From Industry to Home: Rapid Development of a ZigBee-Based Indoor Positioning System for Use in Private Residences

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***Abstract*—Smart home technology is a heavily researched topic. However, many considerable discontinuities remain in the literature – namely, research on applying new technologies – in this case, indoor positioning systems (IPSs) – for use in a smart home. Even with the numerous indoor positioning methods, many are not suitable for use in the home because they have been developed for industrial, commercial, and retail settings. It is necessary that new technologies – such as IPSs – are implemented into smart homes as it has been shown numerous times, though surveys, interviews, and experiments, that smart home users are quite underwhelmed by the current capabilities of the systems, saying that they are essentially glorified remote control systems and they would benefit from a greater level of automation. IPSs are a well-established technology that would give smart homes a greater level of automation; however, they must be adapted from their commercial origins to be ideal for use in the home. It is important that a general process for adapting technologies from industry to the home is developed though future research, such as this.**

***Keywords*—Localization; Indoor positioning; Indoor localization; IPS; Smart homes; Smart home technology; Technology in the home; Adapting technology from industry.**

I. Introduction

IN RECENT YEARS, many technologies, previously unrealistic for use in the average household because of cost or complexity, have made inroads to the average American home. One such technology that has made this transformation is the concept of the internet of things (IoT) [1], [2]. According to Govindraj et al., IoT is a concept “in which the objects of regular daily life will be furnished with [the processors and] appropriate protocols that will make them ready to communicate with each other and with users” [1]. When used in the home, IoT is usually called smart home technology [1].

Smart home technology allows the user to automate or remotely control various common tasks of household appliances, systems, etc. – the former is generally more favorable, as it allows the user to seamlessly interact with the technology. Some examples are turning on bedroom lights when the user wakes up, adjusting the thermostat from a mobile device, or turning on a fan when the temperature rises above a set point. This is a positive development in many ways; the use of smart home technology can promote home energy conservation [3], [4], allow the elderly to live in their own homes [5], [6], and provide solutions to various other modern problems [1], [7], [8].

II. Literature Review

A. *Consumer Reception of Smart Home Technology*

Despite the many promises smart home technology holds, many current users are all but underwhelmed. According to a survey by Sanguinetti et al. among residents of California (adjusted to fit average American demographics), more than 1 in 3 smart home owners said the technology is not worth the price given the current capabilities [9]. Similarly, S. Mennicken and E. M. Huang found, through a series of interviews with smart home owners, that almost all owners “described the effects of the technology as small conveniences rather than substantial support for routines or tasks” [10]. Furthermore, through a meta-analysis of 74 smart home surveys, K. Gram-Hanssen and S. J. Darby found that smart home technology is typically “unsatisfactory unless it offers scope for interaction and responds well to human control” [11]. This means the users felt the systems were not actually “smart” enough. Users said that, currently, smart home technology offers remote control, but not automation partially because of a lack of sensing capabilities [11]. In a report for the European Council for an Energy Efficient Economy (ECEEE) the authors agreed with the 3 former sources and go on even further to provide hard, experimental data. In the study, smart plugs were placed in homes and the usage was analyzed over a period of 15 weeks. It was found that the plugs, which were unautomated and relied on explicit user input, were forgotten about and very rarely used toward the end of the period. They found, in a second trial, that if the plugs were automated and acted upon implicit input (movement, daily patterns, etc.), they were used more often and more consistently. The amalgamation of these findings shows that consumers are excited and ready to adopt smart home technology, but they desire more automation in the systems, which can be made possible through a more thorough integration of sensors into the system.

B. IPSs

Indoor Positioning Systems (IPSs) are a technology that, much like global positioning systems (GPSs), determine a target object's physical position in space. GPSs, however, are not exceedingly accurate when the target is behind blocking objects such as roofs, walls, or other large buildings – this is where IPSs come in [12]–[15]. Since the conception of IPSs in the late 90s, they have been almost exclusively tested and deployed in commercial, industrial, and retail settings, or in small, open spaces such as apartments and nursing home rooms [15]–[19].

