ZenseTag: Real-Time Passive RFID Sensing

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Abstract

Sensing allows us to interact with and quantify the natural world. Despite the advancements in sensor versatility, sensing systems still suffer from limited adoption due to their dependence on batteries, complex interfaces, energy-harvesting modules, and readout latency. To address these challenges, we present ZenseTag — a miniaturized, sticker-like platform that can interface commercial sensors directly with COTS RFID tags. ZenseTag exploits the impedance response of COTS sensors to the measured stimulus at Radio Frequencies, tuned to the UHF RFID band. It combines reliable hardware realization of differential analog sensing with robust software for accurate, low-latency sensor readouts, even in the presence of multipath effects.

CCS Concepts

• **Hardware** → **Sensor devices and platforms**; **Wireless integrated network sensors**; **Sensor applications and deployments**; *PCB design and layout*.

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1 Introduction

Sensors quantify natural phenomena, enabling human interaction with their environment and automation of daily tasks. Examples include touch detectors [1], moisture sensors [2], and light sensors [3]. However, reliance on wires and toxic batteries makes them bulky, maintenance-intensive, and environmentally hazardous [4–8]. This starkly contradicts the deploy-and-forget paradigm essential for the ubiquitous adoption of sensor technologies [9].

Passive sensing can effectively address these concerns by eliminating the dependence on batteries. Digital sensing platforms still use Analog to Digital Converters, making them bulky and slow to provide real-time readouts [10, 11]. Alternatively, their analog counterparts directly modulate carrier signal parameters [12–15].

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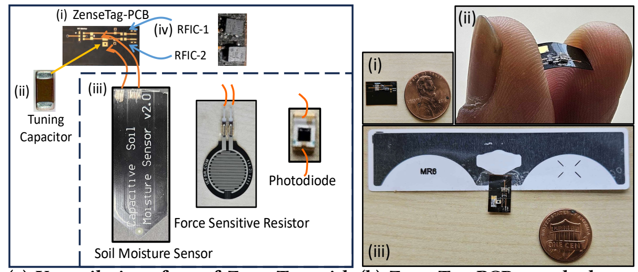


(a) Versatile interface of ZenseTag with COTS sensors **(b) ZenseTag PCB attached to a COTS RFID antenna**

Figure 1: Implementation of ZenseTag in a flexible, miniaturized,sticker-like form factor

To this end, RFID tags, which are small, inexpensive, and flexible, can act as potential passive sensing platforms [16–19]. Previous efforts have attempted to use them as sensors by exploiting their interaction with the environment [16, 20, 21]. However, these methods lack reliability because tags are also affected by environmental stimuli other than the ones they intend to measure [22]. Other works have developed novel dedicated sensors to measure several stimuli like force, temperature, etc. despite the existence of commercially proven sensors [17, 18, 23]. Interfacing COTS sensors with RFID has been challenging due to severe performance degradation from parasitics at RF [22].

Interfacing commercial sensors directly is challenging because they are not designed for RF [24]. Unlike at low frequency, sensors exhibit complex impedances at RF [22, 25]. Moreover, reliable near real-time sensing is hindered by analog readouts' susceptibility to multipath interference and other channel effects [16, 19, 20].

In this work, we present ZenseTag, a novel RFID sensing tag that overcomes these challenges by accurately characterizing sensor impedance, leveraging RF resonance, and achieving true differential analog modulation using a twin-tag-single-antenna architecture as shown in Fig. 1. Our work interfaces commercially available sensors such as a soil-moisture sensor[26], force sensitive resistor (FSR) [27] and a photodiode [28] to an inexpensive and flexible RFID sticker using an ultra-miniature, flexible PCB measuring only 15mm x 10mm as shown in Fig. 1. Further, we have built a high performance software to achieve low-latency, accurate sensor readouts which can work robustly even in the presence of moving objects and people. Using a PyQT driven GUI, we show near real-time sensor readout, as highlighted in our demo videos for soil moisture sensing, force sensing and light sensing [29–31].

2 Design Overview of ZenseTag

The design of ZenseTag comprises of two key components: *hardware design* and *real-time sensing algorithm.* These elements work together to address the challenges outlined previously, with the hardware providing a robust passive interface for sensors using commercial RFID tags, and the algorithm facilitating near real-time analog readout of sensor response changes.

