Soil Moisture Sensing with Commodity RFID Systems

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ABSTRACT

Intelligent irrigation based on measurements of soil moisture levels in every pot in a greenhouse can not only improve plant productivity and quality but also save water. However, existing soil moisture sensors are too expensive to deploy in every pot. We therefore introduce GreenTag, a low-cost RFID-based soil moisture sensing system whose accuracy is comparable to that of an expensive soil moisture sensor. Our key idea is to attach two RFID tags to a plant's container so that changes in soil moisture content are reflected in their Differential Minimum Response Threshold (DMRT) metric at the reader. We show that a low-pass filtered DMRT metric is robust to changes both in the RF environment (e.g., from human movement) and in pot locations. In a realistic setting, GreenTag achieves a 90-percentile moisture estimation errors of 5%, which is comparable to the 4% errors using expensive soil moisture sensors. Moreover, this accuracy is maintained despite changes in the RF environment and container locations. We also show the effectiveness of GreenTag in a real greenhouse.

CCS CONCEPTS

• **Computer systems organization** → **Sensor networks**.

KEYWORDS

Soil Moisture, Greenhouse, RFID

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1 INTRODUCTION

Greenhouses provide optimum growing environments for plants despite adverse climatic conditions [49], making them important in an area of changing climate. There are more than 9 million greenhouses worldwide [31] and it is reported that their market value will increase to about 1.3 Billion USD in 2022 [38]. Thus, improving the productivity of greenhouses has the potential for significant real-world impact.

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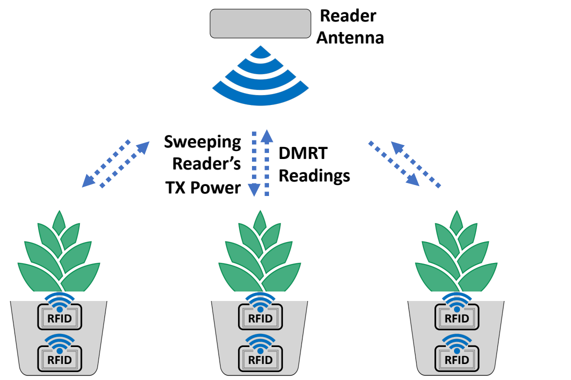

Figure 1: GreenTag senses the soil moisture of pots by using commodity RFIDs. Two RFID tags are attached to each pot where their DMRT readings at the reader side are used for soil moisture estimation.

A typical greenhouse hosts between a thousand and a million plants in pots that contain soil.[1] Measuring soil moisture levels in these pots frequently (e.g., every day) is very important: maintaining suitable moisture levels not only improves plant productivity and quality but also saves up to 25% of irrigation water [43],[33]. One would ideally want a soil moisture sensor in each pot to monitor its moisture level [30]. However, most existing sensors are expensive, making this cost-prohibitive. For example, an ECHO-EC5 soil moisture sensor costs 169 USD [21], in addition to the need for an Arduino controller that costs around 35 USD [4]. Given that low-cost (0.04-0.05 USD) commodity RFID tags are already widely used in greenhouses for tracking and managing plants [39, 50], some RFID-based soil moisture sensing systems have been proposed [5, 6, 37]. However, existing RFID-based moisture sensing systems either detect moisture changes at a coarse grain (e.g., soil is dry or wet) or are not robust to changes in the RF environment and tag locations.

In this paper, we design and implement GreenTag, an RFID-based soil moisture sensing system whose accuracy is comparable to that of precision soil moisture sensors. GreenTag is also robust to changes in the RF environment and pot/tag locations. Our key idea is to attach two RFID tags to a pot, then estimating soil moisture level using a low-pass filtered value of the Differential Minimum Response Threshold (DMRT) metric [46] at the reader to cancel out variations due to environmental changes and pot location changes (Fig. 1). Unlike other RFID-based soil moisture sensing systems, which can only differentiate between dry and wet soil conditions because of their use of Received Signal Strength (RSS) as the sensing

[1]Some greenhouses uses hydroponic irrigation with no soil; we exclude these from the scope of our work.

Figure 2: GreenTag deployment in a greenhouse, where two commodity RFID tags are attached to each pot.

metric [5, 6, 37], GreenTag has fine-grained resolution and is more robust to environmental variations.

We build a prototype of GreenTag studying how to map DMRT values to moisture values, which location on a pot is best, and which tag type works best. Results in a laboratory setting show that, despite changes in the RF environment, GreenTag achieves a 90-percentile moisture estimation error of 5%, which is only 1% more than the error of a high-precision soil moisture sensor. Finally, our case study in a real-world greenhouse (Fig. 2) demonstrates the effectiveness of GreenTag in enabling intelligent irrigation.

Contributions: Our contributions are as follows:

- We introduce GreenTag, the first battery-free, low-cost, and robust soil moisture sensing system, whose accuracy is comparable to that of expensive high-precision sensors.
- We show through both theoretical analysis and real-world measurements that DMRT-based sensing of soil moisture is more robust than RSS-based sensing in a dynamic RF environment.
- We implement our system using commodity RFID devices and comprehensively demonstrate its effectiveness both in a laboratory and a field greenhouse setting.

Paper outline: We discuss the related work in Section 2, and then present background regarding greenhouses and RFID systems in Section 3. We detail GreenTag's design in Section 4. The implementation is described in Section 5, followed by micro-benchmark experiments and the evaluation in Section 6 and Section 7. We conclude our work in Section 8.

2 RELATED WORK

Related work falls into roughly the following three categories:

Dedicated sensors for soil moisture sensing. Many sensors are commercially available for sensing soil moisture [13, 14, 16, 35, 36, 44, 51]. For example, Watermark moisture sensors [44] and electromagnetic soil moisture sensors [14] are used for irrigation scheduling. MEMS moisture sensors [35] and SHT15 humidity sensors [13] are used for monitoring the moisture of concrete structures. To reveal the fine-grained, dynamic moisture changes in an outdoor landscape, a reactive soil moisture sensor network is designed by Cardell *et al.* [16]. Although those sensors can measure the soil moisture, most of them are expensive with a price higher than 50 USD [36], which is not cost-effective to measure soil moisture of all plants in a greenhouse.

In contrast, GreenTag utilizes very cheap commodity RFID tags as soil moisture sensors but still achieves a comparable accuracy to specialized sensors.

RFID-based soil moisture sensing. Some early studies bury commodity RFID tags into soil and use the tags as soil moisture sensors [5, 6, 37]. For example, Aroca *et al.* [5, 6] use the RSS and reading rate of tags to detect a coarse-grained moisture changes. However, they can only detect moisture changes at a coarse grain. Similar to our work, Pichorim *et al.* [37] use two tags for soil moisture sensing. One tag close to the soil surface is sensitive to moisture changes, while the other one far from the soil surface is insensitive. Then, the reader's transmission power difference between the two tags is used as an indicator of soil moisture changes. However, this work has three limitations. First, it only detects whether the soil is dry or wet. Second, the proposed system is not robust to RF environment changes and requires a fixed distance between tags and the soil surface. Third, it requires expensive and customized reader (i.e., Voyantic Tagformance system [45]). The reader needs to operates over 200 MHz (i.e., 800−1000 MHz) bandwidth, which is much wider than the FCC unlicensed band (i.e., 902−928 MHz). Smartrac DogBone RFID tag [9] is a commercial RFID-based moisture sensor for sensing three moisture levels in the air. However, it has limited resolution and is not designed for sensing soil moisture.

To improve the resolution of soil moisture sensing, researchers also build customized RFID tags by adding sensors. For example, Alonso *et al.* [3] changes the structure of tag antennas for sensing five-level moisture. In addition, other studies add a monopole probe [23], a capacitive sensor [17, 28], or a thermometer sensor [22] to an RFID tag for fine-grained moisture sensing. However, these systems require custom tag designs, putting them out of the reach of most researchers, besides raising their cost. Moreover, some of them even require additional batteries to power up the added sensors, which limits their real-world applications.

