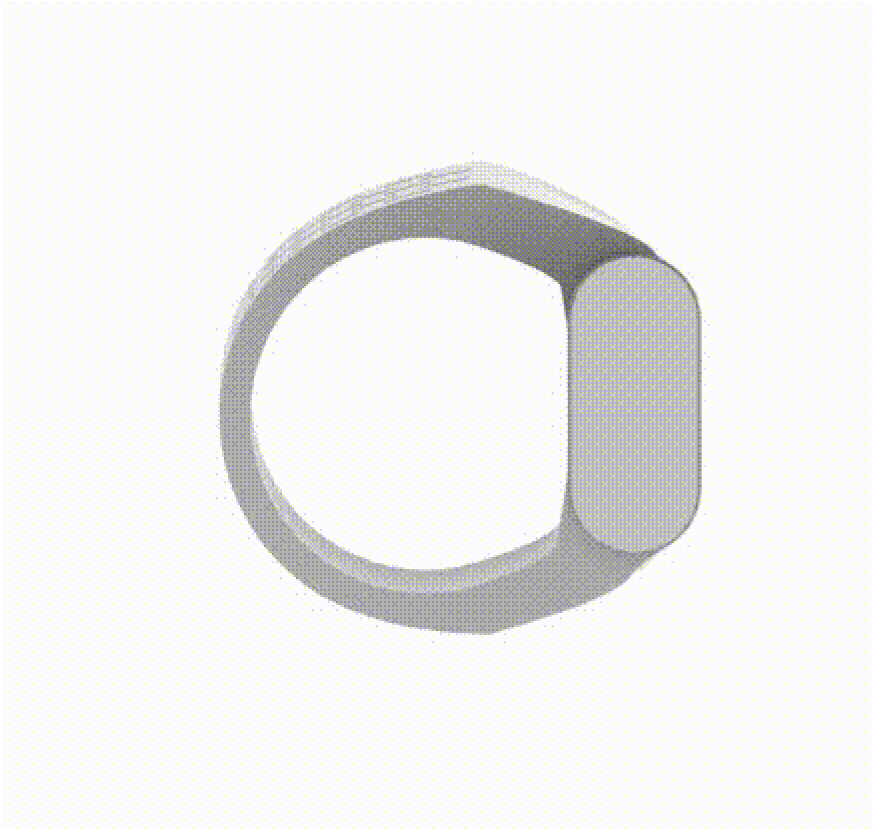
Resource-constrained Interaction

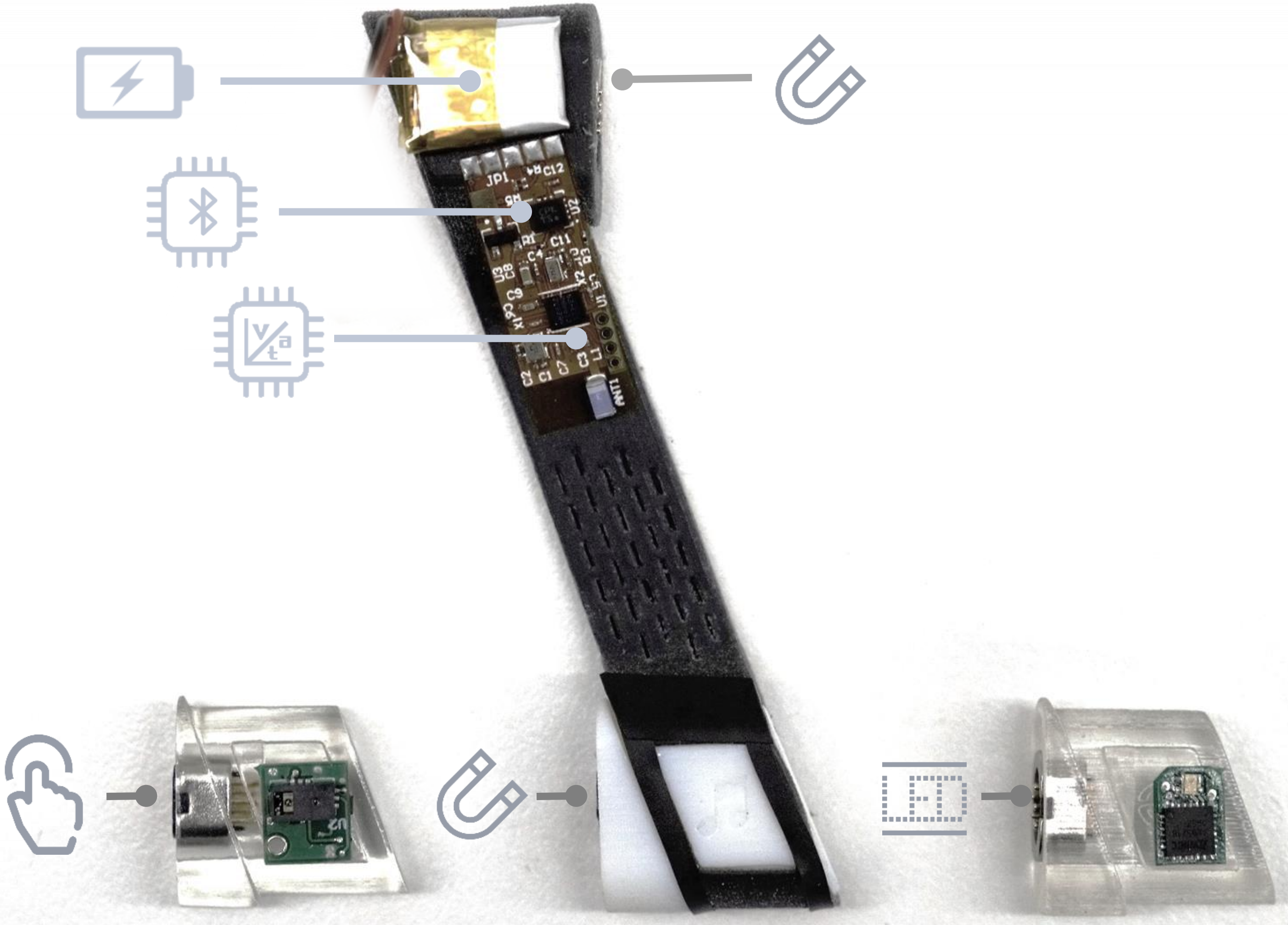
Tap-to-Pair (IMWUT 18)
SyncSelect (IMWUT 19)
BoldMove (in progress)