IPSs are data-heavy systems – meaning they generate lots of data and require considerable processing power to parse – this is why they have not been deployed in the average household. One principle of IoT is that the many systems connected within the system send the generated data to a central computer which can either process the data in-house or send the data to a cloud computing service. Today, with a greater accessibility to cheap, fast data processing and storage in the cloud and on-site, it is easier than ever to begin integrating data-heavy systems such as IPSs into the average home [20]. However, according to Shimosaka et al. from the Tokyo Institute of Technology, even with the recent development of smart home technology in homes, IPSs are still not found there [21].

Adding IPSs to smart homes would allow more specific location-based services (LBSs), which, according to G. Cullen, K. Curran, J. Santos, G. Maguire, and D. Bourne, are very much needed in order to further automate smart homes. Currently smart homes only use yes/no LBS scenarios – meaning they only consider if the user is at home or away (usually using the GPS location on the user's mobile device) [22]. The reason why LBSs have not been utilized beyond home/away is that GPS is typically not precise enough to locate what room/area of the house the user is in. However, according to research presented at the *IEEE 2014 Tenth International Conference on Intelligent Information Hiding and Multimedia Signal Processing*, "[LBSs] enable location scenario control, making home appliance control easier and enhancing the power utilization efficiency," meaning LBSs are part of the solution to increasing user satisfaction in smart home technology.

C. IPSs in the Home

As mentioned earlier, IPSs have been in the technological realm for quite some time. However, as also mentioned earlier, they had not commonly been tested or deployed in homes. This means that, although there are well established IPSs in use, they are not necessarily ideal for a home setting for a number of reasons.

There are countless IPS methods. The most popular is wireless local area network (WLAN) localization (typically Wi-Fi), usually through use of a received signal strength indicator (RSSI) [13], [15]. This is ideal, as Wi-Fi is a common communication type that operates at about the same range as needed for IPSs. On top of this, most industrial, commercial, and retail settings that RSSI WLAN IPSs are used in have multiple WLAN access points (APs) already in place for Wi-Fi access, meaning the user will not have to buy any additional transmitters [13]. However, this is not ideal for the home, as it requires at least 3 WLAN APs and the average household has only one, and adding more APs purely for this system would increase cost and power consumption [23]. Other types of WLAN IPSs are time of arrival (ToA) and angle of arrival (AoA); however, these types also require at least 3 APs.

Another type – commonly researched and tested but not implemented as often as WLAN RSSI – is pulse width modulated (PWM) light emitting diode (LED) [14], [24]. PWM LED systems are almost exclusively used in retail settings, especially in malls to target ads to visitors [14]. These systems use existing ceiling lights that are flashed on and off – more quickly than the human eye can register – to relay a code of the location for that specific bulb. This system is not incredibly cost intensive and would, to some level, would increase the efficiency of the home; however, PWM LED systems can only track targets when the receiver (usually a mobile device) is out in the open [24]. This is problematic, as one cannot expect a user to always be carrying their mobile device in the open at home.

There are many more IPSs than the 2 most popular listed above [13], [18], [25]; however, just as the prior 2, they are not necessarily fit for use in a home setting. Some more obstacles to home implementation, not present in other settings, are that, in homes, there are many physical blockers such as irregularly placed walls and furniture (which can introduce yet another level of chaos in that it is frequently moved) – all standard systems must be reworked and adjusted to be suitable for usage in the home [21].

D. The Need for Smart Home-IPS Research

Although, in recent years, there has been extensive research done in both the academic and private sectors, according to Gram-Hanssen and Darby, "There are still considerable gaps in the research literature" [11]. One gap is that of the integration of new technology; Gram-Hanssen and Darby go on to state "in future evaluative studies of smart homes – sorely needed – we suggest the inclusion of questions about how meanings of the home might change along with new technologies" [11]. One of those "new technologies" could be the IPS. Additionally, there is even less research literature on the development, testing, and deployment process that new technologies naturally go through when being adapted from industry to the home. There is a substantial need for research in this area since, to become more automated as users want, smart homes must integrate new technology. The research should 1) be fully open in documentation of the hardware and software specifications of the device used, 2) analyze results of testing the prototype, and 3) include a discussion of how the findings suggest the technology should be modified to be used in a home setting and highlight the changes that were made to the prototype to be suitable for us in the home. Future research that utilizes the aforementioned process will allow for the more rapid adoption of newly available technologies into the home.

