Automatic Light Switch Controller

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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 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. This is 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. Other forms include controlling the switch via an app, which does not provide the autonomous nature of our device.

1.3 High-level requirements list

1. At least 95% success rate in determining the absence/presence of user at home via distance measurement.
2. At least 95% success rate in turning lights on/off upon signal of presence/absence from master bluetooth microcontroller.
3. Battery life of at least one week for portable device.

2. Design

2.1 Block Diagram

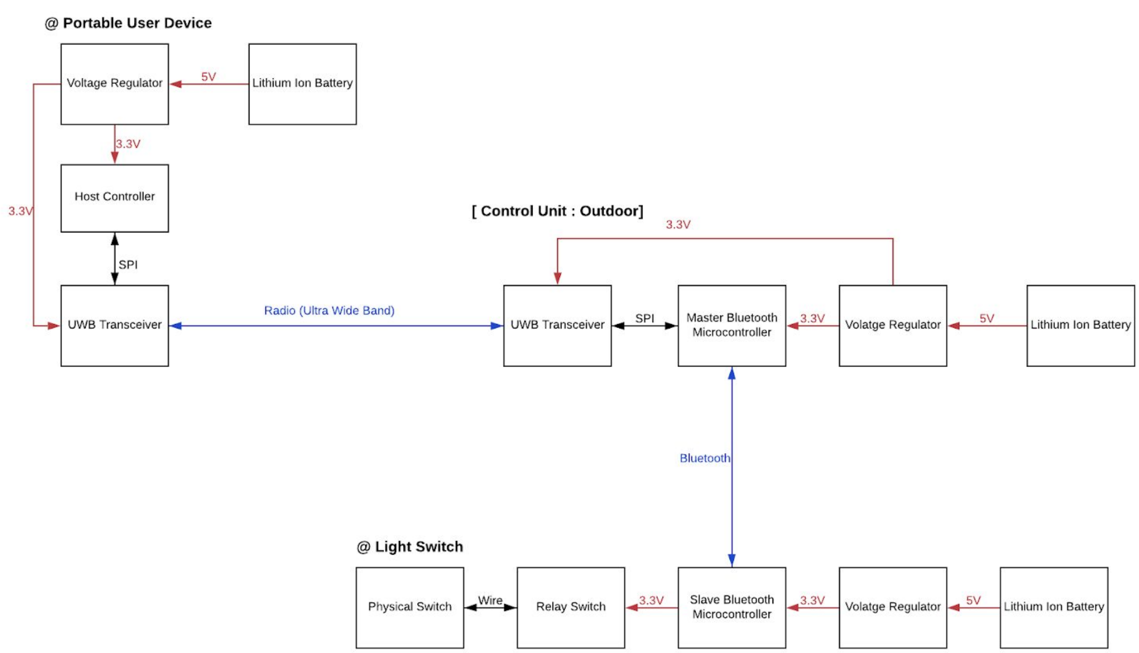

Figure 1: Block Diagram - Transmitter/Receiver, Power, Control Units

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 the 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.

