Room Occupancy Estimation Through WiFi, UWB, and Light Sensors Mounted on Doorways

Hessam Mohammadmoradi, Shengrong Yin, Omprakash Gnawali
University of Houston
{hmoradi,syin,gnawali}@cs.uh.edu

ABSTRACT

Recent studies have shown that adjusting HVAC systems based on the number of people inside the room can save at least 38% of energy consumed for reheating. Besides, accurate estimate of room's occupants is useful in improving the safety and security of the buildings. There are many research proposals and commercial products for reliable and efficient people counting, however, these solutions are expensive, hard to deploy, or obstructive to people flow. We investigate the possibility of utilizing wireless and light sensing technologies in the doorways to track the entrances/exits to/from the room. Our solution is inexpensive, unobtrusive with much fewer deployment constraints compared to existing people counting solutions. For RF based sensing, we use ultra-wideband signals at center frequency of 4 GHz with 500 MHz bandwidth and narrowband wireless signals (WiFi) at the center frequency of 2.4 GHz with the bandwidth of 20 MHz. We also evaluate the possibility of using existing WiFi infrastructure to count people. Ambient light is second physical phenomenon which we utilize for accurately counting number of people walk through the doors. We place low cost photodiode on door frames to detect changes in light illuminance level when there are people walking through the door. Light based people counting requires an installation of just one inexpensive photodiode at the doorway which makes our solution highly applicable for large scale deployments. We evaluated our solution via several controlled and uncontrolled real-world environments. The results show an average of 96% accuracy in estimating the number of occupants in rooms.

CCS CONCEPTS

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

KEYWORDS

People Counting, Wireless Sensing, Channel State Information

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1 INTRODUCTION

The energy lost in buildings is almost 40% of total energy consumed in residential and commercial buildings in the US [4]. Previous studies show that efficient management of HVAC system can reduce a significant amount of energy wastage (25% as in [3]) inside the buildings. Accurately estimating the number of people inside the room is a key enabler in the efficient management of HVAC system. Recent advancements in IoT and sensor network brought an excellent opportunity to estimate occupancy of the room using inexpensive and reliable sensors. Accurate estimation of room's occupancy also can be utilized in other areas related to smart buildings like safety and marketing.

People from both research and industry communities have tried to utilize different sensing technologies to count the number of people inside the rooms. RGB cameras are most common solution for people counting but they raise serious privacy concerns especially in public buildings like schools and work offices. Break-Beam sensors are the cheapest people counting solution available commercially. There is an active IR line between 2 nodes which are deployed on the doorway facing each other. Every break in the link is counted as a human walk. Despite the simplicity and reliability of Break-Beam sensors, there are tight restrictions on Break-Beam sensors mounting. Also, Break-Beam sensors are not reliable in the situations where multiple people enter or exit simultaneously which is more likely to happen in crowded buildings with wider doors. Ultrasonic waves also are utilized for accurately counting people inside the room. Room conditions such as material of walls and room size have serious impact on the accuracy of ultrasound based people counting and those types of solutions require significant amount of training to achieve reasonable accuracy. Human body temperature also has been used as an indicator for counting entrance and exit events. Temperature based solution utilize a thermal imager to monitor thermal patterns inside the room. Commercial thermal imagers are about $250 which makes this solution not scalable for large building deployments.

In this paper, our goal is to investigate feasibility of using inexpensive and reliable wireless sensing technologies for people counting. Our key idea is placing wireless transmitters and receivers on the doorways to keep track of the number of entrance and exit events through the doors and estimate number of people inside the rooms. Basically, we place a wireless transmitter on one side of the door and a wireless receiver on the other side. Sender continuously broadcasts packets and receiver monitors the wireless channel characteristics. Our hypothesis is that presence of humans between sender and receiver changes the wireless channel characteristics which can be used to detect entrances or exits through the door.