III. METHOD

A. The System

1) Overview:

For this research, a prototype IPS, has been designed and constructed. The schematic, function layout, a photo, and other relevant design aspects are shown in (Appendix I). The system is of original design for this research. Each module uses an XBee 3 with PCB Antenna as the ZigBee transceiver, and an Arduino Pro Mini 328, 3.3V/8MHz as the coprocessor. The system as a whole uses multiple ZigBee transceivers emitting an RSSI to triangulate the targets location on 2 dimensions, this information is read-out and stored on the target module. The signal transmission, reception, and aggregation firmware on the coprocessors is shown in (Appendix II). To calculate the target position, the system utilizes a common Delaunay triangulation algorithm; the CGAL 4.14 2D Triangulation library, also running on the co-processor. This program is a standard in industry and academia [26]. This is a similar system to some IPSs that have been successfully tested for agricultural usage [23]. To operate the system, 3 emitting modules are placed on far corners of the area. Because the test is using a quasi-experimental approach, it is desirable that the positioning of the emitting modules varies between trials as this is how the technology would be used in the real world. Next, the coordinate position of each module is determined. The X component and the Y component are set in the firmware. This allows the target module to use the Delaunay triangulation algorithm from CGAL to determine its own position.

2) A Word on ZigBee

ZigBee is a wireless protocol, operating on the 2.4 GHz to 2.5 GHz (2.45 GHz nominal) range. Although this is the same range as some common home-use Wi-Fi specifications (802.11.ac, 802.11.g, etc.), and it has been shown that Wi-Fi does cause a lowered (up to 90%) packet delivery rate (PDR) between ZigBee devices [27], this effect is not reciprocated, meaning Wi-Fi transmissions can have some effect on ZigBee transmissions; however, ZigBee transmissions have no effect on Wi-Fi PDRs. This means there is no concern of the IPS affecting Wi-Fi transmissions; however, this will cause the IPSs to use more power in order to ensure all packets are delivered using ZigBee [27]. However, some of this effect will be mitigated by the fact that home Wi-Fi devices are now migrating towards the 5 GHz band which does not interfere with ZigBee and is not interfered with by ZigBee.

B. Testing

This research will utilize quasi-experimental testing to determine both the accuracy and precision of the IPS. Prior to the tests, a grid system (using inches) will be devised, one 1st floor corner of the house being the origin – having a coordinate value of (0, 0). All measurements will be taken at floor level. For the first trial, an ADH GP-735T 56 channel GPS receiver and the IPS target will be place at a randomly selected coordinate on the grid. 3 more coordinates will also be generated for each of the emitting modules and they will be placed correspondingly. The location will be collected 10 times on each of the systems and averaged. This will be repeated 4 more times for a total of 5 trials.

C. Measures for Control

A major limitation of the experiment is that, because of the scope of this research, it is not practical to build new homes to test within or to publish the exact specifications; thus, why a quasi-experimental method was chosen. However, this, to some degree, is more authentic, as the research is aiming to encourage the development of a technology that works in "the average home," which is not a definite set of specification, but rather a whole range of very different structures. Nonetheless, measures will still be taken to allow the research to maintain some level of consistency throughout the trials. The main measure that will be taken is that the home(s) chosen must adhere to the following standards: 1) the home must be free of occupants during the testing, 2) the home must have no metal netting or screen within the interior walls, 3) all interior doors should be open during the testing, 4) there can be no wireless signals (other than those of the IPS and GPS) may be transmitted or received within the home during the testing. Most of these standards are based on recommendations for wireless IPS testing from an IPS exploration study from an IEEE publication [13].

D. *Ethical Considerations*

Because no humans or animals participated in the study, an independent review board (IRB) was not necessary. Measures were taken, however, because the tests took place in homes. A Letter of Authorization was collected from all homeowners that could have possibly participated or did participate in the testing. The letter outlined the terms of the test and is shown in (Appendix V). Additionally, all of the GPS latitude and longitude data that was stored was truncated to leave only the numbers after the decimal in such a manner that all of the data was still viable for the analyzation, but it could not be used to find the actual location of the house. All GPS data that was published was already scaled as to be even more secure.

