Affordable in home internet of things temperature sensor

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Abstract

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1 Introduction

The project is the design of a internet of things (IoT) temperature sensor. The intent of this product is to enable home renters to collect accurate temperature data as evidence that a home may be too cold in the winter. The solution must be low cost, have enough storage for a month of data collections and must be small and easy to hide in a home.

The internet of things is a concept where devices are internet connected to allow remote control or remote data collation and management. These systems can provide modern convenience to many different parts of the home, such as in smart lighting. This space has become very popular in the last several years, with large companies such as Nest and Ring designing intelligent internet of things products. These companies has been bought by Google and Amazon, this demonstrates the consumer's and industry's demand for a smarter home.

Over the last few years, several different technologies have emerged to accommodate this market, the first is ZigBee, an open licence project using the IEEE 802.15.4 standard for mesh networks. This technology has been widely adopted by the internet of things industry and is used in products like Phillips Hue lighting. The second major technology used in this field is Bluetooth, with recent versions of Bluetooth the energy consumption of these devices has been reduced this is Bluetooth low energy (BLE). Also, recently Bluetooth supports mesh networking, making it good for use in smart home and IoT applications.

2 Requirements

The main requirements for this project are that the design must be low cost and last between two and four weeks for both data collection and battery usage. The device should be able to connect to the internet, allowing the data to be accessed remotely as well as allowing the sensors to offload data to external storage.

2.1 RF Connectivity

The system should include some form of internet connection interface to allow the data to be put into a cloud storage system. A form of wireless communication between the modules and a phone, this could either be implemented with all modules communicating to each other and having a master node that connects to the users device or with every node connecting to the users device separately.

2.1.1 Zigbee vs WiFi vs Bluetooth Low Energy

The main competitors in the RF connectivity space is Zigbee, WiFi, and Bluetooth low energy. ZigBee is based on the IEEE 802.15.4 standard, this technology allows low power mesh network transmission at 2.4GHz frequency. This connectivity system is widely used in the IoT industry with standards such as light link being used to connect smart lighting products by manufactures like Phillips and Xiaomi. The next technology is WiFi the advantages of WiFi is the ability to use it to seamlessly access the wider internet, however the system is complicated as each unit would have to be completely independent, with each sensor in the network connecting directly to the users private network. WiFi is also uses a significant amount of power. Finally Bluetooth Low Energy (BLE) is power efficent, and can also connect directly to a users phone or computer with Bluetooth compatability.

2.2 Data Collection

Data collection is an important part of the sensor as the hardware must be able to store between two and four weeks to meet the specifications. All data collected will need to contain the sensor data, as well as a time component, this time component will most likely have to be sourced from a real time clock (RTC) as the specifications require operation even when internet is unavailable. This amount of data will most likely require some external storage in the form of EEPROM, electronically erasable read only memory. This data when offloaded into the cloud will need to be kept secure to avoid user data breaches. Different database and storage solutions will need to be considered for the cloud storage aspect of the solution.

2.3 Power Consumption

For this project the power use is very important as the system should be able to seamlessly record data for a complete two to four week period. This means that keeping power consumption is important in the success of the design.

3 Hardware

The chosen final specifications for the design were chosen to meet the requirements, focusing on the simple usability of the design as well as keeping the power consumption low enough so the device may run uninterrupted.

3.1 Processor

The chosen processor is from ST Microelectronics, specifically the STM32WB55CEU6. This MCU was chosen as it integrates both ZigBee and BLE support on one chip. This has two benefits, the first is cost as the unit integrates both the MCU and the transmit/receive functionality the cost is reduced as only one relativity affordable chip is required, with the chip costing \$6.65 for a single unit and \$3.76 each in 1,000 quantity all in USD.

This chip also has advantages for power consumption, as the package consists of two separate Arm cortex processors. The first is a Cortex M4 this is dedicated to running the application and is a very low energy part. The second is a Cortex M0+ this is dedicated to running the communication stack. The network stack in this processor is capable of calling interrupts, this means that the the low power M4 processor can be put into deep sleep mode to conserve power and can be woken by a central node over the network to process the current temperature then send it over the network before returning to deep sleep.

