ECE 445 SENIOR DESIGN
FINAL REPORT

AUTOMATIC LIGHT SWITCH CONTROLLER

By Team 44

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Abstract

Our goal of our project is to save energy by guaranteeing that all lights are turned off when people leave their homes. The original project offered to solve the problem by using the difference in pressure sensor values on a coat hanger to identify the presence of the homeowner. Our project aims to solve the same problem using distance as the indicator of the user state, offering a more practical, user-friendly solution.

Contents

1. Introduction

1.1 Problem and Solution Overview

Many homeowners experience coming back from work or trips to realize that they had forgotten to turn the lights off in one of the rooms if not multiple. Although it may not seem to be the most critical mistake, people would be surprised at how much energy and money they are wasting from such an overlooked mistake. In fact, lighting accounts for approximately ten percent of electricity in homes**[1]**. An average of 1,105kWh of energy has been consumed in 2015 in households in the U.S.**[1]**

With around 25% of households having 40 or more bulbs**[1]**, a considerable amount of waste of energy can be prevented by making sure lights are turned off when the owner leaves his or her home. To guarantee that the user would be turning all lights off when leaving the house without having to prioritize the action, we would use a device that can be attached to a necessity that the user would never leave the home without. A pair of devices installed outside the door and carried around would detect whether the user has left or entered the home and control the lights accordingly. With a system that simply calculates time of flight from a portable tag, the user would not be worrying about wasting energy or electricity bills.

1.2 Background

Our device would tackle the same problem of leaving the house without turning off the lights in the coat hanger light switch controller project with a completely distinct solution. Instead of using a pressure sensor device on a coat hanger to detect the absence of a coating/purse, our device would consist of an ultrawideband(UWB) transmitter and receiver pair that would be used to calculate the distance between the two modules, with the transmitter residing indoors near the entryway and the receiver on the user's item of interest. If the detected distance exceeds 100m, controllers attached to the light switches will turn off the lights. If there is no detected distance (due to exceeding the range of the device or attenuation), the lights will also turn off.

Other products with similar intentions can be seen in the market, some of which use motion sensors to detect the presence of the person in the room and turn off the switches immediately if not. The solution proposed by Katherine Eaton and Birgit Alitz in Fall 2017 using pressure sensors on a coat hanger. Both solutions are different from our intended design, since we wish to detect that the user is completely out of the home and turn the light switches off if they were forgotten. We also offer the flexibility of using physical switches when the user is present by normally closing the light system circuits. Other forms include controlling the switch via an app, which does not provide the autonomous nature of our device.

1.3 High-Level Requirements

1. Detection of the absence/presence of user at a 100m range from home (>100m indicating absence)
2. Turns lights on/off upon detection of presence/absence of user
3. 95% accuracy of distance measurement yielding correct state of user

