Occupant Locating System Using Restricted Detection Range in Wireless PIR Sensor Network

In Hwan Baek, Xiangrui Liu, and Shubham Khandelwal
Department of Electrical Engineering, University of California Los Angeles
Henry Samueli School of Engineering and Applied Science
Email: chris.inhwan.baek@gmail.com, xrliu@ucla.edu, khandelwal_d_shubham@yahoo.com

***Abstract*—Occupant locating plays an important role in many smart home and smart building applications, such as energy efficient smart work places. Among several techniques proposed for locating occupants in such an environment is motion sensing-based occupant tracking using PIR sensors. However, the current PIR sensor-based locating systems have high computational complexity in order to track multiple occupants. Furthermore, they are not easily scalable and the multiple occupant locating algorithm must be modified based on the dimension of the room, number of sensors used, and the sensor placement. In this project, we propose an idea to achieve multiple occupant locating without adding computational complexity as well as to ensure easy scalability. Current systems must have probabilistic algorithm because the overlapping PIR detection regions can bring confusion. In our system, the detection range of PIR sensors are restricted with aluminum so that we can remove undesirable overlapping regions. Our system works as follows: Activity fingerprints are captured by the PIR sensor, which relays this information to the Intel Edison through the IR transmitters and receivers. This information is then uploaded to the cloud over Wi-Fi by Intel Edison. The cloud hosts a web server and thus a browser can be used to access the web page which shows the location of the user in a 2m $\times$ 2m section graphically. Extensive experiments showed that each subsystem is very reliable.**

I. Introduction

Occupancy detection is used in many buildings to reduce energy consumption. Occupancy information can be used directly by building control systems to reduce the energy consumption of air conditioning, lighting, IT infrastructure, and other building systems. Occupancy detection can provide information to these building systems to allow them to operate proportionally to the number of occupants in the building. For lighting there are potential energy savings of 50% with good occupancy detection. For HVAC, occupancy driven control could enable energy savings of 20%. Significant energy savings are possible by controlling desktop PC power on and sleep states as a function of usage. This is evidenced by a growing number of commercial products (for example, [1]) and research efforts in this area (for example, [2]). At the heart of these methods is occupancy detection of PC users.

Occupancy detection in current buildings is typically accomplished using passive infrared (PIR) and ultrasonic motion detectors. These dedicated occupancy sensors are installed expressly to determine occupancy and control building systems to reduce energy. Drawbacks to such explicit occupancy sensing include limited accuracy, incorrect installation, failure after installation, and lack of networking capabilities for data collection. Energy savings from using PIR sensors to control lights can vary from 10% to 45% depending on the type of room and the detector settings. PIR sensors are particularly effective for controlling lighting in infrequently occupied closed spaces such as storage rooms, but are ineffective for more open layouts such as offices. The lack of communication among these sensors precludes the sharing of occupancy information with other systems and fusion of information from multiple sensors.

In this project we try to address some of these issues. We have tried to redesign some PIR based sensor modules which are energy effective. These efficient modules are then combined with some unique algorithms which optimize the accuracy of detection and also help in reducing power consumption. In addition to this we make use of Intels low power platform called Intel Edison for establishing connectivity between various sensors. This helps in sensors exchanging meaningful data. To help our design be more robust and scalable and to avoid transmission losses we make use of infrared communication between PIR sensors and Intel Edison platform. Our system also enables use of a remote cloud server. This cloud server receives data from Intel Edison which is then useful to display the location of user on a webpage which is useful for remote monitoring.

II. Background and Related Work

A. PIR Sensor

Every object that has a temperature above perfect zero emits thermal energy (heat) in form of radiation. Human body radiates at wavelength of 9 - 10 m always. The PIR sensors are tuned to detect this IR wavelength which only emanates when a human being arrives in their proximity. The pyroelectric sensor is made of a crystalline material that generates a surface electric charge when exposed to heat in the form of infrared radiation. When the amount of radiation striking the crystal changes, the amount of charge also changes and can then be measured with a sensitive FET device built into the sensor. The sensor elements are sensitive to radiation over a wide range so a filter window is added to limit detectable radiation to the 8 to 12 m range which is most sensitive to human body radiation.

B. Abstraction of the Detection Region of a PIR Sensor

There are three important properties about detection region of a PIR sensor. First, the shape of detection region of a PIR sensor is a sector form as shown in Figure 1. Second, the sector form has a constant radius which is a maximum detection distance of the PIR sensor. Third, the sector form also has a central angle which is a detection range of the PIR sensor.

