Healthy Diapering with Passive RFIDs for Diaper Wetness Sensing and Urine pH Identification

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ABSTRACT

In this paper, we present RFDiaper, a commodity passive RFID based healthy diapering system, which can sense the diaper wetness (i.e., wet/dry) and identify pH value of urine absorbed by the diaper. To do so, we leverage the coupling effect between the urine absorbed by the diaper and RFID tag, thereby the phase and amplitude variation can indicate urine pH and diaper wetness. However, rich scattering and dynamic environment exhibit a great challenge for accurate diaper wetness sensing and urine pH identification. Therefore, we propose a twin-tag based dynamic environment mitigation approach for robust and healthy diapering. Specifically, by extracting the differential amplitude and phase from the co-located sensing tag and reference tag (i.e., twin-tag) attached on the diaper, the multipath effect and the other dynamic factors (e.g., diaper wearer's body, tag's orientation and temperature, etc.) can be mitigated. Then, we detect the diaper wetness and estimate the urine pH based on differential amplitude and phase. We have implemented RFDiaper's design and evaluated its effectiveness with the experiments using commercial off-the-shelf (COTS) RFID tags attached on the diaper worn by the doll and the human subjects. RFDiaper can achieve the median accuracy of around 96% for diaper wetness sensing and urine pH estimation error of around 0.23 in dynamic environment.

CCS CONCEPTS

• **Computer systems organization** → **Sensor networks**; • **Human-centered computing** → *Ubiquitous and mobile computing systems and tools*; Human computer interaction (HCI).

KEYWORDS

Commodity passive RFIDs, RFID sensing, Healthy diapering, Diaper wetness sensing, Urine pH identification

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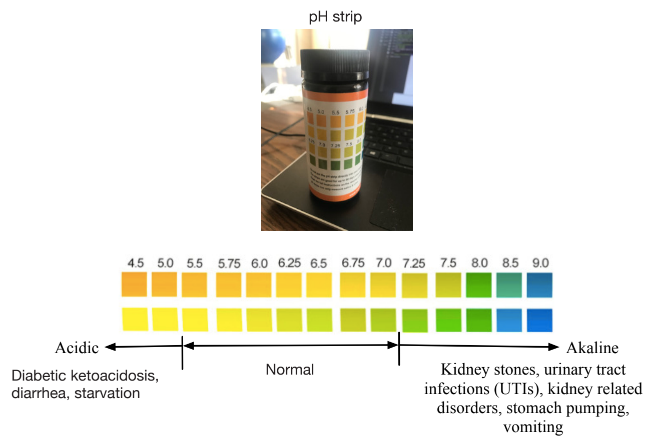

Figure 1: $pH = 7.0$ indicates neutral urine, $pH \geq 7.0$ indicates alkaline urine and $pH \leq 5.5$ indicates acidic urine. Either alkaline urine or acidic urine might signal some medical conditions as shown in the above figure.

1 INTRODUCTION

There is a large fraction of people who needs to use diapers in daily life. For example, urinary incontinence individuals, infants, hospital patients and elderly individuals (i.e., suffering the dementia and Alzheimer) highly rely on the diapers to provide necessary health care. The purpose of using diaper is to absorb urine, such that the diaper wearers can remain dry and comfortable. The caregivers are supposed to attend the diaper wearers and regularly replace the wet diaper with the new and dry diaper. This is because the wet diaper will cause diaper rashes (e.g., irritant diaper dermatitis), discomfort and bacterial infection to the diaper wearers without timely replacing the wet diaper with the dry diaper [23, 37, 48]. Therefore, it is important to monitor the diaper wetness for healthy diapering.

Moreover, the wireless health monitoring applications [55, 56] proliferate the clinical diagnosis, which can achieve real-time medical attention [30]. Among the different vital parameters (e.g., glucose [42], blood pressure [28] and blood oxygen [27]), urine pH value can potentially monitor and diagnose some severe medical conditions [22–24, 48] as shown in Fig. 1. Moreover, the urine pH is an indicator of dietary acid-base load [63]. Normally, the urine pH value is within the range of 5.5-7 with an average of 6.2 [52]. Acidic urine (i.e., $pH \leq 5.5$) or alkaline urine (i.e., $pH \geq 7$) can cause some diseases such as kidney stone, bladder inflammation and renal tubular acidosis [45]. So, urine pH monitoring is essential

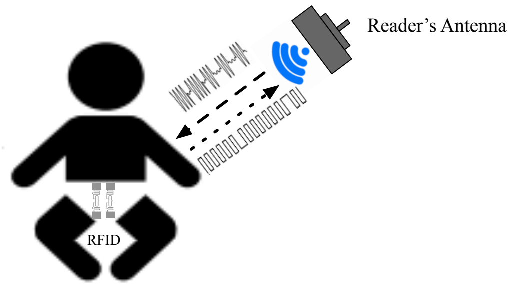

Figure 2: RFDiaper. Twin-tag (i.e., reference tag and sensing tag) is attached to the diaper properly. We can extract the backscattered signals from the reader to sense moisture level of the diaper (i.e., dry/wet diaper) and identify urine pH.

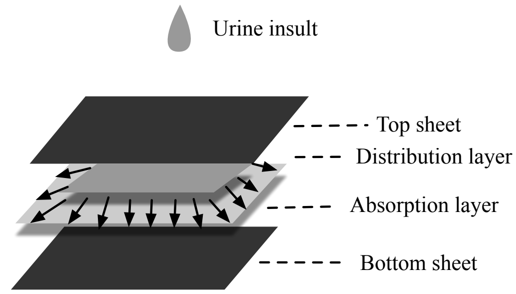

Figure 3: Four layers of a diaper. The figure shows the cross section and constituent layers of a diaper. The black arrows trace the spread and absorption of urine insult thorough the layers.

for personalized health-care and dietary management. Especially, we can monitor the diaper wearer's urine pH based on the urine absorbed by the diaper.

To achieve the predictive health care and at-point diagnostics for diaper wearers, the embedded sensors and customized RFID tags [46, 53, 53, 54, 64, 66] are designed to alert the caregivers, whenever the diaper is wet and needs to be replaced. The sensor based diaper wetness detection system is bulky [7, 9, 15, 39], which needs to be hooked to the commodity diaper uncomfortably. Most commodity diapers [10, 16] use the passive color-changing wetness indicator to indicate the diaper wetness, which is not visually available in dynamic environment (e.g., the diaper is covered by the garment). Usually, the urine pH is detected by the labour-intensive approach. For example, the urine pH test strip requires us to match both pads of the strip to the color chart as shown in Fig. 1, which is prone to be erroneous. The digital pH meter [17] has to be calibrated for high accuracy, whenever we use it. The paper based urine pH estimation sensors are prone to be erroneous and need to be carefully designed [41, 65]. Therefore, it's important to achieve ubiquitous diaper wetness sensing and urine pH identification for healthy diapering.

In this paper, we design and implement RFDiaper, a general-purpose commodity passive RFID based diaper wetness sensing and urine pH identification system as shown in Fig. 2. Since the RFID tag is carefully designed to be resonance at the frequency band of 902-928MHz, the coupling effect between the tag's antenna and the urine absorbed by the diaper will change the backscattered signals accordingly. Based on this observation, RFDiaper can just analyze the backscattered signals from the tag to achieve diaper wetness sensing and urine pH identification. To mitigate the effect of the rich scattering and dynamic environment (e.g., diaper wearer's body movement, tag's orientation, temperature, etc.), we propose to use the twin-tag framework to analyse the differential amplitude and phase of backscattered signals from the co-located sensing tag and reference tag (i.e., twin-tag) attached on the diaper for diaper wetness sensing and urine pH identification.

We build the prototype of RFDiaper to study the accuracy of diaper wetness sensing and urine pH estimation. The evaluation of RFDiaper reveals the following two main results. First, RFDiaper can achieve the median accuracy of 96% for diaper wetness sensing in dynamic environment. Second, RFDiaper can identify the urine pH value with a median estimation error of 0.23 in dynamic environment.

Contributions. We summarize the contributions of the paper as follows:

- First, we design RFDiaper, a system that can sense the diaper wetness and urine pH simultaneously for diaper wearers with commodity passive RFIDs.
- Second, it's the first time that we employ the existing twin-tag framework with commodity passive RFIDs in urine pH identification to suppress the multipath effect in dynamic environment. Furthermore, we discover the differential backscattered signals could be used to identify the urine pH.
- At last, our extensive experiments show the robustness and effectiveness of RFDiaper on sensing diaper wetness and urine pH with dolls and human subjects across different indoor environments.

Paper Roadmap. The rest of the paper is structured as follows. We first show the related work on diaper wetness sensing and urine pH identification in Sec. 2. Then, we present the background and primer on diaper manufacture and commodity passive RFID system in Sec. 3. After introducing the overview of RFDiaper system in Sec. 4, we describe RFDiaper's design in Sec. 5 followed by the implementation in Sec. 6 and evaluation in Sec. 7. We discuss the future work and improvement of RFDiaper system in Sec. 8. At last, we conclude our work in Sec. 9.

2 RELATED WORK

Past literature have exploited the diaper wetness sensing with the dedicated wetness detection sensors and customized RFID tags. The urine pH identification is mainly measured with the dedicated sensors.