2.2 Physical Design

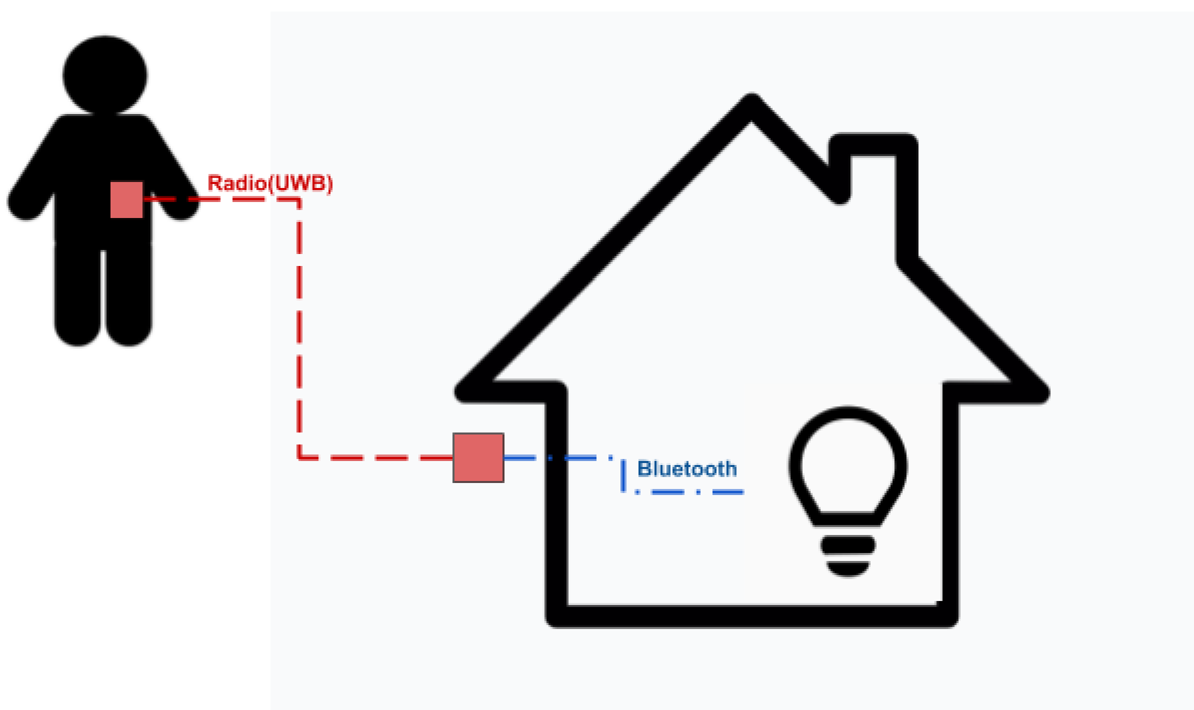

Figure 2: User, At-Home Controller. Light Unit

2.3 Subsystems

2.3.1 Control Unit

The control unit consists of the master bluetooth microcontroller and its UWB IC. This UWB IC together with the UWB in the receiver module performs distance measurement. More information on this process is available in the transmitter unit section below. 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.

Bluetooth microcontroller (Master):

This module will be an nRF52832 module or similar. This is a bluetooth enabled SoC containing an ARM M0 core and on-chip memory. This module must also maintain a serial connection with the UWB IC to receive and compare distance measurement with the 100m and 5m cutoffs**[2]**.

The BLE protocol stack used at Nordic (producer of our chip) allows a limit of 20 devices IDs to be stored. Therefore the 6 slaves used in our design will not be a problem.

Requirement	Verification
- Must support SPI interface as external host to interact with UWB chip (general-purpose processor) - Must support multiple slave controllers and distinguish between each individual slave - Must be powered by a low voltage ~ 3.3V.	- ARM core should function as an external processor as designed. If preamble data is received from the UWB IC, the functionality is verified. - Master controller will send specific sequence, which should be received by all slave controllers. - If sequence is received by intended slave controller, individual master-slave communication is verified. - Low voltage requirement verified by chip datasheet

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Transmitter DW 1000 Chip:

The transmitter unit will be an UWB IC. The transmitter unit and receiver unit will together implement a protocol known as single-sided two-way ranging (SS-TWR). **[2]**