There are various other ethical considerations considering the technology of IPSs as a whole, and these are discussed at length in the "Conclusion" section below.

IV. Results

A. *Data*

The collected data are shown in (Tab. 1). The data shown here includes averaged target location calculated by the IPS and GPS [GPS data is converted to inches and scaled from (0, 0)], and the actual location of the targets. These are the exact values readout form the IPS and GPS. All units are in inches and all figures are rounded to the nearest whole.

Tab. 1

Test Results			
	Actual Location	**IPS Calculation**	**GPS Calculation**
Trial 1	(143, 44)	(140, 43)	(50, 23)
Trial 2	(92, 93)	(99, 98)	(100, 94)
Trial 3	(174, 52)	(170, 56)	(130, 41)
Trial 4	(10, 190)	(20, 192)	(26, 210)
Trial 5	(37, 201)	(32, 205)	(42, 219)

B. *Analysis*

The data was analyzed using method typically used for finding the accuracy of GPSs – root mean square error (RMSE) analysis [28], [29]. RMSE works taking the cartesian (x, y) coordinates and finding the distance between the actual and calculated coordinates using the formula [28]–[30]:

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

This result is a radius that can be projected around the calculated point to show the reasonable estimated error range [30]. These calculations produce the results shown in (Tab. 2).

Tab. 2

RMSE Calculations			
	Actual Location	**IPS Error Radius (in.)**	**GPS Error Radius (in.)**
Trial 1	(143, 44)	3.16	95.34
Trial 2	(92, 93)	8.60	8.06
Trial 3	(174, 52)	5.66	45.35
Trial 4	(10, 190)	10.20	25.61
Trial 5	(37, 201)	6.40	18.68

Next, the average (showing accuracy) and standard deviation (showing precision) were found for each category – IPS error and GPS error, shown in (Tab. 3).

Tab. 3

RMSE Calculation Statistics		
	IPS RSME (in.)	**GPS RSME (in.)**
Average	6.80	38.61
Standard Dev.	2.72	34.51

Lower values indicate a greater level of accuracy/precision. The IPS was more accurate than the GPS by a factor of 5.7 and more precise than the GPS by a factor of 12.

Another metric that benefits the analysis is the area of the estimated error range. The error range area is calculated by the basic formula for area of a circle:

$$A = \pi r^2$$

The averages and standard deviations for each system are shown in (Tab. 4).

Tab. 4

Estimated Error Range Areas		
	IPS RSME Area (in.^{2})	**GPS RSME Area (in.^{2})**
Average	163.99	7676.17
Standard Dev.	116.20	11917.85

C. Discussion

At the most basic level, the synthesis of the results shows that the IPS is both more accurate and more precise than the GPS. Accuracy demonstrates a system's ability to calculate the correct position, while precision demonstrates a system's consistency. Seeing that the IPS was more accurate and precise in this context, it is more desirable for use in smart homes for sensing functions.

V. Conclusion

D. Limitations of the Employed IPS

Aside from the aforementioned limitation, numerous others exist, therewith degrading the quality of the findings to some extent. Although, that extent is somewhat difficult to gauge, it is, nonetheless, beneficial to be aware of the specific sources.

A major limitation is that the IPS utilized for the testing was far less developed than any that would be commercially available. The system functioned, but with a lower accuracy than many commercially available IPSs [17], [31]. However, it did prove to be more accurate and precise than a GPS; however, most future commercially available systems will likely have considerably more capital – the likes of which are not available for this study – dedicated to research and development.

One alteration that previous IPSs tested in one-room apartments have employed with success is the placement of additional modules throughout the area with known positions [21]. These modules serve to constantly calibrate the locating modules, rather than the traditional method with calibration only at the beginning. This increases the accuracy considerably; however, this would effectively double the cost.