2.1 The Dedicated Diaper Wetness Detection Sensors

The straightforward approach to detect the diaper wetness is to use the specific sensors [39] such as Diapersens [7], O'PRO9 [15] and

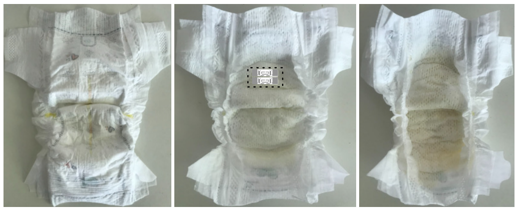

Figure 4: (a) The left figure shows commodity diaper. (b) The middle figure shows the commodity diaper with reference tag and sensing tag deployed between the absorption layer and bottom sheet. (c) The right figure shows the commodity diaper after pouring the adult's urine.

Geecare [9]. These sensors can be paired with the smartphone to monitor the diaper wetness through Bluetooth Low Energy (BLE). To do so, the sensors have to be hooked to the diaper, cover the sensor with adhesive strips and remove the sensor after the diaper is contaminated. So, the sensor based diaper wetness detection is not practical due to labor-intensive changeover and the requirement of battery. Most off-the-shelf diapers [10, 16] use the passive color-changing wetness indicator to indicate the diaper wetness, which requires proximity to the diaper wearer and is not visually available in dynamic environment (e.g., the diaper may be covered by the garment). Even though RFID reader is hundreds of dollars, the commodity RFID tag is very cheap (i.e., around 0.05 USD) and we can use the ubiquitous smartphone as the RFID reader that is exploited in [20, 31]. Moreover, the commodity passive RFID tags have very simple circuit design printed on the substrates, which can enable RFID tags to be ubiquitous and comfortable for wearable sensing tasks [36, 60].

2.2 Customized RFID Based Diaper Wetness Sensing

The existing RFID based diaper wetness sensing systems are built on the customized RFID tags [53, 54, 64, 66], which need to design the specific tag's antennas and circuits. These customized and complex RFID tags rely on expensive and customized reader to power them up. For example, the semi-passive HF RFID tag [54] is designed, which can combine with complex sensors with two units to detect the diaper wetness. The sensing units turn into the voltage cell, which can activate a self-oscillator circuit for transmitter. The complex circuit components require much more power to activate the tag, which will cause low reading range (<30cm). The passive HF RFID tags [64, 66] are designed, which are expensive and require the displacement of the diaper material. The UHF RFID tag [53] is designed for diaper wetness sensing based on the hydrogel sensing. The metal and hydrogel are used for the specific diaper geometry, since the diaper consisting of the super absorbent polymer (SAP) can be leveraged in tag's antenna design. Some of these tags have very long response time (e.g., 5 minutes), which violates the goal of real-time diaper wetness sensing. More importantly, these customized RFID tags cannot sense the urine pH for diaper wearer's health monitoring. The comfortability of wearing these customized RFID tags are questionable, since most of them are made of metal sheet. But, the commodity passive RFID tag is comfortable and ubiquitous to wear in wearable sensing [36, 57, 60].

Figure 5: The urine samples stored in non-sterile specimen cups and the commodity diapers.

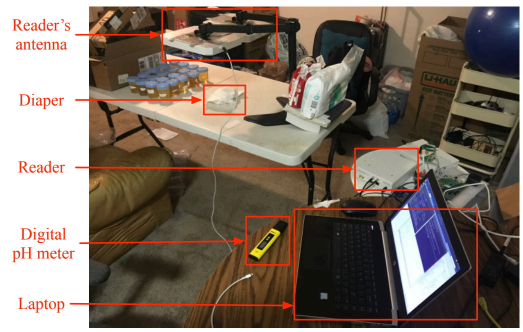

Figure 6: Measurements study on diaper wetness sensing and urine pH identification.

2.3 Urine pH Identification with Dedicated Sensors

The standard approach to measure the urine pH requires a glass electrode and a pH meter, which is bulky and requires complex instrumentation process [21, 35]. In dipstick testing, the reagent strips are used to estimate the urine pH based on the changing color of the reagent strip, which is a coarse grained estimation and not robust. These approaches are labour-intensive and cannot provide the real-time urine pH estimation. Then, the paper based urine pH estimation sensors are developed [25, 38, 41, 44, 51, 65] based on voltammetry, I-V measurement, and potentiometry. However, these sensors will affect the physical and chemical properties of urine, which will cause the erroneous urine pH identification [29, 49]. Moreover, these urine identification papers are not ubiquitous and need to be carefully designed to have best performance.

2.4 Summary

The above approaches cannot achieve the goal of diaper wetness sensing and urine pH identification simultaneously and ubiquitously. However, RFDiaper uses commodity passive RFID tags as sensors to sense the diaper wetness and identify urine pH, which can provide low-cost, robust and effective diaper wetness sensing and urine pH identification in dynamic RF environment with high accuracy. Note, the twin-tag framework has been first introduced in [58] for crafting RFID tags with COTS sensors. Then, the twin-tag framework has been employed for different sensing applications

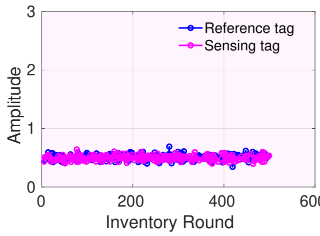

Figure 7: Amplitude readings from twin-tag, when the diaper is dry and static.

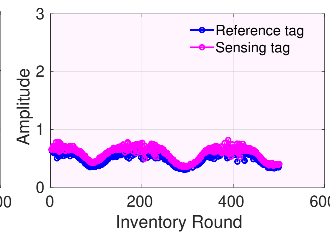

Figure 8: Amplitude readings from twin-tag, when the diaper is dry and dynamic.

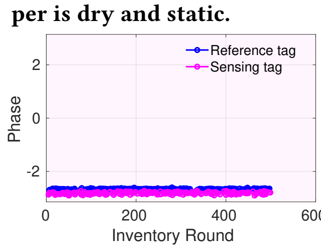

Figure 9: Phase readings from twin-tag, when the diaper is dry and static.

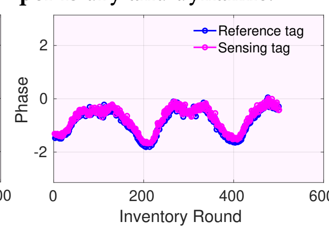

Figure 10: Phase readings from twin-tag, when the diaper is dry and dynamic.

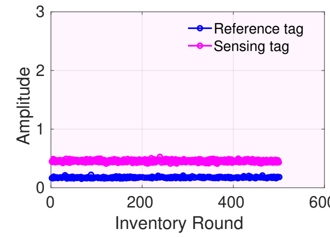

Figure 11: Amplitude readings from twin-tag, when the diaper is wet and static.

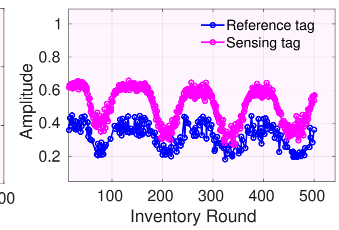

Figure 12: Amplitude readings from twin-tag, when the diaper is wet and dynamic.

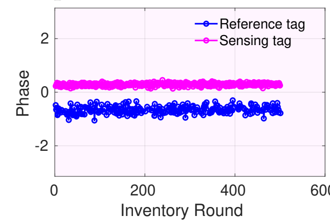

Figure 13: Phase readings from twin-tag, when the diaper is wet and static.

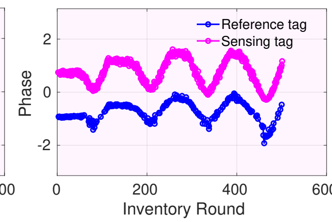

Figure 14: Phase readings from twin-tag, when the diaper is wet and dynamic.

(e.g., GreenTag [59] uses it for soil moisture sensing, RTSense [50] uses it for temperature sensing and [47] uses it for moisture sensing in automaker industry). However, RFDiaper is the first system using twin-tag framework for diaper wetness and urine pH sensing.

3 BACKGROUND

In this section, we first present the primer on the architecture commodity diaper and commodity passive RFID system. Then, we show the measurement study on using twin-tag framework to sense diaper wetness and identify urine pH, whereby we derive three observations to show the feasibility of our design.

3.1 Commodity Diaper

Diaper is widely used for health care among infants, elderly adults and disabled individuals. The diaper typically consists of four layers as shown in Fig. 3: top-sheet (i.e., hydrophilic layer), distribution layer, absorption layer and bottom-sheet (i.e., hydrophilic layer). The top-sheet can absorb the urine to ensure the skin stays dry. The distribution layer attempts to disperse the moisture to the absorption layer, which can absorb and retain the moisture inside the diaper. The absorption layer is the core layer of the diaper, which consists of Super Absorbent Polymer (SAP) containing fluff to facilitate the rapid absorption and moisture retention. The bottom-sheet can repel the moisture and prevent seepage. Also, there are some other associated features (e.g., leg cuff, elastic and tape) to ensure the diaper wearer's comfort and prevent leakage. The performance of diaper depends on the rate of urine absorption, retention and leakage resistance under pressure, which is standardized by ISO [1].

3.2 Commodity Passive RFID System

The commodity passive RFID system [12, 26] consists of an reader and RFID tags. The commodity RFID system employs EPC Gen2 standard using the slotted ALOHA protocol [8]. The time is divided into inventory rounds (i.e., frames), which includes multiple time slots determined by parameter Q. Since the passive RFID tags are battery-free, they need to harvest the energy from the reader to be activated and communicate with the reader. The reader transmits the continuous wave (i.e., cw) to activate the passive RFID tags. The passive RFID tag can change its internal impedance to reflect or not reflect the high-power RF signal from the reader using ON-OFF keying modulation. To represent a '0' bit, the tag does not reflect the incident signal (i.e., impedance match). If tag reflects the incident signal (i.e., impedance mismatch), it represents a '1' bit. The reader can read tag's identifier from the backscattered signal, and extract received signal strength and received signal phase [33] to achieve ubiquitous sensing.