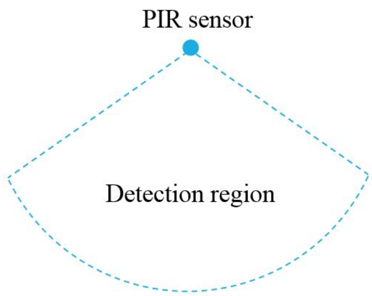

Fig. 1. Detection region of a PIR sensor

C. Region-Based Tracking Algorithm

For occupant locating system, PIR sensors are usually used since they do not require any signal or devices on the occupant to be tracked and they can work in dark environment as well. As shown in the Figure 2, when we use only one PIR sensor, the only information we can obtain is existence of an occupant (technically, the motion of an occupant) within the detection region of that one PIR sensor. However, if we deploy two PIR sensors, we can divide a space into 3 different regions. Therefore, the more PIR sensors we deploy, the more different regions we can divide a space into, and then the more accurate occupants location information we can obtain.

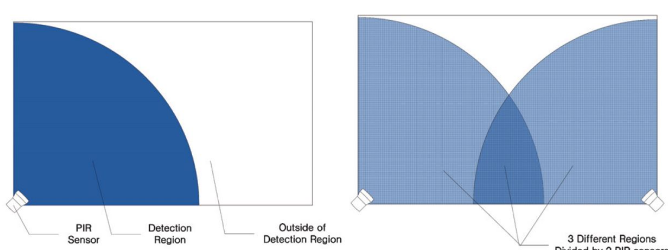

Fig. 2. Sensor deployment with only one PIR sensor and two PIR sensors

[3] proposed a region-based tracking algorithm that aims to find out which region an occupant is located by using output signals of several PIR sensors. For example, there are thirteen different regions in the example of Figure 3. If the output signals of the all PIR sensors are high, which means that they are detecting an occupant in their own detection region, the occupant is in the center region A of the small room because it is intersection of the detection regions of each PIR sensor. Therefore, in general, region-based tracking algorithm can be summarized as calculating the detection regions of each sensor that detects the occupant and the regions outside the detection regions of each sensor that do not detect the occupant.

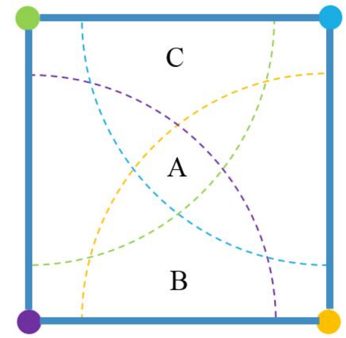

Fig. 3. A possible deployment example for a small room with 4 PIR sensors

However, the region-based tracking algorithm proposed by [3] has a big limitation. Considering the scenario of Figure 3, if one occupant is located in the region A, the output signals of all PIR sensors are high. But, if one occupant is located in the region B and another occupant is located in the region C in the meanwhile, the output signals of all PIR sensors are also high. So, the region-based tracking algorithm proposed by [3] cannot figure out whether there is just one occupant in the region A or there are two occupants in the region B and the region C in the meanwhile. As a consequence, it cannot locate multiple occupants.

There have been efforts to solve the multiple occupants tracking problem. [4] proposed multiple target tracking scheme using joint probabilistic association and consensus filtering. However, this proposed method brings more computational complexity to the region-based tracking algorithm.

III. System Design

We propose a system that incorporates region-based motion tracking using PIR sensor network. Our system solves the multiple occupants tracking problem without adding computational complexity. In fact, our system simplifies computation even further. This is done by removing overlapping detection regions of PIR sensors and it is described in details in III-A.

We also considered low-power wireless communication in our system. Our system includes four sensor modules and one center unit placed as shown in Figure 4. The sensor modules read PIR sensor outputs. Whenever there is a change in the PIR sensor outputs, the modules send the sensor information to the center unit wirelessly. We considered several aspects of wireless technologies. Among the aspects are network topology, protocol complexity, and power efficiency. We concluded that wireless infrared (IR) communication technology is suitable for our system. III-B describes how we concluded that Wireless IR communication is suitable and how we designed a protocol for our system.

For our system prototype, we used an Intel Edison board for the center unit that communicates with the sensor modules and a server. Intel Edison features a powerful dual core Intel Atom CPU that consume much more power than microcontoller. In order to reduce the power consumption of the Intel Edison, we designed a MCU-based power control.

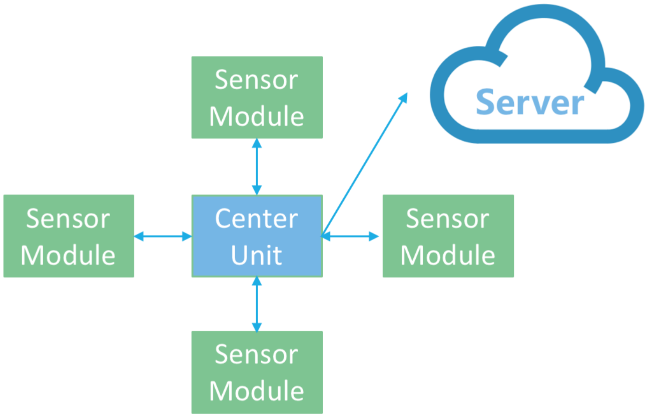

Fig. 4. Overall System Module Placement

We incorporated the Internet-of-things design into our system. The center unit communicates with a server to further interact with other systems as shown in Figure 5 as an example.