Table 1: State of the Art People Counting Solutions

Solution	Application	Cost ($)	Privacy Preserving Level	Scalability	Training Required	Flexibility
Break Beam Sensors	Counting	≤ 10	High	Yes	No	No
PIR Sensors	Presence	≤ 10	High	Yes	No	Yes
Ultrasonic Sensor	Counting	≤ 100	Moderate	No	Yes	No
RGB Cameras	Counting	≤ 100	Low	Yes	No	No
IR Imager	Counting	≤ 25	High	Yes	Yes	No
Our Solution	Counting	≤ 25	High	Yes	No	Yes

Our experiments show that wireless signals can be blocked or reflected by the human body. We can use this effect to build an inexpensive, robust and easy-to-install people counting system based on wireless sensing. WiFi is the leading wireless solution to connect people to the Internet. They are ubiquitous and can be served as multi-purpose when they are deployed. UWB technology has been proved to be the leading wireless technology used in indoor localization. It is highly possible that future smartphones will integrate the UWB chip to serve as the "GPS receiver" for indoor localization. Visible light has been used for illumination since the beginning of 20th century. Researchers has also applied visible light for communication in the past 20 years. We study the wireless signal variances by deploying WiFi, UWB and light-sensing devices on doorways to count people going through the door. We also build a model to detect entrance and exit events through the doorways based on the signal variance.

The contributions of this paper are as follows:

- We studied the pattern of human body presence on the WiFi, UWB and light signals and proposed an efficient and simple solution to utilize this pattern to count people while they walk though the door. In crowded scenarios, our solution can count up to 4 people when they are walking through the door at the same time.
- We develop a real-time occupancy estimation solution that is easier to deploy compared to similar solutions, privacy preserving, and very inexpensive. We used commodity WiFi, UWB and low power photodiodes in our design. We evaluated the system's performance in an academic building and it achieved 96% accuracy estimating number of people inside the rooms.

2 RELATED WORK

There have been many proposals trying to estimate room's occupancy accurately. Despite reasonable results achieved by previous work, each solution has its limitations. We summarize state of the art people counting solutions with their advantages and disadvantages in table 1.

Break-Beam sensors: Break-Beam based people counting solutions require the installation of 2 nodes in a particular height. They have very restricted mounting requirements. Another failure scenario is crowded cases once multiple people walk side by side. Break-Beam sensors simply do not work in such a situations and count just one entrance or exit event.

Ultrasonic sensors: Ultrasonic waves have been investigated for people counting solutions by different research groups [8, 16, 18]. The basic idea is generating ultrasonic chirps and detecting the presence of humans based on reflected signals[8]. The accuracy of ultrasonic based solutions is heavily dependent on room's condition such as size and material [18]. Ultrasonic transponders with capability of generating higher frequency signals (which improves the accuracy) are more expensive.

IR Array Sensors: The basic idea is mounting IR array sensors and monitoring room's temperature pattern looking for sudden changes due to human presence. In [15], authors deployed a cheap, low resolution IR array imager in the doorway and counted entrance and exit events. The major limitation of that work is the inability to count multiple people at the same time accurately. Also, thermal imagers are very prone to errors in longer distances which makes those solutions inapplicable in wider doors.

RGB cameras: RGB cameras are very popular solutions for people counting and tracking [2, 22]. Although RGB cameras can achieve relatively accurate results in estimating the number of people inside the rooms but they are not deployable in all the places due to serious privacy concerns.

WiFi signals have been used for communication and also sensing. In most related work[6], RSSI values for WiFI signals have been utilized for counting number of people walking in the specific area. Although this approach is device-free and also preserve user privacy, the approach verified to be effective for small scales, up to 10 participants. Also, as mentioned in the paper, the performance significantly drops inside the buildings. Channel state information recently has been used by many people to extract interesting patterns in WiFi signals [19], [17].

UWB signals are mostly used for indoor localization. To the best of our knowledge, we are the first group who utilizes UWB signals for people counting in indoor environments.

Light-based sensing: The idea is to use photodetectors (such as photodiode or spectrometer) to convert light signals to electrical signals (amplitude). ADC is then applied to convert analog electrical signals (amplitude) to digital signals. It is a quantization process for photodetectors to be digitized for further analysis. Researchers have proposed two light-based sensing techniques for human activity recognition. One is active sensing, it requires specific LEDs to act as the transmitter, photodiode as the receiver. The user can configure the LEDs to send beacon information for visible light based localization service. This idea has been heavily investigated in LED-to-LED, LED-to-Camera, LED-to-Photodiode communication systems that are used to provide visible light based positioning [11], [20], [12]. The other is passive sensing, it does not require users to wear any equipment for data collection. Researchers in [13], [21] have utilized photodiode to sense ambient light levels and flickering frequencies for human skeleton reconstruction and indoor location. Ibrahim et al. has deployed photodiode in the ceiling to demonstrate the feasibility to recognize activity with small light level change in [9].