3.3 Measurements and Observations

We first present the preliminary studies and the corresponding observations on diaper wetness sensing and urine pH identification, using commodity passive RFID system.

Experimental settings. We use the commodity diaper in our experiments as shown in Fig. 4(a). The twin-tag is co-located on the diaper as shown in Fig. 4(b). The reference tag is shielded by the hydrophobic material, which can be shielded from the urine absorbed by the diaper. In section 5, we will discuss how to combat the mutual coupling effect between the reference tag and sensing tag. Then, we pour the urine on the diaper as shown in Fig. 4(c). To have the best performance, the twin-tag is deployed between the bottom sheet and the absorption layer [53] as shown in Fig. 27. Fig. 5 shows

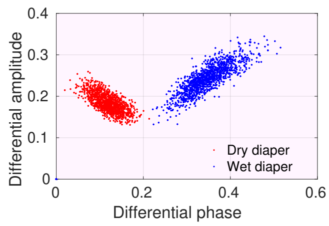

Figure 15: Differential amplitude and phase measurements for wet and dry diaper. As we can see, we can use differential amplitude and phase as features to clearly classify wet and dry diaper.

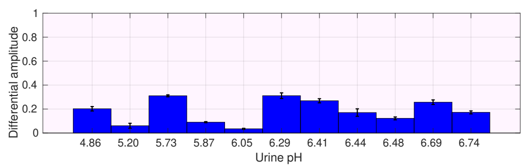

Figure 16: Differential amplitude over different pH value of urine samples.

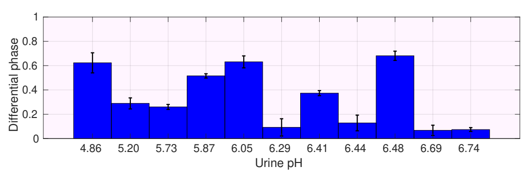

Figure 17: Differential phase over different pH value of urine samples.

urine samples stored in non-sterile specimen cups and diapers we use during the experiments. Fig. 6 shows the experimental settings at an apartment room. The details about the experimental settings and impact of diaper wetness sensing and urine pH identification will be exploited in Section 7. We have following three observations about using twin-tag framework to identify urine pH and sense diaper wetness.

Observation 1. We observe that the twin-tag will experience the same multipath propagation, when the sensing tag and reference tag are co-located. Fig. 7 and Fig. 9 show the amplitude and phase readings from twin-tag attached to the static and dry diaper. Fig. 8 and Fig. 10 show the amplitude and phase readings from twin-tag, when we move the dry diaper around within the reader's communication range. As we can see, the twin-tag experiences the same multipath propagation, since they are co-located.

Observation 2. Next, we pour the adult's urine to the diaper. We observe that the differential amplitude and phase readings of backscattered signals from twin-tag can be used to detect the dry/wet diaper. Fig. 11 and Fig. 13 show the amplitude and phase readings from twin-tag, when we pour adult's urine to the static diaper. Fig. 12 and Fig. 14 show the amplitude and phase readings from twin-tag, when we pour adult's urine to the diaper and move the diaper around within the reader's communication range. We can see that

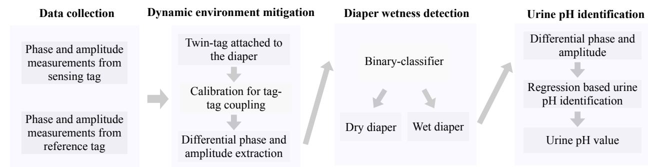

Figure 18: The workflow of RFDiaper system.

the coupling effect between sensing tag and diaper causes the obvious phase and amplitude offset due to the urine absorbed by the diaper.

Observation 3. We observe that the relationship between the urine pH and differential phase/amplitude can be used to identify the urine pH and sense diaper wetness. For diaper wetness sensing, we can design a binary classifier to predict the diaper wetness (i.e., wet/dry diaper) based on the differential amplitude and phase. Fig. 15 plots the differential amplitude and phase measurements for wet and dry diaper. As we can see, the wet/dry diaper can be easily differentiated based on the differential amplitude and phase.

For urine pH identification, we can formulate a regression model to elaborate and estimate the relationship between the urine pH and differential amplitude/phase. Fig. 16 and Fig. 17 plot the measurements of differential amplitude and phase for different urine pH value. As we can see, different urine pH value is corresponding to the different differential amplitude and phase. However, we cannot only rely on differential amplitude or phase to estimate the urine pH. For example, differential phase for urine pH at 5.20 is similar to the differential phase for urine pH at 5.73. But, the differential amplitude for urine pH at 5.20 is quite different from the differential amplitude for urine pH at 5.73. Even though the urine pH value is not linearly related to the differential phase and amplitude, we can still rely on machine learning model using differential amplitude and phase as features to estimate the urine pH value.

Remark. Based on the above three observations, we can see that it is promising to use twin-tag framework to sense diaper wetness and identify the urine pH by harnessing the coupling effect between the sensing tag and the diaper. Before we elaborate RFDiaper's core design, we first present the overview of RFDiaper's workflow below.

4 RFDIAPER OVERVIEW

We mainly use twin-tag (i.e., reference tag and sensing tag) attached to the diaper for diaper wetness sensing and urine pH identification. Two tags are deployed on the diaper next to each other, such that they can experience the same multipath propagation. The coupling effect between the tag and the diaper can help us to achieve diaper wetness sensing and urine pH identification. We mitigate the tag-tag coupling through one-time calibration.

The workflow of RFDiaper is shown in Fig. 18, which includes four main modules: data collection module, dynamic environment mitigation module, diaper wetness detection module and urine pH identification module.

- **Data collection module:** RFDiaper collects the phase and amplitude measurements of the backscattered signals from the sensing tag and reference tag.

- **Dynamic environment mitigation module:** To achieve accurate diaper wetness sensing and urine pH identification, we need to suppress the multipath effect and mitigate the effect of dynamic factors (e.g., diaper wearer's body movement, tag orientation, temperature, etc.). So, we deploy reference tag and sensing tag next to each other on the diaper. We take the differential phase and amplitude from two tags, thereby the multipath effect and dynamic factors can be mitigated as shown in Section 5.2.
- **Diaper wetness detection:** Then, we start to detect the diaper wetness (i.e., wet/dry diaper). To do so, we employ KNN classifier to predict the wet/dry diaper based on the differential amplitude and phase as shown in Section 5.4.
- **Urine pH identification:** After the wet diaper is detected, we should identify the pH value of the urine absorbed by the diaper. To do so, we use the support vector machine (SVM) to regress the pH value of the test measurements by using the differential phase and amplitude as features shown in Section 5.4. Note that the KNN classifier and SVM regression model can be built once in open space and used for the rest of the test measurements, since the twin-tag framework has already resolved the multipath effect and effect of the dynamic factors in different environments.

5 SYSTEM DESIGN

In this section, we mainly present the physical principle of using RFID tag to sense the diaper wetness and identify urine pH, using twin-tag framework.

5.1 Principle of Coupling Effect between Tag and Diaper

RFID tags are configured to alter the reflection co-efficient of RFID tag's antenna by changing its internal impedance. So, RFID tag's antenna is designed to be conjugately matched with the input impedance of RFID tag's chip. When the tag is attached to the diaper, there is a coupling effect (i.e., happening in the near-field) between RFID tag's antenna and the diaper. This is because the electromagnetic field of RFID tag's antenna is affected by the material contents. Since the magnitude and distribution of the coupling effect depend on the dielectric permittivity that is the function of the material's electrochemical and electrophysical properties, the changes of material contents (e.g., the diaper changes from dry to wet by absorbing urine with different pH value) result in the change of coupling effect. Specifically, the backsccattered signals from the RFID tag is $S_{out} = \frac{Z_a - Z_c}{Z_a + Z_c} S_{in}$ where Z_a and Z_c are the impedance of RFID tag's antenna and chip's circuit respectively, given an incoming signal S_{in}. So, the change of Z_a and Z_c resulting from the coupling effect will change the backscattered signal, which can be detected by the reader.

RFDiaper leverages the property of coupling effect to detect the diaper wetness. RFDiaper senses the variation of the RFID tag's response due to the changes of the permittivity of the material that RFID tag couples with. The backscattered signals from the RFID tag are affected by the coupling effect. Suppose that the material's dielectric is denoted as ϵ. The RFID tag's antenna gain is

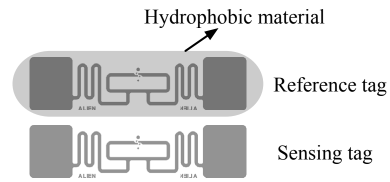

Figure 19: Twin-tag. Reference tag and sensing tag are deployed next to each other on the diaper. The reference tag is covered with the hydrohobic material, and the sensing tag is exposed to the physical environment.

$h_{tag} = |h_{tag}| e^{j\theta_{tag}}$, which is the function of the material's dielectric. So, we have $h_{tag}(\epsilon) = |h_{tag}(\epsilon)| e^{j\theta_{tag}(\epsilon)}$. Therefore, we can sense the backscattered signals from the RFID tag to estimate the diaper wetness and identify the urine pH. Note that RFDiaper's core technique is inspired by the RF dielectric spectroscopy. We leverage the property of coupling effect to sense the diaper wetness and identify urine pH through the difference of backscattered signal from the sensing tag and reference tag. In comparison to using the ratio of backscattered signal for sensing, the difference of backscattered signal is more consistent.