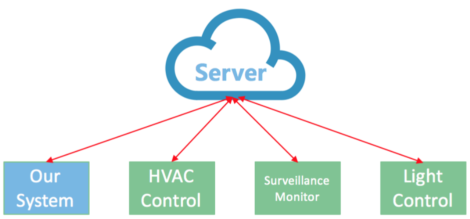

Fig. 5. An exemplary IoT adaptation of our system

A. Region-Based Multiple Occupants Locating

Overlaps between detection regions of PIR sensor leads to confusion when we apply region-based tracking algorithm proposed by [3] to multiple occupants locating. To solve the problem, we proposed a method to constrain the detection range of the PIR sensor. Since aluminium serves as an excellent reflector (as much as 98%) of medium and far infrared radiation [5], we cover an aluminium cylinder on the Fresnel lens of PIR sensor in order to block parts of infrared radiation, as shown in Figure 6.

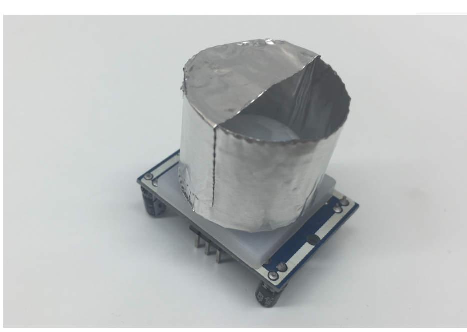

Fig. 6. Aluminum cylinder

Adding an aluminium cylinder on the Fresnel lens of PIR sensor can cause the constraint of the detection range of the PIR sensor. As shown in Figure 6, the original detection range of the PIR sensor covers a large space. With the help of aluminum cylinder, parts of infrared radiation are reflected, and thus the detection range of the PIR sensor is significantly constrained.

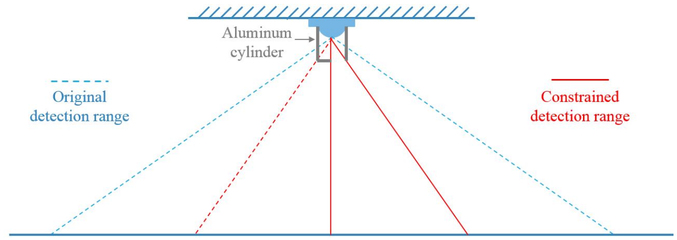

Fig. 7. Side view of the PIR sensor detection range constraint

The radius R of the constrained PIR sensor detection region can be calculated with equation 1

$$R = r \times \frac{H}{h} \tag{1}$$

where r is the radius of Fresnel lens of the PIR sensor, h is the height of aluminum cylinder and H is the height of PIR sensor above the ground. Considering the PIR sensors and the aluminium cylinders we used in our system prototype and the positions where the PIR sensors are mounted, the radius of the constrained PIR sensor detection region is 2 meters.

In addition, in our prototype system, we put two PIR sensors in each sensor module. Each PIR sensor in each sensor module has a sector-shaped detection region with 90° detection angle and 2 meters maximum detection distance, as shown in Figure 8. What's more, there is no overlap between the detection regions of two PIR sensors in a sensor module, which can reduce the confusion for multiple occupants locating.

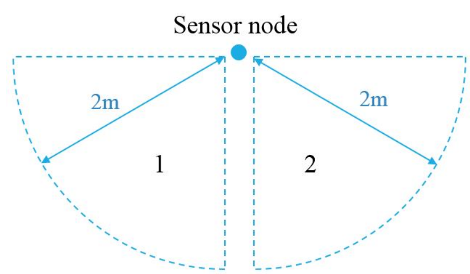

Fig. 8. Top view of the a sensor module detection range

Based on above-mentioned design in III-A, our region-based multiple occupants locating algorithm is quite simple but effective. As shown in Figure 9, our prototype system covers a 4m × 4m space with four sensor modules and divides the space into four 2m × 2m square sub-regions. In our algorithm design, four square sub-regions do not influence each other. For each square sub-region, if the output signal of corresponding PIR sensor(s) is high, it means that there must be occupant(s) in this square sub-region. For example, if the output signal of the left PIR sensor in the sensor node 1 is high or the output signal of the right PIR sensor in the sensor node 2 is high, there must be occupant(s) in the upper-left square sub-region. Note that here we already achieve 2m $\times$ 2m detection accuracy theoretically. If higher detection accuracy is required, we can further constrain the detection angle of the PIR sensors and add more PIR sensors for each sensor node, because in this way each square sub-region will be further divided into more smaller regions and thus the detection accuracy is improved.