3 APPROACH

The key idea in our design is placing a wireless transmitter on one side of the door and placing a wireless receiver on the other side and count people once their presence changes wireless channel characteristics once they are passing through the door. In our work, the feasibility of using different portions of the electromagnetic spectrum is investigated. We study the behavior of WiFi, UWB and visible light signals in the presence of human body.

The sender and receiver nodes are deployed in the room in a way that, there is an active communication link between them by transmitting data or sensing the ambient light and any change in the characteristics of this link is detectable by receiver node. The receiver can count the number of people who are walking through the door. To detect the direction of movement, we need to have 2 different receivers with short distance to each other. In the final solution, there is one wireless transmitter on one side of the door and there are two wireless receivers on the other side which are placed in a short distance from each other in horizontal line. Based on the first receiver which detects the presence of people, the direction of movement is very easy to determine. By knowing number of people enter to and exit from the room, total number of people inside the room can be estimated. Figure 1, shows the whole process as a flowchart.

In following subsections, each wireless sensing technology (WiFi, UWB and visible light) is explained in details alongside with designed algorithm to utilize that technology to estimate the number of people inside the room.

3.1 Utilizing WiFi Signals to Count People

WiFi based sensing also is a very well-investigated area. Most of the works in this field are using RSSI (Received Signal Strength Indicator) values as a sensing metric. RSSI values suffer from temporal disruption due to environmental noise change.

IEEE 802.11n defines 56 sub-carriers for 20 MHz bandwidth and 114 sub-carriers for 40 MHz bandwidth [7]. The defined sub-carriers carry data in parallel to improve the data transmission speed and also resilience to noise. CSI is the amplitude and phase information of received signal for all these sub-carriers.

Channel state information which is provided by WiFi card includes amplitude and phase information for sub-carriers in received signal. The idea here is utilizing the fact that different sub-carries face different levels of fading due to human walking and improve the accuracy of our proposed people counting solution. In addition, analysis of signal shape per sub-carrier improves the ability of proposed solution to deal with the situations where multiple people walk through the door at the same time or very close distance to each other.

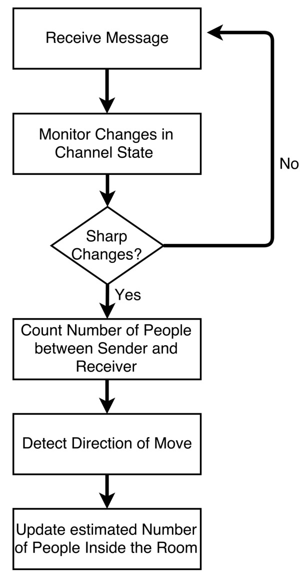
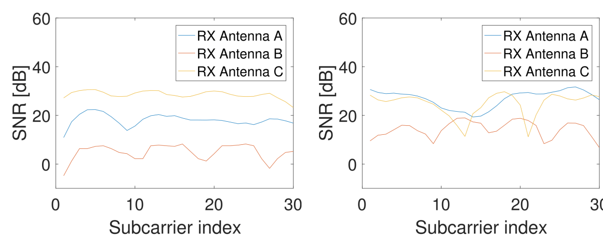


Figure 1: People Counting Algorithm

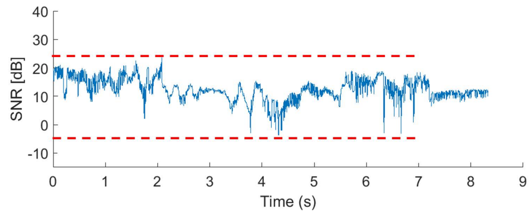


(a) No One between Sender and Receiver **(b) 2 Persons are Standing between Sender and Receiver**

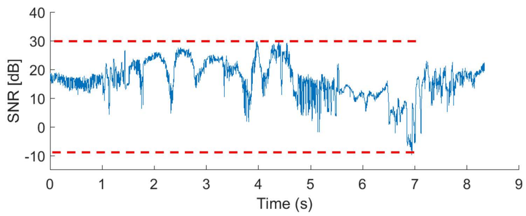
Figure 2: SNR across Different Sub-carriers

We place one commodity WiFi transceiver at the doorway and make a continues communication with anther WiFi node (Access point or same type WiFi transceiver) and monitor CSI information for received signal. Our hypothesis is that once people walk through the door, their presence is detectable by sharp changes in the CSI information (amplitude and phase across sub-carriers). Figure 2 shows results of a simple experiment. The WiFi transmitter and receiver are placed in a 100 cm distance and SNR values for received signals while one one is in between sender and receiver and also once two persons are standing between sender and receiver have been plotted.