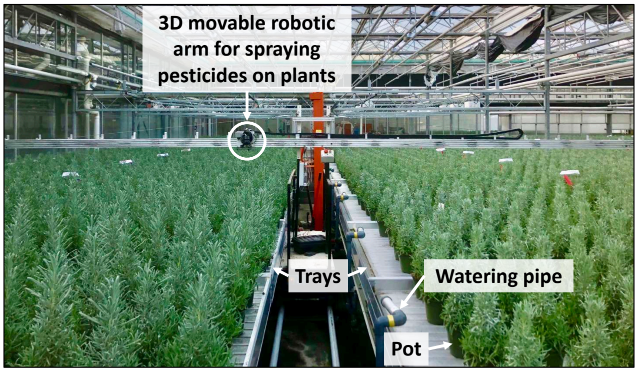

Figure 3: A typical greenhouse. We deploy an RFID reader antenna to a movable robotic arm and RFID tags to pots.

Unlike the existing RFID-based moisture sensing systems, GreenTag works with commodity RFID devices, has a fine-grained resolution, and is robust to environmental variations.

Other RF-based sensing techniques. Some studies use the microwave technology for remote sensing of soil moisture [26, 32, 48]. However, these systems can only detect near-surface (0-5 cm) soil moisture changes. Ground Penetrating Radar [29] and Time Domain Reflectometry [34] techniques provide a good resolution for soil moisture sensing, due to the large bandwidth signal. However, these techniques require specialized equipment, which is not cost-effective for greenhouses.

Recently, Wi-Fi based soil moisture sensing system has also been proposed [19]. Although it can estimate soil moisture precisely, two significant limitations prevent its practical application to greenhouses. First, the size of the antenna array used in their system is larger than the dimension of most pots in a greenhouse. Thus, it is impossible to bury an antenna array into a pot for soil moisture sensing. Second, the antenna array requires multiple RF cables to connect it to Wi-Fi devices. Thus, it is inconvenient to deploy in our setting (unlike in a farm field, which is their deployment scenario).

In summary, compared to prior work, GreenTag uses cheap RFID tags as soil moisture sensors, which can cost-effectively sense moisture in every pot in a greenhouse. GreenTag also achieves high sensing accuracy.

3 BACKGROUND

This section presents some background about greenhouses and RFID systems.

3.1 Greenhouses

A greenhouse provides a highly controlled, pest-free environment for growing plants. A typical greenhouse houses between a thousand and a million plants. To fix ideas, the greenhouse operated by our partner (which is admittedly somewhat atypical in its scale and level of automation) is shown in Fig. 3. Note that plants are grown in pots with soil. Many pots are deployed on trays with a separation of few decimeters. To prevent damage to leaves, plants are watered by filling trays with water and letting the plants absorb water from the tray.

Maintaining proper soil moisture level is important: low soil moisture can cause plants to grow slowly or even die; excessive moisture can cause fungal diseases to thrive. To maintain a proper soil moisture level, greenhouse staff manually check the moisture level of all pots every day, using their bare fingers as probes. When the soil moisture level is below a threshold, the watering pipe adds water into the tray. Some modern greenhouses have a 3D movable robotic arm for spraying pesticides on plants, as shown in Fig. 3. The distance between the arm and the plants is less than 1.2 meter.

Three points about this greenhouse are relevant to our GreenTag system. First, it is possible to attach RFID tags to all pots since the tag is cheap (each costs 0.05 USD), and RFID tags have already been used in this greenhouse for tracking and managing plants [39, 50]. Second, locations of pots rarely change. Third, we can deploy the reader's antenna on the robotic arm, incurring nearly zero extra cost for the greenhouse facility. We expect that other modern greenhouses with similar levels of automation will also be able to deploy our system at little extra cost. However, traditional greenhouses which relying on sprayers or humans for watering do not have the requisite level of automation to benefit from our work.

3.2 RFID Systems

A typical passive RFID system [27, 47] is consists of two parts: a reader and a passive tag. The passive tag has no battery, thus it requires a reader to transmit a high-power RF signal to active it, i.e., the tag harvests energy from the reader's signal to power up itself. Then, the tag replies to the reader by reflecting the high power signal using ON-OFF keying modulation. Specifically, reflecting the reader's signal represents a '1' bit; otherwise it is a '0' bit [1]. Besides the tag's ID information, commodity RFID readers provide us three signal features: Minimum Response Threshold (MRT), RSS, and phase. Next, we discuss these three parameters.

A wireless signal S is typically represented as a complex number with amplitude $|S|$ and phase θ, i.e., $S = |S| \cdot e^{j\theta}$. Suppose that $S_{TX} = |S_{TX}| \cdot e^{j\theta_{TX}}$ is the reader's transmission signal. Then, the signal received by a tag can be expressed as:

$$S_{Tag} = S_{TX} \cdot h_{Air} \cdot h_{Tag}, \tag{1}$$

where $h_{Air} = |h_{Air}| \cdot e^{j\theta_{Air}}$ and $h_{Tag} = |h_{Tag}| \cdot e^{j\theta_{Tag}}$ are channel parameters over the air and the tag's antenna, they are also complex numbers. Note that, in order to active a tag, the power of the tag's receiving signal S_{Tag} must be higher than a threshold, i.e., the receiving sensitivity of a tag's chip. Suppose the receiving sensitivity of the tag is $P_{rx-sen} = 20\log|S^{min}_{Tag}|$, where S^{min}_{Tag} is the weakest tag's receiving signal that can active the tag. Then, the required minimum transmission power, i.e., MRT, of a reader to activate the tag is:

$$MRT = 20\log|S^{min}_{Tag}| - 20\log|h_{Air}| - 20\log|h_{Tag}|, \tag{2}$$

where, $20\log|h_{Air}|$ (<0) and $20\log|h_{Tag}|$ (<0) are the one-way power loss over the air and the tag's antenna [46].

When a tag received a reader's signal, it reflects the received signal for communication. The reflection is controlled by the tag's chip, and the reflection coefficient $\Gamma = |\Gamma| \cdot e^{j\theta_\Gamma}$ is a constant for a given RFID chip. Then, the tag's reflection signal received by the

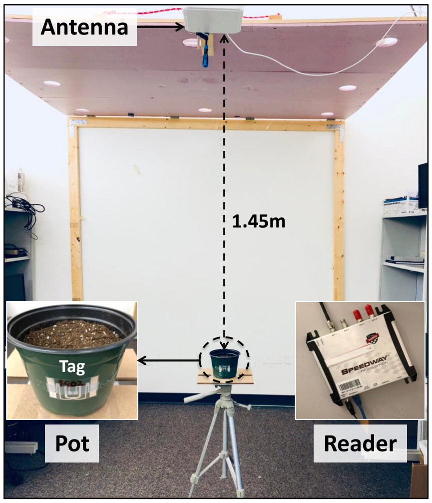

Figure 4: Experimental setup for validating the basic idea of RFID-based soil moisture sensing.

reader can be expressed as:

$$\begin{aligned} S_{RX} &= S_{Tag} \cdot \Gamma \cdot h_{Tag} \cdot h_{Air} \\ &= S_{TX} \cdot \Gamma \cdot h^2_{Air} \cdot h^2_{Tag} \\ &= |S_{TX} \Gamma h^2_{Air} h^2_{Tag}| e^{j(\theta_{TX}+\theta_\Gamma+2\theta_{Air}+2\theta_{Tag})}. \end{aligned} \quad (3)$$

The RSS and phase measured at the reader side are:

$$\begin{aligned} RSS &= 20\log|S_{RX}| = 20\log|S_{TX}| + 20\log|\Gamma| \\ &\quad + 40\log|h_{Air}| + 40\log|h_{Tag}|, \quad (4) \\ Phase &= \theta_{TX} + \theta_\Gamma + 2\theta_{Air} + 2\theta_{Tag}. \quad (5) \end{aligned}$$

where, $20\log|S_{TX}|$ (>0) is the transmission power of an RFID reader, $20\log|\Gamma|$ (<0) is the reflection power loss, $40\log|h_{Air}|$ (<0) and $40\log|h_{Tag}|$ (<0) are the round trip power loss over the air and the tag's antenna.

Summary: The MRT, RSS, and phase features of an RFID tag are related only to the channel parameters over the air and the tag's antenna, i.e., h_{Air} and h_{Tag} because other parameters in Eqn. (2)-(5) are constants, e.g., the receiving sensitivity P_{sen} of a tag, the reflection coefficient Γ of a given RFID chip, and the reader's transmission signal S_{TX} of a given reader setup.