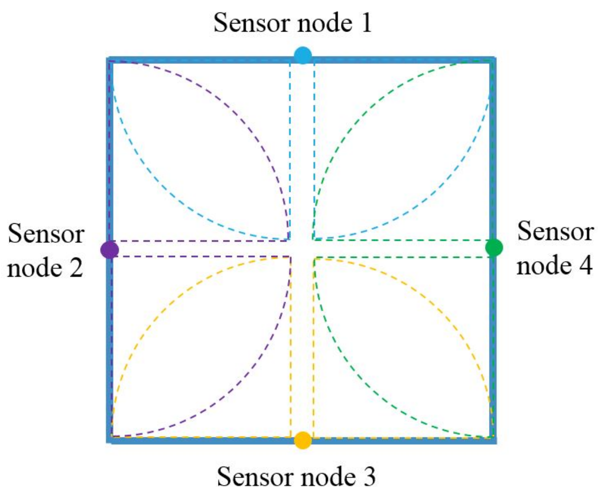

Fig. 9. The placement of PIR sensor nodes

B. Wireless Infrared Communication

As our system consists of wireless sensor network, we considered low-power wireless communication. There are several wireless technologies available and we considered several aspects of these technologies. Among the aspects are network topology, protocol complexity, and power efficiency. Our choice of the network topology is point-to-point because the sensor modules directly communicate with center unit. The information sent from the sensor modules only consist of command, module address, and PIR sensor data. Therefore, we do not want huge overhead of extra protocol stacks of Bluetooth or WiFi. Also, we want the sensor module's transmitter and the receiver to be active only when the PIR sensor outputs change.

We concluded that wireless infrared (IR) communication technology is suitable for our system. Compared to radio technologies such as Bluetooth, IR transmitter and receivers are capable of high speed communication at low cost [6]. Other advantages of IR over radio are unregulated bandwidth, easy secure implementation, and freedom from multipath fading [6]. Often considered drawbacks of IR communication do not affect our system. First, the IR's difficulty of operating outside is not likely a problem because our system is indoor occupant locating. Second, IR's inability to penetrate through walls also means that there is no interference from outside the room. Thus, it is much easier to implement secure communication. Third, IR communication is direct line-of-sight. However, our sensor modules and the center unit are mounted on the ceiling and the wall in a room, so we can easily align the IR transceivers of each subsystems during the setup.

Our IR communication protocol is based on Sony 12-bit SIRC protocol. The logical ones and logical zeros are formed the same way as in Sony SIRC protocol, in which a burst of $1200\mu s$ followed by a space of $600\mu s$ forms logical one and a pulse of $600\mu s$ followed by a space of $600\mu s$ forms logical zero [7] as shown in Figure 10.

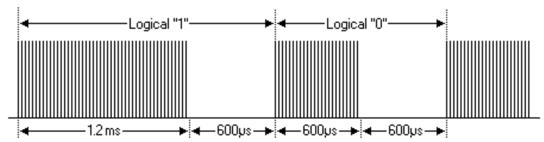

Fig. 10. SIRC Protocol

However, the coded bits carry different information in our protocol. Each 12-bit signal consists of three parts. Most significant four bits are the command, the next four bits are the module address, and the least significant four bits are sensor data as shown in Figure 11 and the information sent as bits for each type is described in Table I. The bit patterns are designed for more robust communication. Although it is not likely to happen, if one bit is misinterpreted and also passed by the SIRC protocol checker, the transmitted signal is ignored as there is no matching pattern and the receiver requests another transmission. Each bit pattern has at least two bits that are different from another within the same type.

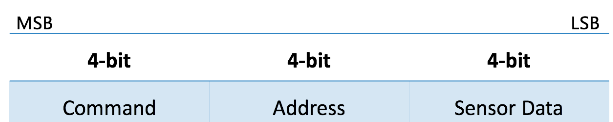

Fig. 11. 4-bit IR code

Type	Bits	Description
Command	1001	Send data
	0110	Send ACK
Address	0000	"Up" sensor module
	0101	"Down" sensor module
	1010	"Left" sensor module
	1111	"Right" sensor module
Sensor Data	0000	None of sensors on
	1100	"Left" PIR sensor on and "Right" sensor off
	0011	"Left" PIR sensor off and "Right" sensor on
	1111	Both sensors on

TABLE I
4-BIT IR CODE

In order to further improve the reliability of the IR communication, we designed a simple two-way handshake as illustrated in Figure 12. When a sensor module has a change in it sensor data, it send a message to the center module with "send data" as the command, its module address, and the sensor data. Once the center unit receives the message,

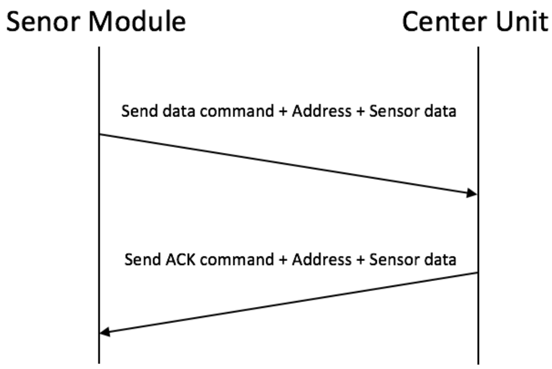

Fig. 12. IR two-way handshake

it replies with an acknowledgement, which consists of ACK command and the original sensor module address and data received. If the sensor module does not receive an ACK messsage from the center unit, it retransmit the message. If the sensor module receives a message, it extracts the address and the data and compare them with those in the original message. If there is a mismatch, the sensor module retransmit the message.