In figure 2, the different fading levels for different sub-carriers are shown. We used one sender antenna and three receiver antennas and figure 2 shows SNR changes across different sub-carriers for all the three different receiving antennas.



(a) 1 Person



(b) 2 Persons

Figure 3: (a) SNR values in Presence of 1 Person(b) SNR values in Presence of 2 Persons.

3.1.1 Multiple People between Sender and Receiver. Even in narrow doors (<100 cm width), there are cases in which multiple people walk through the door side by side. Our experiments show that amount of changes in SNR values have a direct relationship with the number of people who are standing in the doorway. Figure 3 shows the difference in observed SNR values in a particular sub-carrier once just one person walks through the door compared to the situation when two people walk side by side.

In figure 3, the red lines show the maximum and minimum SNR values during the presence of people and amount of drop in SNR while there are two people are standing between sender and receiver, is obvious. Based on the observations similar to figure 3, changes in observed SNR values are utilized to determine number of people who are walking through the door simultaneously.

3.1.2 Proposed WiFi based People Counting Algorithm. To accurately estimate number of people inside the room, the challenging part is counting number of people who are walking through the door at the same time. The proposed solution follows an easy to understand technique to count people while they are passing through the door. Algorithm 1 elaborates detailed steps of proposed people counting algorithm.

All the sub-carriers are searched to find the one which is highly impacted by the presence of people. Based on the amount of drop in SNR value, the number of people who are walking through the door is estimated. Our experiment indicated that using three thresholds, the proposed algorithm can detect up to three individuals at the doorway. After extensive experiments with different settings, we set α to 80%, β to 55% and finally γ to 25%. For cases with more than 3 persons at the doorway, we could not find a reliable threshold to count people accurately. However, the chance of seeing more than 3 persons walking at the same time in indoor scenarios with narrow doors is very rare.

Algorithm 1 CSI based People Counting

procedure COUNT NUMBER OF PEOPLE WHO ARE WALKING THROUGH THE DOOR
  $cnt \leftarrow$ *Number of People*
  $cnt_{max} \leftarrow$ *Maximum Number of People*
  $CSI \leftarrow$ *Channel State Information*
  for `sc in CSI sub-carriers` **do**
    $snr \leftarrow$ *SNR value for sc*
    $snr_{avg} \leftarrow$ *Average SNR seen for this sub-carrier*
    if $|snr - snr_{avg}| > \alpha * |snr_{avg}|$ **then**
      $cnt \leftarrow 3$
    else
      if $|snr - snr_{avg}| > \beta * |snr_{avg}|$ **then**
        $cnt \leftarrow 2$
      else
        if $|snr - snr_{avg}| > \gamma * |snr_{avg}|$ **then**
          $cnt \leftarrow 1$
    if $cnt_{max} < cnt$ **then**
      $cnt_{max} \leftarrow cnt$
  return cnt_{max}

3.2 Utilizing UWB Signals to Count People

By definition, every wireless signal which its bandwidth is bigger than 20% of its center frequency is called ultrawideband (UWB) signal. IEEE 802.15.4 defined the standard way to use the UWB signals for communication and localization. Since these signals have a very wide bandwidth; their transmission power is limited (-41 dBm/MHz) to avoid interference with other devices which use wireless spectrum.

The very short length of UWB pulses provides the opportunity at the receiver side to easily identify the reflected signals from the original one. This feature is utilized in UWB based localization systems to identify first path signal which traveled line of sight (shortest path) from sender to receiver. This unique feature enables UWB based indoor localization systems to locate assets inside the buildings with less than 50 cm accuracy. On the side, very large bandwidth of UWB signals makes them a promising solution for short range, high data rate applications such as room level video streaming. Our idea is using changes in first path signal's power level (due to the presence of human body) as an estimator for people counting.

Human presence changes the characteristics of the communication channel between sender and receiver. Channel impulse response (CIR) is a good representative of the communication channel characteristics. Since the type of transmitted signals in UWB communication is in the form of pulses, the characteristics of the communication channel between sender and receiver can be presented as changes have been made to original pulse while it was passing through the channel. CSI values are channel characteristics explained in frequency domain but CIR values are channel's features measured in time domain. UWB chips report CIR values by sampling the received signals every 1 nanosecond.