E. Other Considerations Concerning the Quality of the Study

Another factor that could possibly degrade the quality of the study is that the test was only performed in one house. It would have been desirable that it would have been carried out in multiple homes of similar specifications. This was made difficult by the fact that, like most commercial IPSs [17], [21], the IPS used in the tests took considerable time and effort to calibrate before testing. The home did not need to be free of occupants during this calibration period; however, the lengthy calibration is somewhat intrusive.

F. Future Implications

1) Ethical Considerations for the Expanded use of IPSs

There are various ethical factors that must be taken into consideration as the use of IPSs spread. The XBee 3s used in the testing used the default-configured 16-bit encryption for communication among themselves, meaning there is almost no fear of signals within the IPS being intercepted. The concerns come mostly from the fact that IPSs track individuals. This IPS can only track a user if they are carrying the target; however, some IPSs have been configured to use the users cell phone as the target. This raises concerns over how to manage who IPSs track and how to receive consent from the individual being tracked. These concerns are outside the scope of this study, but are greatly needed nonetheless, as it seems that there are only a small handful of studies that have explored this area.

2) Future Extensions to the Technology and the Research

As aforementioned, studies on the ethical aspects of IPSs are very much needed; however, there are a few other areas of IPSs that must be further explored as well. Firstly, there must be future iterations of this study to solidify its validity.

Another area that must be explored is the actual development process to create an IPS – or any emerging technology, for that matter. This study did include the documentation needed to replicate the IPS; however, studies are needed that solely explore the process taken to develop new technologies. This is necessary because, today, the technology industry relies on rapid development of new products and upgrades, but there is little to no current literature on the processes taken for this rapid development or how the rapid development affects the end quality of the technology.

Additionally, more research is needed on the integration of IPSs into smart homes. There are numerous studies on IPSs (not necessarily in homes, however), smart homes, and some that conclude IPSs should be used in smart homes; however, none test IPSs usage in these smart homes. A study is needed to determine consumers reactions to having an IPS in their smart home.

These are just a few of the topics in dire need of more research literature in the area of IPSs, IoT, and smart homes. However, there will always be more and more every year as the technology progresses and consumers wants evolve.