C. *MCU-based Power Efficient System*

Our prototype uses an Intel Edison board for the center unit as a gateway that communicates with the sensor modules and our server. An Intel Edison is a powerful IoT platform, which may suffer from high power consumption compared to ultra low-power microcontroller-based systems.

Acutually, Intel Edison board features an Intel Atom dual-core processor running Linux as its host CPU and a Minute Intel architecture processor running Viper as its microcontroller unit (MCU), as shown in Figure 13. The power consumption of the microcontroller unit is significantly lower than the host CPU, so we can utilize this feature to reduce the power consumption of the Intel Edison board. In order to achieve

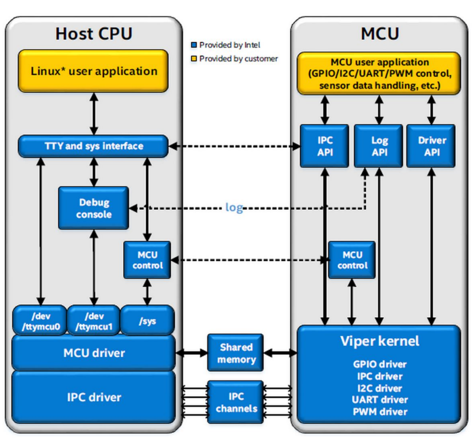

Fig. 13. Host CPU and MCU on Intel Edison

the power saving on Intel Edison board, we can have the host CPU rest in a sleep status while the MCU is kept active to collect data that comes from four sensor modules and wake up the host CPU only when the occupants location information changes. Figure 14 shows the workflow of our MCU-based power efficient system.

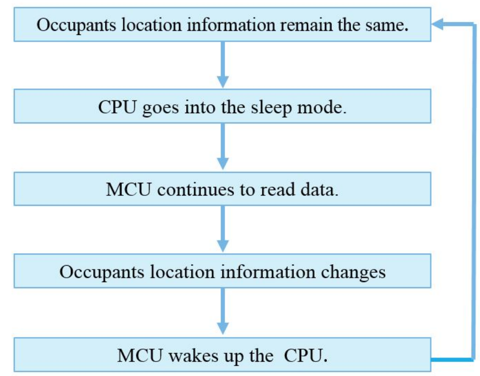

Fig. 14. The workflow of MCU-based power efficient system

D. *Server Interaction*

Our objective is to enable remote monitoring of user location. Also to enable platform independence we make use of simple web browser based page over which location can be monitored. Use of web page helps us to remove any dependency on platforms, Operating Systems or softwares. Our solution can be used from tablets, smartphones, laptops, personal computers etc. Communication mechanism used for communication from cloud to Intel Edison is secure and encrypted as it uses SSH (secure shell). Also data need to uploaded is very minimal and is less than 1KB. This helps us to keep the system power efficient and secure and protected.

IV. System Implementation

For our prototype implementation, we used Arduino Unos, an Intel Edison, PIR sensors, IR transmitters, IR receivers, a Linux machine, and other miscellaneous components as shown in Figure 15.

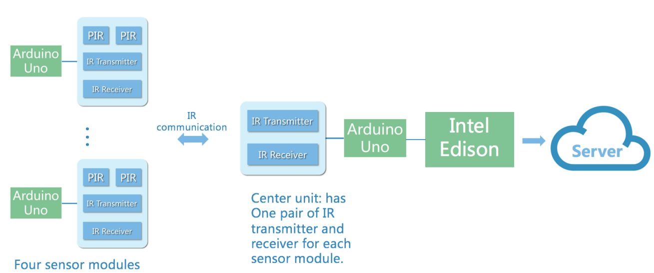

Fig. 15. Overview on system implementation

A. *Sensor Module*

Our sensor module is implemented with an Arduino Uno, two PIR sensors, an IR emitter (LED), an IR receiver, two

2.7V 400mAh LiPo batteries, and other miscellaneous components. Figure 16 is our sensor module mounted on a wall. The sensor module base and the housing of the PIR sensors are 3D printed. An Arduino-compatible protoshield is used to put all electric/electronic components together.