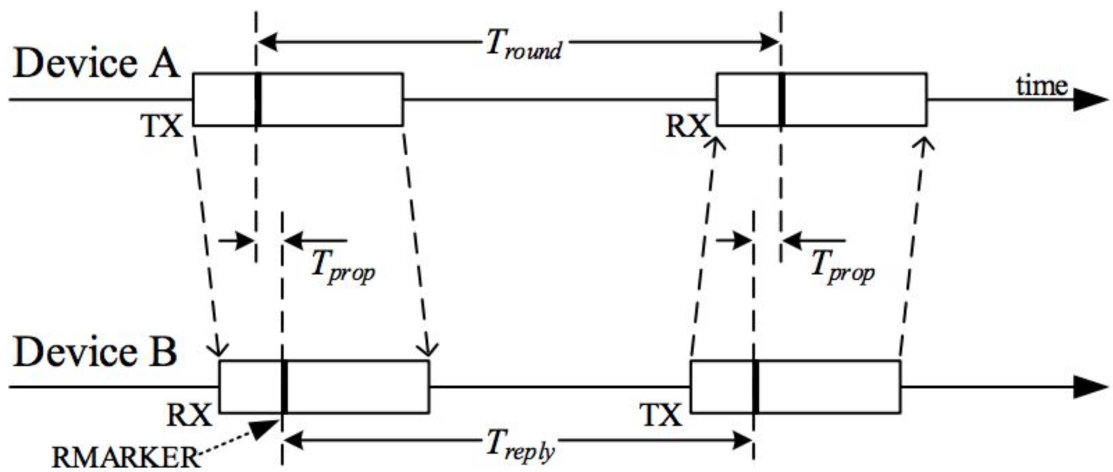

Figure 3: Single-sided Two-Way Ranging Protocol

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, 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).

When the protocol completes, the transmitter module will send a distance estimation to the user-interface microcontroller via SPI.

Requirement	Verification
- Must support communication to Bluetooth microcontroller to signal broadcast - Must support at least 6GHz RF band - Must be powered by a low voltage at or below 3.3V (lithium-ion battery).	- For all requirements listed, the chip will function as intended if the device meets specifications of the datasheet. **[2]**

Current Consumption:

1. In Mode 4 (6.8Mbps data rate), DS-TWR protocol
    a. 173*2 = 346 μs to complete packet path
    b. Draws average of 67 mA current
2. In SLEEP state, draws 2 μA current for 300ms between wake-ups
3. Then average current consumption = 67mA*(.346ms/(300.346ms) + 2μA*(300/300.346) = 79 μA

2.3.2. Receiver unit

As aforementioned, the receiver module will consist only of an UWB IC and power supply. The requirements and use of this module have been specified in the above section. Since the UWB IC needs to be connected to a master controller to function as a slave, we will use a generic microcontroller LPC8N04. The receiver does not need to send measurement data to an external processor, but does need to maintain an SPI interface with a logic/state machine that will trigger transmission of packages.

Receiver DW 1000 Chip:

Requirement	Verification
- Must support at least 6GHz RF band - Must be powered by a low voltage at or below 3.3V (lithium-ion battery).	- For all requirements listed, the chip will function as intended if the device meets specifications of the datasheet. **[2]** - Can check operating mode of receiver to verify operating in sleep mode at far distance from home.

Host Controller:

We will use a 32-bit ARM Core that is required to use the DW1000 receiver module. It will have no other purpose in our system.

Requirement	Verification
- Must support slave SPI communication for DW module functionality - Must be powered by a low voltage at or below 3.3V (lithium-ion battery)	- For all requirements listed, the chip will function as intended if the device meets specifications of the datasheet. **[3]**

2.3.3 Light Switch Subsystem

The light switch subsystem must replace 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 relay has pins for power and one control pin. The power (5V) and GND pins will be connected to the lithium ion battery which is powering the microcontroller. The control pin will be wired to an output pin on the microcontroller. 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.

Based on these requirements, a Songle SRD-05VDC-SL-C will be used, as it can handle up to 10A load for a 125V DC source, far above the requirements of our circuit, with a coil control voltage of 3V.

Requirement	Verification
- Must be able to turn on/off by microcontroller's pin output voltage(3.3~5V) - Must be able to supply around a 0.36W current as typical for 120V lightbulb	- Replace switch with relay and make pin connections as specified. Assert output pin high on microcontroller and verify that light turns on. - Measure current and voltage across the lightbulb with multimeter to

	ensure it is receiving close to nominal 110-120V and 0.36A values.

Bluetooth Microcontroller (Slave):

Each slave controller will be installed alongside the light switches. After receiving input signals from the master Bluetooth controller, depending on the input signal it will generate a pin output that will turn the switch on or off. We will use the same nFR52832 chip and operate in the slave mode.