5.2 Twin-tag Design for Dynamic Environment Mitigation

From the above discussions, we can see that the dielectric property of the diaper is changed after it absorbs the urine. Thus, the amplitude and phase of the received signals at the reader are changed accordingly. However, the backscattered signals from the RFID tag are determined by many factors such as the RF environment, hardware of RFID system and the orientation of the RFID tags. It is difficult to know if the change of backscattered signal is caused by the urine absorbed by the diaper.

Since the reader has to initiate the communication to activate the tags, the reader transmits $S_{reader_{Tx}} = |S_{reader_{Tx}}| e^{j\theta_{reader}}$. The tag will receive the following signal:

$$S_{tag} = S_{reader_{Tx}} h_{reader \to tag} h_{tag} \tag{1}$$

$$h_{reader \to tag} = |h_{reader \to tag}| e^{j\theta_{reader \to tag}} \tag{2}$$

$$h_{tag} = |h_{tag}| e^{j\theta_{tag}} \tag{3}$$

where $h_{reader \to tag}$ denotes the wireless channel from the reader to the tag, and h_{tag} denotes the tag's antenna gain. Since the tag uses ON-OFF keying modulation, the tag will reflect or not reflect the received signal from the reader to modulate the data, which is controlled by the tag's chip. Suppose that the reflection coefficient is $\alpha = |\alpha| e^{j\theta_\alpha}$, which is a constant value given the specific RFID tag. Then, the reader will receive tag's reflection signal as follows:

$$\begin{aligned} S_{reader_{Rx}} &= S_{tag} \alpha h_{tag} h_{tag \to reader} \\ &= S_{reader_{Tx}} \alpha h_{tag}^2 h_{air}^2 \\ &= \left| S_{reader_{Tx}} \alpha h_{tag}^2 h_{air}^2 \right| e^{j(\theta_{reader} + \theta_\alpha + 2\theta_{air} + 2\theta_{tag})} \end{aligned} \tag{4}$$

where $\theta_{air} = \theta_{reader \to tag} = \theta_{tag \to reader}$ and $h_{air} = h_{reader \to tag} = h_{tag \to reader}$ due to the reciprocity property of the wireless channel. As we can see, the backscattered signals are related to the gain of

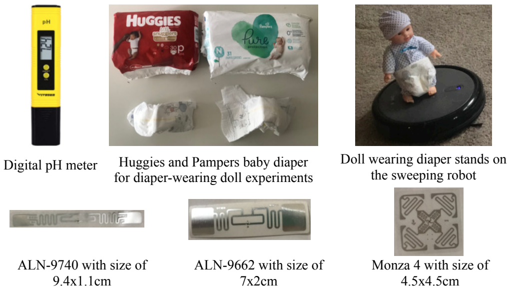

Figure 20: The digital pH meter can measure the urine pH with range of 0-14pH and resolution of 0.01pH, which can be used to collect the ground-truth urine pH value. Huggies and Pampers baby diapers are used for diaper-wearing doll experiments. The doll wearing the diaper stands on the sweeping robot to move around on the floor. Three kinds of general-purpose commodity passive RFID tags are used in our experiments.

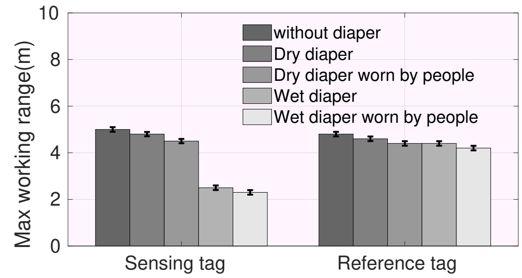

Figure 21: The max working range of sensing tag and reference tag in different scenarios.

tag h_{tag}, backscattered channel h_{air} and gain of reader h_{reader}. The small variation in h_{tag} caused by the coupling effect will be drown in the variation of h_{air} due to the diaper wearer's movement and dynamic environment. So, we have to suppress the multipath effect and extract the change of h_{tag} for diaper wetness sensing and urine pH identification.

To suppress the multipath effect and obtain the clean channel affected by the coupling effect, we deploy two tags next to each other on the diaper as shown in Fig. 19, where one tag is exposed to the physical environment (i.e., sensing tag) and the another tag is urine-proof (i.e., reference tag). Note that using the oxide/polymer-based hydrophobic surfaces and coatings with exceptional water repelling properties are introduced in [34, 40], which is validated to be effective. Since the reference tag and sensing tag are so close, the coupling effect also exists between two tags. We will discuss how to combat the tag-tag coupling in the next subsection. Then, the backscattered signal from the sensing tag is $a_1 e^{j(\theta_{reader}+\theta_\alpha+2\theta_{air}+2\theta_{sen\ tag})}$ where $a_1 = \left|S_{reader_{Tx}} \alpha h^2_{sen\ tag} h^2_{air}\right|$, and the signal from the reference tag is $a_2 e^{j(\theta_{reader}+\theta_\alpha+2\theta_{air}+2\theta_{ref\ tag})}$ where $a_2 = \left|S_{reader_{Tx}} \alpha h^2_{ref\ tag} h^2_{air}\right|$.

We can see that the difference of backscattered signal from reference tag and sensing tag is from $h_{ref\ tag}$ and $h_{sen\ tag}$, where $h_{sen\ tag}$ is affected by the urine due to the coupling effect, and $h_{ref\ tag}$ is barely affected by the urine due to the hydrophobic material that covers the reference tag. So, we can compare the difference of backscattered signals from the twin-tag to achieve diaper wetness sensing and urine pH identification, which has been demonstrated through the measurement study in Sec. 3.

5.3 Combating Coupling Effect between the Reference Tag and Sensing Tag

We have already shown that the coupling effect occurs in the near-field between the diaper and RFID tags. The coupling effect also occurs between reference tag and sensing tag, which will distort the phase and amplitude readings. This is because the signals backscattered from the responding tag will generate the resonate voltage in the antenna of the nearby tags. Then, besides the responding tag, the nearby tags will also emit signals, which will affect the signal received at reader. We can compensate the tag-tag coupling effect by capturing the mutual impedance between tags, which depends on the antenna structure and material. But, it is difficult to mitigate the tag-tag coupling effect by modeling the mutual impedance between tags [62].

To address this problem, we have to calibrate the channel readings of backscattered signal from the reference tag and sensing tag. Specifically, when the reference tag and sensing tag are deployed on the diaper next to each other, we can obtain the difference of backscattered signal from them denoted as ΔS, which depends on tag coupling and is constant over time [62]. Therefore, we can mitigate the tag-tag coupling effect with ΔS from the received signal at the reader. Since we use the difference of backscattered signal from the reference tag and sensing tag to sense the diaper wetness and identify the urine pH, this mitigation should be effective. Since the coupling effect between the reference tag and sensing tag depends on tags themselves, we can just compensate this once and use it for the rest lifetime of the twin-tag.

5.4 Diaper Wetness Sensing and Urine pH Identification

To achieve wet/dry detection of the diaper, we have two steps. In the first step, we collect the differential phase/amplitude measurements for dry and wet diapers in the open space and store them in our database, which will happen only once due to the twin-tag framework. In the second step, we employ KNN classifier [13] to predict the wet/dry diaper with our database.

To identify the urine pH, we formulate a regression model. There are two steps to estimate the urine pH based on differential amplitude and phase. In the first step, we collect the differential phase and amplitude measurements for urine samples with different pH values in the open space and store them in our database. Note that this process will just happen once, since the twin-tag framework has already accounted for the effect of different dynamic environments. Then, we employ support vector machine (i.e., SVM) to estimate the urine pH value through regression.

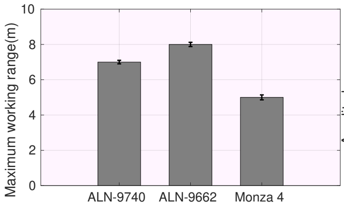

Figure 22: Maximum working range of three types of commodity passive RFID tags.

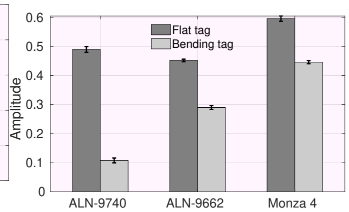

Figure 23: Variation of amplitude for flat-shape and bending-shape tags.

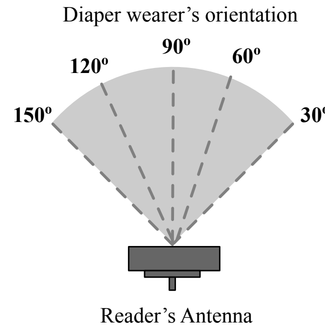

Figure 24: Diaper wearer's orientation with respect to the reader's directional antenna.

6 IMPLEMENTATION

Hardware. USRP N210 equipped with SBX daughterboard is used in our experiments as RFID reader, where we can extract the amplitude and phase measurements of backscattered signals from twin-tag. It can operate in the frequency band of 902-928MHz, which is accordance with FCC regulation. The directional antenna [3] is attached to the reader to activate and communicate with the RFID tags. In our experiments, we use three general-purpose commodity RFID tags: Alien Squiggle ALN-9740 [5], Alien Short ALN-9662 [4] and Impinj Monza 4 [11] shown in Fig. 20. We use two commodity disposable diapers: Huggies [10] and Pampers [16] with different size shown in Fig. 20, which will be worn by the doll standing on the sweeping robot for micro benchmarks. We also measure the performance of RFDiaper using the adult's diaper [2] worn by the adults for case study.