4 SYSTEM DESIGN

In this section, we discuss the design of GreenTag. We first model RFID signals to understand the signal changes caused by the soil moisture. Then, we discuss key issues in our design, including signal feature selection, tag type selection, and tag deployment location selection. Next, we show how to design a robust system that is resilient to changes in the RF environment and pot locations. Finally, we show how to calibrate our system and summarize the system design steps.

4.1 Soil Moisture and RFID Signals

We now describe the basic physical principle that enables GreenTag to estimate soil moisture levels from RFID signals. In Section 3.2, we show that the MRT, RSS, and phase features of an RFID tag are related only to the channel parameters over the air and the tag's antenna, i.e., h_{Air} and h_{Tag}. For the sake of simplicity, we rewrite the Eqn. (2), Eqn. (4) and Eqn. (5) as follows:

$$\begin{aligned} MRT &= C_1 - 20\log|h_{Air}| - 20\log|h_{Tag}|, \quad (6) \\ RSS &= C_2 + 40\log|h_{Air}| + 40\log|h_{Tag}|, \quad (7) \\ Phase &= C_3 + 2\theta_{Air} + 2\theta_{Tag}, \quad (8) \end{aligned}$$

where, C_1, C_2 and C_3 are constants. C_1 is the receiving sensitivity of a tag. C_2 and C_3 are related to the amplitude and phase of both the reader's transmission signal and the reflection coefficient of the tag's chip. Next, we use these equations to show why the soil moisture can change the MRT, RSS, and phase readings.

When an RFID tag is attached to a pot with soil, there is a coupling effect between the tag's antenna and the soil, since the tag is very close to the soil. This coupling happens even if the RFID tag is not in direct contact with the soil and it changes the electromagnetic field of the tag's antenna, resulting in changes to the channel h_{Tag} over the tag's antenna. The amount of coupling is affected by the soil moisture level. Thus, when soil moisture varies, the channel h_{Tag} over a tag's antenna will also change, causing changes to the MRT, RSS, and phase readings at the RFID reader.

To validate this idea, we conduct a benchmark experiment in a controlled indoor environment where we can assume the channel h_{Air} over the air is fixed. Based on the greenhouse setup introduced in Section 3, we deploy an antenna connected to an Impinj Speedway R420 reader [24] on the ceiling, and attach an AD-383u7 RFID tag [12] to a pot with soil, as shown in Fig. 4. The distance between the reader's antenna and the pot with a tag is 1.45 m. We aim to measure the MRT, RSS, and phase changes for different soil moisture levels. To change the soil moisture, we add different amounts of water to the pot. A high-precision soil hygrometer (Bluelab Pulse Meter [15]) is used to measure the true soil moisture. By doing so, we get a set of moisture levels, i.e., 6%, 21%, 31%, 52%, 61%, 73%, and 82%. For each soil moisture level, we fix the reader's transmission power to be 32.5 dBm and measure more than 1,000 samples for MRT, RSS, and phase readings. To measure the MRT readings, we sweep the reader's transmission power and identify the minimum power (i.e., MRT) required to activate the tag [46].

Figure 5–Figure 7 show the soil moisture levels versus MRT, RSS, and phase readings. As we can see, all the three feature values vary when the moisture changes. For example, MRT increases when the soil moisture increases, as shown in Fig. 5, because the water inside the soil absorbs the signal received by the tag. The more the amount of water added to the soil, the greater the signal attenuation over the tag's antenna, and thus a reader needs to transmit more power (i.e., a large MRT) to activate the tag. Similarly, the RSS decreases as the soil moisture increases, as shown in Fig. 6. The phase also changes over different soil moisture, as shown in Fig. 7, since the soil moisture changes the channel h_{Tag} over a tag's antenna.

Overall, this experiment implies *RFID-based soil moisture sensing is feasible.* In the next few sections, we detail our system design.

4.2 Signal Feature Selection

We discuss which signal feature is the best one for sensing moisture.

The phase does not change linearly when soil moisture changes (see Fig. 7). Hence, two different soil moisture levels may share the

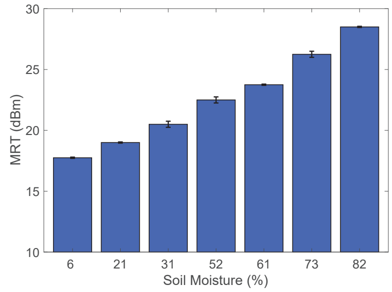

Figure 5: MRT versus soil moisture.

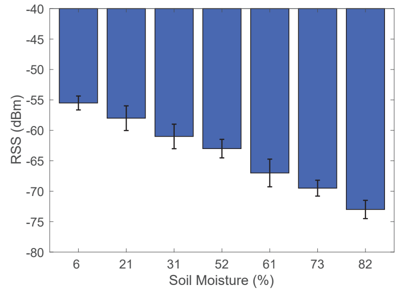

Figure 6: RSS versus soil moisture.

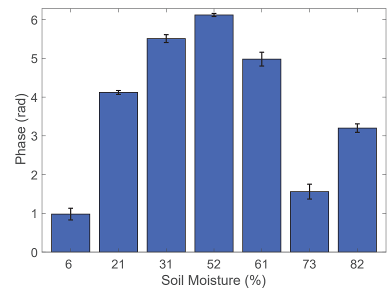

Figure 7: Phase versus soil moisture.

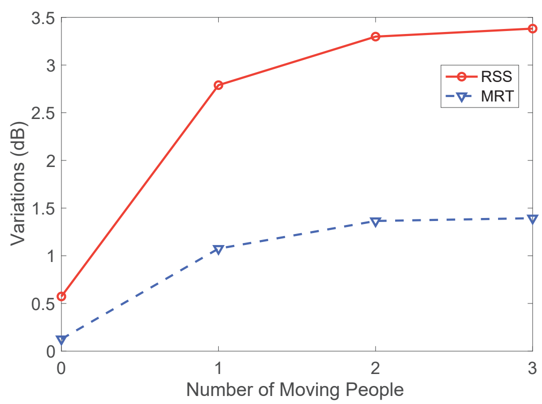

Figure 8: Variations of RSS and MRT in a dynamic environment with different number of moving people.

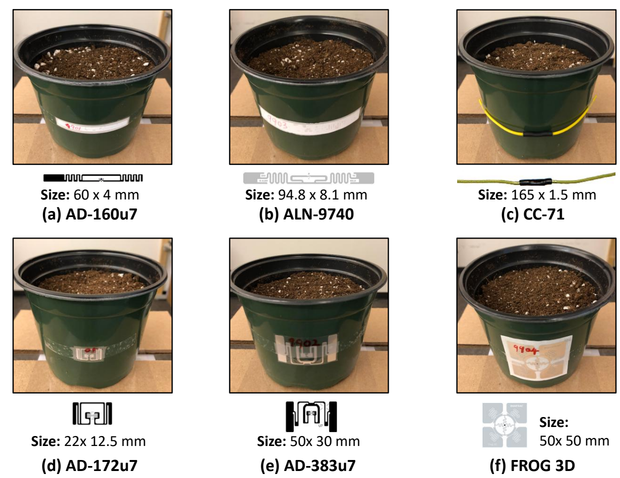

Figure 9: To select the right tag for soil moisture sensing, we test the working range of six types of widely used RFID tags.

same phase value. Thus, we do not use the phase for soil moisture sensing. We next show, through both theoretical analysis and real-world experiments, that MRT is more robust than RSS.

First, based on Eqn. (6) and Eqn. (7), note that MRT is related to the one-way channel between reader and tag, but the RSS is related to the round trip channel. Thus, intuitively, MRT should be less sensitive to environmental variations than RSS. More precisely, suppose that there is a channel change Δh_{Air} over the air due to a change in the RF environment. We assume that the soil moisture level does not change over this short time period, so that h_{Tag} is a constant. Then, MRT variation ΔMRT and RSS variation ΔRSS can be expressed as:

$$\begin{aligned} \Delta MRT &= 20\log|h_{Air} + \Delta h_{Air}| - 20\log|h_{Air}| \\ &= 20\log|1 + \frac{\Delta h_{Air}}{h_{Air}}|, \qquad (9) \\ \Delta RSS &= 40\log|h_{Air} + \Delta h_{Air}| - 40\log|h_{Air}| \\ &= 40\log|1 + \frac{\Delta h_{Air}}{h_{Air}}|. \qquad (10) \end{aligned}$$

Based on Eqn. (9) and Eqn. (10), we see that $\Delta MRT = \frac{\Delta RSS}{2}$, i.e., the variation of MRT is only the half of the RSS's variation. Note that it is half in dB, thus the amplitude variation of MRT would be the square root of the amplitude variation of RSS. This implies that, when there are changes in the RF environment, MRT is more robust than RSS.