Requirement	Verification
- Must be able to control relay through pin output voltage - 5±5% VDC voltage supply.	- Test output pin connected to switch to test switch performance with LED circuit - Attach one end of the multimeter to voltage regulator output and the other to the push motor and measure voltage

2.3.4 *Power Subsystem*

Two lithium-ion batteries, voltage regulators, and an accompanying power bus will drive the circuitry in both the master/slave control and transmitter/receiver units.

Lithium-ion Battery:

Requirement	Verification
- Must be able to provide a steady 1.7~3.6 VDC power supply to the control, transmitter, and receiver units or their corresponding voltage regulators. **[4]**	- Attach one end of the multimeter to voltage regulator output and the other to the push motor and measure voltage

Voltage Regulator:

We will use a LDO voltage regulator to provide each unit with a voltage supply sufficient to power each device. In particular, we plan to use LP 2950 that is capable of supplying both 3.3V as well as a 100µA current.**[8]** Since the Bluetooth Microcontroller, Transmitter, Receiver, Host Controller units require a voltage of 1.7~3.6V, the chip suffices all requirements.

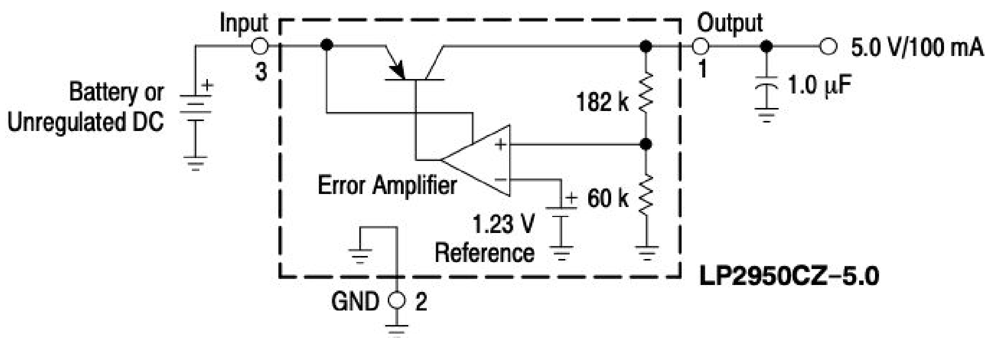

Figure 5: LDO 3V Regulator

Requirement	Verification
- Must convert a 5~5.5V input voltage from battery to ~3.6V to supply Bluetooth microcontroller, transmitter, receiver, and host controller units.	- Measure V_in using a multimeter connected in parallel. - Measure V_out using a multimeter connected in parallel. - Ensure V_in measures between 4.75~5.25V - Ensure V_out measures between 3.14~3.47V

