An RF Doormat for Tracking People's Room Locations

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ABSTRACT
Many occupant-oriented smarthome applications such as automated lighting, heating and cooling, and activity recognition need the room location information of residents within a building. Surveillance based tracking systems can be used to track people in commercial buildings, but are considered privacy invasive in homes. In this paper, we present the *RF Doormat* - a RF sensing system that can accurately track people's room locations by monitoring their movement through the doorways in the home. We present a set of guidelines and a visualization to easily and rapidly setup RF-Doormat on any doorway. To evaluate our system, we perform 580 doorway crossings across 11 different doorways in a home. Results indicate that our system can detect doorway crossings made by people with an average accuracy of 98%. To our knowledge, the RF Doormat is the first highly accurate room location tracking system that can be used for long time periods without the need for privacy invasive cameras.

Author Keywords
RFID, Room-location tracking, Visualization

ACM Classification Keywords
C.3 Special-Purpose and Application-Based Systems: Real-time and embedded systems

General Terms
Algorithms, Design, Experimentation, Human Factors

INTRODUCTION
Tracking people's movement in the home is an essential requirement in many occupant-oriented smarthome applications such as elderly monitoring, activity recognition, and automated heating and cooling. The 'room' is a fundamental entity in buildings around which many concepts revolve: activities, furniture, heating, lighting and appliances. Knowing people's room location is important in inferring their Activities of Daily Living (ADLs) as well as the usage pattern of the building. Therefore, a logical level of tracking in the home is *room location tracking*: tracking the room in which each person is located. Currently this can only be done with surveillance based tracking systems that use information rich sensing systems such as cameras or microphones. These systems have been successfully used in commercial buildings [6], but are considered too privacy invasive for use in homes [3]. Many other systems detect when a doorway is crossed or track occupants' (x,y) coordinates, but none of these systems can accurately detect people's room locations.

Existing technology broadly falls into two categories: 1) doorway crossing sensors and 2) coordinate tracking systems. *Doorway crossing sensors* use a laser or infrared tripwire at the doorway to detect when a doorway is crossed by a person, but they cannot infer the person's identity. *Coordinate tracking* systems use wireless beacons to identify and locate people indoors, and can typically achieve a room-level granularity of 10-30 ft [4]. This granularity, however, is not sufficient for tracking the exact room locations of residents. Rooms are separated by a small distance across a wall or the threshold of a doorway, and people often sit on furniture near walls or walk very near and even into doorways without actually passing through them. Therefore, a coordinate tracking system must have sub-meter granularity in order to avoid locating people on the wrong side of a wall or a doorway. As a result, one coordinate tracking system that could achieve 10 ft granularity (approximately the size of a room), was shown to achieve only 37% accuracy at room location tracking [5].

In this paper, we present a RF based room location tracking system for a multi-person home that can accurately track the room locations of residents. This approach requires very fine-grained location information near doorways (centimeter level) to distinguish through-door events (a person moves through the doorway from one room to another) from near-doorway events (a person walks near a doorway but does not walk through it) and in-doorway events (a person walks into a doorway but does not walk through it). However, it does not require any tracking capabilities in the rest of the room. We present a set of guidelines and a visualization to easily and rapidly setup our system on any doorway.

To monitor doorway crossings, we create two RF sensing zones, one on each side of the doorway. If the sensing zones were visualized, they would appear as two doormats on either side of the doorway. For this reason, we call this approach the *RF Doormat*. By knowing which of the two sensing zones of the doorway was crossed first, the direction of motion can be determined. This approach differs from the single-zone approach commonly used in anti-theft systems in stores, where information about direction of movement of goods across the store's entry/exit is not important. To be detected by the RF doormats, people must wear bracelets around the ankles. These bracelets can contain passive RFID tags so they can be waterproof, do not require batteries and do not need to be recharged. The combination of RF door-

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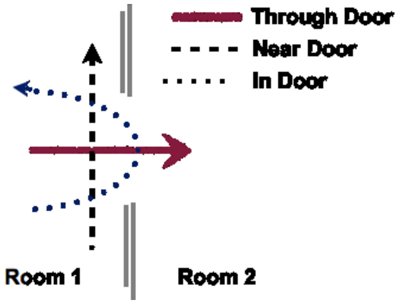

Figure 1. Low power wireless localizations schemes have low accuracy in distinguishing between in-door and near-door vs. through-door events

mats and ankle bracelets simplify sensing: ankles are always at a consistent orientation and distance from the floor when walking, thereby converting a 3D positioning problem to a much simpler 2D presence/absence decision. During evaluation, our system was able to detect 98% of 580 doorway crossings made by 3 people across 11 doorways in a home. Ankle bracelets may be too intrusive for casual use in a home, but can be useful for medical monitoring or for ground truth room location tracking during long-duration, in-situ studies of the home. To our knowledge, the RF Doormat is the first system that can track room location with high accuracy over long time periods without the use of privacy-invasive cameras.