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



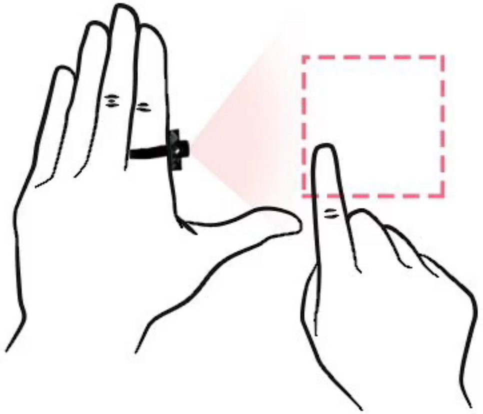


Wearing Mechanism

1

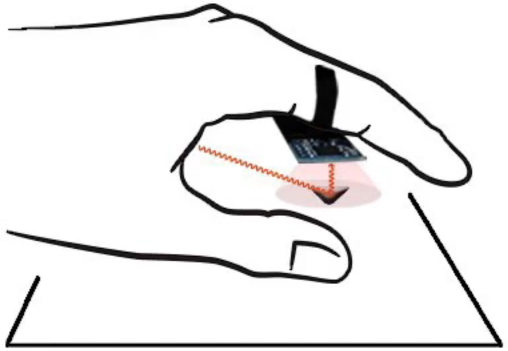
2

3



ThermalRing

Gesture and Tag Inputs Enabled by a Thermal Imaging Smart Ring

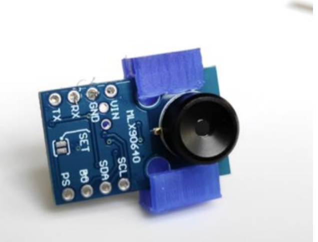


Tengxiang Zhang (ztxseuthu@gmail.com), Xin Zeng, Yinshuai Zhang, Ke Sun, Yuntao Wang, Yiqiang Chen

中国科学院计算技术研究所 INSTITUTE OF COMPUTING TECHNOLOGY, CHINESE ACADEMY OF SCIENCES Lenovo HUAWEI 清華大學 Tsinghua University