1.4 Visual Aid

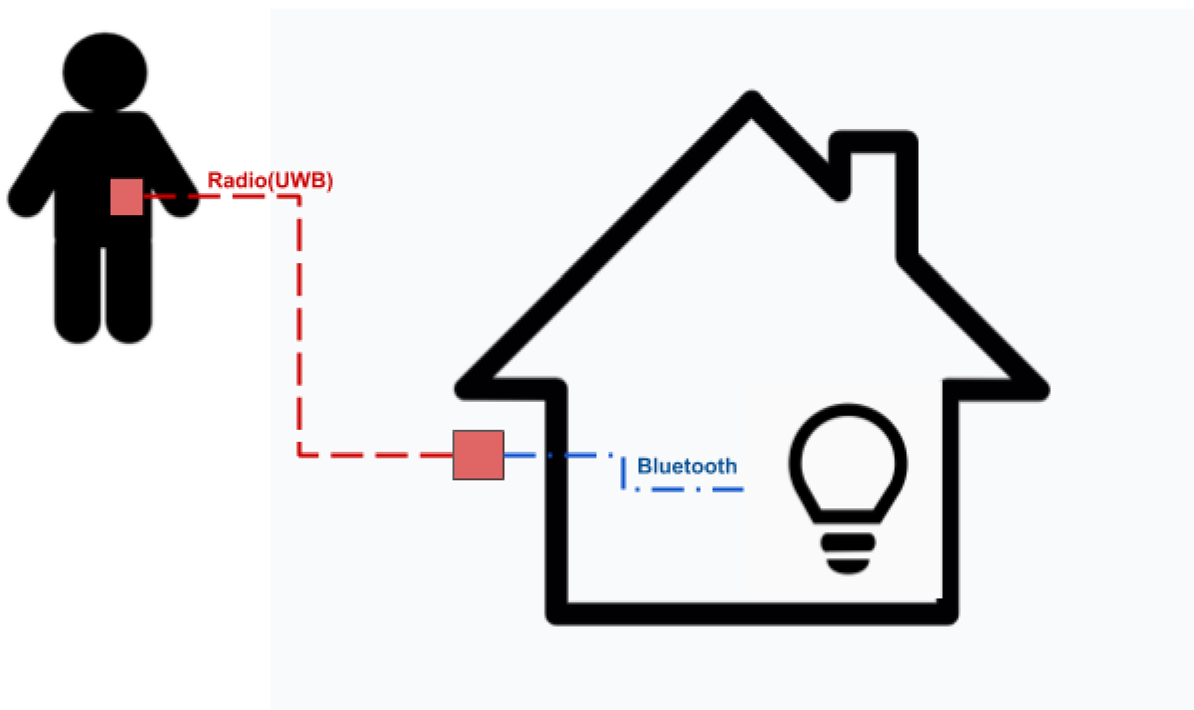

Figure 1: User, At-Home Controller. Light Unit

Figure 1 is a simplified version of the overall system. The portable device from the user will receive packets from a static at-home device. Upon receiving an acknowledgement from the user, the main system will order subsystems that will control each light system. The figure indicates a light system with one lightbulb.

1.5 Block Diagram

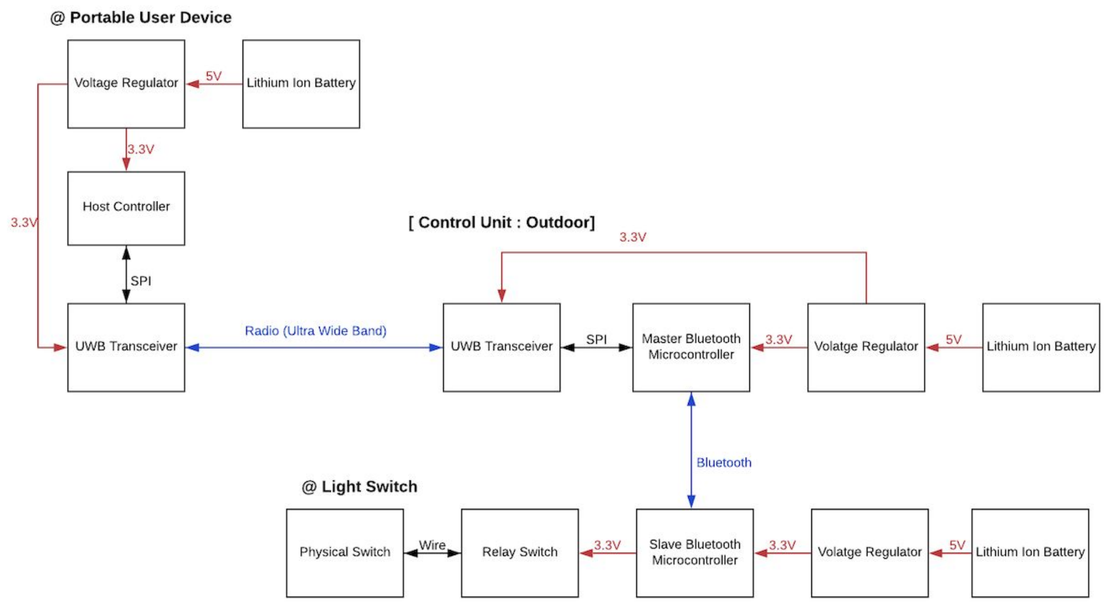

Figure 2: Block Diagram - Transmitter/Receiver, Power, Control Units

Figure 2 shows an overall layout of the subsystems of our device with a single light subsystem. However, in our actual implementation, we expect an average of 5 light systems to be connected to the master control unit.

