Toward Printable Ubiquitous Internet of Things with Capacitive Sensing, Communications and Identification Tags

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INTRODUCTIONS

Many types of human activities involve interactions with passive objects. Thus, by wirelessly sensing human interactions with such “things”, one can infer activities at a fine resolution, enabling a new wave of ubiquitous computing applications. On the one hand, the ability to sense touch in the physical world can form the basis of the tangible user interface allowing individual to use omnipresent objects as a control interface to the digital world [13, 31, 35, 36]. On the other hand, the sequence of objects used can enable inference of human activities [26, 30]. Logs of objects touched can become the basis of “experience sampling” [5] or “life-logging” [17] that try to reconstruct a user’s day. Post-processing of the logs can support many activity-aware applications, such as stroke rehabilitation assessment in homes, consumer analytics for retail stores [15, 22] *etc.*

To harvest these benefits, a practical system needs to satisfy two requirements. First, such system needs to *sense touches* on different spots of the same object, and be able to *distinguish touches* on different objects. Second, it requires to be simple, flexible and cheap enough so that users are able to fabricate them using the off-the-shield inkjet printer or paints in large scale without professional engineering skills. Although many existing sensors can detect object usages and touch interactions using heterogeneous computer vision and machine learning algorithms *e.g.* motion sensors [30] and cameras [9, 16, 21], they often require augmenting the objects with batteries/circuits, or may provoke strong visual privacy concerns [6]. RFID technology can overcome such limitations by attaching energy-harvesting tags on objects [36]. However, their antennas are typically made of metal pieces using screen printing approach and cannot be easily attach on non-flat surface of irregular objects. Beside, they are barely used in common consumers’ daily life due to the high costs compared to printed barcodes [35].

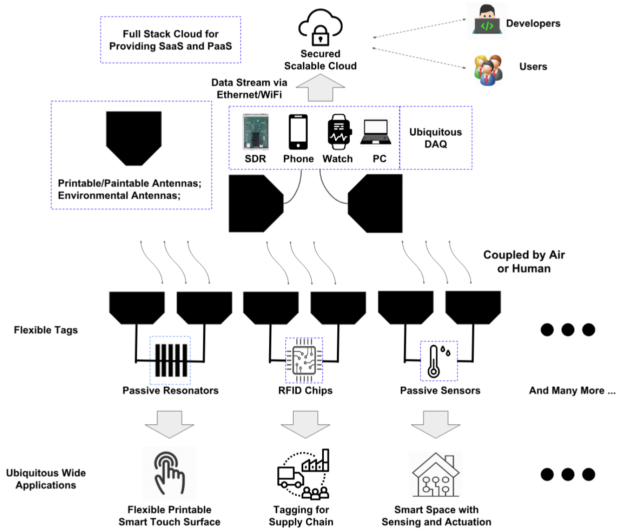

Figure 1: Conceptual diagram of *CapTags*. We envision these tags can be widely used for heterogeneous applications. For example, by combining printing antenna with discrete resonators, it is possible to create multi-touchpoints where different touch locations can be identified from resonance frequencies in spectrum. With the supports of the RFID chips and passive sensors, these tags can be widely used in supply chain and surroundings inferences in smart space [20] where data can be decoded from time-series samples. To build a printable IoT, we also propose an industrial standardized cloud, where both developers and users can utilizing the off-the-shield *Platform as a Service* (PaaS) and *Software as a Service* (SaaS).

PROPOSED WORKS

This project explores the feasibility and limitations of long range inkjet printable ***Cap****acitive Communications, Sensing and Identifications* ***Tags*** (CapTags), empowering a new paradigm of communications and sensing modality for future generation *printable* IoTs. Figure 1 shows our long-term vision where CapTag is a passive paper-like tag, comprised of chipless or chip-based capacitive communication/sensing components, together with printable electrodes (capacitive ”antennas”). Owing to its passive nature and thin form factor, CapTag can be attached on everyday objects and even woven into clothes, thus truly advancing Weiser’s vision of ubiquitous computing [37]. Our project aims to tackle two fundamental questions:

- **Tag Design and Fabrications:** How to **design the printable capacitive-coupled tags** as well as interaction surfaces, such that any user can customize and print the tags to accommodate their own sensing/identification applications?
- **Sensing and Communication Algorithms:** How to **extend the capacitive sensing range** for both air-coupling and body-coupling communications?