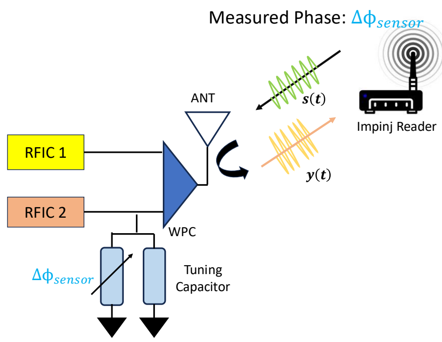


Figure 2: ZenseTag achieves reliable differential analog modulation using Twin-tag Single Antenna architecture

2.1 Hardware Design:

The hardware design consists of three simple steps that can help us interface a commercial sensor with our passive wireless sensing platform. **Direct-to-RF Interface and Sensor Characterization:** The commercially available sensor is stripped off of any interfacing electronic circuits and connected to a simple FR4 PCB using small copper leads. The impedance profile of the sensor is measured using a Vector Network Analyzer. This profile is then used to optimize sensor sensitivity at the UHF RFID band. **Resonance Tuning:** The impedance profile reveals resonance points near the UHF RFID frequency band (within ±200 MHz). We then fine-tune the resonance using passive components like capacitors and inductors to align with the desired frequency bands. Once tuned, the sensor's terminal impedance changes in response to stimuli are captured directly at RF. **Single-Antenna-Twin-Tag Interface:** To prevent corruption of the sensor response by multipath effects, ZenseTag employs a twin-tag configuration: one tag is modulated by the sensor, while the other remains untouched. Both tags are connected to a single compact RFID tag antenna, eliminating phase ambiguities from varying signal paths [32].

In conclusion, ZenseTag integrates a direct-to-RF interface between commercial sensors and a differential twin-tag single-antenna RF PCB, as shown in Fig. 2.

2.2 Real-Time Sensing Algorithm:

We use a host PC that communicates with the Impinj reader's FPGA using the Simple Low-Level Reader Protocol, *SLLURP* [33] implemented as a Python Library which provides the real-time data for phase, channel and RSSI from each tag that it reads. ZenseTag translates changes in sensor impedance at RF into a differential phase value between the two tags. This phase difference is recorded as a time series and processed to provide accurate, near real-time sensor readouts. The Impinj reader should ideally read both tags the same way, as they experience identical channel conditions and roundtrip phases, with the exception of the phase introduced by the sensor to one of the tags. However, since the reader can only read one tag at a time in a sequential fashion, we observe a time-domain shift between the two. To correct for this artificial effect, we use the Dynamic Time Warping algorithm [34] implemented as a Python Library called *fastdtw* [35] to compute the true differential phase introduced by the sensor. In order to enable near real-time sensing, we take into account the latest 5 seconds of data for every subsequent computation when matching the sequences, corresponding to 150 data reads per tag.

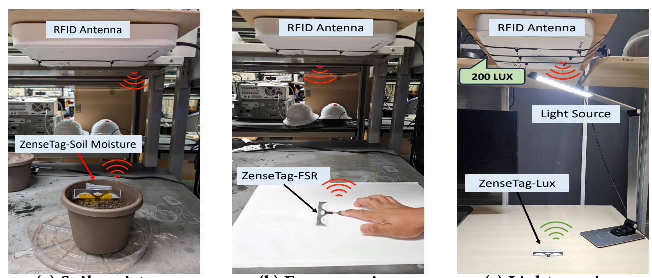
Dynamic Time Warping Algorithm: Dynamic Time Warping (DTW) aligns temporal sequences of varying speeds or lengths to measure similarity, useful in applications like time series analysis.

3 Presentation of ZenseTag

The demonstration will showcase the capability of ZenseTag to detect sensor responses in near real-time.

3.1 Experimental Setup:

The demonstration will require a PC to be connected to an Impinj RF reader which in turn is connected to a high-gain antenna that is kept within range of the ZenseTag that is being trialed. The tag, as shown in Fig. 1, will consist of the ZenseTag PCB interfaced to a sticker-like antenna and two RF ICs; one of the RF ICs will be interfaced to a sensor meant for the necessary application. Illustrating the use of soil-moisture tag will need a pot and some soil while the light sensor will need an external light source. The overall setup for each sensor will look like Fig. 3.