The upper left-hand-side of the block diagram would be attached to the user's everyday belongings, which consists of a battery and voltage regulator as a power unit and a generic host controller and an always-on UWB transceiver (mainly receiver). The right-hand-side of the portable device would be the main controller module of the design. As the detected distance from each receiver module exceeds 100m, it will communicate with the master Bluetooth microcontroller via SPI. Then, the master Bluetooth microcontrollers will signal the slave controllers at each light source to assert a low input to its relay, opening the circuit. The bluetooth microcontrollers and the host controller for the UWB chip will be powered by standard lithium-ion batteries with a voltage regulator to provide a 5V power supply.

Concerns were previously raised regarding the behavior of the system when the user is inside but has moved to a room far enough away (or through multiple walls) such that the main lights turn off. After further consideration, we believe this is not a significant problem, as the user will likely not be moving their item of interest with them throughout the house, and can just leave it by the door upon entry. While it is possible to support this behavior, it would add cost for additional parts to our design which we do not deem necessary.

2. Project Implementation

2.1 Design Description and Justification

The success of our device depends mostly on three distinct functionalities:

1. Communication between master/slave bluetooth controllers (2.1.1)
2. Data transmission/interpretation at UWB modules and bluetooth controller (2.1.2)
3. Connection of relay switch between light source and physical switch (2.1.3)

The first and third functionalities would verify the second high-level requirement and the second functionality would ensure the first and third requirements. Moreover, the battery life of the portable UWB device is guaranteed to last around a week by the low-powered choice of DW1000 chip as well as the lithium-ion battery.

Thus, the following sections provide a detailed implementation of each subsystem or interaction between the respective systems.

2.1.1 Master and Slave Controller Units

In this section we provide an implementation of the DW1000 single-sided two-way ranging scheme. The SPI interface and DW1000 API library are used in these two C programs which would exist on each chip's BLE host controller . Note that a few assumptions are made, namely that the BLE protocol between the two controllers is implemented for us, and that data can be transferred via memory-mapped ports on each system. The focus of this implementation is therefore on the UWB IC protocol and SS-TWR. In the images below, the code on the left-hand side is the code on the master bluetooth controller which is the initiator of the protocol. The code on the right-hand side is that of the slave bluetooth controller which receives the protocol. Note that as these pieces of code exist on separate systems, there is no conflict over variable naming.

transmitter.c

```c
//transmitter DW1000 IC implementation

//assume memory-mapped IO with slave bluetooth devices
volatile unsigned int* BLEfromRec = 0x60;
unsigned int propogation_speed = 3e8;
unsigned int* BLEtoLightController = 0x70;

//initialize
dwt_initialize(0x1);
//set up configuration struct
dwt_config_t config;
//configurations for optimal 6.8MBps, 64MHz transmission
//best suited for high range and high resolution\

//using channel 1
config.chan = 1;
//set preable length and pulse repetition frequency
config.prf = DWT_PRF_64M;
config.txPreambLength = DWT_PLEN_64;
//use same tx/rx code and set PAC for 64 octet preamble
config.rxPAC = 8;
config.txcode = 9;
config.rxcode = 9;
config.nsSFD =1;
//using 6.8Mbps data rate and standard header size
config.dataRate = DWT_BR_6M8;
config.phrMode = DWT_PHRMODE_STD;
```

receiver.c

```c
//receiver DW1000 IC implementation
//initialize

//assume memory-mapped IO to other bluetooth device
volatile unsigned int* BLEtoMaster = 0x80;

dwt_initialize(0x1);
//set up configuration struct
dwt_config_t config;
//configurations for optimal 6.8MBps, 64MHz transmissi
//best suited for high range and high resolution\

//using channel 1
config.chan = 1;
//set preable length and pulse repetition frequency
config.prf = DWT_PRF_64M;
config.txPreambLength = DWT_PLEN_64;
//use same tx/rx code and set PAC for 64 octet preamble
config.rxPAC = 8;
config.txcode = 9;
config.rxcode = 9;
config.nsSFD =1;
//using 6.8Mbps data rate and standard header size
config.dataRate = DWT_BR_6M8;
config.phrMode = DWT_PHRMODE_STD;

dwt_configure(configuration);
```