To validate this analysis, we conduct a benchmark experiment using the setup shown in Fig. 4. We fix the soil moisture level and ask a number of 0, 1, 2, 3 people to move around the experimental setup. The moving people introduce RF noise and additional reflection paths for the RFID signal, which cause variations in MRT and RSS readings. We aim to compare the variations of the two features in this dynamic environment.

Fig. 8 shows that MRT has a much smaller variation compared with RSS in a dynamic environment with different number of moving people. Thus, *we use MRT for soil moisture sensing.*

4.3 Tag Type Selection

It is important to choose the right type of tags for soil moisture sensing because different types of tags vary in antenna structure and chip type, and consequently have different working ranges, size, and price. We aim to select a tag type that has a relatively long working range so that a reader can still read the tag at some distance even when the soil moisture is high, because we use signal attenuation to sense moisture level. The higher the soil moisture level, the greater the attenuation in RFID signal, resulting in a reduced working range.

We test the working range of six types of widely used commercial RFID tags, as shown in Table 1. We attach one tag of each type to a pot, as shown in Fig. 9. Tags are deployed at the same location

Table 1: TAG TYPES

Type	Description
A	Avery Dennison AD-160u7 [10]
B	Alien Squiggle ALN-9740 [2]
C	Embeddable CC-71 [42]
D	Avery Dennison AD-172u7 [11]
E	Avery Dennison AD-383u7 [12]
F	SMARTRAC Frog 3D [40]

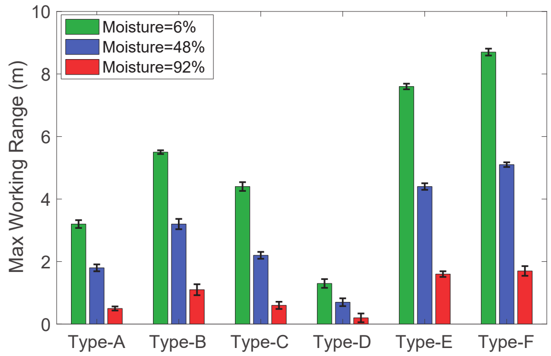

Figure 10: The working range of different types of tags over different soil moisture.

of five identical pots that have the same amount of soil. By adding water into pots we can change the soil moisture.

Next, we set the reader's transmission power to maximum (i.e., 32.5 dBm) and measure the maximum working range of each tag when the soil moisture is 6%, 48% and 92%. For each soil moisture, we measure a tag's working range over 10 different deployment angles, making sure that the tag is still within the antenna's beamwidth. Fig. 10 shows the maximum working range of six types of tags versus different soil moisture levels. As we can see, tags of Type-E and Type-F are better than other tags, since they achieve working ranges of more than 7 m when the soil moisture is 6% (dry soil), and more than 1 m when the soil is moisture level is 92% (very wet soil). We prefer Type-E tags to Type-F tags because they are smaller, allowing us to measure soil moisture level even in small pots. Moreover, they costs six times less.[2] To summarize, *we select the Type-E tag, i.e., AD-383u7 tag for soil moisture sensing.*

4.4 Tag Location Selection

There are many locations on a pot that one can potentially deploy an RFID tag. Here, we discuss which location on a pot is the best for sensing soil moisture.

Fig. 11 illustrates four possible locations on a pot that one might deploy a tag, i.e., the inside or outside of a pot; the bottom or top of a pot.[3] To empirically determine the best deployment location, we measure MRT readings when the tag is deployed at each of the four locations. For each location, we first measure MRT values when the pot is empty. 12 minutes after the start of the experiment, we fill the pot with dry soil, and make sure the soil surface is below the top of the pot, which is the case in typical greenhouses. For the next 10 minutes, we measure MRT with dry soil. Next, we add water twice into the pot and measure MRT values when the soil moisture is ~80% and 100%.

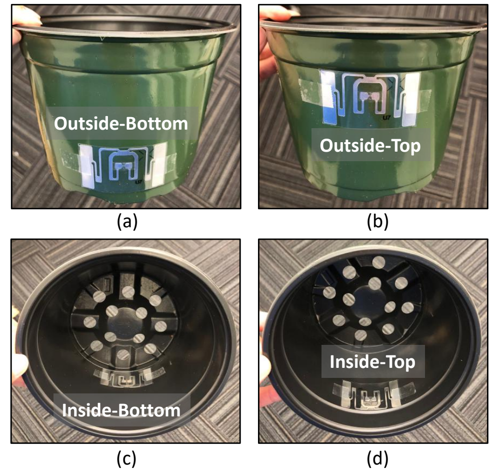

Figure 11: Four possible locations of deploying a tag on a pot.

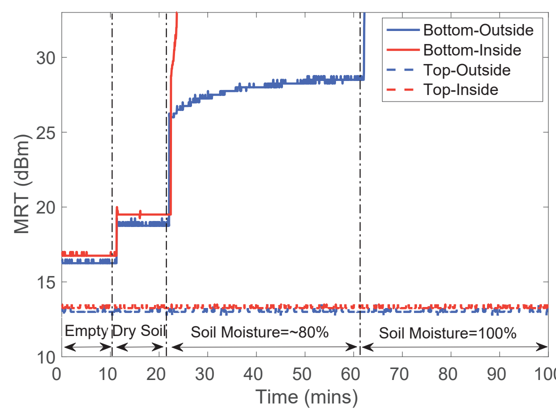

Figure 12: MRT readings when a tag is attached to different locations of a pot.

The MRT values for the whole experiment are shown in Fig. 12. We first discuss the top and bottom locations. As we can see, when a tag is deployed at the top of a pot, MRT does not change for different moisture levels, since the soil surface is below the tag. When a tag is deployed at the bottom of a pot, MRT increases whenever adding soil into the pot or increasing the soil moisture. This implies that, compared with the top location, the bottom of a pot is a better tag deployment location. Next, we discuss the inside and outside locations when a tag is deployed at the bottom of a pot. For the inside location, the tag stops responding even when the soil moisture is only 80%, since the tag's antenna is in direct contact with the water. In contrast, when the tag is deployed at the outside of a pot, the tag has no response only when the soil moisture is 100%. It implies that one should deploy a tag at the outside of a pot to estimate the whole range of soil moisture levels.

In summary, *the bottom and outside of a pot is the best deployment location of a tag for soil moisture sensing.*

[2]The price break of 100 tags for 'Type-E' tag and 'Type-F' tag are 25 USD [18] and 150 USD [7], respectively.
[3]A tag can not be deployed on the horizontal bottom of a pot, since plants are watered from the horizontal bottom in the greenhouse, as we explained in Section 3.

4.5 Resilience to Changes in the RF Environment and Pot Locations

Ideally, we want the MRT reading to only be related to the soil moisture level. However, changes in the RF environment or locations of pots (i.e., tags) may cause variations in the channel h_{Air} (in Eqn. (6)) over the air, which results in noisy MRT readings and causes errors in soil moisture estimation. This section deals with the impact of environment variations and the pot/tag location changes on our soil moisture sensing system.

4.5.1 Resilience to Environment Variations. To understand the impact of the environment variations on our soil moisture sensing system, we conduct two experiments using the same setup (see Fig. 4) but for different environments: a static environment and a dynamic environment. The static environment is located in a corner of an empty room, and the dynamic environment is located in a hallway, where multiple people move around the setup when they pass the hallway. For each experiment, we first collect MRT readings for half a day when the soil is dry. Then, we add water into the soil so that the moisture reaches 100%. In the next few days, we continue to collect MRT readings until the soil is dry again.