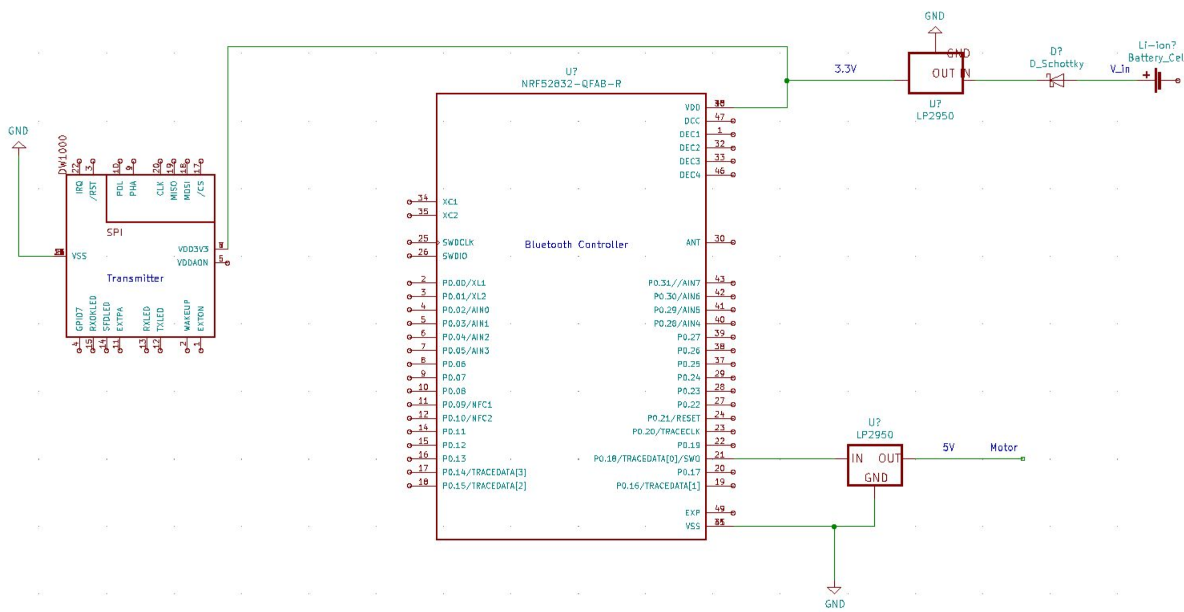

Figure 6: Transmitter, Control Units with LP2950 Voltage Regulators

2.4 Tolerance Analysis

The most important and critical part of our device would be using the internal timestamp differences to calculate the distance at which the spray will be activated using SS-TWR as described in Figure 5. Since the timestamp difference would be multiplied by the speed of light, it is critical that we guarantee minimal error in the time of flight estimation. Such an error has been guaranteed to be very little by the user manual**[7]** of DW1000 IC as explained below.

clock error / T_{reply}	2 ppm	5 ppm	10 ppm	20 ppm	40 ppm
211 µs total 6.81 Mbps 64 Symbol Preamble 96 µs response delay	0.2 ns	0.5 ns	1.1 ns	2.1 ns	4.2 ns
275 µs total 6.81 Mbps 128 Symbol Preamble 96 µs response delay	0.3 ns	0.7 ns	1.4 ns	2.8 ns	5.5 ns
403 µs total 6.81 Mbps 256 Symbol Preamble 96 µs response delay	0.4 ns	1 ns	2 ns	4 ns	8 ns

Note: An error of 1 ns is equivalent to a 30 cm error in measured distance.

Figure 7: T_reply vs Clock Error from DW1000 User Manual

As specified above, a clock error of 1ns results in a distance measurement error of 30cm. With an accurate crystal clock, the error would be much less.

There are other ways that we can implement to further reduce the error. Double-sided Two-way Ranging using 3 or 4 messages can reduce the time of flight error to as low as a picosecond range with 20ppm crystals using the equation 2.