To address these challenges, we will design the tag structure to ensure easy fabrication on off-the-shelf inkjet printers [3, 4] without professional skills. Compared to standardized inductive and RF coupled approaches, we propose to use *capacitive coupling*

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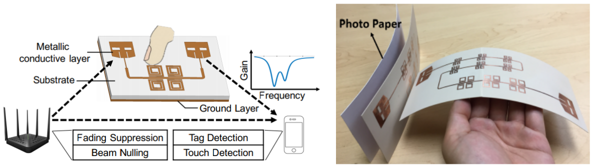
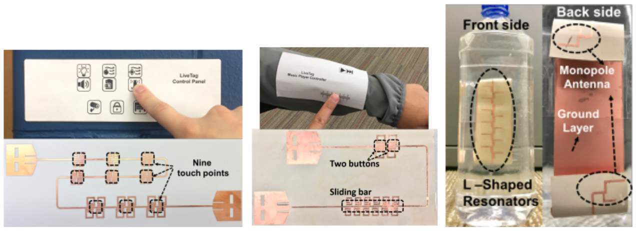
[*] Ke Sun will join Department of Computer Science and Engineering at UC San Diego as a Ph.D. student from Fall 2019.

[44] as the sensing and communication method because it does not have strict requirements on the resistance and shape of antenna, indicating conductive inks having moderate resistance can be used to fabricate such antennas [11, 12, 23, 24, 35]. Based on our previous works on chipless passive RFID [13] and prior art in CPT (capacitive wireless power transfer) [7, 19, 38], we introduce an approach to achieve *hardware featurization* where the resonating frequencies of passive printable resonators on the tag are used to encode information that can be read remotely by an interrogator.

To enable long range sensing with high reliability, we propose a novel sensing approach, named as *High Frequency Swept Frequency Resonating Sensing* (HF-SFRS). Unlike prior works that examine spectrum less than 5MHz [27, 39–42], CapTag's features will be sensed up to 800MHz frequencies. Evidence from high pass characteristics of capacitors and PAN (*Personal Area Network*) [18, 25, 43] supports the intuitions that higher frequency allows more displacement current passing through the coupling region, leading to long sensing range and higher reliability. Furthermore, we introduce a mixture of *closed-form* and *data-driven* approaches to identify human-tag interactions and surrounding sensings. This means the *constant resonating properties* created by resonators of CapTag can be used to mark unique touch points, while the *dynamic resonating properties* reveal the characteristics resulting from diverse surroundings and movements. This allows us to interpret the physical environment and identify human-tag interactions under the same settings.



(a) Conceptual diagram of liveTags. **(b) Sample livetags.**



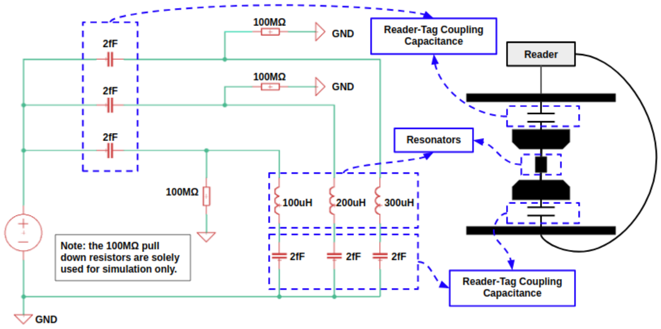
(c) Livetag as a control panel. **(d) Livetag as a music control slider.** **(e) Livetag as a water level detector.**

Figure 2: Our predecessors' work, LiveTags, are able to detect and differentiate tags using everyday WiFi signal. The diagrams are captured from [13].

PRELIMINARY STUDY

The initial preliminary study was based on our predecessors' work, the *LiveTag* [13] that used WiFi signals to identify and differentiate tangible touches. (see figure 2) [1]. The work has successfully proved that the touches and tags information can be encoded and retrieved by analyzing the detunning characteristics in spectrum. However, as Gao *et al.* pointed out, one limitation of the work is that the tags are fabricated by metal foils on thin substrate with carefully designed transmission lines and resonators [13]. We envision to tackle these issues through *capacitive coupling* mechanisms proposed in CapTag.