We place UWB transceivers in the doorway (one sender and one receiver). The nodes continuously transmit packets and the receiver monitors CIR information for received packet. Our hypothesis is that presence of human is noticeable from CIR information. Figure

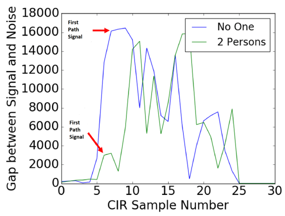


Figure 4: CIR in presence of 2 persons vs no person

4 shows the CIR samples received in the presence of two people between sender and receiver compared to the situation when there is no one in between.

It is shown in figure 4 that in presence of people in the line of sight path between transmitter and receiver, the signal amplitude for first path signal goes down and reflected signals have higher power. UWB CIR information gives us very accurate (100%) results detecting presence of people in LOS path. For detecting multiple people who are walking through the door simultaneously, we used amount of reduction in LOS signal's power and used it as an estimator for number of people who are standing between transmitter and receiver. To identify direction of movements, our solution requires mounting 2 receivers in small distance to each other or 2 antennas in a short distance (approximately 2 cm).

3.2.1 Proposed UWB based People Counting Algorithm. Above mentioned results from CIR pattern, leads us to algorithm 2 to count people between sender and receiver when there is active communication between two UWB antennas.

Algorithm 2 CIR based People Counting

procedure COUNT NUMBER OF PEOPLE WHO ARE WALKING THOUGH DOOR
  $fp_{power} \leftarrow$ *First Path Signal Power*
  $noise \leftarrow$ *Background Noise*
  $cnt \leftarrow$ *Number of People*
  if $fp_{power} - noise < \alpha * fp_{power}$ **then**
    $cnt \leftarrow 0$
  else
    if $fp_{power} - noise < \beta * fp_{power}$ **then**
      $cnt \leftarrow 1$
    else
      if $fp_{power} - noise < \gamma * fp_{power}$ **then**
        $cnt \leftarrow 2$
      else
        if $fp_{power} - noise < \phi * fp_{power}$ **then**
          $cnt \leftarrow 3$
  return *cnt*

The algorithm is similar to CSI based people counting but CIR information is used here. Presence of humans between sender and receiver reduces the power level for first path signal and this reduction can be used as an estimator for number of the people between sender and receiver. After conducting extensive experiments, we achieved to following thresholds for counting number of people between sender and receiver. α = 75%, β = 60%, γ =30% and finally ϕ = 20%.

3.3 Utilizing Ambient Light Sensing to Count People

The third sensing technology which is investigated in our work in visible light sensing. The key idea is monitoring ambient light's luminance level and use changes in the level of light as an indicator for presence of people. The main advantage of this approach is the fact that just one sensor is enough to detect presence of people between sender and receiver (the sender node is not required). The basic idea is the photodiode continuously measures ambient light level and our assumption is sharp changes in measured light are due to human presence. To detect the direction of movement, light sensors can be deployed as an array (two sensors are enough). In order to utilize light sensor, we used a simple thresholding technique to detect presence of people. Our experiments in different

Algorithm 3 Light Sensing based People Counting

procedure DETECT PRESENCE OF PEOPLE
  $lum_{avg} \leftarrow$ *Average Luminance Level in Empty Background*
  $lum \leftarrow$ *Measured Luminance Level*
  $presence \leftarrow$ *Is Someone There?*
  if $lum - lum_{avg} > \alpha * lum_{avg}$ **then**
    $presence \leftarrow True$
  else
    $presence \leftarrow False$
  return *presence*

environments suggest the value of 60% as threshold for α. The key fact about ambient light sensing is that presence of multiple people in between sender and receiver is not detectable by monitoring changes in the ambient light level and this the key limitation of this approach.

4 PERFORMANCE EVALUATION

In this section, the performance of proposed algorithms for utilizing wireless sensing technologies at the doorways to accurately count people inside the room is evaluated. We investigate characteristics of each technology by performing micro-benchmarking to study its performance on different scenarios.