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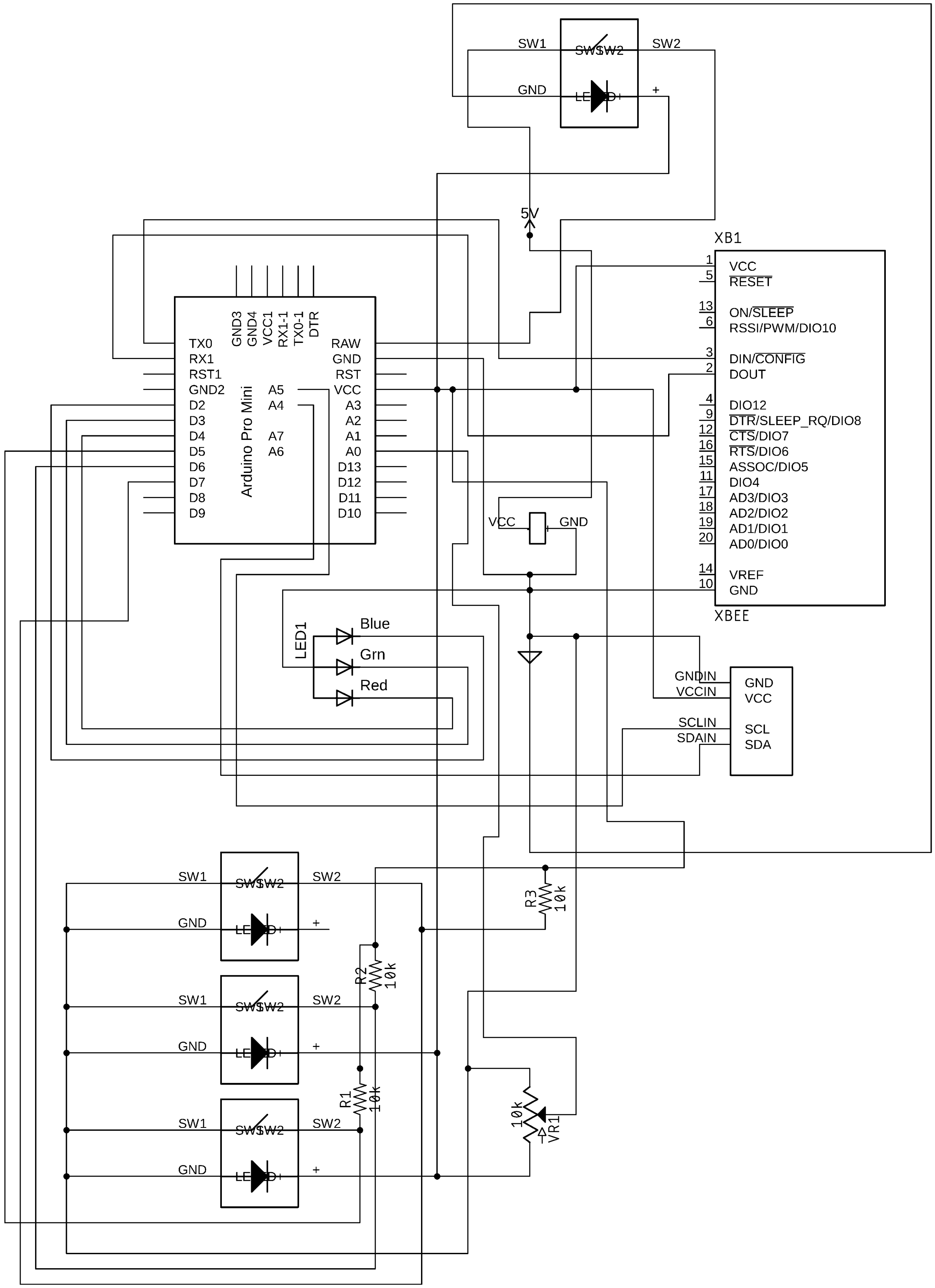
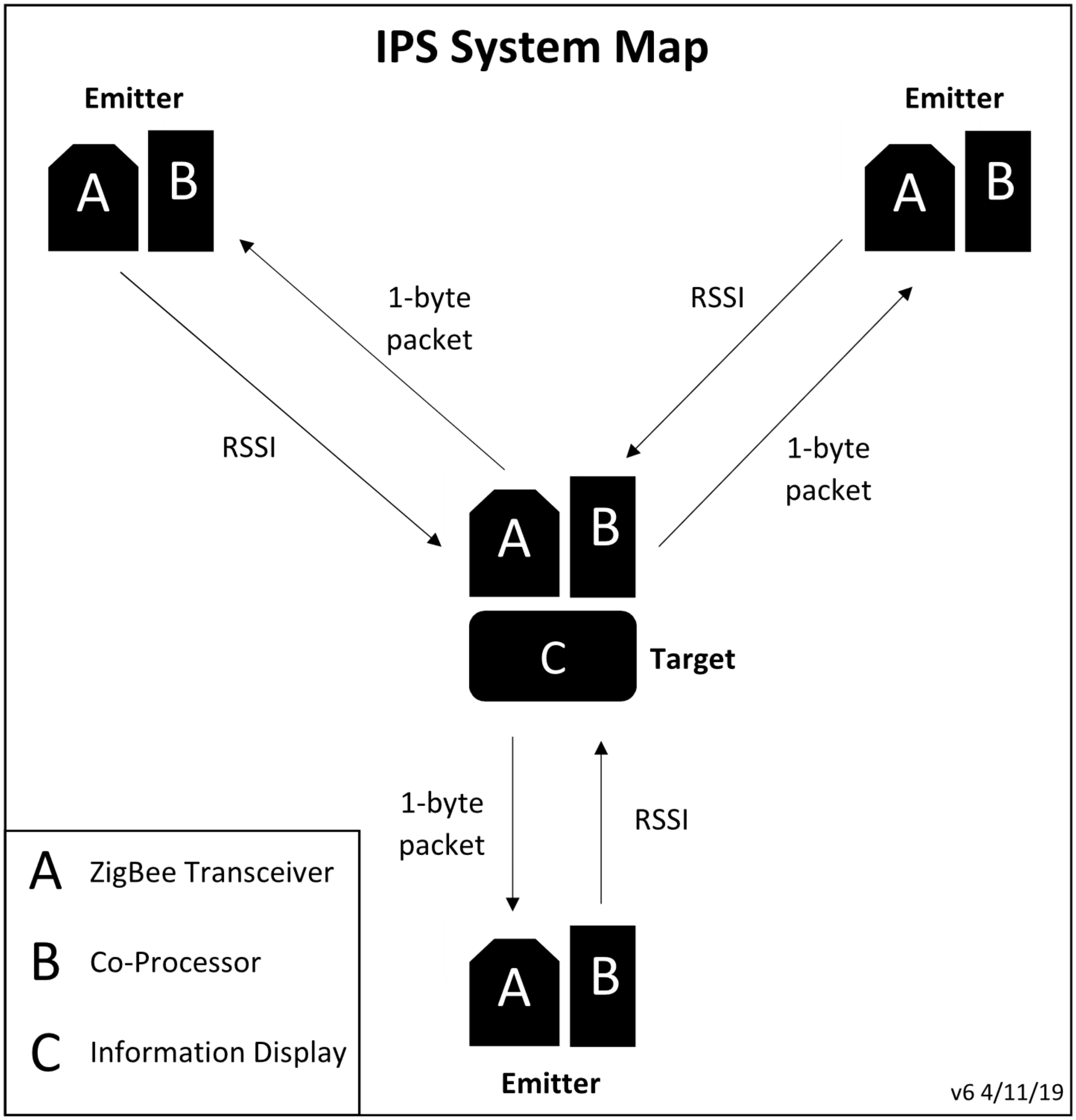
Appendix I