Figure 3: DW1000 Code Page 1

transmitter.c

```c
dwt_configure(configuration);

//configure additional tx settings
dwt_txconfig_t tx_config;

//set recommended channel 1 64MHz power output and recommc
tx_config.PGdly = 0xC9;
tx_config.power = 0x67676767;

dwt_txrfconfigure(tx_config);

//main event loop
while (1) {
  //default no signal from receiver BLE
  *BLEfromRec = 0;
  //default light is on
  *BLEtoLightController = 1;
  //set up header and data packet to send via SPI
  uint8* hbuf;
  uint8* buffer;
  //set write, no sub index, and write to transmit buffer
  uint8 hbuf_data = 0x89;
  uint8 buf_data = 0;
  //data sent from master does not matter
  hbuf = &hbuf_data;
  buffer = &buf_data;
```

receiver.c

```c
dwt_configure(configuration);

//configure additional tx settings
dwt_txconfig_t tx_config;

//set recommended channel 1 64MHz power output and recommc
tx_config.PGdly = 0xC9;
tx_config.power = 0x67676767;

dwt_txrfconfigure(tx_config);

//main event loop
while (1) {
  //enable receiver
  dwt_rxenable(0);
  //optionally set SNIFF_MODE to improve efficiency
  dwt_setsniffmode(1, 7, 100);

  volatile uint8 rx_stamp = 0;
  uint8* rx_stamp_ptr = &rx_stamp;
  //read from timestamp register until stamp is made (mess
  while (rx_stamp == 0) {
    dwt_readrxtimestamp(rx_stamp_ptr);
  }

  //resend packet to transmitter with tx stamp
  uint8 tx_stamp = 0;
```


Figure 4: DW1000 Code Page 2

transmitter.c

```c
  buffer = &buf_data;
  //both buffers of length 1
  writetospi(1, hbuf, 1, buffer);
  //now write control register to send tx packet and enabl
  //extend to address sub-register
  uint8 hbuf_arr[2] = [0xCD, 0x00];
  buf_data = 0x82;
  hbuf = hbuf_arr;

  writetospi(2, hbuf, 1, buffer);
  uint8 tx_stamp = 0;
  uint8* tx_stamp_ptr = &tx_stamp;
  //get tx timestamp
  dwt_readtxtimestamp(tx_stamp_ptr);

  //read rx timestamp until message is received
  volatile uint8 rx_stamp = 0;
  uint8* rx_stamp_ptr = &rx_stamp;
  //read from timestamp register until stamp is made (mess
  while (rx_stamp == 0) {
    dwt_readrxtimestamp(timestamp_ptr);
  }

//wait for turnaround time to be sent by the receiver BLE
  while (!*BLEfromRec) {

  }
```

receiver.c

```c
  //resend packet to transmitter and record tx stamp
  uint8 tx_stamp = 0;
  uint8* tx_stamp_ptr = &tx_stamp;

  uint8* hbuf;
  uint8* buffer;
  //set write, no sub index, and write to transmit buffer
  uint8 hbuf_data = 0x89;
  uint8 buf_data = 0;
  //data sent does not matter here
  hbuf = &hbuf_data;
  buffer = &buf_data;
  //both buffers of length 1
  writetospi(1, hbuf, 1, buffer);
  //now write control register to send tx packet, do not e
  //extend to address sub-register
  uint8 hbuf_arr[2] = [0xCD, 0x00];
  buf_data = 0x80;
  hbuf = hbuf_arr;

  writetospi(2, hbuf, 1, buffer);
  //get tx timestamp
  dwt_readtxtimestamp(tx_stamp_ptr);

  //compute turnaround time for receiver
  uint8 T_turn = tx_stamp - rx_stamp;
```



```c
//compute the round-trip time and then the distance
unsigned int distance = (((rx_stamp - tx_stamp) - BLEfrc
//turn light off if distance of 100m exceeded, on otherw
*BLEtoLightController = distance > 100 ? 0 : 1;

sleep(1000);
```

```c
  uint8 T_turn = tx_stamp - rx_stamp;

  //send BLE packet to the master with turnaround time
  *BLEtoMaster = T_turn;

  //stall for 1 second before repeating SS-TWR
  sleep(1000);
}
```