3.2 Temperature Sensor

3.3 Power Delivery

The main module has a simple 3.3V regulator, this part is built into the main data collection and ZigBee board. This keeps the auxiliary more simple, keeping manufacturing costs low as auxiliary modules have smaller production than the ZigBee/data collection board. As the STM microcontroller and temperature sensor operate at 3.3V V_{DD} for the board is at 3.3V. For potential expansion boards an external regulator can be used on board to supply required voltages before feeding into the main board.

Due to the variability of the design the power delivery is done on the auxiliary modules, this means this if a unit, such as the base station is designed to powered externally as it is expected to always be online. Where as batteries can be attached to make the design portable within the home.

3.4 Modules

The design is to be modular to keep the production costs low as the entire system will have a low initial production run of 5,000 units and to keep the PCB and component assembly cost as low as possible each the main unit containing the STM MCU and the temperature will feature a six pin connector with Voltage in, voltage out, ground and USART as well as one GPIO pins for future expansion. These pins will interface with external battery pack or base station modules.

3.4.1 Data Collection Board

The data collection board is design to contain the STM processor as well as the temperature sensor. Alongside these two the board contains supporting peripherals such as power delivery components and the PCB antenna, with the required components. The PCB antenna is used to keep the unit affordable as extra costly external components are not required.

The 3D render of the board shown in Figure 1. This render shows how compact the board is. It was determined that the board should be small to allow for greater options in future expansion. As 3D footprints were not availble for all components some appear as coloured boxes, some such as the microprocessor were made manually to aid visual representation.