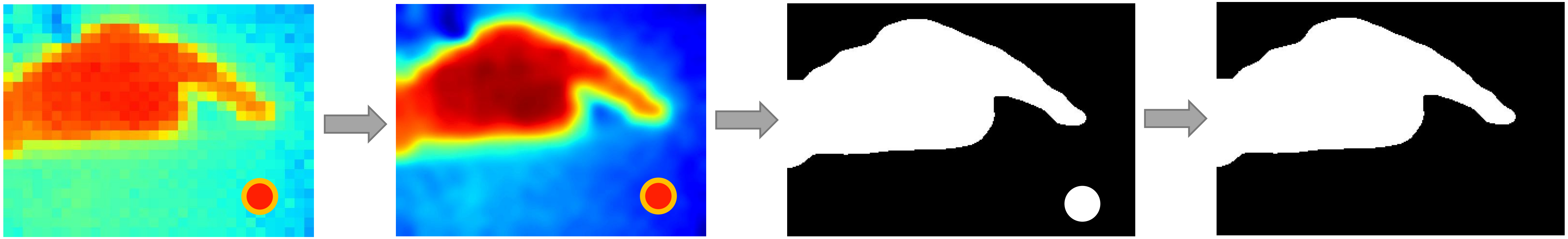
ThermalRing

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

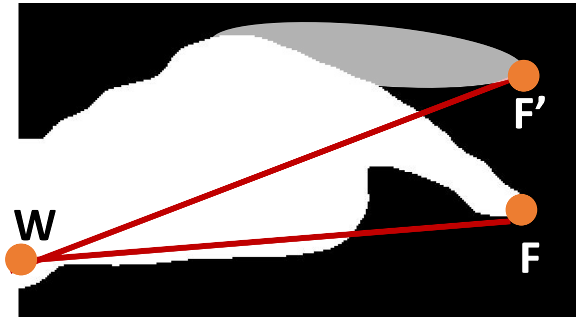
Drawing Gesture Sensing

- 6 step sensing flow

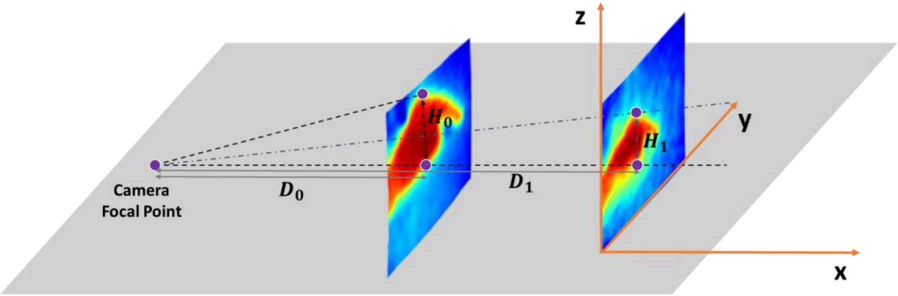
1. Fingertip Extraction
2. Finger Lift Detection