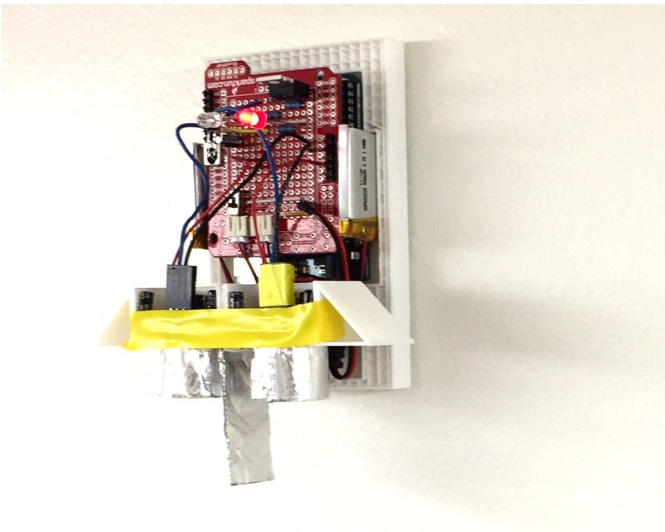

Fig. 16. Sensor module mounted on wall

1) PIR Sensor: In our sensor module prototype, we used HC-SR501 PIR motion sensor. The output signal of the PIR sensor will be high when it detects human motion. Under the repeatable trigger mode we used, during the delay period, if there are still human motions in its detection region, the output signal of the PIR sensor will always remain high until the people leave. After the delay period, the output signal of the PIR sensor will change from high to low. In additon, we adjust the distance potentiometer on the board to increase the detection distance to the maximum detection distance (about 7 meters) and adjust the delay potentiometer on the board to decrease the delay to the minimum delay (5 seconds).

2) IR Transmitter and Receiver: Each sensor module includes a pair of an IR transmitter and an IR receiver. IR transmitters are implemented with an IR leds. A PWM signal generated by Arduino's ATmega328 is used to modulate and code the IR signals. The pin that is mapped to the PWM output of ATmega328 cannot supply enough power to the IR LED to achieve the range we need. Arduino Uno's 5V output pin, on the other hand, is capable of supplying enough power. Therefore, we connected the IR LED to an N-channel MOSFET, whose gate is connected to the PWM pin as shown in Figure 17.

We used VS1838 38kHz IR receiver to simplify our implementation. Although we constraint to use 38kHz carrier frequency due to its hardware configuration, the line-of-sight nature of IR communication allows us to use 38kHz for all sensor module communication without much interference.

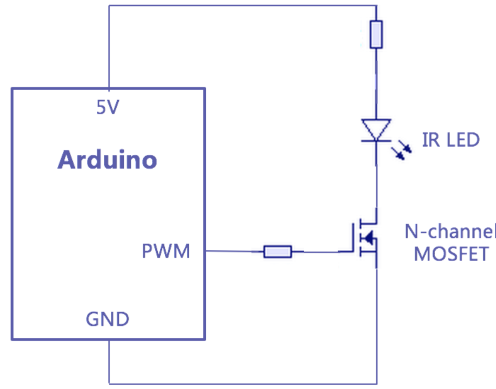

Fig. 17. IR transmitter

B. Center Unit

The center unit is implemented with an Arduino Uno and an Intel Edison connected via GPIO pins as shown in Figure 18.

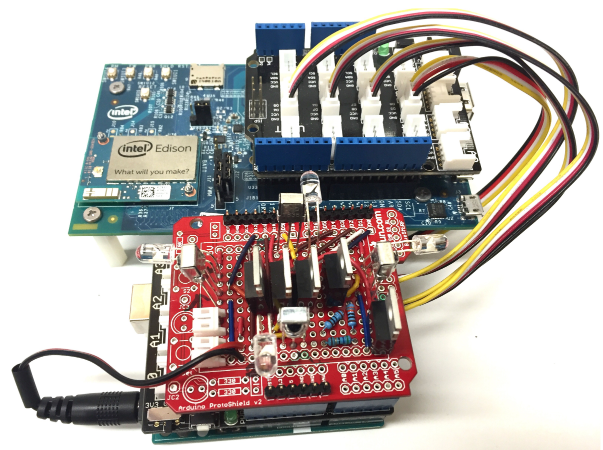

Fig. 18. Center unit

1) IR Transmitter and Receiver: The center unit needs to communicate with four sensor modules and hence four pairs of IR LEDs and IR receivers are installed. The Arduino Uno can only supply one PWM signal for the IR modulation. Thus, four MOSFETs are used as switches to select the IR LED to be used for transmission as shown in Figure 19.

2) MCU: The MCU API developed by Intel provides an interface that allows us to control the peripherals that connect to the MCU, and communicate with the host CPU system. In our project, we built an application for MCU using the MCU SDK, an Eclipse-based software development kit which is used to create applications for MCU on Intel Edison borad. In this application, we use gpio_setup API to set up the input mode for four GPIO ports that are connected to the Arduino UNO in the center unit and then use gpio_read API to read the value of four GPIO ports all the time. When the value

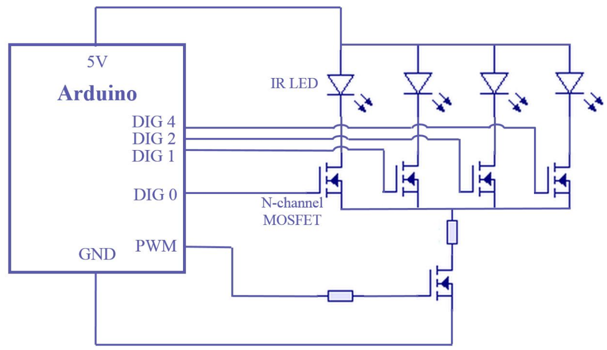

Fig. 19. IR LED configuration on center unit

of four GPIO ports changes, the MCU can wake up the host CPU using host_send APIs.