Figure 5: DW1000 Code Page 3

2.1.2 Master Controller and Transceiver Units

The control unit, consisting of a master Bluetooth controller and its UWB IC, performs distance measurement. When a distance between the two modules is greater than 100m or transmission is lost, the bluetooth microcontroller will send packets to its slave microcontrollers which will turn off the lights. The control unit must also send an ON signal to the other microcontrollers when the distance drops below 5m so that the user may control the lights with physical switches that are connected in series to the relay switch.

The figure below is a schematic of the control unit. Both the controller and transmitter modules are powered by a power unit. The transmitter SPI output pin (POL) is connected to an analog input in the controller. The pins are configured to enable correct SPI behavior, although not all are present in the below schematic.

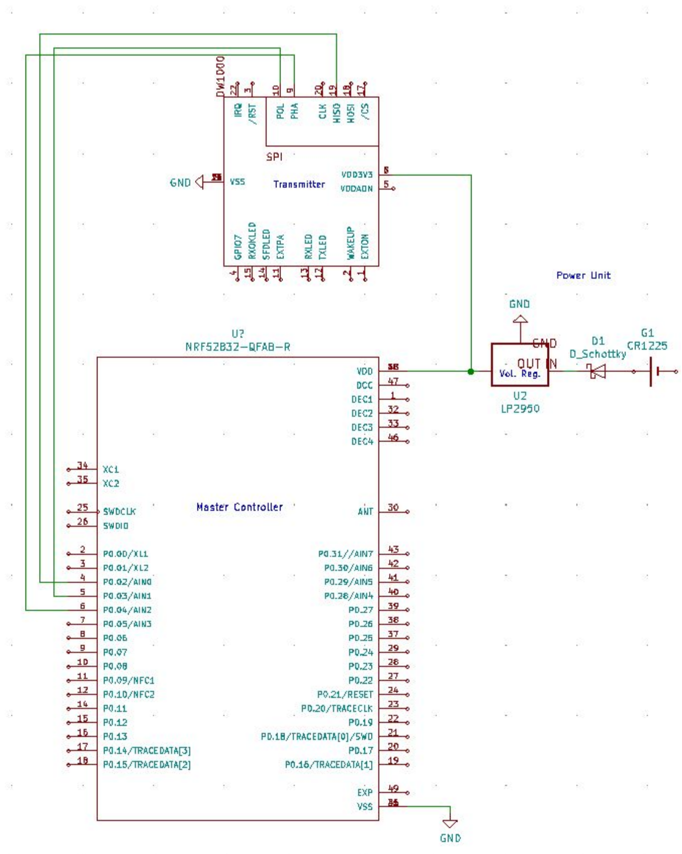

Figure 6: Schematic - Transmitter, Master Controller with Voltage Regulator

2.1.3. Light Switch Subsystem

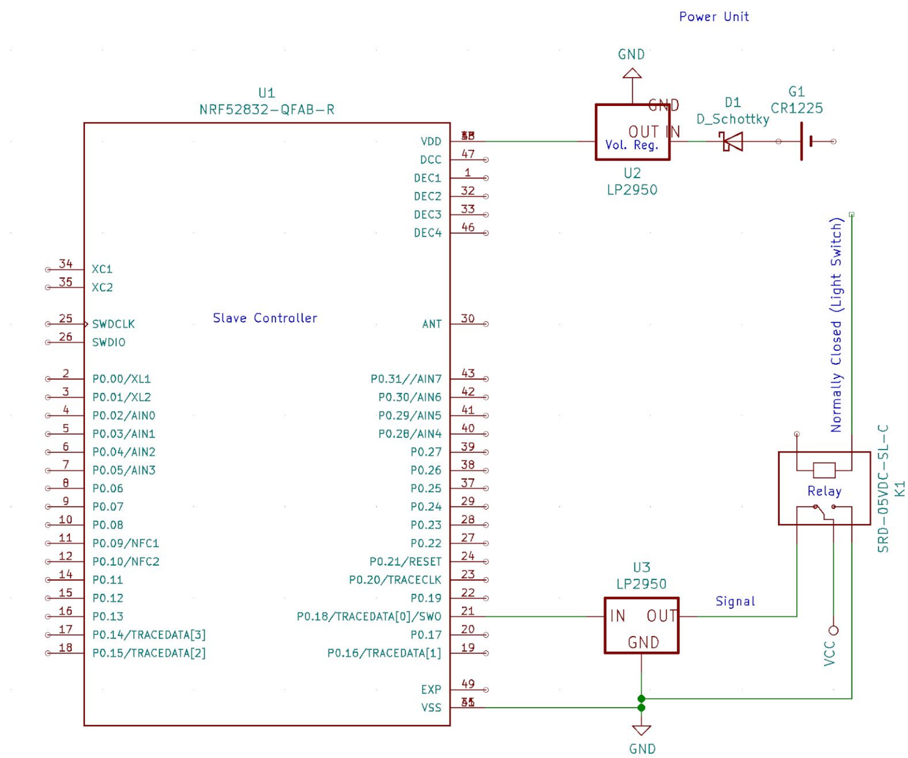

Figure 7: Schematic - Slave Bluetooth Controller and Relay Switch

Figure 4 is a circuit schematic of the light switch subsystems, which consists of the slave Bluetooth controller, its power unit, and a relay switch, which is connected to the physical switch at the normally closed pin of the switch.

The subsystem will be placed in series to the original switching circuit in the user's home. Since the microcontroller must control the state of the bulb, we will use a relay (electromechanical switch) which will sit between the wall voltage of 120V and the load lightbulb. The microcontroller will be connected to a lithium ion battery amplified by a regulator (5V) and a GND pin. The relay has pins for wall power supply (VCC in Fig. 7) and one control pin (Signal in Fig. 7). The control pin will be wired to an output pin on the microcontroller (Pin 21 in Fig. 7). When a low voltage is asserted on the control pin, the switch is open. When a high voltage is asserted on the control pin the switch is closed.

2.2 Supporting Material and Explanation

Distance measurements from the communication between two UWB modules is a critical part of our project. Since radio waves travel around 299,792,458 m/s, a time of flight measurement as small as 1 microsecond may result in a distance measurement error of up to 300 meters. However, with the use of the DW1000 modules that do not require clock synchronization and crystal clocks to minimize local clock drift, a measurement of the 100m target distance, with a tolerance of 10% should be achievable. The transmitter unit and receiver unit will together implement a protocol known as single-sided two-way ranging (SS-TWR).