3. X/Y Coordinates Estimation
4. Kalman Filtering

5. Bag of Words Feature Extraction
6. SVM Prediction

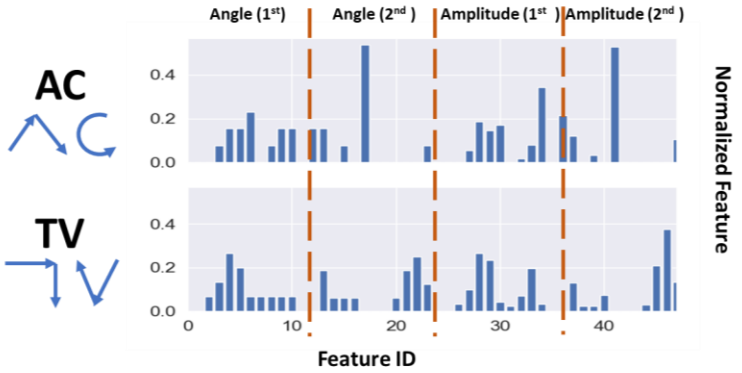


Slope calculation



Triangular similarity

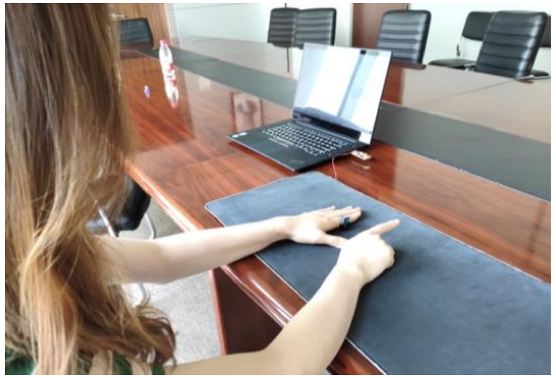
$$FL = \frac{H_{real} \times D}{H}$$

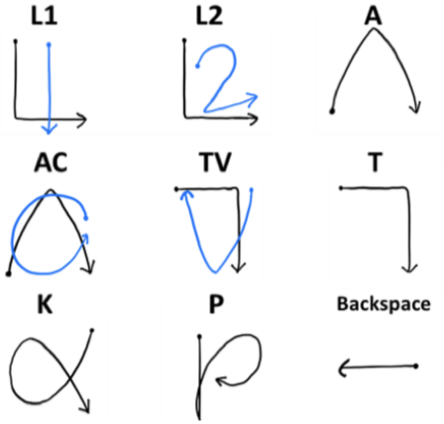


$$\theta = \arctan\left(\frac{\Delta y}{\Delta x}\right)$$

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

User Study


Experiment Setup



Graffiti Gesture Set

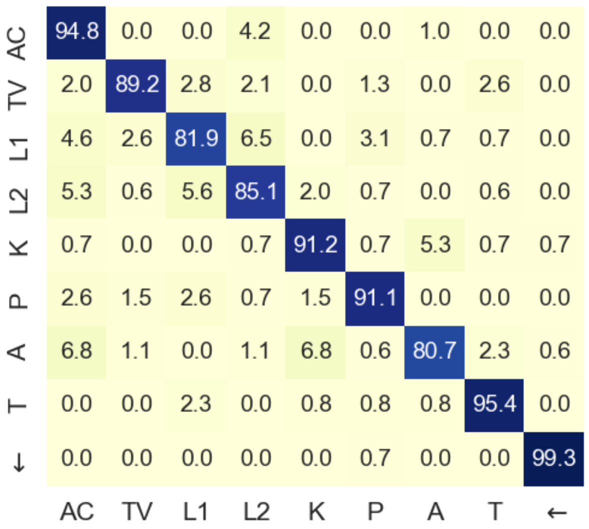
Task: Smart Device Pairing

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

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

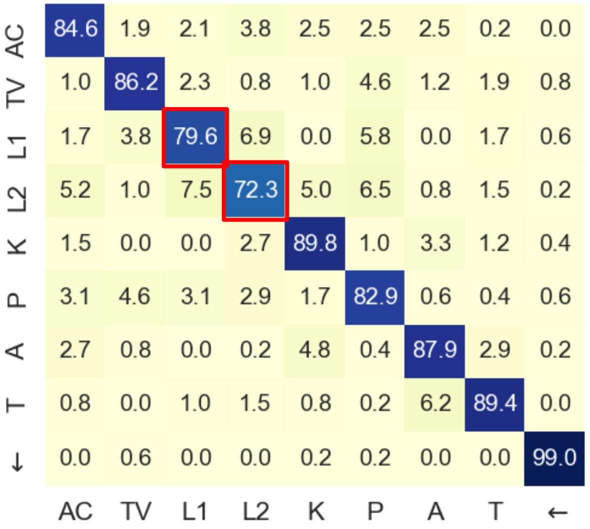
Data: 3240 trials, 360 for each gesture

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



	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

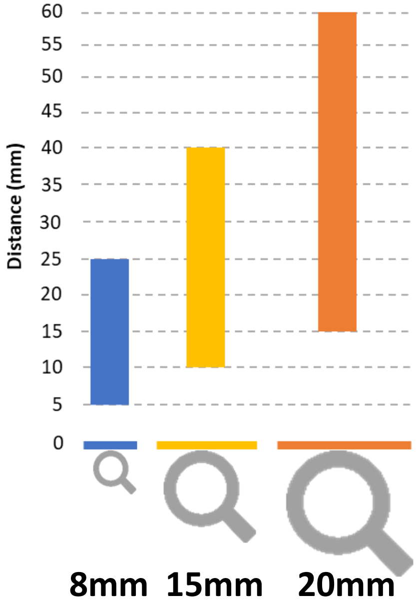
Between-user Confusion Matrix

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

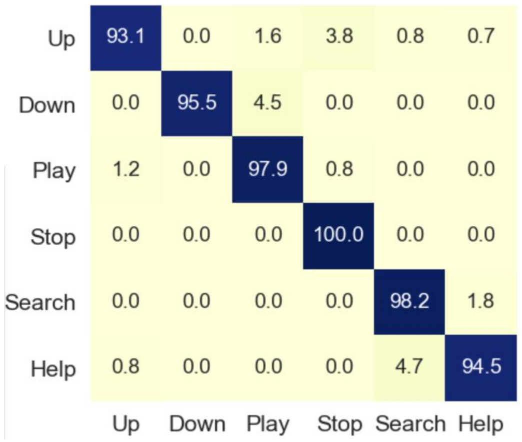
Camera with a higher frame rate for faster drawing

ThermalTag Identification



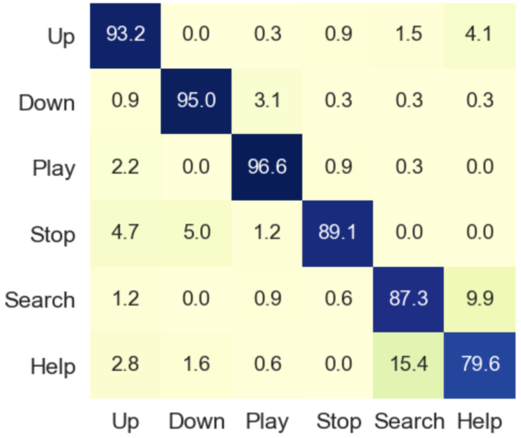
- ThermalTag: Thin and Passive Tags made of high heat reflection materials in DIY manner
- Imaging Principle: ThermalTag reflects heat from the hand
- Interaction: Touch-Lift-Hold
- Tag size: 20mm Square