In order to evaluate the feasibility of our proposed works, firstly, we used discrete components to simulate the capacitance coupling impacts by the customized designed resonators. Referencing to the approximations from multiple literature [18, 43, 44] and theoretical approximations of idea parallel palate capacitance shown in figure 3c, we used $2fF$ capacitors to model the tag-reader coupling as a conservative choice. However, in practice, this value may be even smaller due to the unpredictable shunting effects result from surrounding conductors. Figure 3a shows the schematic that we used to model the CapTag system and the SPICE [10] simulation results can be referred to figure 3b where three *spikes* can be observed visually due to the tag resonating characteristics.



(a) Schematics for simulating tag responses. In this example, we used $2fF$ to model the tag-reader coupling capacitance, as well as $100\mu H$, $200\mu H$, and $300\mu H$ inductors to model 3 tag resonators. For simplicity, we ignore the resistance since they will not change the effective reactance.

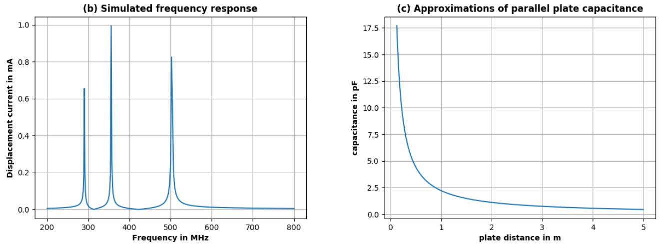


Figure 3: Preliminary study of features caused by tag resonating characteristics. (b) The simulated frequency response where the three *spikes* are caused by the resonation characteristics of three different size inductors. (c) The approximations of parallel plate capacitance, where the effective area is chosen to be $40cm^2$ and the relative dielectric constant is chosen to be 1.

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[1] For more interesing applications, please refer to the online video, available at: https://goo.gl/JjKNaD.

Based on the simulation, we built a rudimentary platform which emulates the the field of views of CapTag reader to measure the coupling performance through quasi-static electric field. Figure 4a demonstrates our initial platform including two *reader electrodes* being able to excite field with variable frequency, and *tags resonators* capable of varying induced displacement current. Ultimately, we will harvest the surrounding environments to overcome the bulky physical setups. Figure 4b shows the initial measurements which proved that the resonating characteristics can be observed visually with frequency sweeping up to $600MHz$ in long spatial range up to around $1m$. From this measurement, the detunning phenomenon resulting from resonator vanishing can be visually observed from three traces, although features caused by unpredictable environmental parasitic capacitance also show up in the response. These demonstrate the aforementioned *constant* and *dynamic resonating properties* allowing readers to sense tags and surroundings simultaneously. As part of our challenges, we envision to expand the sensitivity continuously by both hardware and software approaches, *e.g. electric field repeater* that is widely used in long range capacitive power transfer [38] and increasing the effective coupling areas *etc.*

Finally, besides tagging, we will investigate the potentials for incorporating CapTags into scalable printable IoT infrastructures, for realizing printable human-object interaction surface, supply-chain tagging and resonating-characteristics based biometric authentications *etc.* Referencing to multiple prior arts [14, 24, 42], we have started with experimenting with two printing/painting materials with moderate resistance including carbon/graphite and nickel paint [3]. We envision to harvest the everyday pervasive infrastructures such as floors and furniture *etc.* as the *environmental antenna*, truly embedding the sensing and communications into ubiquitous background [37] and realizing the vision of *printable ubiquitous computing*.

RESEARCH PLAN

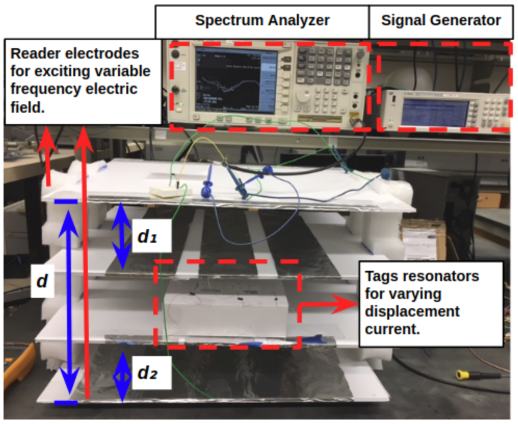
As an initial proposed plan, this project will be executed in 3 phases:

- **Phase 1: Sensing Modality Evaluations:**
  - Evaluate and benchmark the sensing modality via capacitive coupling in terms of sensing range, electrical field plate antenna size as well as the communication medium, *e.g.* air and human body *etc*;
  - Evaluate the potentially of using customized designed discrete resonators, off-the-shelf RFID chips and the passive sensors to distinguish different touch points on time domain and frequency domain;
  - Performance measurements of using inkjet printing approach, *e.g.* [1] and commercially available paints *e.g.* [3];