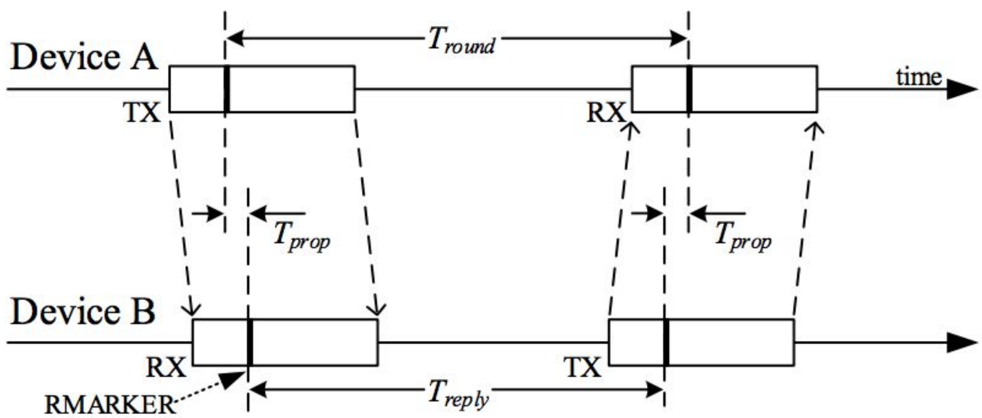

Figure 4: Single-sided Two-Way Ranging Protocol

When a packet is sent by the initiator (TX), it is timestamped. Similarly, the packet is also timestamped by the receiver upon arrival. When the packet is sent back and timestamped again by each device, the reply time and round-trip time can be computed independently. Because both T_{reply} and T_{round} are computed with respect to each device's local clock, synchronization is unnecessary. The propagation time can then be estimated as below.

$$T_{prop} = \frac{1}{2}(T_{round} - T_{reply})$$

Eq. 1: Propagation time for SS-TWR

Error in distance estimation increases as T_{reply} grows large, so it is possible that we may implement double-sided two way ranging (Fig. 5), an improvement on the above method that requires an additional round-trip of a second packet. Even with 20ppm clock drift, a distance resolution of up to 2.2mm with a range of 100m is attained (DW1000 User Manual).

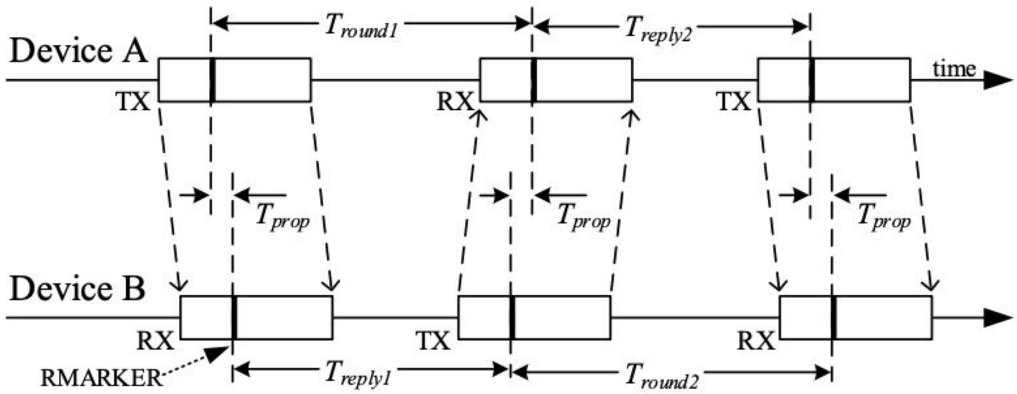

Figure 5: Double-sided two-way ranging with three messages (DS-TWR)

$$\hat{T}_{prop} = \frac{(T_{round1} \times T_{round2} - T_{reply1} \times T_{reply2})}{(T_{round1} + T_{round2} + T_{reply1} + T_{reply2})}$$

Eq. 2: Propagation time for DS-TWR

2.3 Results and Explanation

The previous project (FA 2017, Coat Hanger Light Switch Controller) uses pressure sensors from coat hangers to detect whether the user is present or not. This will only be useful if it is guaranteed that the person would wear the piece to head out, not because it was cold inside the house. Moreover, for clothing items to generate a substantial pressure on the pressure sensor, a certain amount of weight from the pieces is required, which would be useful only in the colder seasons. Our implementation exploits a device that is carried around regardless of season and with a significant guarantee that the location (distance value) of the item is highly correlated to the presence of the user.

Thus, our failure rate to detect whether the user is present in the home is much lower than the former implementation, as a failure of detection is related more so to the success rates of each hardware subsystem than to the idea itself. Moreover, with a distance tolerance of around 10%, an inaccurate estimation of user state may occur at the range of 90~100m or 100~110m from the transmitter device. However, we do not consider this to be a critical problem as the device will identify the correct user state as he or she moves further from or closer to the control unit eventually.