User Study



	Up	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

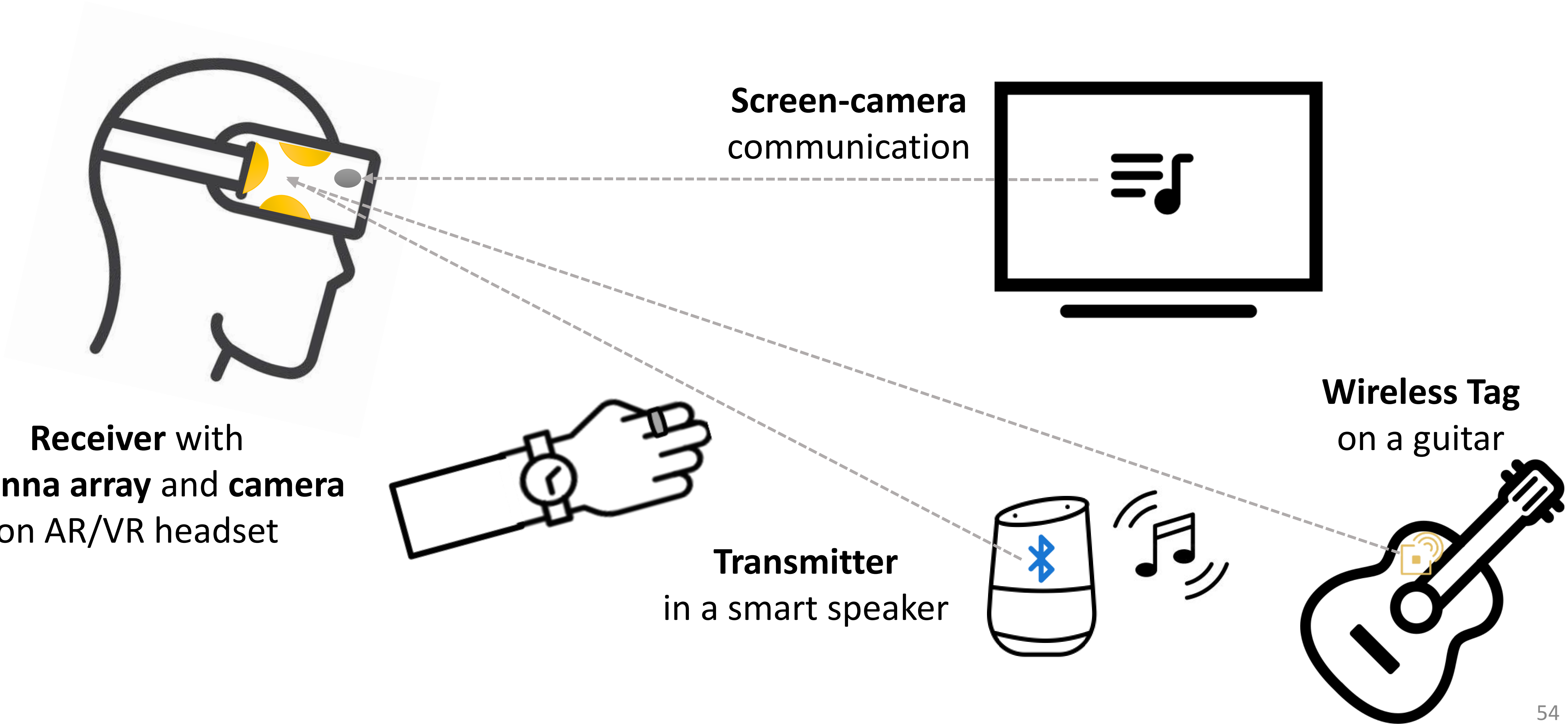
Feature: Hu's Moments

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



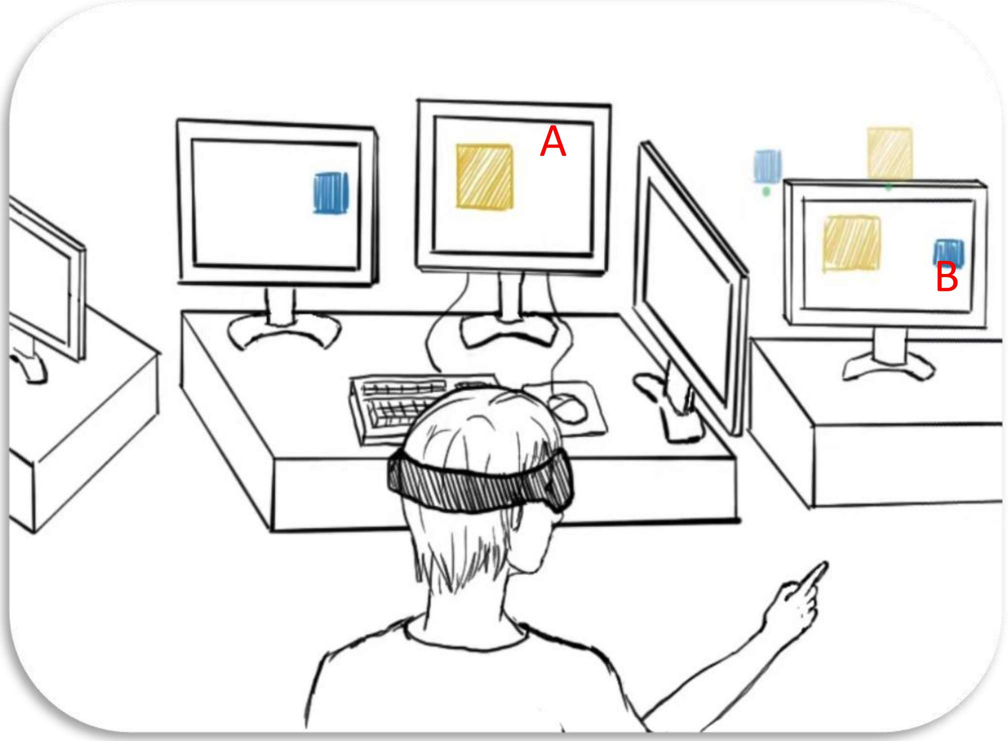
Screen-camera communication

Receiver with **antenna array** and **camera** on AR/VR headset

Wireless Tag on a guitar