OVERVIEW OF RF-DOORMAT

The RF Doormat system has three components: 1) RF sensing zones, 2) RF Ankle Bracelets, and 3) a doorway crossing detection algorithm.

RF Sensing Zones - Location and Size

RF Doormat monitors doorway crossings using two non-overlapping RF sensing zones on either side of the doorway. When a person crosses a doorway, his/her direction of motion can be determined by knowing which sensing zone was crossed first. The main challenge in setting up sensing zones is determining the extent of coverage of the zones. The zones need to be large enough to detect at least one footstep on each side of the doorway during the doorway crossing.

By definition, a person walking has one foot planted on the ground temporarily while the other leg is moving in stride. With RF anklets, only the tag on the stationary foot can be detected because the other foot is moving too quickly. Therefore, *foot planting* is a major issue with a 2D RF sensing system. To ensure that a person always plants at least one foot within the sensing region, each doormat must have a radio coverage area that is longer than one *stride length*: the average length of one step from heel to heel. Also, the width of each doormat must be equal to the width of the doorway, so a person is not able to walk around the sensing zone and cross the doorway. Based on these insights, the constraints for the RF sensing zones can be defined as:

- Non-overlapping zones on either side of doorway
- Length of zone greater than a single stride length
- Width of zone greater than width of doorway

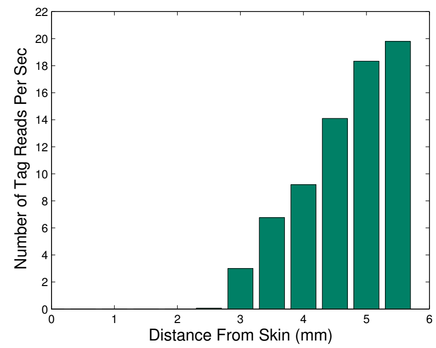

Figure 2. RFID tags reach maximum read rate at a distance of 5.5 mm from the skin

RF Ankle Bracelets

To use the RF-Doormat, people must wear RF ankle bracelets – called *anklets* – that contain passive RFID tags that do not require a battery, are very light weight and can be easily water-proofed. In fact RFID anklets are already used as a popular way to track runners as they progress though marathons [1]. The anklet approach minimizes the effect of body shadowing because no matter how the anklet is rotated around the ankle, there is at least one tag facing outwards on each foot such that it can be read by the RFID reader.

To study the attenuation of RFID tag reads by human body, we placed a RFID tag on a person's skin and observed the number of reads per second as the distance of the tag from the person's skin was increased. The result of this experiment, as shown in Figure 2, implies that RFID tags need to be placed at least 5.5 mm away from the body to transmit at the highest rate. To ensure 5.5 mm separation of RFID tag from the skin, we use double-layered beaded anklets, where the beads are slightly larger than 5.5 mm. Two RFID tags are slipped between two layers of beads, so that the inner layer keeps the tag from touching the skin while the second layer of beads covers the tags visually, in order to make it look like jewelry. RF anklets work unattenuated even when residents wear clothes that cover the anklets because fabric has a low RF attenuation coefficient and therefore does not block RF signals.

Doorway Crossing Detection Algorithm

To detect precisely when a person crosses a doorway, the anklet readings are processed in two stages. In the first stage, temporally sequenced anklet readings are converted into clusters of possible doorway crossing events. In the second stage, each cluster is analyzed further to determine the actual doorway crossings. A doorway crossing is detected if there are consecutive sets of readings from both the detection zones of a doorway.

In the first stage, *DBScan* algorithm groups the raw RFID data from the sensing zones in each doorway into clusters based on their timestamps, as shown in Figure 3. DBScan has a notion of noise in the data and it filters out sparse RFID readings. Each cluster represents a time frame during which a room transition could have possibly occurred. The clustering algorithm provides the list of temporal clusters to investigate

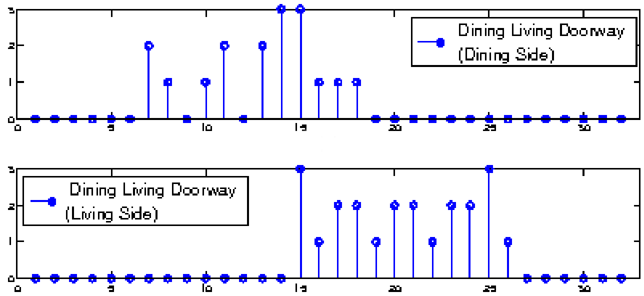

Figure 3. Temporally sequenced raw data stream of RFID tag reads per second from both sides of the doorway