3) CPU: Whenever the host CPU on the Intel Edison wakes up, it read the occupant location data from the Arduino Uno of the center unit via GPIO pins. The location data is then uploaded to the server via SSH.

C. Server

We make use of a file present on the server to maintain the data needed and use a web browser to parse this data and show the location of user. Intel Edison is responsible for updating the data stored in this file. Intel Edison over Wi-Fi uses SSH and then writes the new data inside this file. A PHP based web page, as shown in Figure 20 has been developed which reads and parses the data from this file. This PHP page also has been enabled to auto refresh after every 1 second. Thus the current user location is updated automatically. Intel Edison updates data in server whenever it senses some human motion in the room. This interaction enables real time monitoring of the room as well as remote monitoring thus increasing the overall security feature of the system. The data sent by the Intel Edison on to the server is over a secure shell and thus is encrypted and secure Also very minimal data is needed to be sent to the server (< 1 KB)

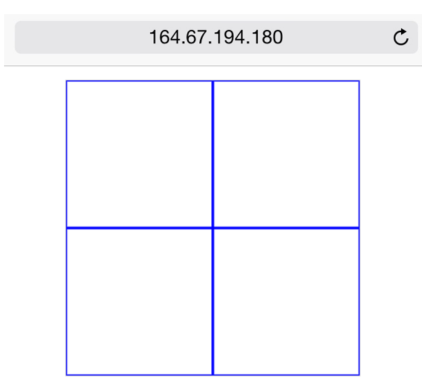

Fig. 20. Web page that visualizes the occupants location information

V. Evaluation

Figure 21 shows the indoor experimental setup and corresponding divided regions.

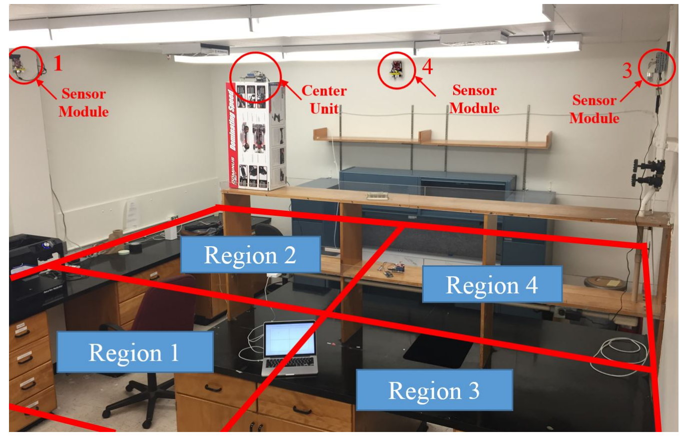

Fig. 21. The indoor experimental setup and divided regions

The result of the indoor experiment is depicted in Figure 22 Based on our experiment, our system seems to be very accurate. The only problem we encountered is the PIR sensor delay. In other words, the location information may get updated with a delay when an occupant move to another region. The PIR sensor holds the value "HIGH" for certain amount of time, thus for a short period of time when an occupant is relocating, the system may show that two regions are occupied.

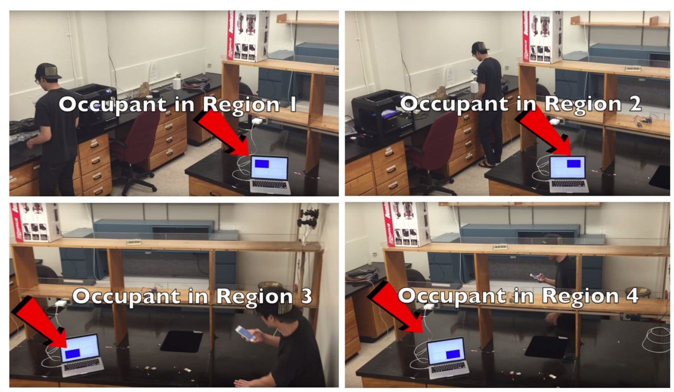

Fig. 22. Result of the indoor experiment

Now, we will also discuss about the evaluation of IR communication subsystem. We tested the IR communication by placing two IR modules separated by two meters, which is the distance between a sensor module and a center unit. Then, we sent forty messages from one module to the other. For each message, we counted how many transmissions it had to try until it receives an ACK message from the other and successfully passes the error detection method. The result is give in Table II. Based on this result, one message needs 1.2 transmissions on average until it is successful. Each transmission is done with high speed, so our IR communication system is fast and robust.