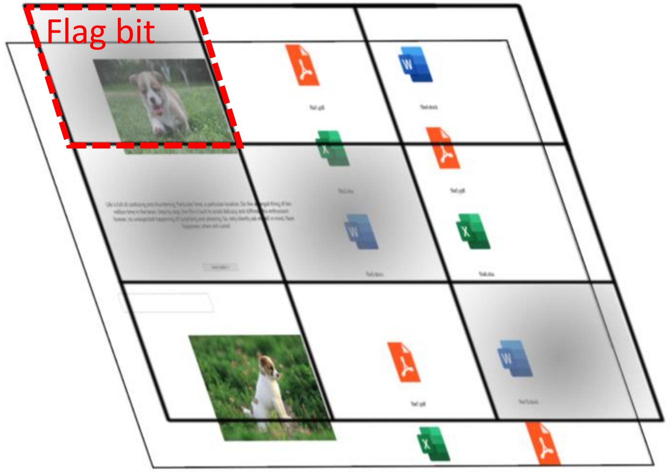
Transmitter in a smart speaker

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



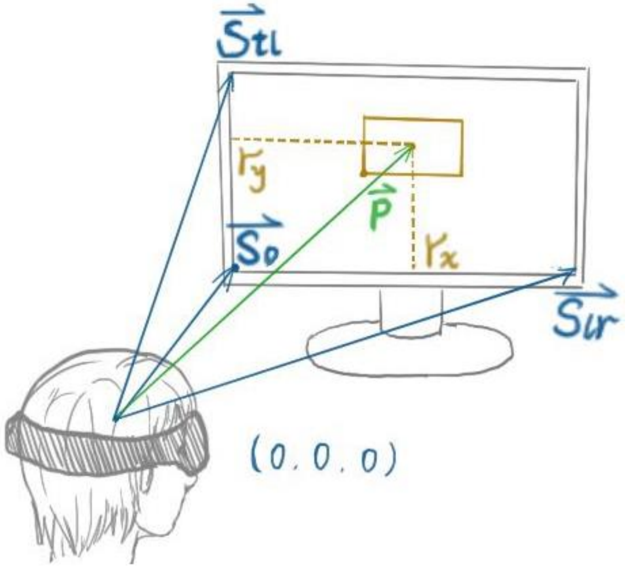
System Functions

Unobtrusive and spontaneous
Screen-camera Communication



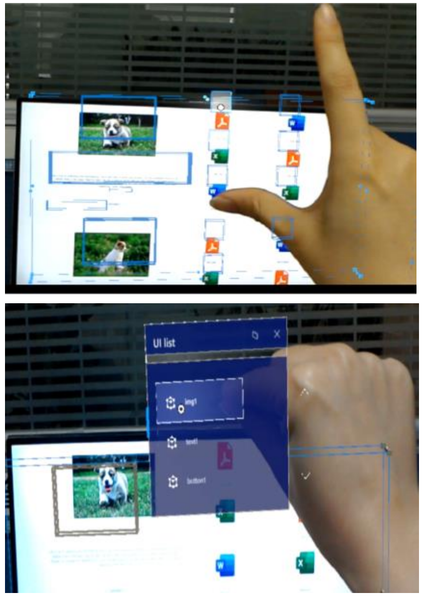
FSK Modulation by
changing grid transparency