3. Project Conclusion

3.1 Implementation Summary

We were able to complete the basic schematic for the light switch system and the control unit, including the master controller and the UWB module. Since the portable receiving device would essentially be a simpler version of the main control unit, we did not think it was necessary to include in the implementation.

Louis completed the code for the UWB ICs, which would be critical to the functioning of our whole system, as most of our device relies heavily on the hardware's input and output control and distance measurement relevant to the user state. Jihyun completed the circuit schematics for both subsystems. Since the code cannot be tested without prior design of the circuit or PCB, this is another important part of our design.

3.2 Unknowns and Uncertainties

Since our design mainly depends on the functionality of the hardware chips/ICs and the interactions between the counterparts involved, we cannot proceed with testing most units of our system.

Our main functionality of calculating the distance between two UWB modules requires two printed circuit boards (PCB) to test the sending and receiving of packets, which is impossible under the current circumstances. Other critical functionalities being the communication from the master controller to the slave controller units or the light switch also require PCBs and a switch to be able to control a LED, we could not test nor complete our project any further.

If we were under different circumstances, we would have ordered the chips and completed the PCB design to start testing each unit separately with their respective verification. The DW1000 user manual has made it very clear about the accuracy of the distance measurement and the way to use the local timestamps, so we assume this would not cause too much trouble. We would predict quite a deal of time would be spent on the Bluetooth controllers and would need to test a smaller lighting system (circuit) than in an actual room environment.

3.3 Ethics and Safety

Although convenient, the implementation of controlling lights depending on the distance from 2 UWB transceiver modules may come with certain safety issues. For instance, a user may have left the home, which would cause the switch to turn the lights off. However, another person may be at home performing a critical task that requires light. The opposite may be the case too. When the sensor system acknowledges the presence of the user device, the main lights would be turned on. If, however, the user is being chased and did not want others to know they were in the house, the automatic lighting system would cause more harm than good.

Another safety issue that may be of concern in our system may come from the fact that the receiver module and processor is being carried around in person. Although there are several concerns on how the exposure to an electromagnetic field emitted by the transceiver modules may affect the human body, at the 3.1-10.6GHz frequency band that our device is operating in, an increase in body temperature seems to be the main effect **[10]**. Moreover, since our system utilizes a distance measurement to acknowledge the presence of the user in a range from the antenna, a security protocol may need to be used to make sure the user's location data is not exposed.

The most important relevant IEEE Code of Ethics**[6]** in the context of our project is the first, which states that our device must prioritize the safety of the consumer and the environment. In the development of the product, we will also make sure to follow the seventh IEEE Code of Ethics**[6]** and openly accept honest criticism of other group members and course staff to help better the design of the product and not take credit of those whose work was involved in the progress. We will also respect all involved so that everyone is respected and not discriminated based on factors implied in the 8th IEEE Code of Ethics**[6]**. The project will involve no injuries caused due to malicious behavior according to the 9th Code**[6]** and keep a professionally supportive environment for all colleagues involved by the last Code of Ethics**[6]**.

3.4 Project Improvements

An area of improvement in the design of our device that was mentioned by the TA in the design review is the limitation in the number of users. Our implementation limits the number to one user, which may be impractical for households with multiple residents, since our device would automatically shut down all connected light systems when the user leaves the house with their portable receiver device.

One way we can address this single-user problem is to keep track of the number of users in the master controller and connect several UWB modules to the controller. This will provide a unit connection pair for each user, since the receiver should be able to identify each distinct user. Another solution to identifying the state of each user without the access hardware would be to specify a different sequence to be sent to the receiver module as an acknowledgement. In other words, the first user may send an ACK with data 0x11111111, then the second user may send 0x22222222. The receiver unit will then be able to identify the different user ID's to keep track of the count. By enabling up to five users, the master controller may only shut down the lighting system only if the detected number of users is zero to enable other users present in the house to use the light switches as needed.

4. References

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