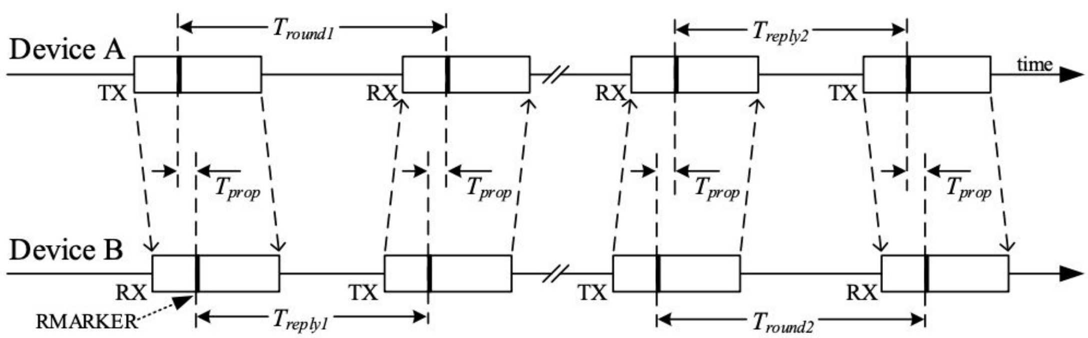

Figure 8: Double-sided Two-way Ranging using 4 messages

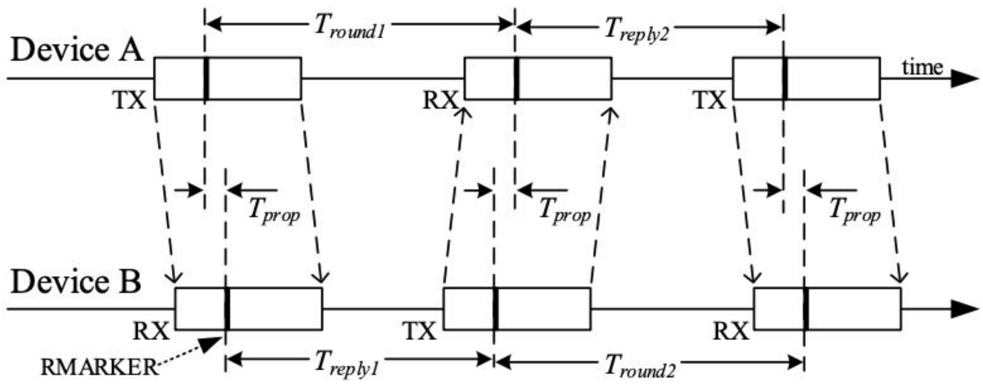

Figure 9: Double-sided Two-way Ranging using 3 messages

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

Eq. 2: Propagation Delay Calculation for DS-TWR

3. Cost and Schedule

3.1 Cost Analysis

The average starting salary of an undergraduate from UIUC is \$78,159. The average working hours for a first year engineer per year is 1920, assuming a 40-hour week (eight hours a day, five days a week) minus 160 hours of vacation . Therefore, development costs are estimated to be \$40.7/hour, 10 hours/week for three people. We consider approximately 85% of our final design in this semester (16 weeks). Finally, the total fixed development cost is \$23k.

Furthermore, the manufacturing cost of our prototype must be considered too. Apart from all the materials and pieces we are going to need, we will include a small percentage for any contingencies that we can find throughout our semester as well as some additional units in case some stop working:

Part	Manufacturer	Units	Cost ($)	Total ($)
DW1000	Abracon Corp.	2	10.92	21.84

UWB Antenna	Taiyo Yuden	3	2.2	6.6
BLE Antenna	Molex	3	3.3	9.9
Sprays	PetSafe	2	11.95	23.9
Host (BTH)	Nordic	6	5.46	32.76
Host (LPC)	NXP	2	2.33	4.66
PCB	Machine Shop	2	3.10	6.2
Li-ion battery	Panasonic	6	9.8	58.8
Crystal (CLK sync)	Abracon Corp.	2	0.98	1.96
Relay Switch	Songle Relay	1	1	1
Delivery Fees	N/A	5	5	25
Contingencies	N/A	N/A	25	25
LDO Regulator	ON Semiconductor	3	0.81	2.43
			TOTAL	198.35

3.2 Schedule

Week	**Jihyun**	**Louis**
02/24/20	Find adequate components	Find suitable communication system
03/02/20	Design schematic with components	Start UWB IC interface and transmission/receival protocol
03/09/20	Start PCB design & order components	Write code for ARM core host processor
03/16/20	Test UWB communication and find threshold values	Relay for light system without microcontroller input

03/23/20	Implement Bluetooth master/slave communication	Relay for light system with Bluetooth microcontroller input
03/30/20	Integrate UWB module with Bluetooth system and test functionality	Test signal reception and switch control of light switch subsystem
04/06/20	Integrate all subsystems	Integrate all subsystems
04/11/20	Test system outdoors/indoors	Test system outdoors/indoors
04/20/20	Prepare final report	Prepare final report
04/27/20	Prepare final presentation	Prepare final presentation

4. Comparison of Differences

The previous project 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. As mentioned in the high-level requirements, we aim to guarantee a success rate in the detection mechanism of 95% and a switch controller accuracy of 95%, which yields a failure rate of the overall system to be around 9.75%.

Link to previous project: https://courses.engr.illinois.edu/ece445/pace/view-topic.asp?id=18829

5. Discussion of 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]**.

5. Citations

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[10] ICNIRP. *"Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)," Health Physics*, vol. 74, no. 4, pp. 494–523, 1998. Retrieved from: https://www.hindawi.com/journals/ijap/2013/291064/