Fig. 13 (a) shows the experimental results in a static environment. As we can see, when the soil is dry in the first half day, the MRT values are small and almost unchanged (i.e., around 17 dBm). When we add water into the soil, MRT increases dramatically to the maximum (i.e., 32.5 dBm) until the tag does not respond. When the tag has no response, we denote this by a value of 33 dBm (slightly above the maximum reader value). In the next few days, MRT readings decrease continuously as the soil dries. Overall, MRT variations in the static environment are small.

Fig. 13 (b) shows MRT readings in the dynamic environment, which are very noisy compared with the MRT values in the static environment. The noisy MRT can cause errors in the soil moisture estimation. To remove variations caused by environment changes, our key observation is that changes of the soil moisture are much slower than changes in the RF environment, e.g., the movement of people. Thus, we apply a low pass filter on raw MRT values to remove environment variations. Let $\{x_1, \cdots x_i, \cdots, x_N\}$ be a set of raw MRT readings. Then, the filtered MRT y_i is given by:

$$y_i = \alpha \cdot x_i + (1 - \alpha) \cdot y_{i-1}, 2 \leq i \leq N, \quad (11)$$

where, $y_1 = x_1$ and α is the smoothing factor. As α decreases, the output samples respond more slowly to a change in the input samples, i.e., the system is less sensitive to environment changes.

To validate the effectiveness of our low pass filter on removing environment changes, we apply the low pass filter on the MRT readings of the dynamic environment. The blue line in Fig. 13 (b) is the filtered MRT readings, where α is 0.2. As we can see, the low pass filter can remove most of the environmental noise. Thus, we use filtered MRT readings for soil moisture sensing.

4.5.2 Resilience to Pot Location Changes. Usually, locations of pots are fixed in a greenhouse, as we mentioned in Section 3. Thus, filtered MRT readings are only related to soil moisture levels. However, pots may be moved in some cases, e.g., plants need more space when they grow. The changes in pot locations will cause variations in MRT readings, resulting in soil moisture estimation errors.

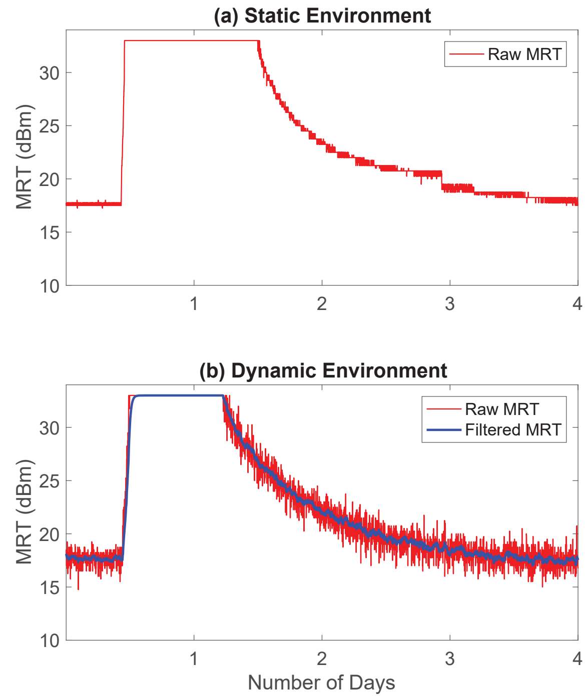

Figure 13: MRT readings (a) in a static environment, and (b) in a dynamic environment.

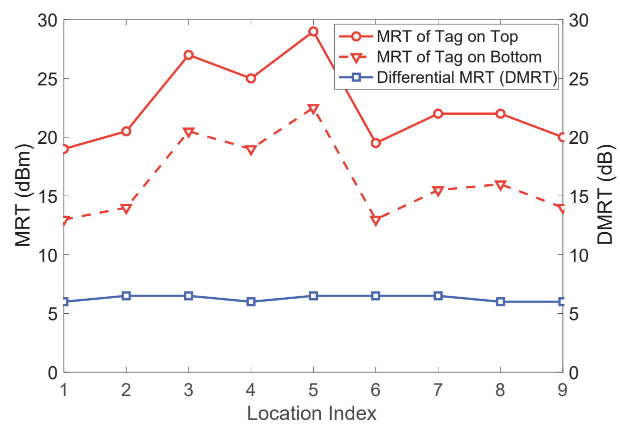

Figure 14: Comparison of MRT and DMRT of two tags on a pot when the pot moves over 9 locations. Note that the lines joining the points are only for readability.

To remove the MRT variations caused by location changes, we use the differential sensing method first presented by Wang *et al.* [46]. Specifically, we co-deploy two tags on one pot: one tag is deployed at the pot's bottom that is close to the soil, and another tag is deployed at the pot's top that is above the soil. The key intuition is that MRT readings of the tag deployed on the bottom are a function of both the soil moisture and the pot's location whereas MRT readings of the tag deployed above the soil are only related to the pot's location. Because the two tags are co-located, they will suffer from almost the same MRT variations caused by location changes. Thus, by calculating the differential MRT (DMRT) of two tags, variations caused by location changes can be cancelled out and DMRT is only related to soil moisture.

To validate the effectiveness of DMRT despite location changes, we conduct a real-world experiment using the setup shown in Fig. 4. We deploy a reference tag on the top of a pot, and a sensing tag on the bottom of the pot. Then, we move the pot to 9 different locations, where the distance between adjacent locations is 1 m. The soil moisture is kept unchanged. For each location, we first measure MRT readings of two tags, then calculate the DMRT value.

Fig. 14 shows the MRT and DMRT values of two tags on a pot when the location of the pot changes over 9 locations. It is evident that even though the soil moisture is unchanged, the MRT changes more than 9 dB. In contrast, DMRT stays nearly constant over different locations. This implies that DMRT is robust to location changes and can be used for soil moisture sensing even when the pot location changes.

4.6 System Calibration

So far we explained how changes in soil moisture affect on tag's DMRT values. In this section, we explain how DMRT readings can be mapped to soil moisture levels (i.e. 0% to 100%). To map DMRT readings to soil moisture levels, first, we need to make sure that tags are always readable for any moisture level between 0% and 100%. To achieve this requirement, the maximum distance between a tag and a reader's antenna must be smaller than working range of the tag at the highest moisture level. This is achievable since the working ranging of the tag is more than 1.2 m and the reader antenna can be attached to a robotic arm that is in less than 1.2 meter away from the plants as shown in Fig.3. Next, we measure DMRT values $[x_1, \cdots, x_i, \cdots, x_I]$ at some discrete soil moisture levels $[M_1, \cdots, M_i, \cdots, M_I]$ (ranging from 0% to 100%). Finally, we find the best coefficients for a polynomial equation $M_i = p_1 x_i^n + p_2 x_i^{n-1} + \cdots + p_n x_i + p_{n+1}$ that maps the DMRT values to soil moisture levels. Using this polynomial equation, we can estimate the corresponding moisture level for any DMRT value.

Fig. 15 shows an example of our calibration method. In this example, we change the soil moisture from 6% to 100% by adding water gradually into the pot. The ground truth soil moisture is measured using a soil hygrometer. The dots in red show the DMRT readings for measured soil moisture levels, and the blue line shows the fitted polynomial when $n = 5$. By using the fitted blue curve, we can estimate soil moisture for a given DMRT value. Finally, it is worth nothing that this calibration needs to be done once and it can be used for all pots in the greenhouse.

4.7 Summary of System Design

GreenTag is an RFID-based soil moisture sensing system which uses two Avery Dennison AD-383u7 RFID tags to sense soil moisture. We deploy one tag at the outside and bottom of a pot, and another tag at the outside and top of the pot. GreenTag monitors tag's MRT at the reader to detect changes in soil moisture level. To make GreenTag robust to changes both in the RF environment (e.g., from human movement) and in pot locations, we use low-pass filter and differential MRT. Finally, we calibrate the system such that we can map the DMRT values to the true soil moisture levels.

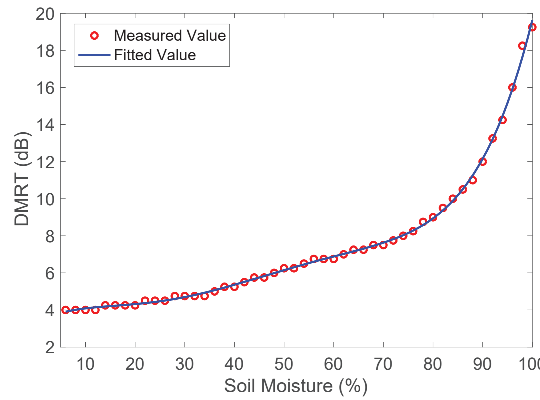

Figure 15: System calibration to map DMRT readings to soil moisture levels.