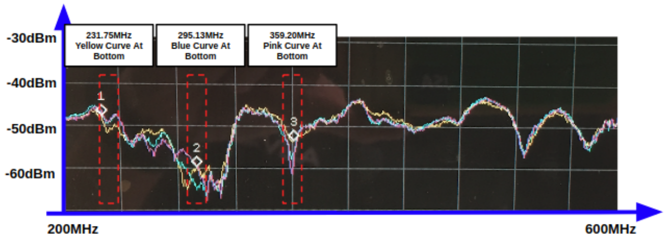
  Provisional Duration: September '18 - February '19;
- **Phase 2: Sensing System Design and Prototyping:**
  - Build the reader for data acquisition and tag hardware, such that the signal can be collected reliably;
  - Investigate the optimal algorithms for detecting spikes from frequency response if discrete resonators are used and bit stream from time-series data if RFID chips are repurposed;
  - Run heterogeneous pilot user study to evaluate the performance and sensing reliability across different individuals, space and time;

  Provisional Duration: February '19 - May '19;
- **Phase 3: Toward a Ubiquitous Printable Internet of Things:**
  - Design and build a scalable backend server that is able to handle sensor stream coming from different nodes;
  - Explore the possibilities that is able to harvest *environmental readers*, *e.g.* ubiquitous touch panel to talk with tags;
  - Scale out the tags and incorporate into various scenarios *e.g.* touch interface and PAN, and continue investigate the potentiality of printable ubiquitous Internet of Things;

  Provisional Duration: May '19 - December '19;



(a) Setups for the preliminary test where 3 tag resonators with values being $100\mu H$, $200\mu H$ and $300\mu H$ are used in this example. Note that the electrodes' size of reader is $40cm \times 40cm$. One of our goal is to push the distances of d, d_1 and d_2 further for enhancing the sensitivities and usabilities.



(b) Frequency response measured by spectrum analyzer with each of three resonators being shorted respectively. Note that the *yellow line* indicate the case when the resonator $300\mu H$ is shorted, the *blue line* indicate the case when the resonator $200\mu H$ is shorted and the *pink line* indicate the case when the resonator $100\mu H$ is shorted. In this measurement, we emulated the actual touch by physically shorting the corresponding resonators.

Figure 4: Preliminary study setups and measurement results where it can be observed that the *notches* caused by tags detunning shown in the spectrum traces.

TEAM MEMBERS

Chen Chen is a first year Ph.D. student at the Department of Computer Science and Engineering, UC San Diego under the advisor of Prof. Xinyu Zhang. He received a Master of Science degree in Electrical and Computer Engineering from the Carnegie Mellon University (Winter 2017) and a First Class Bachelor of Engineering degree in Electrical and Electronic Engineering from the University of Nottingham, UK (Summer 2016). His research interests are broadly include mobile computing, wireless sensing for human-computer interactions as well as large scale distributed and cloud computing for physical and social sensing purpose. His previous research work on Mites/Synthetic Sensor under the advisors of Prof. Yuvraj Agarwal from Institute for Software Research and Prof. Christopher Harrison from Human Computer Interaction Institutes at Carnegie Mellon University was filed under US Patent [2] and is now in the process of being commercialized! For more information about him, please visit: http://cseweb.ucsd.edu/~chc004/.

Ke Sun will join the Department of Computer Science and Engineering, UC San Diego as a Ph.D. student in Fall 2019 under the advisor of Prof. Xinyu Zhang. He is currently a final year Master student advised by Prof. Wei Wang at the Department of Computer Science, Nanjing University, China. He was conferred a Bachelor of Science Degree in Computer Science from Nanjing University of Aeronautics and Astronautics, China with national Outstanding Undergraduate Award (Summer 2016). His research interests mainly include wireless sensing, mobile computing as well as human-computer interactions. As an outstanding HCI innovator, his previous works were frequently published in several top tier conferences including ACM MobiCom 2018 [29] and 2016 [34], IMWUT (UbiComp) 2018 [32], ICPP 2018 [8], MobiSys 2018 [28], and IEEE SECON 2018 [33]. For more information about him, please visit: https://samsonsjarkal.github.io/KeSun/.

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