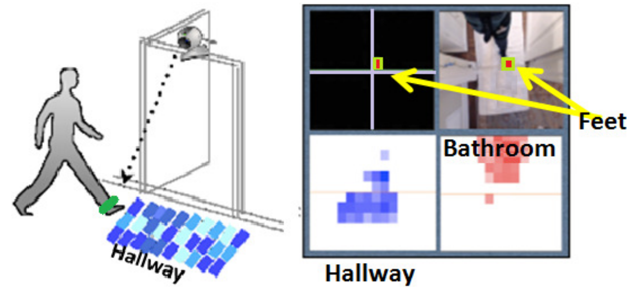

Figure 5. Webcam installed at the top of the doorway locates the foot wearing RFID anklet using color-tracking and plots the RF read strength received at that location

further for doorway crossings. Densely distributed readings over a period of time indicate a potential room transition.

In the second stage, RFID readings in the temporal clusters are further analyzed to detect doorway crossings. Ideally, comparing the average timestamp of readings from zones on either side of the doorway should be sufficient to detect direction of motion across the doorway. However, this simple approach does not work if a person goes back and forth between the two rooms quickly, resulting in multiple doorway crossings in the same cluster. A simple solution would miss multiple doorway crossings since it assumes that only one doorway crossing takes place in a single time-window.

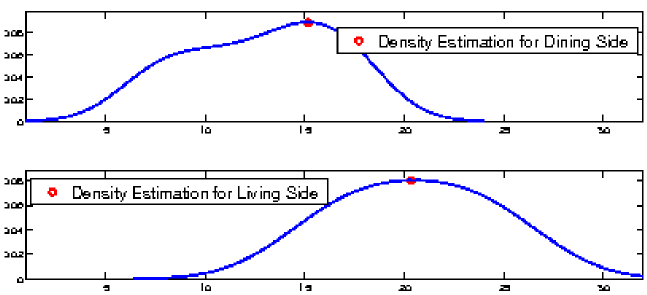

Figure 4. Peaks detected in the ks-density curve are used to determine the number of doorways crossings and direction of motion in a given temporal cluster

To address the issue of multiple doorway crossings in a single time window, we use kernel regression technique called *ks-density* to smooth the number of readings detected at each moment, as illustrated in the Figure 4. Then, we find all peaks of the density curve to find when high numbers of readings occurred. By comparing the timestamps of peaks from both the thresholds of the doorway, the directionality of multiple doorway crossings in the same cluster can be determined. At the end of second stage, we get all the doorways crossings along with the identity of the person crossing the doorway and the time at which he/she crossed the doorway.

VISUALIZATION

Although manufacturer specifications define the coverage and polarization properties of an RF antenna, these features very rarely conform to the ideal specifications when placed in actual buildings with people, objects, and building structure in the way. To understand the coverage of RF sensing zones under actual environmental effects such as shadowing from the human body, we developed a visualization system which represents the radio patterns of the sensing zones in real time. With the assistance of this system we could easily setup the sensing zones on either side of the doorway, according to the guidelines mentioned earlier.

As can be seen in Figure 5, to use the visualization system, an RF anklet is worn by the participant. A webcam installed on the doorway - facing down, tracks the location of the foot wearing RF anklet using a piece of brightly colored paper, placed on the foot. As the foot is moved near the doorway, the visualization system obtains RF beacons from the anklet by a live-feed from the RF antennas. The system then maps the coordinates of the foot with the RF beacon's read rate, to produce a visual map of the sensing zones' coverage areas on screen. We refer to this visual map as *Doorway RF Map*, in which the color intensity of a cell indicates the strength of RF signal at that point. This visual feedback of the deployment helps a deployer decide how to move the antennas near the doorway to improve the configuration of thresholds.

Coverage Index

Based on the Doorway RF maps, we compute a *coverage index*, which represents a level of confidence in deployment correctness of RF Doormats. Cells are identified as Correctly Configured (CC) if they are covered only by the sensing zone on same side of the doorway, Incorrectly Configured (IC) if they have coverage from the sensing zone on other side of doorway and Blank (B) if they have no coverage from either of the two sensing zones. All cells in an ideal sized sensing zone are identified by W. The coverage index is defined as:

$$CI = \frac{CC}{W} \times \alpha - \frac{IC}{W} \times \beta - \frac{B}{W} \times \beta$$

Where, α (additive value) is 1.1 and β (deductive value) is 0.35.