(a) Soil moisture **(b) Force sensing** **(c) Light sensing**

Figure 3: Setups for wirelessly sensing soil moisture, force and light using ZenseTag

3.2 Demonstration:

In order to demonstrate the working of ZenseTag for detecting soil-moisture, force and luminosity, we will vary the soil moisture levels by pouring water in a pot of dry soil, press/depress the FSR using a finger, and cover/uncover the photodiode to showcase the response of ZenseTag for each application which will be visible on the GUI developed with the software. This demonstration will also exhibit ZenseTag's robustness to the presence of objects and the movement of people in and around the deployed sensors. We have evaluated all three sensors: soil moisture (Fig. 3a), force (Fig. 3b) and light (Fig. 3c) using the setup as illustrated in videos: soil moisture sensing, force sensing and light sensing [29–31].

References

[1] Yuzhang Wei and Qingsong Xu. An overview of micro-force sensing techniques. *Sensors and Actuators A: Physical*, 234:359–374, October 2015.

[2] *Humidity and Moisture Sensors*, pages 393–405. Springer New York, New York, NY, 2004.

[3] Bruce R Kinzey, Michael Myer, Michael P Royer, and Greg P Sullivan. Use of occupancy sensors in led parking lot and garage applications: Early experiences.

[4] M.C. McManus. Environmental consequences of the use of batteries in low carbon systems: The impact of battery production. *Applied Energy*, 93:288–295, 2012. (1) Green Energy; (2)Special Section from papers presented at the 2nd International Enery 2030 Conf.

[5] Samuel C. Levy and Per Bro. *Battery Leakage*, pages 43–85. Springer US, Boston, MA, 1994.

[6] Nivedita Arora, Vikram Iyer, Hyunjoo Oh, Gregory D. Abowd, and Josiah D. Hester. Circularity in energy harvesting computational "things". In *Proceedings of the 20th ACM Conference on Embedded Networked Sensor Systems*, SenSys '22, page 931–933, New York, NY, USA, 2023. Association for Computing Machinery.

[7] Ravi Manne and Sneha Chowdary Kantheti. Green iot towards environmentally friendly, sustainable and revolutionized farming. *Green Internet of Things and Machine Learning: Towards a Smart Sustainable World*, pages 113–139, 2021.

[8] Prashobh Karunakaran, Shanthi Karunakaran, Mohammad Shahril Osman, Sreeja Haridas, Prashanth Karunakaran, and Arjun Karunakaran. Farming with the utilization of iot. *Global Journal of Engineering and Technology Advances*, 16(2):124–134, 2023.

[9] W. Keith Edwards and Rebecca E. Grinter. At home with ubiquitous computing: Seven challenges. In Gregory D. Abowd, Barry Brumitt, and Steven Shafer, editors, *Ubicomp 2001: Ubiquitous Computing*, pages 256–272, Berlin, Heidelberg, 2001. Springer Berlin Heidelberg.

[10] Joshua R. Smith, Alanson P. Sample, Pauline S. Powledge, Sumit Roy, and Alexander Mamishev. A wirelessly-powered platform for sensing and computation. In Paul Dourish and Adrian Friday, editors, *UbiComp 2006: Ubiquitous Computing*, pages 495–506, Berlin, Heidelberg, 2006. Springer Berlin Heidelberg.

[11] Rohan Menon, Rohit Gujarathi, Ali Saffari, and Joshua R. Smith. Wireless identification and sensing platform version 6.0. In *Proceedings of the 20th ACM Conference on Embedded Networked Sensor Systems*, SenSys '22, page 899–905, New York, NY, USA, 2023. Association for Computing Machinery.

[12] Xin Na, Xiuzhen Guo, Zihao Yu, Jia Zhang, Yuan He, and Yunhao Liu. Leggiero: Analog wifi backscatter with payload transparency. MobiSys '23, page 436–449, New York, NY, USA, 2023. Association for Computing Machinery.

[13] Vamsi Talla, Bryce Kellogg, Shyamnath Gollakota, and Joshua R. Smith. Battery-free cellphone. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 1(2), June 2017.

[14] Nivedita Arora, Ali Mirzazadeh, Injoo Moon, Charles Ramey, Yuhui Zhao, Daniela C. Rodriguez, Gregory D. Abowd, and Thad Starner. Mars: Nano-power battery-free wireless interfaces for touch, swipe and speech input. In *The 34th Annual ACM Symposium on User Interface Software and Technology*, UIST '21, page 1305–1325, New York, NY, USA, 2021. Association for Computing Machinery.

[15] Vamsi Talla and Joshua R. Smith. Hybrid analog-digital backscatter: A new approach for battery-free sensing. In *2013 IEEE International Conference on RFID (RFID)*, pages 74–81, 2013.