4.1 Experiment Setting

For people counting using WiFi signals, Intel's Iwlwifi NIC 5300 network cards [14] is used. The modified firmware reports 30 subcarriers for each received message, which is about one group for every 2 sub-carriers at 20 MHz or one in 4 at 40 MHz. Each cell in the reported matrix is a complex number with two 8 bit signed integers for real and imaginary parts which are amplitude and phase for each pair of transmitter and receiver antennas. We attached NIC 5300 cards to the laptops (replaced the laptop's original WiFi card) to conduct the experiments and collect data. We place transmitter laptop on one side of the door and receiver laptop on the other side as shown in figure 5. Iperf [10] is used to continuously send packets from sender to receiver. In the experiments with an access point, a 2GB file is downloaded to build an active connection between the laptop (receiver) and access point (sender) during the experimental time. We used Decawave's TREK1000 development kit[5] for our

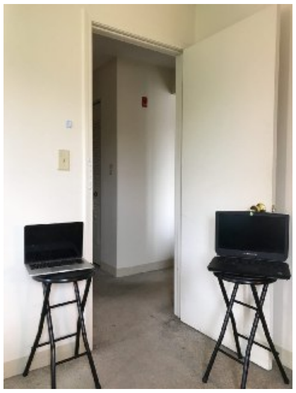


Figure 5: WiFi Experiment Set up

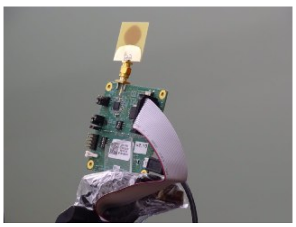


Figure 6: Decawave's TREK1000 Development Board

UWB based experiments. The kit contains four UWB development board. Each board has a DW1000 UWB chip as well as a customized UWB antenna that can send and receive UWB signals. CIR information for received signals is generated with the sampling interval of 1 ns. Figure 6 shows the TREK1000 board used in our experiments. We used one node as the sender and another node as the receiver. The sender broadcasts blink messages every 250 ms. Here are technical details of DW1000 chips [5].

- Supports 110 kbit/s, 850 kbit/s and 6.8 Mbit/s data rates
- Transmit Power -14 dBm or -10 dBm
- Supports Packet Sizes up to 1023 bytes

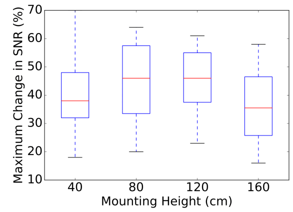
For light sensing experiments, we used TelosB motes. They have built in light sensors (Hamamatsu S1087 Series). We implemented a TinyOS script to log the measured light luminance level and used ambient light's luminance level for people flow measurements.

4.2 Controlled Experiments

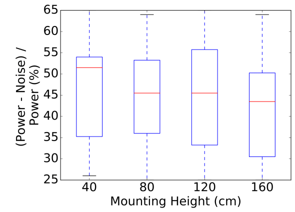
In the first set of experiments, we conducted micro-benchmarking in the lab environment. The behavior of proposed wireless sensing technologies in the different scenarios is studied. The following experiments have also been conducted in our lab. Our lab's door width is 90 cm and its height is 270 cm.

4.2.1 Height Flexibility. One of the key contributions of our work is proposing a deployment flexible solution. Most of the related work in people counting area have restricted deployment and mounting guidelines. In this section, we deploy each technology in different heights and measure the performance.

WiFi Sensing: We placed sender and receiver laptops (equipped with Intel 5300 chips) in four different heights (40 cm, 80 cm, 120 cm and 160 cm) and asked 10 people to enter and exit room 5 times. We monitored amount of change in the Signal Noise Ratio (SNR) values across all the sub-carriers once one person walks through the door. The results are reported in figure 7(a).



(a) Changes in CSI in different heights (WiFi)



(b) Changes in CIR in different heights (UWB)

Figure 7: Mounting Height Resilience

As it is shown in figure 7(a) the height of deployment will have the impact on the absolute values of reported SNRs but as mentioned in algorithm 1, proposed solution is sensitive to amount of changes in previously reported SNR. It detects the presence of people when the maximum SNR changes are larger than 25% of average SNR for that sub-carrier. Hence we claim the proposed algorithm can detect the presence of people regardless of deployment height.

UWB Sensing: To evaluate the performance of UWB sensing in detecting the presence of people with various mounting height, we conducted similar experiment as WiFi sensing. We mounted UWB sender and receiver in both sides of the door in different heights (40 cm, 80 cm, 120 cm, and 160 cm) and asked 10 people to walk back and forth through the door. We logged changes in first path signal power once a person walked through the door and also amount of background noise. The results are reported in figure 7(b). As mentioned in algorithm 2, our system detects presence of people when the gap between background noise and first path signal's power is smaller than 60% of first path power. In all the distances reported in figure 7(b) the gap between first path power and noise is smaller than 60% of first path power which means the designed algorithm detects the presence of people.