Software. Our algorithms are implemented in MATLAB for offline processing. We use HP laptop with Intel Core i7 CPU at 3.6GHz and 32G memory running under Ubuntu 16.04 LTS operating system, which is connected with the USRP reader through Ethernet cable. The USRP reader communicates with RFID tags through EPC Gen2 standard using slotted ALOHA protocol. KNN classifier for diaper wetness sensing and SVM regression model for urine pH identification are implemented in MATLAB.

Experimental settings. We take the urine samples from three human subjects and store them in the non-sterile specimen cups as shown in Fig. 5. Since the urine samples are obtained from the healthy human subjects, the urine pH value varies between 4.5 and 8.0. We have collected 1950 data examples in total. Then, 80% of the collected data will be used for training and the remaining data will be used for test. During the experiments, we will pour the urine to the diaper to obtain the wet diaper. Since different individuals have different urine output between 0.5cc/kg/hr and 1.5cc/kg/hr [14], we pour the urine with volume of about 50cc to the diaper in our experiments [53], which will eliminate the impact of urine volume on diaper wetness and urine pH sensing. Note that urine will be absorbed by the diaper's absorption layer, behind which the twin-tag is attached. Therefore, the urine volume poured to the diaper will not affect the performance of RFDiaper due to the saturation of the diaper's absorption layer.

We do our experiments in the different rooms of an apartment as shown in Fig. 30. (1) We first do experiments to show the impacts on the commodity passive RFID system and RFDiaper design such as tag type selection, diaper wearer's orientation and tag location selection. (2) Then, we do the experiments with the doll wearing the diaper in subsection 7.2. To have the wet diaper, we pour the urine to the diaper and the doll will wear this wet diaper. We measure the performance of RFDiaper in a typical apartment room. To have the dynamic environment and doll's movement, the doll wearing the diaper stands on the sweeping robot [18] to move around within the reader's communication range as shown in Fig. 20. (3) At last, three human subjects will wear the adult's diaper and randomly move around in the apartment room as shown in subsection 7.3 to evaluate the performance of RFDiaper on diaper wetness sensing and urine pH identification.

Ground truth. The ground-truth diaper wetness (i.e., dry/wet) is easy to obtain. If the diaper is poured with the urine, it is a wet diaper. Otherwise, it is a dry diaper. To obtain the ground-truth urine pH value, we use a digital pH meter as shown in Fig. 20 to measure the urine pH. The measurement range of this digital pH meter is 0-14pH with resolution of 0.01pH.

In this section, we evaluate the performance of RFDiaper. We first run micro-benchmark experiments to evaluate the impacts on commodity RFID system and RFDiaper's design. Then, we evaluate the accuracy of diaper wetness sensing and urine pH identification with diaper-wearing dolls in different indoor environments. At last, we show a case study with human subjects on diaper wetness sensing and urine pH identification.

7 EVALUATION

7.1 Micro Benchmarks

7.1.1 Effect of Twin-tag Range. Since the coupling effect between the tag and the diaper will affect sensing tag's efficiency, we first measure the communication range of sensing tag and sensing tag.

Method. To see the range effect of twin-tag, we measure the max working range of reference tag (i.e., covered by the hydrophobic material) and sensing tag (i.e., without covering) in different scenarios (e.g., the tag could be attached on the dry/wet diaper, and the diaper could be worn by people). The max working range is obtained, when the reader can not read tag as we increase the line-of-sight distance between tag and reader. As a comparison, we measure the max working range of sensing tag and reference tag (i.e., Monza 4 tag).

Result. Fig. 21 shows the max working range of sensing tag and

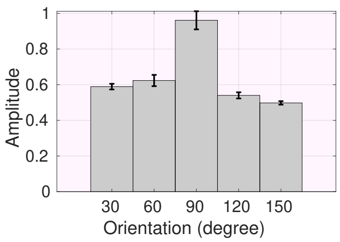

Figure 25: Variation of amplitude over diaper wearer's orientation with respect to the reader.

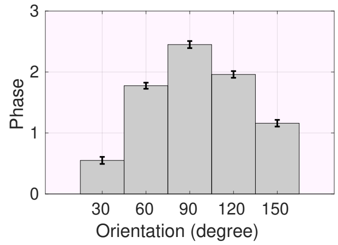

Figure 26: Variation of phase over diaper wearer's orientation with respect to the reader.

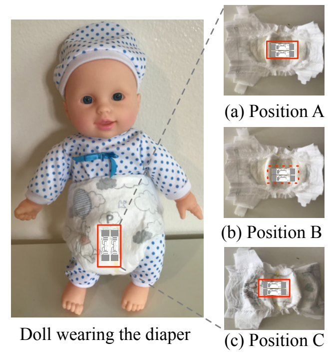

Figure 27: Three possible locations of deploying reference tag and sensing tag on the diaper. (a) Tag position A: on the top sheet of the diaper; (b) Tag position B: between the bottom sheet and absorption layer of the diaper; (c) Tag position C: on the bottom sheet of the diaper.

reference tag in different scenarios. The max working range of Monza 4 is around 5m, when the tags are not attached to the diaper. When the sensing tag and reference tag are attached on the dry diaper worn or not worn by people, the max working range does not decrease significantly. The decrease of max working range is mainly due to the blockage of clothes and diaper itself. However, when the diaper is wet, the sensing tag's max working range is decreased to around 2.5m and the reference tag's max working range is around 4.4m. This is because the reference tag is coated by the hydrophobic material, which will not significantly affected by the wet diaper. The sensing tag is affected by the coupling effect, which will impact the sensing tag's efficiency.

7.1.2 Tag Type Selection. There are different kinds of commodity passive RFID tags in the market. These commodity passive RFID tags are general-purpose.

Method. It is essential to select the right type of tag for diaper wetness sensing and urine pH identification, as the different types of tags exhibit different size and chip type resulting in different working range and performance. Also, since the tag should be attached to the diaper, the tag may be bent and exhibit the C-shape which will affect the tag's performance. Therefore, we aim to choose the tag, which can exhibit stable performance and long working range. To do so, we first measure the maximum working range of three types of tags as shown in Fig. 20. Then, we measure the amplitude of three types of tags, when they are bent as C-shape and compare with flat-shape tag.

Result. Fig. 22 shows the maximum working range of three types of commodity passive RFID tags. As we can see, ALN-9662 has the maximum working range of 8.1m, while ALN-9740 and Monza 4 have the maximum working range of 7.1m and 4.6m respectively. Fig. 23 shows the variation of amplitude for flat tag and bending tag. For the same type of tag, flat tag and bending tag exhibit different amplitude. The amplitude of backscattered signals from bending tag is smaller than the amplitude of backscattered signals from flat tag. We can see that the amplitude of backscattered signals from ALN-9740 is decreased more heavily than the amplitude of backscattered signals from ALN-9662 and Monza 4, after the tags are bent. Based on the above analysis, we choose to use ALN-9662 for diaper wetness sensing and urine pH identification.

Remark. In the above analysis, we compare the max working range of general-purpose RFID tags in different scenarios. The communication range limit of commodity passive RFID system is not inherited from our design. The commodity passive RFID system can have the communication range of 5-15meters at best [61], which is sufficient for the most room-scale applications. Recently, pushing commodity RFID tag's sensing range is exploited by many papers such as PushID [61], In-N-Out [32] and RFly [43], which can provide an opportunity to enhance the sensing range of RFDiaper. Note that the communication range of RFID tags will not affect RFDiaper's sensing accuracy, as long as the reader can receive the backscattered signals from the twin-tag. This is because we leverage the differential backscattered signals for sensing, which can address the tag-reader distance dependence issue.

7.1.3 Diaper Wearer's Orientation. Since the commodity RFID tag exhibits non-isotropic radiation, it mainly backscatters the reader's signal surrounding the tag body and has blind direction along its radial direction [62]. In the worst case, the diaper wearer's body may block the direct-path between the reader and tag, whereby the tags may not be activated properly. So, the diaper wearer's orientation with respect to the reader's directional antenna will affect performance of RFDiaper system.

Method. To measure the impact of diaper wearer's orientation, we measure the amplitude and phase of backscattered signals from one RFID tag attached to the diaper worn by the doll. Specifically, we deploy the doll wearing diaper at the angle of 30°, 60°, 90°, 120° and 150° with respect to the reader's directional antenna as shown in Fig. 24.

Result. Fig. 25 shows the variation of amplitude over diaper wearer's orientation with respect to the reader. Since the distance between the reader and the diaper is same over different orientations, the variation of amplitude is due to the directional property of the reader's antenna. We can see that the change of amplitude is significant due to the directional antenna gain. Since we obtain the amplitude measurements for five different orientations (i.e., 30°, 60°, 90°, 120° and 150°), the amplitudes over different orientations are symmetric at the orientation of 90°. In theory, the phase values

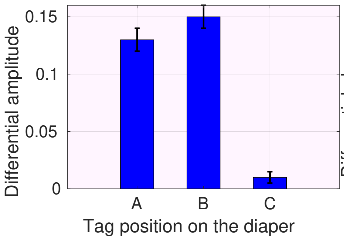

Figure 28: Differential amplitude of backscattered signals from twin-tag attached at tag position A, B and C of the diaper, when we pour urine to the diaper.

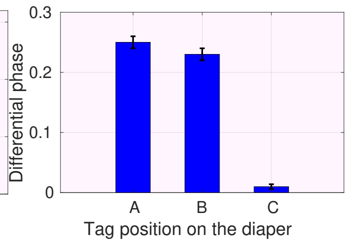

Figure 29: Differential phase of the backscattered signals from the twin-tag attached at tag position A, B and C of the diaper, when we pour urine to the diaper.