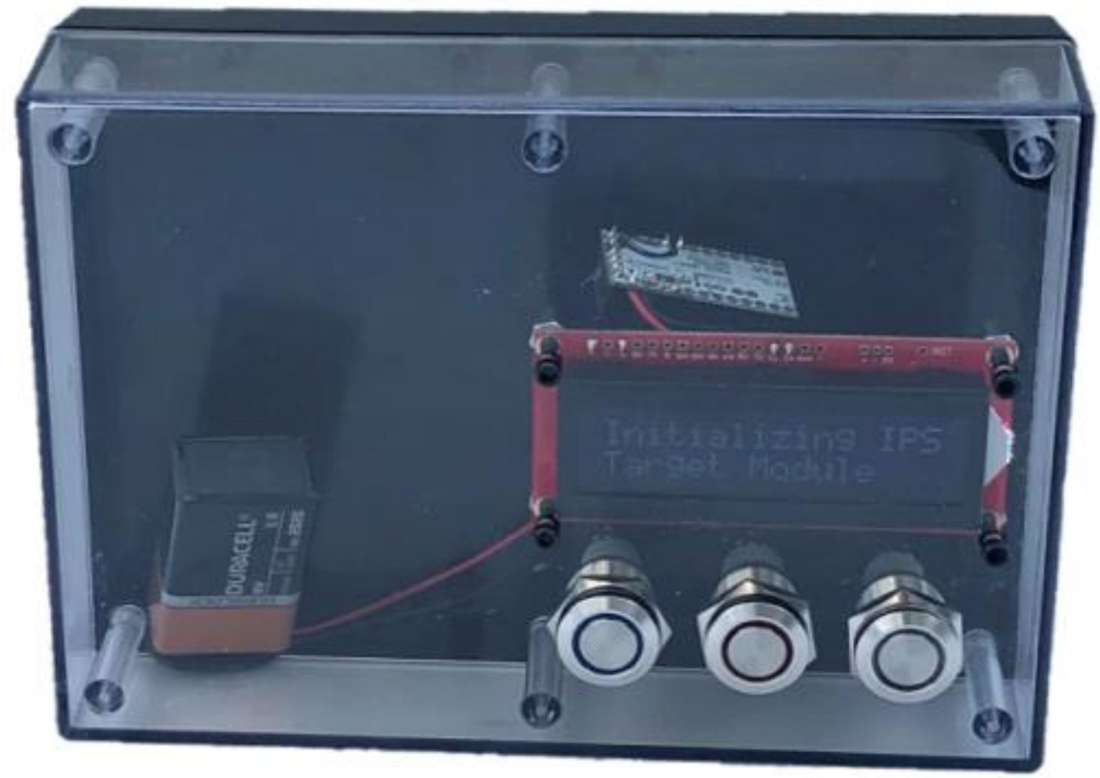
A. Design Schematic of the IPS Modules Used in the Tests.