Light Sensing: We conduct the same experiment with people walking through the door using light sensor mounted on the doorway. The counting accuracy is similar to the accuracy achieved with WiFi, but it only requires one detector. We placed a TelosB mote as the detector on one side of the door at a height of 120 cm from the floor. We used a simple thresholding algorithm to detect presence of a person walking through the door and achieved 93% accuracy in counting people. Light sensor accurately detected presence of a person. However, it can not detect multiple persons walking through the door at the same time. Fig.8 represents a strong correlation between walking-through event and the decrese of illuminance level. The proposed light-sensing system will first calculate the threshold when people walking through the door for multiple times. Then the system will use this threshold to detect whether people have walked through the door.

4.2.2 Walking Speed. Average human walking speed is 1.4 m/s [1]. In this section, we measured the minimum distance from human to the wireless sensor (WiFI chip, UWB chip or light sensor) in which presence of body impacts the received signal and use that information to understand if the performance of the system will be affected by the walking speed.

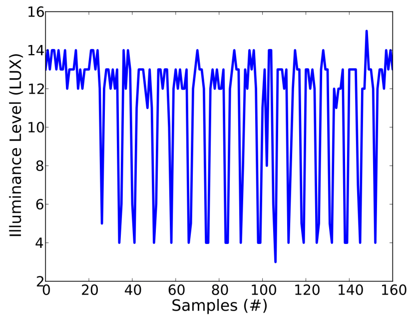
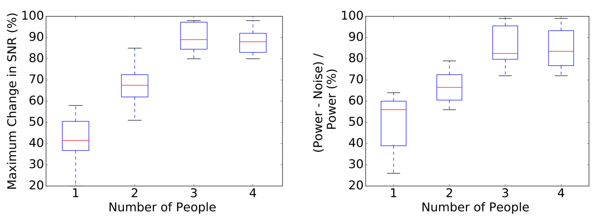


Figure 8: Illuminance level collected when subjects are walking through the door



(a) Changes in CSI with different people standing at the Doorway

(b) Changes in CIR with different people standing at the Doorway

Figure 9: Multiple People Standing at the Doorway

For WiFi chips, our experiments showed that once people are in 40 cm distance from the sensor, the CSI values start changing. 40 cm from each side of the virtual line between sender and receiver means the area of impact is around 80 cm. Our solution uses 10 samples per second which means even if people walk with 8 m/s speed, still there is at least on sample that our system captures while the person walks through the door.

First path signal in UWB starts changing once people are in at least 20 cm distance to the virtual line between sender and reviver which means total impact area is 40 cm and with sampling rate of 10 samples per second, walking with up to 4 m/s easily is detectable by our system.

For light sensing, after people go close to around 50 cm of the sensor, the measured light starts changing which means the system is able to cover walking speed with 10 m/s.

4.2.3 Multiple People. Counting people in crowded scenarios is a key challenge in people counting solution.

WiFi Sensing In the first experiment, we place sender and receiver nodes in the height of 120 cm from the ground (door width is 90 cm) on each side of the door. We asked 1, 2, 3 and 4 peoples walk through the door, and we measured the changes in SNR values. Figure 9 (a) shows the recorded values. As it is shown in figure 9(a), changes in SNR values once there 1, 2 and 3 peoples are different and in our algorithm (1) we utilized this difference to count number of people who are standing at the doorway but the measurements do not show a noticeable difference between scenarios with 3 people standing at the doorway and four people standing at the doorway which means our system can not count the accurate number of people in scenarios with higher occupancy but the cases that four individuals walk through the door at the same time in narrow doors are very rare.