On-screen digital resource
Localization in World Coordinates



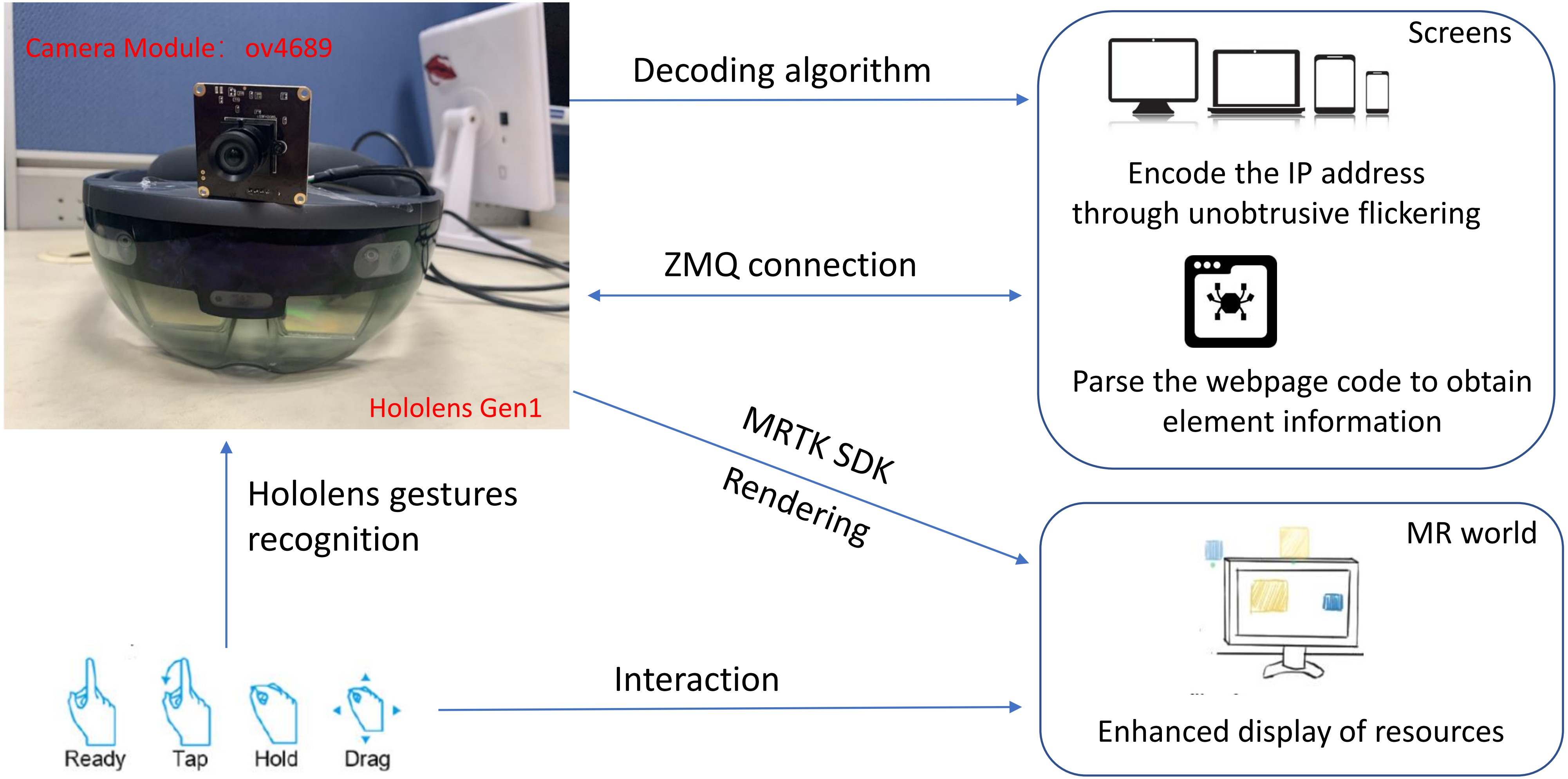
$$\vec{p} = \vec{s_0} + r_x \cdot (\vec{s_{lr}} - \vec{s_0}) + r_y \cdot \ (\vec{s_{tl}} - \vec{s_0})$$