B. System Map of IPS Used in the Tests



C. Photo of the Target Module



APPENDIX II

A. Firmware on Emitting Modules

```
#include <SoftwareSerial.h> //Enables usage of serial monitor
                            //and XBee simultaneously

SoftwareSerial XBee(2, 3); // Rx, Tx

void setup()
{
  XBee.begin(9600);
  pinMode(13, OUTPUT);
  delay(2000);
}

void loop()
{
  digitalWrite(13, HIGH);

  XBee.write('H');          //Send 1 byte
  delay(2000);

  digitalWrite(13, LOW);
  delay(500);
}
```

B. *Firmware on Target Modules*

```
#include <SoftwareSerial.h>

char okArray[2] = {'A', 'A'};
char temp;
unsigned int i = 0;

SoftwareSerial XBee(2, 3);

void setup()
{
  XBee.begin(9600);
  Serial.begin(9600);
  delay(1000);
  Serial.println("Ready for Tx");
  Serial.println();
}

void loop()
{
  if (XBee.available())
  {
    Serial.print("Recieved: ");
    while(XBee.available())
    {
      Serial.write(XBee.read());
      delay(100);
    }
    Serial.println();
    Serial.print("RSSI: ");

    delay(500);

    XBee.print("+++");

    i = 0;
    while(okArray[0] != 'O' && okArray[1] != 'K')
    {
      i++;
      if(XBee.available())
      {
        okArray[0] = okArray[1];
        okArray[1] = XBee.read();
      }
      delay(10);
    }

    okArray[0] = 'A';
    okArray[1] = 'A';

    XBee.print("ATDB");
    XBee.write(13);
    XBee.read();

    delay(5);

    //All below RSSI to CGAL

    i = 0;
    while(i <= 1)
    {
      temp = XBee.read();
      if(temp != -1)
      {
        Serial.write(temp);
        i++;
      }
    }

    Serial.println();
    Serial.println();

    XBee.println("ATCN");
    while(okArray[0] != 'O' && okArray[1] != 'K')
    {
      if(XBee.available())
      {
        okArray[0] = okArray[1];
        okArray[1] = XBee.read();
      }
    }

    okArray[0] = 'A';
    okArray[1] = 'A';

    delay(10);
    XBee.flush();
    delay(5);
  }
}
```

Appendix III.

A. *Copy of the Authorization Letter Collected from the Homeowner*

Letter of Authorization

Homeowner at specified address,

I am seeking your authorization to conduct a research study at your home (at the specified address) that is designed to assess the accuracy and precision of an indoor positioning system.

I would like to collect various location data throughout the house using GPS and an indoor positioning system. This study is a requirement to compete the AP Research exam. Participation in this study is entirely voluntary. You are free to withdraw from the study at any time without fear of penalty. The only requirements are that the house must be empty at the time of testing, and that all Wi-Fi signals and microwave ovens are turned off. The latitude/longitude data from the GPS will be truncated at the decimal, making it impossible to discern the location of the home. All other identifying information (address, etc.) will never be recorded other than this form and will not appear in the final paper. The different homes will be recorded as trial 1, trial 2, etc.

The risks involved with participating in this study should be no more than the time needed to conduct the test, which I estimate to be about one to one half of an hour.

If you have any questions or concerns about participation in this study, you may contact me.

Respectfully,

- -

I authorize the researcher to conduct a research study at the specified address concerning the effectiveness of accuracy and precision of an indoor positioning system for up to one half of an hour. I understand that he will be collecting location data throughout my house (at specified address).

____

____

____

____

Address of Home

___________________________ ______________

Homeowner’s Signature Date