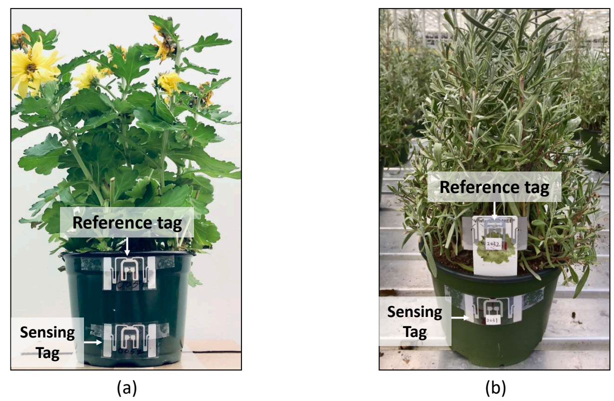

Figure 16: Illustration of the tag setup on pots: (a) setups for the laboratory environment, and (b) setups for the real greenhouse environment.

5 IMPLEMENTATION

Hardware implementation: An Impinj Speedway R420 reader [24] is used in our experiments without any hardware or firmware modification. The R420 reader operates in a frequency range of 902.75 – 927.25 MHz, and in accordance with FCC regulations. The default antenna used by R420 reader is a directional antenna with a 9 dBi gain and 70° elevation and azimuth beam widths [8]. We use low-cost Avery Dennison AD-383u7 tags [12] in our experiments.

Backend implementation: Our algorithms are implemented in C# and MATLAB code. We use a laptop with a 2.4 GHz CPU (Intel i5-6200U) and 8 GB memory to run our software. The laptop is connected to the RFID reader through an Ethernet cable, and they communicate using the RFID reader protocol [25].

6 MICRO-BENCHMARK

We first run two micro-benchmark experiments: (i) computing MRT values for a regular and periodic irrigation; (ii) determining the effectiveness of DMRT on removing the effect of pot location changes on moisture sensing accuracy.

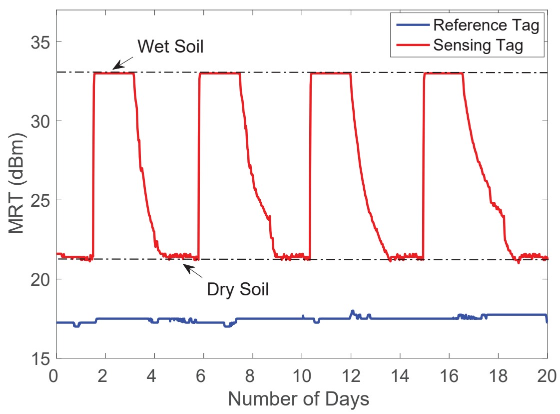

Figure 17: When the soil moisture changes periodically from dry (6%) to wet (100%), the MRT values of the sensing tag (red) also changes periodically, while the MRT of the reference tag (blue) does not change over different soil moisture levels.

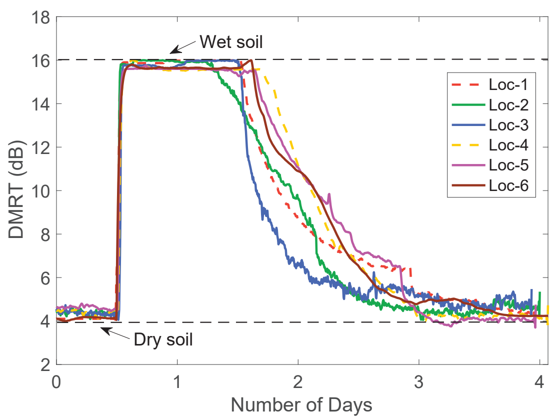

Figure 18: DMRT values when we change both the location and the soil moisture of a pot.

6.1 MRT Changes for a Periodic Irrigation

To better understand how GreenTag works in a periodic and regular irrigation process, we design an experiment to monitor the MRT of a pot equipped with two RFID tags, as shown in Fig. 16(a). We start the experiment with dry soil. Then, we add water into the soil and wait until the soil dries again. We repeat this irrigation process and continuously collect MRT readings over 20 days.

Fig. 17 shows the result of this experiment. As we can see, when the soil moisture changes periodically from dry (~6%) to wet (100%), the MRT values of the sensing tag deployed on the pot's bottom also changes periodically from low (~18 dBm) to high (32.5 dBm). We also note that, as we explained in Section 4.4, the MRT of the reference tag deployed on the pot's top does not change over different soil moisture levels. This experiment demonstrates that the relationship between the MRT and the soil moisture level has the same pattern over time. Therefore, a single calibration done at the beginning is enough for GreenTag to estimate the moisture level from DMRT values over the long term.

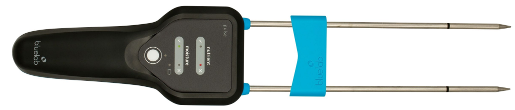

Figure 19: A soil hygrometer: Bluelab Pulse Meter.

6.2 Effectiveness of Differential MRT

In this experiment, we evaluate the effectiveness of DMRT on removing the effect of change in the location of a tag or pot. We move a pot over 6 locations in a 1D space, where the distance between two locations is 30 cm. For each location, we keep the soil dry for half a day, and then water the plants and leave it for few days until the soil gets dry. We continuously collect MRT values of two tags for all locations.

Fig. 18 shows the DMRT values for all 6 locations. As we can see, all locations have very similar pattern in their DMRT changes. Specifically, when the soil is dry, the DMRT values are all around 8.5 dB. On the other hand, when the soil is wet, the DMRT values are all around 16 dB. Note that there is a slight difference between their falling slopes, this is due to the fact that some pots dried faster because of their locations, and possibly higher temperature or air flow. This experiment illustrates the effectiveness of DMRT on removing the impact of changes in the location of a tag/pot.

7 EVALUATION

In this section, we evaluate the accuracy of GreenTag system in estimating soil moisture. We first compare the accuracy of our system with two dedicated soil moisture sensors, and then discuss the impact of different parameters (e.g., environment changes, pot location or rotation changes, and setup changes) on our system's accuracy. Finally, we show a case study of our system in a real-world greenhouse for enabling intelligent irrigation.

7.1 Evaluation Setup and Metric

Setup: We implement our GreenTag system in two environments: a laboratory environment, as shown in Fig. 4, and a real-world greenhouse, as shown in Fig. 2. In our lab setups, we deploy one reader with one antenna on the ceiling, and attach two RFID tags to each pot which has a plant, as shown in Fig. 16 (a). In the greenhouse setup, since all pots are full of soil, we attach one tag to a pot and another tag on the label of the pot, as shown in Fig. 16 (b). Unless specifically mentioned, in our experiments, we set the distance between reader antenna and tags to 1.2 m.

Performance Metric: We use the absolute error between the estimated soil moisture and the true soil moisture as the performance metric, which is defined as the 'soil moisture estimation error.' To measure the ground truth, we use a soil hygrometer (Bluelab Pulse Meter [15]), as shown in Fig. 19. This meter costs more than 400 USD and allows us to get an accurate soil moisture.

7.2 Comparison with Dedicated Sensors

We first compare the performance of our GreenTag system with two dedicated soil moisture sensors, i.e., a SEN-13637 sensor [20] which costs 10 USD and an ECHO-EC5 sensor [21] which costs 169 USD, as shown in Fig. 20.

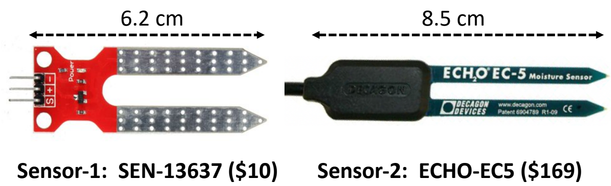

Figure 20: Two kinds of dedicated soil moisture sensors.