Msg.	# of trans.	Msg.	# of trans.	Msg.	# of trans.	Msg.	# of trans.
#1	1	#11	1	#21	1	#31	1
#2	1	#12	1	#22	2	#32	3
#3	1	#13	1	#23	1	#33	1
#4	1	#14	2	#24	1	#34	1
#5	1	#15	1	#25	1	#35	1
#6	1	#16	1	#26	1	#36	1
#7	1	#17	1	#27	1	#37	1
#8	2	#18	1	#28	1	#38	1
#9	1	#19	2	#29	1	#39	1
#10	2	#20	2	#30	1	#40	1

TABLE II
NUMBER OF TRANSMISSION FOR EACH MESSAGE

VI. FUTURE WORK

One of the major concerns about our system is that the IR receivers are always active and checking for IR signals. This may result in unnecessary power consumption. In the futre, we would like to add a photodiode-based IR receiver power control unit for each receiver. Figure 23 shows the design of the power control unit. We can set a threshold value on

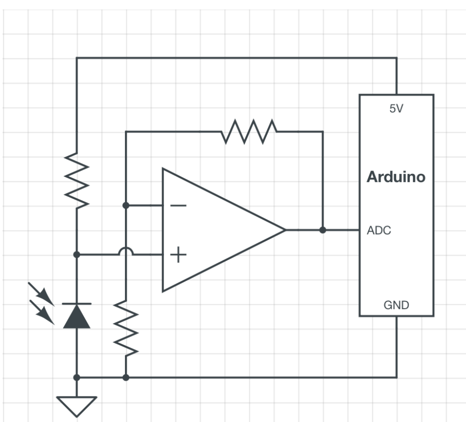

Fig. 23. Photodiode-based IR receiver power control unit

the ADC, so a value beyond the threshold indicates strong presence of IR. Only in the strong presence of IR, we turn on the receiver.

Another potential improvement is converting our point-to-point Wireless sensor network into wireless mesh sensor network. Our prototype works well as it is. However, if our prototype system is scaled and adapted in a bigger room, we need to multiple Intel Edison boards as the gateways, each of which interacts with the server. This may not be the most cost effective. We may have only one gateway for a room of any size. If each sensor module directly communicate with the gateway via IR communication, the power consumption is be significant. The power consumption is proportional to the square of the distance between the transmitter and the receiver. If we use mesh network topology as shown in Figure 24, the power consumption will scale linearly.

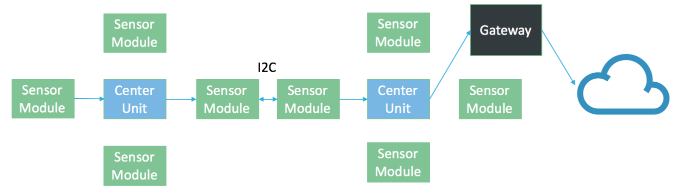

Fig. 24. Wireless Mesh Sensor Network

VII. CONCLUSION

Our developed system has many advantages. The system uses very basic and power efficient components. The PIR sensor range restriction removes the need of probabilistic algorithms. Hence the computational complexity is very low. Design is modular and robust and thus is easily scalable to rooms of any geometry and size. System does not make use of any wires and thus can be added to existing rooms as well along with new construction. Inexpensive components help to keep the cost of system under \$150 including the Intel Edison which can further be used for implementing smart HVAC system. Simple and lucid code helps maintaining and updating software a trivial operation. Software for cloud is very simple and is less than 30 lines and does not require any high computation servers. Browser based monitoring of room helps in real time monitoring and also platform independence is maintained. Bandwidth requirement for the system is very less as $<$ 1KB of data is transferred each time Edison updates the data in cloud. In this system we have tried to improve some areas which were not yet explored, thus increasing overall system efficiency, power efficiency and cloud interaction.

ACKNOWLEDGMENT

The authors would like to thank Professor Lei He and Teaching Assistant Xiao Shi.

REFERENCES

[1] Aptean.com *Verdiem::SURVEYOR*, http://www.verdiem.com/surveyor.aspx, 2011.
[2] J. Reich, M. Goraczko, A. Kansal, and J. Padhye *Sleepless in Seattle No Longer*, Proceedings of the USENIX Annual Technical Conference, June 2010.
[3] Byunghun Song, Haksoo Choi, Hyun Su Lee *Surveillance Tracking System Using Passive Infrared Motion Sensors in Wireless Sensor Network*, International Conference on Information Networking, pp.1-5, Jan 2008.
[4] Qi Hao, Fei Hu, Jiang Lu *Distributed Multiple Human Tracking with Wireless Binary Pyroelectric Infrared (PIR) Sensor Networks*, IEEE Sensors, pp.946-950, Nov 2010.
[5] P. Berdahl *Pigments to Reflect the Infrared Radiation From Fire*, J. Heat Transfer, pp.355-358, May 1995.
[6] Joseph M. Kahn, John R. Barry *Wireless infrared communications*, Proceedings of the IEEE,Volume 85, Issue 2, pp.265-298, Feb 1997.
[7] Nhivekar, G. S., R. R. Mudholkar *Microcontroller based IR remote control signal decoder for home application*, Adv Appl Sci Res,Volume 2, Number 4, pp.410-416, 2011.