Figure 30: A two-floor town house with two bedrooms, one dining room and one living room

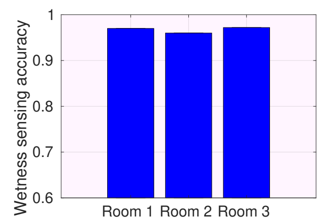

Figure 31: Accuracy of diaper wetness sensing in different rooms.

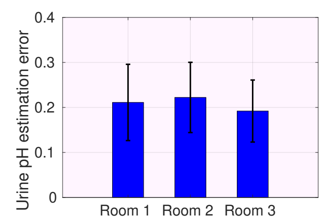

Figure 32: Urine pH estimation error in different rooms

over the five different orientations should not change. This is because the distance between the reader and the diaper is constant over five orientations. Fig. 26 shows the variation of phase over different orientations with respect to the reader. As we can see, the phase changes as the diaper wearer's orientation changes. This is because the tag's orientation changes as the diaper wearer's orientation changes. RFDiaper employs the twin-tag framework, whereby the reference tag and sensing tag will have the same orientation in comparison to the reader's antenna. Therefore, the diaper wearer's orientation will not impact the performance of RFDiaper on diaper wetness sensing and urine pH identification, as long as the reader can read the tag successfully.

7.1.4 Tag Location Selection. As illustrated in Sec. 3, the commodity diaper has multiple layers with different functions.

Method. It's important to select the best location on the diaper to attach the twin-tag, such that the coupling effect between the tag and diaper is effectively harnessed. To select the best location to deploy reference tag and sensing tag, let's first recall the structure of the diaper mentioned in Section 3. There are four layers: top sheet, distribution layer, absorption layer and bottom sheet. To minimize the interference of urine absorption and retention, we can choose three possible locations to deploy two tags as shown in Fig. 27: two tags attached to top sheet (i.e., tag position A), two tags attached between the absorption layer and bottom sheet (i.e., tag position B) and two tags attached to bottom sheet (i.e., tag position C). Therefore, we deploy reference tag and sensing tag at tag position A, tag position B and tag position C of the diaper. Then, we measure the channel variation of two tags, after we pour urine to the diaper.

Result. Fig. 28 and Fig. 29 show the differential amplitude and phase of backscattered signals from twin-tag attached to the position A, B and C of the diaper, when we pour urine to the diaper. As we can see, the differential amplitude and phase is around 0.12 and 0.25, when twin-tag is deployed at tag position A or B. However, the differential amplitude and phase is close to zero, when twin-tag is deployed at tag position C. This is because the bottom sheet blocks the urine, such that the twin-tag is barely affected. Note that twin-tag will touch infant's skin directly, if we deploy twin-tag at tag position A. To maximize the performance of diaper wetness sensing and minimize the effect of urine retention and absorption, the twin-tag is deployed between the bottom sheet and the absorption layer (i.e., tag position B). Note that this deployment is also adopted by the other customized tag's design [53].

7.2 Accuracy of Diaper Wetness Sensing and Urine pH Identification

In this subsection, we evaluate the accuracy of diaper wetness sensing and urine pH identification in static and dynamic environment with the diaper-wearing doll.

7.2.1 Impact of Different Environments. We first evaluate the performance of RFDiaper in different environments. Specifically, we measure the accuracy of diaper wetness sensing and urine pH estimation in different rooms of an apartment.

Method. The doll wearing the diaper stands on the sweeping robot in different rooms of the apartment as shown in Fig. 30: bedroom (room 1), dinning room (room 2) and living room (room 3). Then, we collect the measurements of differential phase and amplitude. We estimate the wetness of diaper and the urine pH with the trained model obtained from the experiments in an open space.

Result. Fig. 31 shows the accuracy of diaper wetness sensing, when the diaper wearer is in different rooms. As we can see, RFDiaper can achieve a high accuracy of around 96% in each room for diaper wetness sensing. Fig. 32 shows the urine pH estimation error, when the diaper wearer is in different rooms. The average urine pH estimation error is around 0.20, which is better than pH strips based urine pH identification with resolution of around 0.5 [17]. As we can see, the sensing accuracy is different for different rooms. This

Actual diaper wetness \ Estimated diaper wetness	Dry diaper	Wet diaper
Dry diaper	1	0
Wet diaper	0.04	0.96

Figure 33: Confusion matrix of diaper wetness sensing, when diaper wearer and environment are static.

Actual diaper wetness \ Estimated diaper wetness	Dry diaper	Wet diaper
Dry diaper	0.97	0.03
Wet diaper	0.02	0.98

Figure 34: Confusion matrix of diaper wetness sensing, when the other people move around.

Actual diaper wetness \ Estimated diaper wetness	Dry diaper	Wet diaper
Dry diaper	0.98	0.02
Wet diaper	0.05	0.95

Figure 35: Confusion matrix of diaper wetness sensing, when the diaper wearer moves around.

is because the different rooms have different scales and multipath effects.

7.2.2 Impact of Environment Variation. The environment variation (e.g., the other people move around) may affect differential phase and amplitude readings, which will affect the sensing accuracy. Therefore, we evaluate the impact of environment variation on the accuracy of diaper wetness sensing and urine pH identification.
Method. To have the dynamic environment, we ask people to randomly move around the diaper wearer during the experiment. The diaper wearer is a doll wearing the diaper. The doll will keep static during the experiment, since we try to measure the impact of the other people's movement on sensing accuracy. Then, we pour urine to the diaper. We measure the accuracy of diaper wetness sensing and urine pH estimation error.
Result. Fig. 33 shows the confusion matrix of diaper wetness sensing, when environment and diaper wearer are static. The average accuracy of diaper wetness sensing is around 98%. Fig. 34 shows the confusion matrix of diaper wetness sensing, when the other people move around the diaper wearer. As we can see, RFDiaper can achieve average accuracy of around 97%, which is comparable to the sensing accuracy when the diaper wearer and environment are static. This is because the twin-tag can mitigate the multipath effect. Fig. 36 shows the CDF of urine pH estimation error for static environment and dynamic environment (i.e., diaper wearer moves around or other people move around). As we can see, the median urine pH estimation error (i.e., 0.20) for static environment is very close to the median urine pH estimation error (i.e., 0.22) when the other people move around. Therefore, RFDiaper's diaper wetness sensing and urine pH identification are robust to the dynamic environment due to the twin-tag framework.

7.2.3 Impact of Diaper Wearer's Movement. The diaper wearer's movement will affect the amplitude and phase readings of the backscattered signals from twin-tag. Thus, we measure the impact of diaper wearer's movement on the accuracy of diaper wetness sensing and urine pH estimation error.
Method. We measure the accuracy of diaper wetness sensing and urine pH identification, when the diaper wearer is static and mobile. The doll wearing the diaper stands on the sweeping robot in front of the reader's directional antenna within distance of 1m. We start the experiments with the dry diaper, and measure the differential amplitude and phase from reference tag and sensing tag. Then, we pour urine to the diaper, and measure the differential amplitude

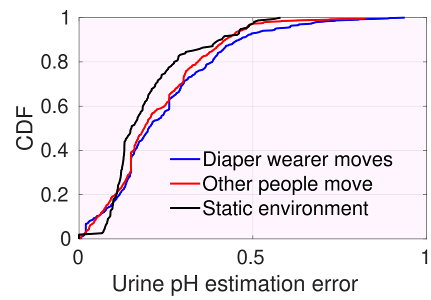

Figure 36: Urine pH estimation error for static environment and dynamic environment (i.e., diaper wearer moves around or other people move around).

and phase from reference tag and sensing tag. To have the mobile diaper wearers, the doll wearing the diaper stands on the sweeping robot.
Result. Fig. 35 show the confusion matrix of diaper wetness sensing, when the diaper wearer is mobile. When diaper wearer moves around, the average accuracy of diaper wetness sensing is around 96%, which is comparable to the accuracy of diaper wetness sensing when the environment and diaper wearer are static. As we can see, RFDiaper is robust to the dynamic RF environment and diaper wearer's movement. This implies the effectiveness of RFDiaper in enabling intelligent health care and at-point diagnostic. Let's get back to Fig. 36 to see the impact of diaper wear's movement on urine pH estimation. As we can see, the median urine pH estimation error (i.e., 0.20) for static environment is close to the median urine pH estimation error (i.e., 0.24) when the diaper wearer moves around. The median urine pH estimation error for two dynamic environments (i.e., diaper wearer moves or the other people move) is quite close. This potentially indicates that RFDiaper does not depend on the change of environments due to the twin-tag framework.

7.3 Case Study

In this subsection, we evaluate the performance of RFDiaper with human subjects wearing the diaper and moving around in the apartment room.
Method. We show a case study of RFDiaper with human subjects wearing the diaper and moving around in an apartment room. Note that the adult's diaper has the structure as mentioned in Section 3.

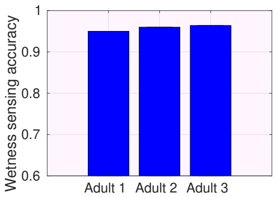

Figure 37: Accuracy of diaper wetness sensing, when three adults wearing the diaper move around in the apartment room.

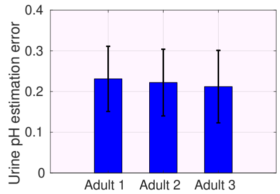

Figure 38: Urine pH estimation error, when three adults wearing the diaper move around in the apartment room.

During the experiments, we pour the urine samples to the diaper and each human subject will wear the dry/wet diaper moving around in the apartment room.