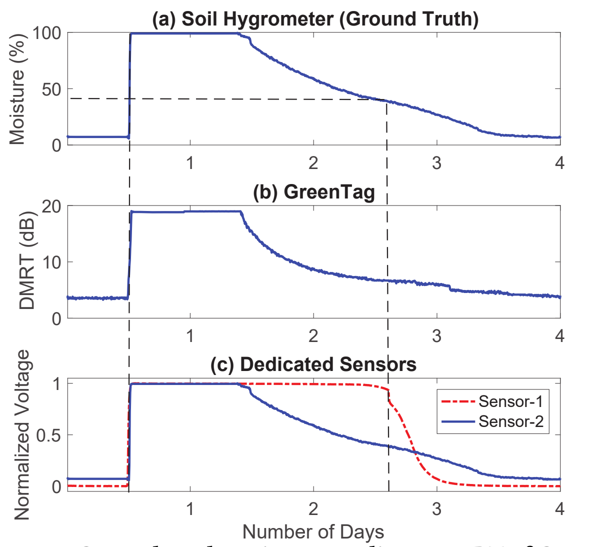

Figure 21: Ground truth moisture readings, DMRT of GreenTag, and voltage readings of two sensors.

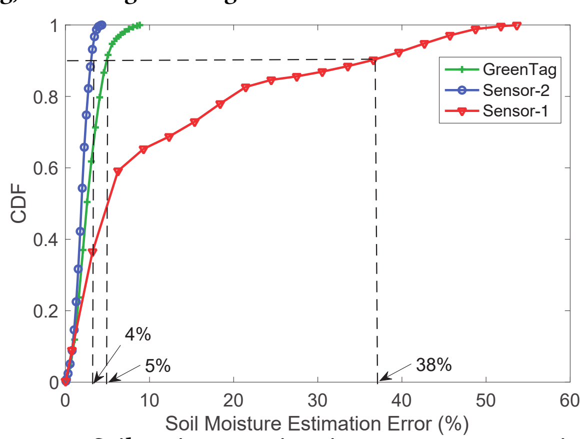

Figure 22: Soil moisture estimation accuracy comparisons between our system using RFID tags and two commodity soil moisture sensors.

We insert both sensors into a pot. The sensors are connected to an Arduino UNO controller [4], so that we can read their values. The output of both sensors are voltage values sampled by the Arduino's ADC. We also attach two RFID tags to the same pot. We measure sensor values and DMRT readings of two tags. At the beginning of the experiment, the soil is dry and we collect data for half a day. Then, we add water into the pot until the soil moisture reaches 100%. Next, we continuously collect data until the soil is dry again. During the experiment, we use a soil hygrometer to get the ground truth soil moisture.

Fig. 21 shows the true moisture values, DMRT readings and sensor values over four days, where 'Sensor-1' is the SEN-13637 sensor and 'Sensor-2' is the ECHO-EC5 sensor. Since the output voltages of the two sensors are different,[4] we normalize their voltage values for a fair comparison. The figure shows that both GreenTag and 'Sensor-2' measurements have similar pattern to ground truth measurements while 'Sensor-1' does not follow the same pattern. Fig. 22 shows the cumulative distribution function (CDF) plot of soil moisture estimation errors obtained for our system and two dedicated sensors. Note, 'Sensor-1' and 'Sensor-2' are calibrated based on their data-sheet before soil moisture estimation. We make the following observations from our results:

- The response time of GreenTag is as good as the commodity soil moisture sensors, as illustrated in Fig. 21. First, when water is added into the pot, both DMRT values and normalized voltage values increase immediately. Second, when the soil moisture decreases from 100% to 0%, both DMRT values and voltage values of 'Sensor-2' decrease accordingly.
- The accuracy of GreenTag is comparable to that of the ECHO-EC5 sensor (i.e., 'Sensor-2'), which cost 169 USD, as shown in Fig. 22. The 90-percentile estimation error of GreenTag and 'Sensor-2' are 5% and 4%, respectively.
- The accuracy of GreenTag is much better than that of the SEN-1363 sensor (i.e., 'Sensor-1'), which cost 10 USD. Specifically, the 90-percentile error of 'Sensor-1' is as high as 38%. Such large error is due to insensitivity of 'Sensor-1' for high soil moisture levels: note that when the soil moisture decreases from 100% to 45%, the normalized voltage of 'Sensor-1' does not change.

In conclusion, this experiment demonstrates that the performance of GreenTag is comparable to that of an expensive, dedicated soil moisture sensor, though costing only a few cents per tag.[5]

7.3 Impact of Environment Variations

Environment variation (e.g., the movement of human body) may cause MRT variations, which will result in estimation errors. Thus, we evaluate the impact of environment variations on the accuracy of GreenTag.

To create a dynamic environment, we ask N people to move around our experimental setup, where N=0, 1, 2, 3, 4, and 5. We first calibrate our GreenTag system when the environment is static, i.e., $N = 0$. Then, for each N, we add different amount of water into the pot to get 15 different soil moisture levels. For each soil moisture level, we get the true moisture by using a soil hygrometer and the estimated moisture by using our GreenTag system.

Fig. 23 shows the soil moisture estimation errors when there are different number of moving people around our setup. We compare the estimation errors with and without using the low-pass filter introduced in Section 4.5.1. As we can see, without the low-pass filter, the average moisture estimation error is more than 14% when there are 5 people moving around the setup. On the other hand, when we use the low-pass filter, the soil moisture estimation error

[4]When soil moisture changes from 100% to 0%, the output voltage of 'Sensor-1' changes from 0.88 v to 0; while the output voltage of 'Sensor-2' changes from 2.5 v to 0.
[5]Of course, the tag reader costs a few hundred USD, but only a single reader is needed for the entire greenhouse.

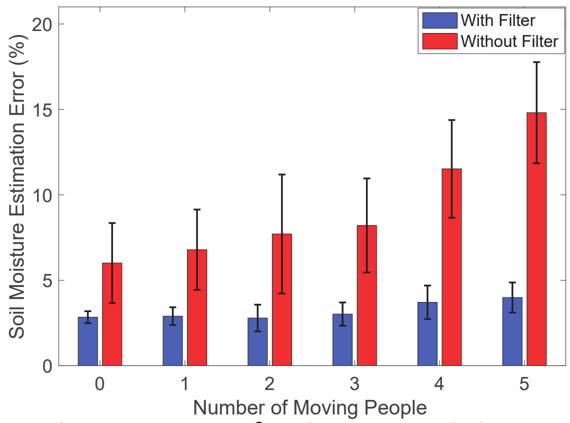

Figure 23: Impact of environment variations.

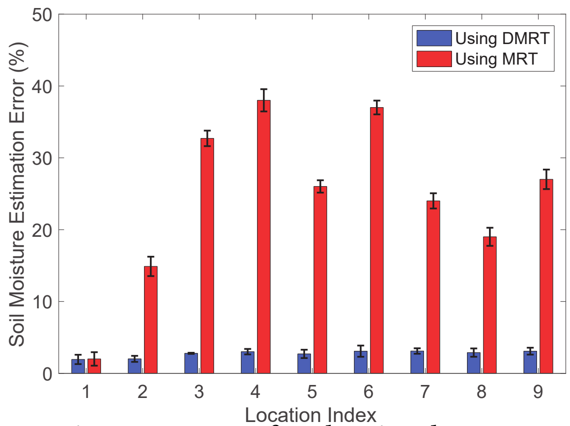

Figure 24: Impact of pot location changes.

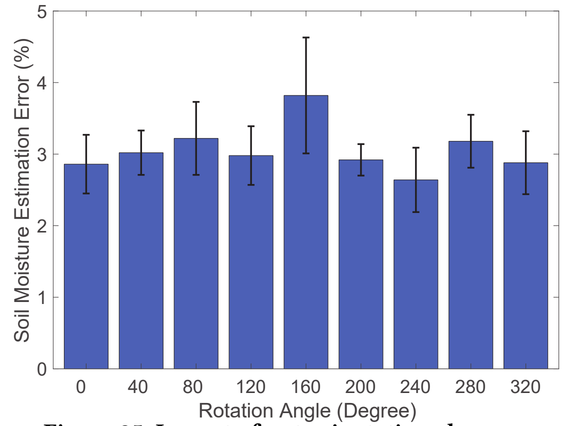

Figure 25: Impact of pot orientation changes.