Table 2: Accuracy of Counting People inside the Room in a Door with 90 cm Width

Event	# Ground Truth	# WiFi (%)	# UWB (%)	# Light (%)
Entrance	55	53 (96%)	54 (98%)	52 (95%)
Exit	55	52 (95%)	55 (100%)	53 (96%)

Table 3: Accuracy of Counting People inside the Room in a Door with 160 cm Width

Event	# Ground Truth	# WiFi (%)	# UWB (%)	# Light (%)
Entrance	60	56 (93%)	58 (96%)	54 (86%)
Exit	60	55 (91%)	59 (98%)	54 (86%)

Table 4: Accuracy of Counting People inside the Room in Uncontrolled Environment

Event	# Ground Truth	# WiFi	# UWB	# Light
Entrance	73	66 (90%)	68 (93%)	60 (82%)
Exit	70	62 (88%)	66 (94%)	60 (85%)

UWB Sensing To evaluate the performance of UWB sensing in the presence of multiple people, UWB placed the transmitter on one side and the receiver on the other side of the door in the height of 140 cm from the ground. During 20 rounds, we asked 1,2,3 and 4 people walk through the door at the same time. We measured the rate of change in first path signal power. Figure9(b) shows the results in which the amount of change in first path signal power is obvious in the case of 1 or 2 and 3 people. Higher number of people walking through the door, is not detectable from first path signal changes.

4.2.4 Door Width. One of the factors which impacts the performance of proposed solution is the distance between sender and receiver. In this section, we evaluate the performance of proposed solution in two different doors with different sizes (90 cm and 160 cm).

At it is shown in tables 2 and 3, UWB signals have the best performance in both door sizes. In worst case accuracy of each technology does not go below 86% which is reasonable considering the low power and low cost features of utilized technologies.

4.3 Uncontrolled Experiments

In this phase, we deploy all the 3 solutions in a computer lab in our department which is a popular place for students to spend their time. The door width is 90 cm and door height is 270 cm. We place WiFi chips, UWB transmitters and TelosB's (light sensors) on both sides of the door in approximately same height (140 cm from the ground) and monitored flow of people for 5 hours. We manually logged entrance and exit events for ground truth collection. Table 4 shows the results of deployment of the system in an uncontrolled environment.

Table 5: Performance Evaluation in Uncontrolled Environment - Combined Solution

Event	# Ground Truth	# Combined Solution
Entrance	73	70(96%)
Exit	70	68 (97%)

The results from uncontrolled environment are consistent with results from controlled experiments. The reason for drop in accuracy in uncontrolled experiment, is some abnormal behaviors by students in the front door. For example people move back and forth so quickly in front of the sensor (return back to the room before completely exiting) or stay in the doorway while others passing through the door. These kinds of unusual cases are rare and that is the reason the performance of uncontrolled scenarios are comparable to controlled experiments.

4.3.1 Combined System. One promising idea is combining the 3 sensing technologies to improve the final accuracy. To evaluate improvements by combining the 3 technologies, we implemented a simple majority vote technique. As mentioned earlier, in our uncontrolled environment tests, we deployed all the sensors in almost same location. During the uncontrolled experiment, we also logged all the information from the 3 sensing technologies. We implement a simple majority vote algorithm and run it over collected data from the experiment. Basically in each case, about counting number of people between sender and receiver, we take the majority vote. The results of running this experiment are summarized in table 5.

5 DISCUSSION

In this work, we investigate the feasibility of using low power and low cost wireless sensing technologies for accurate estimation of people inside the room. The novelty of our work is placing the sensors on the front door and detect entrance and exit events. Since, the sensors are deployed on sides of the door, their capability to detect crowded scenarios, especially in wider doors is limited. Our experiments show that WiFI and UWB based sensing techniques can count up to 3 people in the scene accurately but scenarios with higher occupancies are not detectable in current algorithm. However, right now we are just using changes in signal values as indicator for number of people and for building more accurate systems, other features of the wireless signal like phase information, noise level and so on can be used as a feature vector and using advanced machine learning techniques can help us to build very accurate model.

One of the technologies investigated in this paper is light based sensing. The key advantage of light sensing is its prices. A simple photodiode can be purchased with few cents. In this case, simple people counting solution with two photodiodes and a processing unit (Raspberry Pi Zero for instance) can be built with less than $10. The main problem with light sensing is the inability to count multiple people who went through the doorway. It limits the application of this technology for wider doors and crowded scenarios.

6 CONCLUSION

In this work, we investigated the possibility of using low cost wireless sensing technologies (WiFi, Ultra-wideband and visible light) at the doorways to accurately estimate number of people inside the room. The key idea was using the impact that human makes on the wireless signals as an indicator for the presence of humans and counting number of entrance and exit events to the room. Our results indicate the each sensing technology can achieve to pretty reasonable results even in the crowded scenarios and combination of above mentioned technologies can achieve to 96% accuracy in estimating the number of people inside the room.

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