Result. Fig. 37 shows the accuracy of diaper wetness sensing, when human subjects wearing the diaper move around in the apartment room. The accuracy of diaper wetness sensing for each human subject is around 96.38%. Fig. 38 shows the urine pH estimation error, when human subjects wearing the diaper move around in the apartment room. As we can see, the average error of urine pH estimation is around 0.23 for each human subject, which is comparable to the pH strips based urine pH estimation with resolution of around 0.5 [17]. Therefore, RFDiaper can achieve healthy diapering for diaper wetness sensing and urine pH identification.

8 DISCUSSION

The experimental results show the promise of using commodity passive RFID system to sense the diaper wetness and identify urine pH, which can achieve the goal of predictive health care and at-point diagnostics. To build a robust and reliable RFDiaper, we can improve RFDiaper in the following aspects:

- **RFDiaper at edge.** Our current deployment cannot be directly applied in the remote health caring scenario through the edge-cloud system. In the future, the diaper wetness sensing data and urine pH value can be uploaded to the remote cloud and monitored through the smartphones of the caregivers, which can offer more flexibility to the caregivers for large-scale heath care (e.g., attending diaper wearers in a hospital and nursing home). To do so, we need distributively deploy collaborative RFID readers in large-scale indoor environments for diaper wetness and urine pH sensing.
- **Scalability of RFDiaper.** The scalability of RFDiaper is important for large-scale deployments and applications. The deployment cost of RFDiaper mainly comes from one-time calibration for eliminating tag-tag coupling effect, hydrophobic coating and commodity RFID reader (i.e., hundreds of dollars). In the future, we can use smartphone (e.g., TiFi [20]) or accessory-assisted smartphone as RFID reader (e.g., [6, 19, 31]). Since we leverage machine learning approach to predict urine pH, the sensing accuracy highly depends on the well-trained model built on the healthy and unhealthy urine samples. We leave the unhealthy urine sensing for our future work. We believe that the recently developed federated learning could further enhance RFDiaper at edge and the scalability of RFDiaper.
- **Urine components sensing.** To further exploit the healthy diapering, we can sense the urine components of diaper wearers using commodity passive RFID tags. This will enhance the predicative health care and at-point diagnostics. However, we need very fine grained resolution to analyse the urine components accurately. Moreover, it is hard to account for the impact of urine pH on accurate urine components sensing.
- **RFDiaper in the real world.** In the real-world deployment of RFDiaper, we need to consider the impact of thickness of diaper wearer's clothes, height of diaper wearers, etc. on the sensing accuracy. Fortunately, these impacts are automatically included, when we carry out the calibration measurement using twin-tag framework. So, they will not affect the sensing accuracy. But, they will decrease the tag's communication range, since they may block the line-of-sight path between tag and reader. The diaper wearer's body temperature will not affect RFDiaper's performance due to the twin-tag framework and its deployment. The urine pH sensing is predicted, as the absorption layer of the diaper is saturated, i.e., the impact of moisture is accounted for.

After we enable these capabilities, we believe that RFDiaper can enhance the point-of-care healthcare diagnostics and healthy diapering ubiquitously.

9 CONCLUSION

Diapers are widely used among infants, elderly adults, hospital patients and disabled individuals. To enhance health care for this population, the event-alerting based diaper can improve the incontinence management, stopping rashes and infections, and avoiding embarrassment. Most importantly, the pH value of urine absorbed by the diaper can indicate the diaper wearer's health. However, there is no system which can achieve the goal of diaper wetness sensing and urine pH identification simultaneously.

In this paper, we present RFDiaper, a commodity passive RFID system which can provide the diaper wetness sensing and urine pH identification to enhance the predictive health care and at-point diagnostics. We analyze the physical principles of using commodity passive RFID system to sense diaper wetness and identify urine pH. To suppress the multipath effect in static and dynamic RF environment, we propose a twin-tag framework to capture the coupling effect between the sensing tag and the diaper. Our experiments show the accurate diaper wetness sensing and urine pH identification for healthy diapering.

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REFERENCES

[1] Absorbent incontinence aids for urine and/or faeces—General guidelines on evaluation. https://www.iso.org/standard/65740.html.
[2] Adult's diaper. https://www.amazon.com/gp/product/B0792P353S/ref=ppx_yo_dt_b_asin_title_o01_s00?ie=UTF8&psc=1.