UI Rendering and
Manipulation Gestures



Gaze selection
Hand manipulation

System Implementation



Decoding algorithm

ZMQ connection

MRTK SDK

Rendering

Hololens gestures recognition

Interaction

Screens

Encode the IP address through unobtrusive flickering

Parse the webpage code to obtain element information

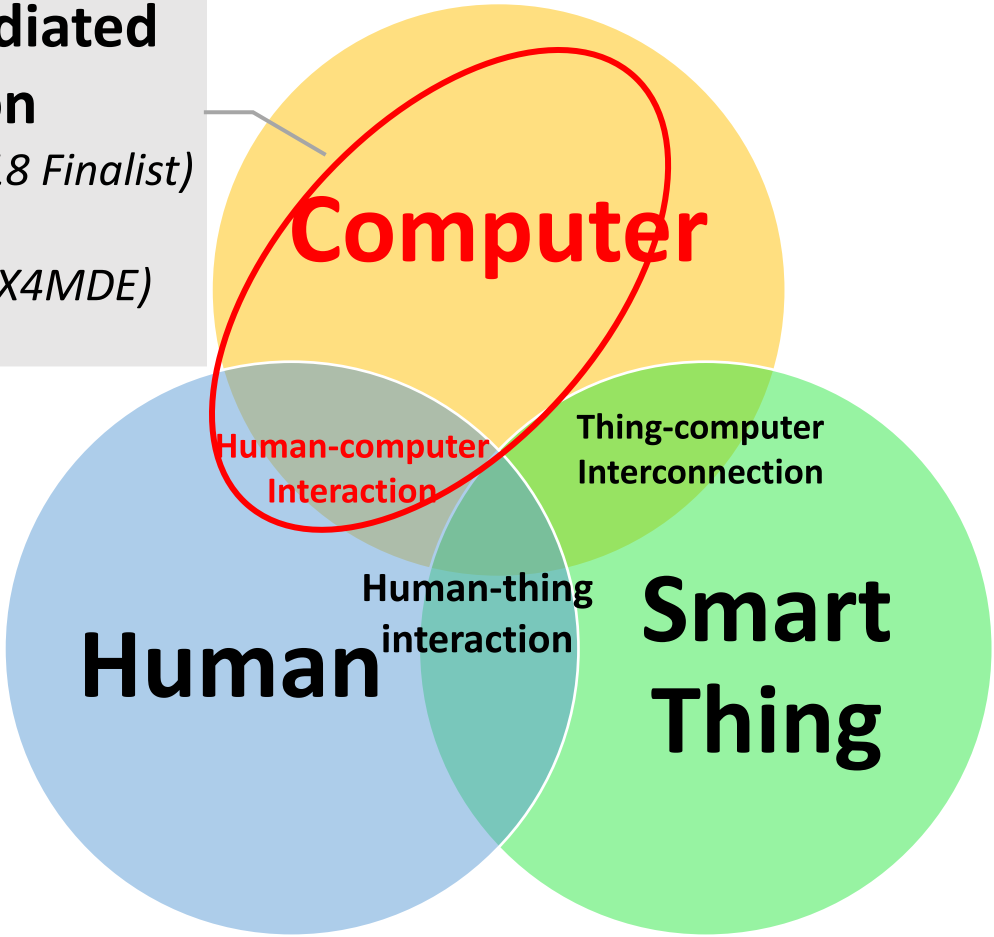
MR world

Enhanced display of resources

Research Summary

Wearable computer-mediated pervasive interaction

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



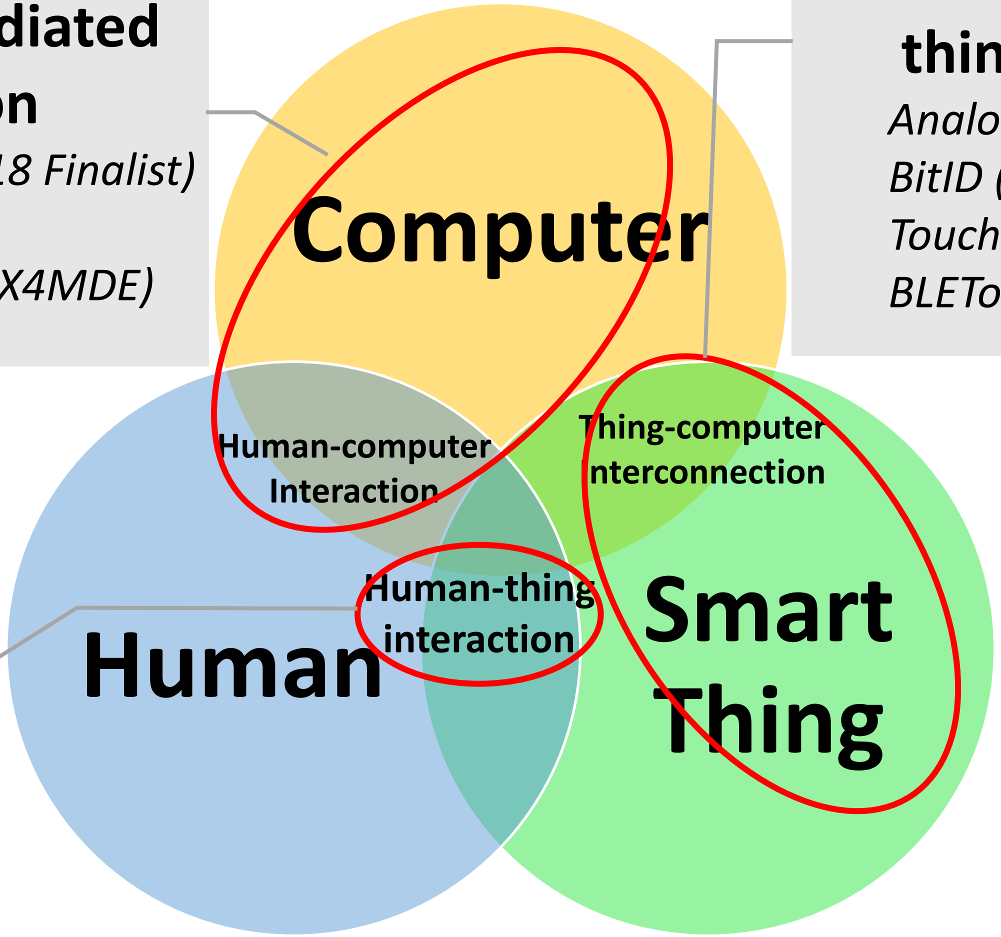
Research Summary

Wearable computer-mediated pervasive interaction

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

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)



Resource-constrained Interaction

Tap-to-Pair (IMWUT 18)
SyncSelect (IMWUT 19)
BoldMove (in progress)

Sustainable and Calm Pervasive Interface