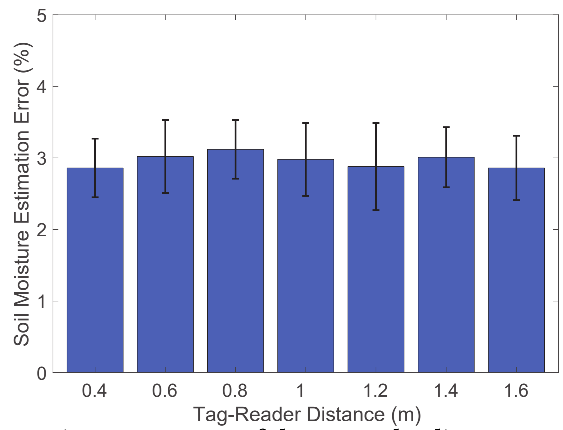

Figure 26: Impact of the tag-reader distance.

is below 5%, regardless of the number of people moving close to our setup.

This experiment implies that using a low-pass filter enables GreenTag to robust to environment changes and can provide high accuracy in soil moisture sensing.

7.4 Impact of Pot Location Changes

Changing the location of RFID tags/pots causes MRT variations even when the soil moisture is fixed. As explained in section 4.5.1, GreenTag uses a differential sensing method, i.e., DMRT, to remove the impact of the location changes in soil moisture sensing. We evaluate if GreenTag can achieve a high moisture estimation accuracy even when locations of pots/tags are changed.

We change the location of a pot (with plants) to 9 different locations, where the distance between adjacent locations is 1 m. We first calibrate our GreenTag at one location, and then evaluate its accuracy over all locations. By adding different amount of water into the pot, we create 15 different soil moisture levels for each location. In order to illustrate the effectiveness of differential sensing, we calculate the estimation error when the moisture is estimated using DMRT and compare it with the one estimated using MRT.

Fig. 24 shows the result of this experiment. It is clear that the estimation error when using MRT is very large (e.g., more than 35%). This is because the MRT changes due to both the pot's location and the soil moisture. In contrast, the estimation error when we use DMRT is below 5%. This implies that using DMRT for soil moisture sensing enables GreenTag to be robust to location changes of pots/tags.

7.5 Impact of Pot Orientation Changes

While working with pots in a greenhouse, they may get rotated. To determine if rotating a pot can affect the accuracy of GreenTag, we change the orientation of a pot from 0° to 320° with a step of 40°. We first calibrate our GreenTag system at 0°, and then measure its accuracy for different angles. For each angle, we create 15 different soil moisture levels by adding different amount of water into the pot, and calculate the estimation error for each soil moisture level.

Fig. 25 shows the result of this experiment. As we can see, the errors are below 5% for all different pot rotation values. This suggests that GreenTag is robust to the pot rotations.

7.6 Impact of Reader-Tag Distance

We evaluate the impact of the tag-reader distance on the accuracy of GreenTag's soil moisture sensing. We change the distance between a reader's antenna and a pot from 0.4 m to 1.6 m with a step of 0.2 m. GreenTag is only calibrated at the distance of 1 m, and then tested at all other distances. For each distance, we calculate the estimation error for 15 different soil moisture levels.

Fig. 26 shows the result of this experiment. Again, we see that the errors are below 5% for all distances. This is because MRT variations caused by the distance changes are canceled out by using DMRT.

In this experiment, we also find that RFID tags have no response when the tag-reader distance is more than 2 m and also the soil moisture level is high. Therefore, the operating range of GreenTag is limited to 2 m. Although, one may improve this range by getting FCC permission and transmitting higher power than ISM band regulations, 2 m operating range is more than enough to deploy GreenTag in our target greenhouse where we can attach a reader's antenna to a movable robotic arm that is no more than 1.2 m away from pots.

7.7 Impact of pot materials, shape, and size

We now discuss the impact of the pot's material, shape and size.

Impact of pot materials. In the current experiments, all pots are plastic, which is a common material used in greenhouses due to its low-cost and flexibility. In rare cases, metal pots may be used. In this case, the RFID signal can't penetrate the metal container, and our system can't estimate the soil moisture. However, as long as the pot's material is non-metallic, such as plastic or ceramic, our system can successfully estimate soil moisture.

Impact of the pot shape and size. The pot shape and size are automatically included when we carry out the calibration measurements. Thus, the effect caused by the pot shape and size is accounted for, i.e., the pot shape and size will not affect the soil estimation accuracy.

7.8 Case Study

Finally, we show a case study of GreenTag in a greenhouse. In this case study, we deploy 60 tags on 30 pots and we attach one reader antenna to a movable robotic arm, as shown in Fig. 2 and Fig. 27. The robotic arm is already deployed in a typical greenhouse and used for spraying pesticides on plants. The distance between adjacent pots is 0.3 m, which is a typical distance between pots in a greenhouse. The distance between the robotic arm (reader antenna) and the tray is 1.2 m. Due to the beamwidth limitation of our reader antenna, at any antenna position, we can only read RFID tags of 12 pots (3×4 pots) for all moisture levels. However, since the antenna on the robotic arm is movable, we read all pots by moving the antenna.

We start the experiments with dry soils (all pots have less than 8% moisture level). Then, we add the same small amount of water into each pot, and measure the DMRT readings and the true soil moisture by using a soil hygrometer. We repeat this until the soil moisture reaches to 100% for all pots. We use the DMRT readings of one pot for calibrating the model that maps DMRT readings to moisture levels, and then we apply the calibrated model to other pots for identifying three moisture levels: dry soil (with moisture of 0-40%), moist soil (with moisture of 40%-85%), and wet soil (with moisture of 85%-100%). The three moisture levels are based on the requirements of the greenhouse, which are important for guiding irrigation and shipment. Specifically, with a dry soil level, plants need to be watered immediately; the moist soil level is the ideal watering range; and wet soil level is an acceptable shipping range.

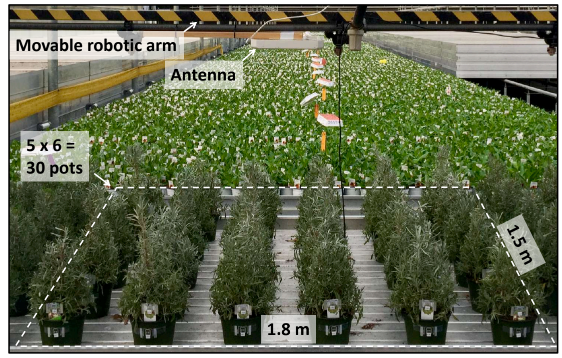

Figure 27: A case study with a deployment of 60 tags on 30 pots in a greenhouse.

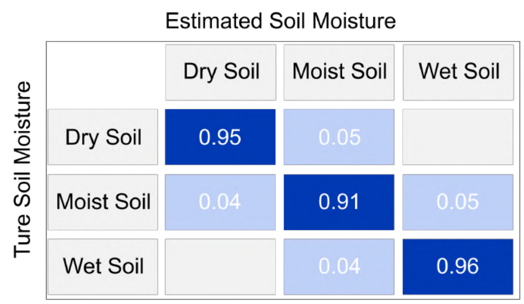

Figure 28: Confusion matrix: soil moisture identification results of 12 pots in a greenhouse.

Fig. 28 shows the result of this case study. As we can see, GreenTag achieves an accuracy of more than 90% for identifying the three moisture levels. This implies the effectiveness of GreenTag in enabling intelligent irrigation. For example, a greenhouse can automatically water plants when soil moisture level becomes dry.

8 CONCLUSION

This paper presents GreenTag, an RFID-based soil moisture sensing system. GreenTag is low-cost and has a comparable accuracy to that of an expensive soil moisture sensor. Our key idea is to attach two RFID tags to a pot, and use a low-pass filtered DMRT to estimate the soil moisture level. GreenTag is robust to changes in the RF environment, pot locations, and pot orientations. Our extensive real-world experiments show that GreenTag achieves high accuracy in estimating soil moisture (the 90-percentile moisture estimation errors is less than 5%). Thus, we believe GreenTag improves the productivity of greenhouses, and can have a significant impact in making irrigation in greenhouses more intelligent.

9 ACKNOWLEDGMENTS

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