[3] Alien RFID directional antenna. https://www.alientechnology.com/products/antennas/alr-a0501/.
[4] Alien Short ALN-9662. https://www.atlasrfidstore.com/alien-short-rfid-clear-wet-inlay-aln-9662-higgs-3/.
[5] Alien Squiggle ALN-9740. https://www.atlasrfidstore.com/alien-squiggle-rfid-white-wet-inlay-aln-9740-higgs-4/.
[6] ALR-S350 Alien hand-held RFID reader. https://www.alientechnology.com/products/readers/alr-s350/.
[7] DiaperSens Adult Incontinence Smart Diaper Sensor for Wet Diaper Alert. https://www.amazon.com/DiaperSens-Adult-Incontinence-Diaper-Sensor/product-reviews/B07DBH8KXK.
[8] EPC UHF C1G2 protocol. https://www.gs1.org/standards/epc-rfid/uhf-air-interface-protocol.
[9] Geecare Thin Smart Baby Wet Diaper Alarm Monitoring Baby Urine Regularity and Lost Prevent with Mobile Phone APP. https://www.amazon.com/Geecare-Diaper-Monitoring-Regularity-Prevent/dp/B06XTQW33B/ref=cm_cr_arp_d_product_top?ie=UTF8.
[10] Huggies diaper. https://www.huggies.com/en-us.
[11] Impinj Monza 4. https://support.impinj.com/hc/en-us/articles/202756908-Monza-4-RFID-Tag-Chip-Datasheet.
[12] Impinj RFID reader R420. https://www.impinj.com/platform/connectivity/speedway-r420.
[13] KNN classifier. https://scikit-learn.org/stable/modules/generated/sklearn.neighbors.KNeighborsClassifier.html.
[14] Normal urine output. https://www.cdc.gov/dengue/training/cme/ccm/page57297.html.
[15] O'PRO9 Smart Wearable Humidity Sensor Instant Alert Notification Reminder Prevent Adult Baby Diaper Rash. https://www.amazon.com/dp/B07934MXY9/ref=twister_B079ZBHNJN?_encoding=UTF8&psc=1.
[16] Pampers diaper. https://www.pampers.com/en-us.
[17] pH meters and reagent test strps. https://www.amazon.com/s?k=ph+meter&ref=nb_sb_noss_1.
[18] Sweeping robot. https://www.ecovacs.com/us/deebot-robotic-vacuum-cleaner/DEEBOT-OZMO-960.
[19] TSL-1128 impinj hand-held RFID reader. https://www.atlasrfidstore.com/tsl-1128-bluetooth-uhf-rfid-reader/.
[20] Zhenlin An, Qiongzheng Lin, and Lei Yang. 2018. Cross-frequency communication: Near-field identification of uhf rfids with wifi!. In *Proceedings of the 24th Annual International Conference on Mobile Computing and Networking*. 623–638.
[21] Labrini V Athanasiou, Panagiotis D Katsoulos, Eleni G Katsogiannou, Zoe S Polizopoulou, Myrto Diamantaki, Constantinos Kamatsos, and Georgios Christodoulopoulos. 2018. Comparison between the urine dipstick and the pH-meter to assess urine pH in sheep and dogs. *Veterinary clinical pathology* 47, 2 (2018), 284–288.
[22] DJ Atherton. 2001. The aetiology and management of irritant diaper dermatitis. *Journal of the European Academy of Dermatology and Venereology* 15 (2001), 1–4.
[23] RW Berg. 1988. Etiology and pathophysiology of diaper dermatitis. *Advances in dermatology* 3 (1988), 75–98.
[24] Ronald W Berg, Kent W Buckingham, and Robert L Stewart. 1986. Etiologic factors in diaper dermatitis: the role of urine. *Pediatric Dermatology* 3, 2 (1986), 102–106.
[25] Souvik Biswas, Arijit Pal, Koel Chaudhury, and Soumen Das. 2020. Polyaniline Functionalized Impedimetric Paper Sensor for Urine pH Measurement. *IEEE Sensors Journal* (2020).
[26] Michael Buettner and David Wetherall. 2010. A" Gen 2" RFID monitor based on the USRP. *ACM SIGCOMM Computer Communication Review* 40, 3 (2010), 41–47.
[27] Nam Bui, Anh Nguyen, Phuc Nguyen, Hoang Truong, Ashwin Ashok, Thang Dinh, Robin Deterding, and Tam Vu. 2017. Pho2: Smartphone based blood oxygen level measurement systems using near-ir and red wave-guided light. In *Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems*. 1–14.
[28] Nam Bui, Nhat Pham, Jessica Jacqueline Barnitz, Zhanan Zou, Phuc Nguyen, Hoang Truong, Taeho Kim, Nicholas Farrow, Anh Nguyen, Jianliang Xiao, et al. 2019. eBP: A Wearable System For Frequent and Comfortable Blood Pressure Monitoring From User's Ear. In *The 25th Annual International Conference on Mobile Computing and Networking*. 1–17.
[29] Samantha J Cloake, Her Shuang Toh, Patricia T Lee, Chris Salter, Colin Johnston, and Richard G Compton. 2015. Anodic stripping voltammetry of silver nanoparticles: aggregation leads to incomplete stripping. *ChemistryOpen* 4, 1 (2015), 22–26.
[30] Shirley Coyle, King-Tong Lau, Niall Moyna, Donal O'Gorman, Dermot Diamond, Fabio Di Francesco, Daniele Costanzo, Pietro Salvo, Maria Giovanna Trivella, Danilo Emilio De Rossi, et al. 2010. BIOTEX—Biosensing textiles for personalised healthcare management. *IEEE transactions on information technology in biomedicine* 14, 2 (2010), 364–370.
[31] Joshua F Ensworth and Matthew S Reynolds. 2015. Every smart phone is a backscatter reader: Modulated backscatter compatibility with bluetooth 4.0 low energy (ble) devices. In *2015 IEEE international conference on RFID (RFID)*. IEEE, 78–85.
[32] Xiaoran Fan, Longfei Shangguan, Richard Howard, Yanyong Zhang, Yao Peng, Jie Xiong, Yunfei Ma, and Xiang-Yang Li. 2020. Towards flexible wireless charging for medical implants using distributed antenna system. In *Proceedings of the 26th Annual International Conference on Mobile Computing and Networking*. 1–15.
[33] Klaus Finkenzeller. 2010. *RFID handbook: fundamentals and applications in contactless smart cards, radio frequency identification and near-field communication*. John wiley & sons.
[34] Ahmadreza Ghahremani, Qin Fu, Dounia Baiya, John Simpson, and Aly E Fathy. 2016. Performance of flexible antennas with protective super-hydrophobic coating layers at RF frequencies. In *2016 IEEE Radio and Wireless Symposium (RWS)*. IEEE, 32–35.
[35] Rebecca Ilyas, Karyee Chow, and J Graham Young. 2015. What is the best method to evaluate urine pH? A trial of three urinary pH measurement methods in a stone clinic. *Journal of Endourology* 29, 1 (2015), 70–74.
[36] Haojian Jin, Zhijian Yang, Swarun Kumar, and Jason I Hong. 2018. Towards wearable everyday body-frame tracking using passive rfids. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1, 4 (2018), 1–23.
[37] WE Jordan, KD Lawson, RW Berg, JJ Franxman, and AM Marrer. 1986. Diaper dermatitis: frequency and severity among a general infant population. *Pediatric dermatology* 3, 3 (1986), 198–207.
[38] Ryotaro Kawahara, Parikshit Sahatiya, Sushmee Badhulika, and Shigeyasu Uno. 2018. based potentiometric pH sensor using carbon electrode drawn by pencil. *Japanese Journal of Applied Physics* 57, 4S (2018), 04FM08.
[39] Tareq Khan. 2018. A smart wearable gadget for noninvasive detection and notification of diaper moister. In *2018 IEEE International Conference on Electro/Information Technology (EIT)*. IEEE, 0240–0244.
[40] Mathieu Le Breton, Laurent Baillet, Eric Larose, Etienne Rey, Philippe Benech, Denis Jongmans, and Fabrice Guyoton. 2017. Outdoor meteorological effects on UHF RFID phase shift: Experimental simulations. In *2017 IEEE International Conference on RFID (RFID)*. IEEE, 103–109.
[41] Kin Fong Lei, Kun-Fei Lee, and Shih-I Yang. 2012. Fabrication of carbon nanotube-based pH sensor for paper-based microfluidics. *Microelectronic engineering* 100 (2012), 1–5.
[42] Tianxing Li, Derek Bai, Temiloluwa Prioleau, Nam Bui, Tam Vu, and Xia Zhou. 2020. Noninvasive glucose monitoring using polarized light. In *Proceedings of the 18th Conference on Embedded Networked Sensor Systems*. 544–557.
[43] Yunfei Ma, Nicholas Selby, and Fadel Adib. 2017. Drone relays for battery-free networks. In *Proceedings of the Conference of the ACM Special Interest Group on Data Communication*. 335–347.
[44] Anni Määttänen, Ulriika Vanamo, Petri Ihalainen, Petri Pulkkinen, Heikki Tenhu, Johan Bobacka, and Jouko Peltonen. 2013. A low-cost paper-based inkjet-printed platform for electrochemical analyses. *Sensors and Actuators B: Chemical* 177 (2013), 153–162.
[45] E Hernández Martín, C López Aparicio, G Calatayud Alvarez, and MA Herrera García. 2001. Vesical uric acid lithiasis in a child with renal hypouricemia. *Anales espanoles de pediatria* 55, 3 (2001), 273–276.
[46] Michael McKnight, Feiyan Lin, Hannah Kausche, Tushar Ghosh, and Alper Bozkurt. 2015. Towards paper based diaper sensors. In *2015 IEEE Biomedical Circuits and Systems Conference (BioCAS)*. IEEE, 1–4.
[47] Joan Melia-Segui and Xavier Vilajosana. 2019. Ubiquitous moisture sensing in automaker industry based on standard UHF RFID tags. In *2019 IEEE International Conference on RFID (RFID)*. IEEE, 1–8.
[48] Saikat Mondal, Saranraj Karuppuswami, Rachel Steinhorst, and Premjeet Chahal. 2019. A Wearable Passive pH Sensor for Health Monitoring. In *2019 IEEE 69th Electronic Components and Technology Conference (ECTC)*. IEEE, 1240–1245.
[49] Kamonwad Ngamchuea, Kristina Tschulik, Shaltiel Eloul, and Richard G Compton. 2015. In Situ Detection of Particle Aggregation on Electrode Surfaces. *Chemphyschem: a European journal of chemical physics and physical chemistry* 16, 11 (2015).
[50] Swadhin Pradhan and Lili Qiu. 2020. RTSense: passive RFID based temperature sensing. In *Proceedings of the 18th Conference on Embedded Networked Sensor Systems*. 42–55.
[51] Rahim Rahimi, Manuel Ochoa, Tejasvi Parupudi, Xin Zhao, Iman K Yazdi, Mehmet R Dokmeci, Ali Tamayol, Ali Khademhosseini, and Babak Ziaie. 2016. A low-cost flexible pH sensor array for wound assessment. *Sensors and Actuators B: Chemical* 229 (2016), 609–617.
[52] C Rose, Alison Parker, Bruce Jefferson, and Elise Cartmell. 2015. The characterization of feces and urine: a review of the literature to inform advanced treatment technology. *Critical reviews in environmental science and technology* 45, 17 (2015), 1827–1879.
[53] Pankhuri Sen, Sai Nithin R Kantareddy, Rahul Bhattacharyya, Sanjay E Sarma, and Joshua E Siegel. 2019. Low-cost diaper wetness detection using hydrogel-based RFID tags. *IEEE Sensors Journal* (2019).
[54] Johan Sidén, Andrei Koptioug, and Mikael Gulliksson. 2004. The" smart" diaper moisture detection system. In *2004 IEEE MTT-S International Microwave Symposium Digest (IEEE Cat. No. 04CH37535)*, Vol. 2. IEEE, 659–662.

[55] Ping Jack Soh, Guy AE Vandenbosch, Marco Mercuri, and Dominique MM-P Schreurs. 2015. Wearable wireless health monitoring: Current developments, challenges, and future trends. *IEEE Microwave Magazine* 16, 4 (2015), 55–70.

[56] Upkar Varshney. 2007. Pervasive healthcare and wireless health monitoring. *Mobile Networks and Applications* 12, 2-3 (2007), 113–127.

[57] Chuyu Wang, Lei Xie, Wei Wang, Yingying Chen, Yanling Bu, and Sanglu Lu. 2018. Rf-ecg: Heart rate variability assessment based on cots rfid tag array. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 2 (2018), 1–26.

[58] Ju Wang, Omid Abari, and Srinivasan Keshav. 2018. Challenge: RFID hacking for fun and profit. In *Proceedings of the 24th Annual International Conference on Mobile Computing and Networking*. 461–470.

[59] Ju Wang, Liqiong Chang, Shourya Aggarwal, Omid Abari, and Srinivasan Keshav. 2020. Soil moisture sensing with commodity RFID systems. In *Proceedings of the 18th International Conference on Mobile Systems, Applications, and Services*. 273–285.

[60] Jingxian Wang, Chengfeng Pan, Haojian Jin, Vaibhav Singh, Yash Jain, Jason I Hong, Carmel Majidi, and Swarun Kumar. 2019. RFID Tattoo: A Wireless Platform for Speech Recognition. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 3, 4 (2019), 1–24.

[61] Jingxian Wang, Junbo Zhang, Rajarshi Saha, Haojian Jin, and Swarun Kumar. 2019. Pushing the range limits of commercial passive rfids. In *16th {USENIX} Symposium on Networked Systems Design and Implementation ({NSDI} 19)*. 301–316.

[62] Teng Wei and Xinyu Zhang. 2016. Gyro in the air: tracking 3D orientation of batteryless internet-of-things. In *Proceedings of the 22nd Annual International Conference on Mobile Computing and Networking*. 55–68.

[63] Ailsa A Welch, Angela Mulligan, Sheila A Bingham, and Kay-tee Khaw. 2008. Urine pH is an indicator of dietary acid–base load, fruit and vegetables and meat intakes: results from the European Prospective Investigation into Cancer and Nutrition (EPIC)-Norfolk population study. *British Journal of Nutrition* 99, 6 (2008), 1335–1343.

[64] Kenji Yamada, Nagakura Toshiaki, Ken Ishihara, Yuko Ohno, Atsue Ishii, Sachiko Shimizu, Tomoyuki Araki, Rie Takahashi, Hideya Takahashi, and Eiji Shimizu. 2010. Development of new type incontinence sensor using RFID tag. In *2010 IEEE International Conference on Systems, Man and Cybernetics*. IEEE, 2695–2700.

[65] Fang Yue, Tan Swee Ngin, and Ge Hailin. 1996. A novel paper pH sensor based on polypyrrole. *Sensors and Actuators B: Chemical* 32, 1 (1996), 33–39.

[66] Mohamed A Ziai and John C Batchelor. 2015. Smart radio-frequency identification tag for diaper moisture detection. *Healthcare technology letters* 2, 1 (2015), 18–21.