The coverage index for the RF-Doormat of a doorway is determined only by the RF coverage of the sensing zones in doorway RF maps. Doorways with a coverage index above 0.95 are categorized as good, between 0.85-0.95 are categorized as acceptable, and below 0.85 are categorized as poor.

	Deployment	Experimental Results		
Doorway	**CI**	**Precision**	**Recall**	**#**
Kitchen-Living	0.98	0.98	0.98	54
Dining-Living	1.00	0.96	1.00	85
Upstairs-Hallway	0.98	1.00	0.98	34
Nursery-Dining	0.93	1.00	0.97	50
Bathroom-Hallway	0.83	0.94	1.00	40
Patio-Kitchen	0.91	1.00	0.94	44
Backdoor-Mudroom	0.80	0.94	1.00	44
Dining-Hallway	0.82	0.82	1.00	60
Hallway-Bedroom	0.72	0.67	0.97	36
Dining-Mudroom	0.70	0.96	0.98	44
~~Livingroom-Porch~~	~~0.55~~	~~1.00~~	~~0.55~~	~~60~~
Livingroom-Porch	0.89	1.00	0.94	30

Table 1. Comparison between Prediction level and experimental results for Precision and Recall for every doorway

EXPERIMENTAL SETUP AND EVALUATION

To evaluate our system, we deployed 11 RF Doormat systems in 11 doorways of a test home. Since we implemented RF anklets using RFID tags, each RF sensing zone in the RF Doormat system, was created using 1-3 RFID antennas (depending on the width of doorway). 47 antennas were connected to 12 Speedway Impinj RFID readers [2], that were connected to a laptop using a 16-port switch. The readers were operating in the MaxMiller mode, which is a dense reading mode with a high data rate. The RFID application software was developed in just 166 lines of code in C# using Octane SDK, which is a software API from Impinj. All readers generated detailed tag reads for the RFID tags detected by them. The entire set of features of all tags were uploaded to an Oracle database off-site To ensure long term deployment, we installed the antennas in the basement facing up through the wooden floor. Most of the flooring in the test home was wooden, except for the porch, which had a steel-reinforced cement floor. We created RF-Doormats in the porch by doubling the number of antennas we had typically used for doorways.

To evaluate our system, 580 doorway crossings were performed over 11 different doorways by 3 people walking around the house wearing RF anklets. The participants were asked to walk across the doorways naturally, and even walk past the doorway without crossing it, to generate near doorway events. The ground truth for this experiment was collected using smartphones. The room location tracking accuracy was measured using the following two metrics: 1. *Recall* - defined as the true positive rate of doorway crossing detection 2. *Precision* - defined as the false negative rate of doorway crossing detection.

Table 1 shows the precision, recall and coverage index of deployment for each doorway. Doorways classified as good by the CI, had high recall and precision, averaging 98% and 92.7% respectively. Most of the doorways have very high recall (greater than 0.94). The hallway-bedroom had a low precision as its sensing zones on either side of the doorway were spilling over to the other side and overlapping. We later fixed this problem by increasing the separation between the two sensing zones. The LivingRoom-Porch doorway had poor CI of 0.55 in the first iteration of experimentation. We left it as such during one round of evaluation, to study its performance as a 'bad doorway'. Later we fixed it according to our guidelines to improve its CI to 0.89, which resulted in a drastic improvement in its recall.

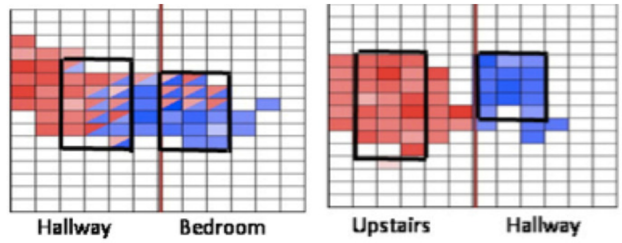

Figure 6. Doorway RF Maps: Hallway-Bedroom with CI of 0.72 has overlapping sensing zones, leading to low precision. Upstairs-Hallway with CI of 0.98 has high precision and recall

CONCLUSION

In this paper, we present "RF Doormat", a system which infers people's room locations in a multi-person home, by monitoring their doorway crossings. Ankle bracelets may be too intrusive for casual use in the home, but can be useful for medical monitoring or for ground truth room location tracking during long-duration, in-situ studies of the home. The user group most benefitted by this system would be researchers who need a system to get reliable room location information for participants in living labs, such as the Aware Home at Georgia Tech, and House_n at MIT. This system can easily work with multiple residents due to the identification mechanism inherently built in the RFID tags in a RFID system. This tracking mechanism can also be used successfully in commercial buildings, where RFID embedded ID cards are commonly used.

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