[16] Wei Sun and Kannan Srinivasan. Healthy diapering with passive rfids for diaper wetness sensing and urine ph identification. MobiSys '21, page 188–201, New York, NY, USA, 2021. Association for Computing Machinery.

[17] Agrim Gupta, Daegue Park, Shayaun Bashar, Cedric Girerd, Nagarjun Bhat, Siddhi Mundhra, Tania K. Morimoto, and Dinesh Bharadia. Forcesticker: Wireless, batteryless, thin & flexible force sensors. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 7(1), mar 2023.

[18] Xingyu Chen, Jia Liu, Fu Xiao, Shigang Chen, and Lijun Chen. Thermotag: item-level temperature sensing with a passive rfid tag. In *Proceedings of the 19th Annual International Conference on Mobile Systems, Applications, and Services*, MobiSys '21, page 163–174, New York, NY, USA, 2021. Association for Computing Machinery.

[19] Unsoo Ha, Junshan Leng, Alaa Khaddaj, and Fadel Adib. Food and liquid sensing in practical environments using rfids. In *Proceedings of the 17th Usenix Conference on Networked Systems Design and Implementation*, NSDI'20, page 1083–1100, USA, 2020. USENIX Association.

[20] Ju Wang, Liqiong Chang, Shourya Aggarwal, Omid Abari, and Srinivasan Keshav. Soil moisture sensing with commodity rfid systems. In *Proceedings of the 18th International Conference on Mobile Systems, Applications, and Services*, MobiSys '20, page 273–285, New York, NY, USA, 2020. Association for Computing Machinery.

[21] Jingxian Wang, Chengfeng Pan, Haojian Jin, Vaibhav Singh, Yash Jain, Jason I. Hong, Carmel Majidi, and Swarun Kumar. Rfid tattoo: A wireless platform for speech recognition. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 3(4), sep 2020.

[22] Ju Wang, Omid Abari, and Srinivasan Keshav. Challenge: Rfid hacking for fun and profit. In *Proceedings of the 24th Annual International Conference on Mobile Computing and Networking*, MobiCom '18, page 461–470, New York, NY, USA, 2018. Association for Computing Machinery.

[23] John Nolan, Kun Qian, and Xinyu Zhang. Keystub: A passive rfid-based keypad interface using resonant stubs. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 7(4), jan 2024.

[24] Ju Wang, Omid Abari, and Srinivasan Keshav. Rfid hacking for fun and profit. *GetMobile: Mobile Comp. and Comm.*, 23(1):21–23, jul 2019.

[25] Mahmoud Wagih, Alex S. Weddell, and Steve Beeby. Battery-free wireless light-sensing tag based on a long-range dual-port dual-polarized rfid platform. *Sensors*, 22(13), 2022.

[26] Capacitive soil moisture sensor. https://www.amazon.com/AITRIP-Capacitive-Corrosion-Resistant-Electronic/dp/B094J8XD83?source=ps-sl-shoppingads-lpcontext&ref_=fplfs&psc=1&smid=A2Z10KY0342329, 2021.

[27] Force sensitive resistor. https://www.interlinkelectronics.com/fsr-400-series, 2021.

[28] Osram. ble-iot. https://www.mouser.com/datasheet/2/588/prd_pim_datasheet_28478303_EN_pdf-3392393.pdf, 2021.

[29] Moist diff-z-tag: Demonstration for a soil moisture sensor modulated diff-z-tag. https://www.youtube.com/watch?v=CDn5hxnWvCo, 2024.

[30] Force diff-z-tag: Demonstration for a force sensor modulated diff-z-tag. https://www.youtube.com/watch?v=ToExp731PGk, 2024.

[31] Lite diff-z-tag: Demonstration for a photo sensor modulated diff-z-tag. https://www.youtube.com/watch?v=4Gx3-WtXr2U, 2024.

[32] Ju Wang, Liqiong Chang, Shourya Aggarwal, Omid Abari, and Srinivasan Keshav. Soil moisture sensing with commodity rfid systems. In *Proceedings of the 18th International Conference on Mobile Systems, Applications, and Services*, MobiSys '20, page 273–285, New York, NY, USA, 2020. Association for Computing Machinery.

[33] ransford. Pure-python client for llrp-based rfid readers. https://github.com/sllurp/sllurp, 2023.

[34] Stan Salvador and Philip K. Chan. Fastdtw: Toward accurate dynamic time warping in linear time and space. 2004.

[35] slaypni. fastdtw. https://github.com/slaypni/fastdtw, 2019.