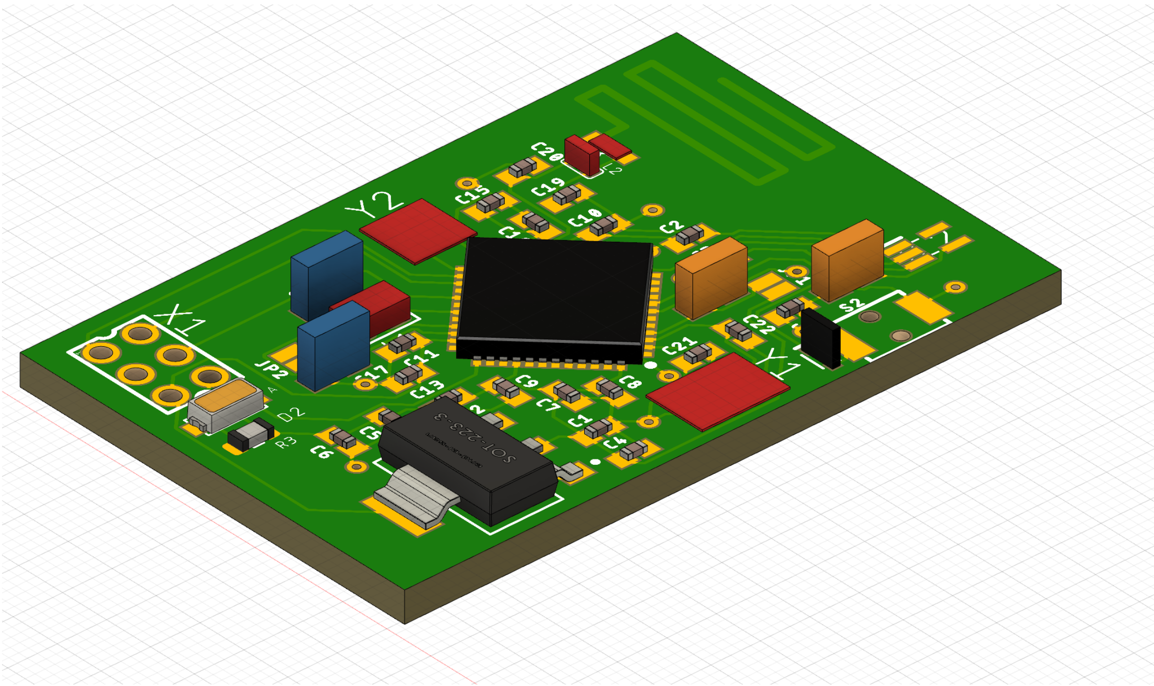

Figure 1: 3D CAD layout of the data collection board

The PCB and schematic layouts shown below show that most of the components are used for power delivery to the microprocessor. Specifically, some of the power delivery shown in Figure 2 as C17, C18 and L1 allow the processor to run in SMPS mode, this allows the processor to run in a lower power mode if V_{DD} is high enough, around 2.0V or above. The schematic also shows the two different oscillators, with one operating at 32MHz and the other at 32.768kHz. The former is used for the RF and system clock and the latter is used bu the real time clock.

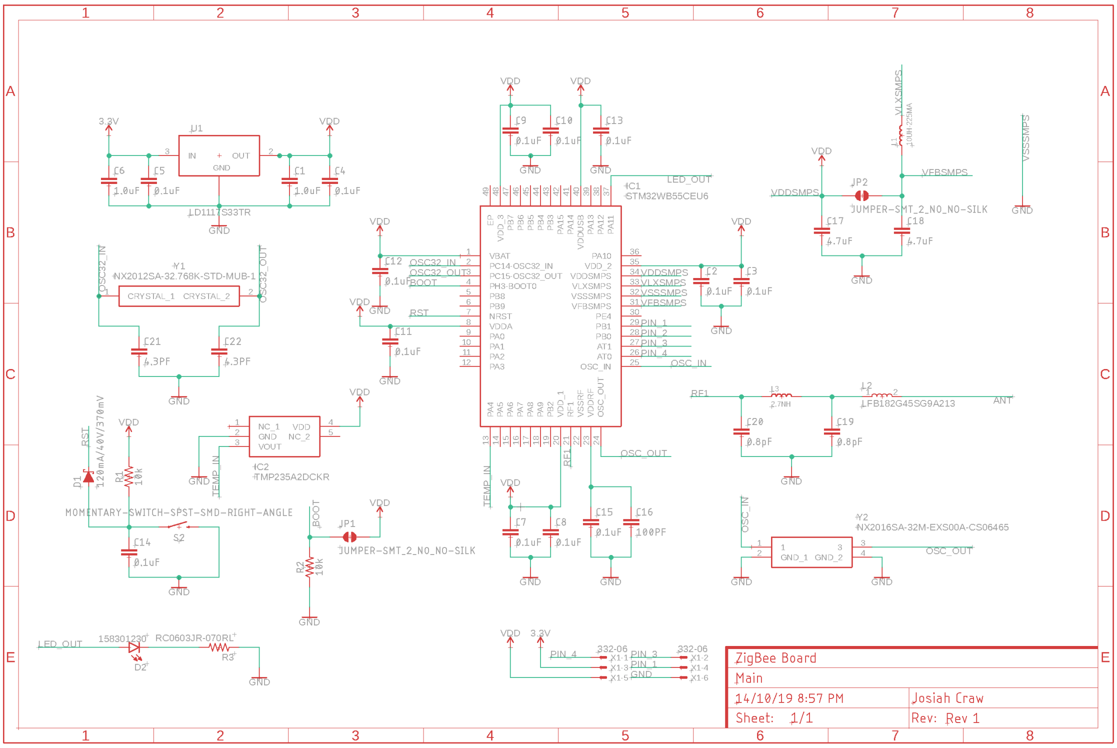

Figure 2: Schematic of data collection board

Finally below in Figure 3 is the PCB layout for the data collection board. As shown in this image there are cut outs in the ground plane, this first of which is under the antenna this is a requirement for the antenna layout given by STM in the application guides. The next ground plane cut out is under the temperature sensor, this has been done to thermally isolate the temperature sensor as many components dissipate heat on to the ground plane. Also shown are several vias to the ground plane, these were placed to reduce the distance to ground for many components, for parts such as decoupling capacitors this is very important as it reduces noise in the system.

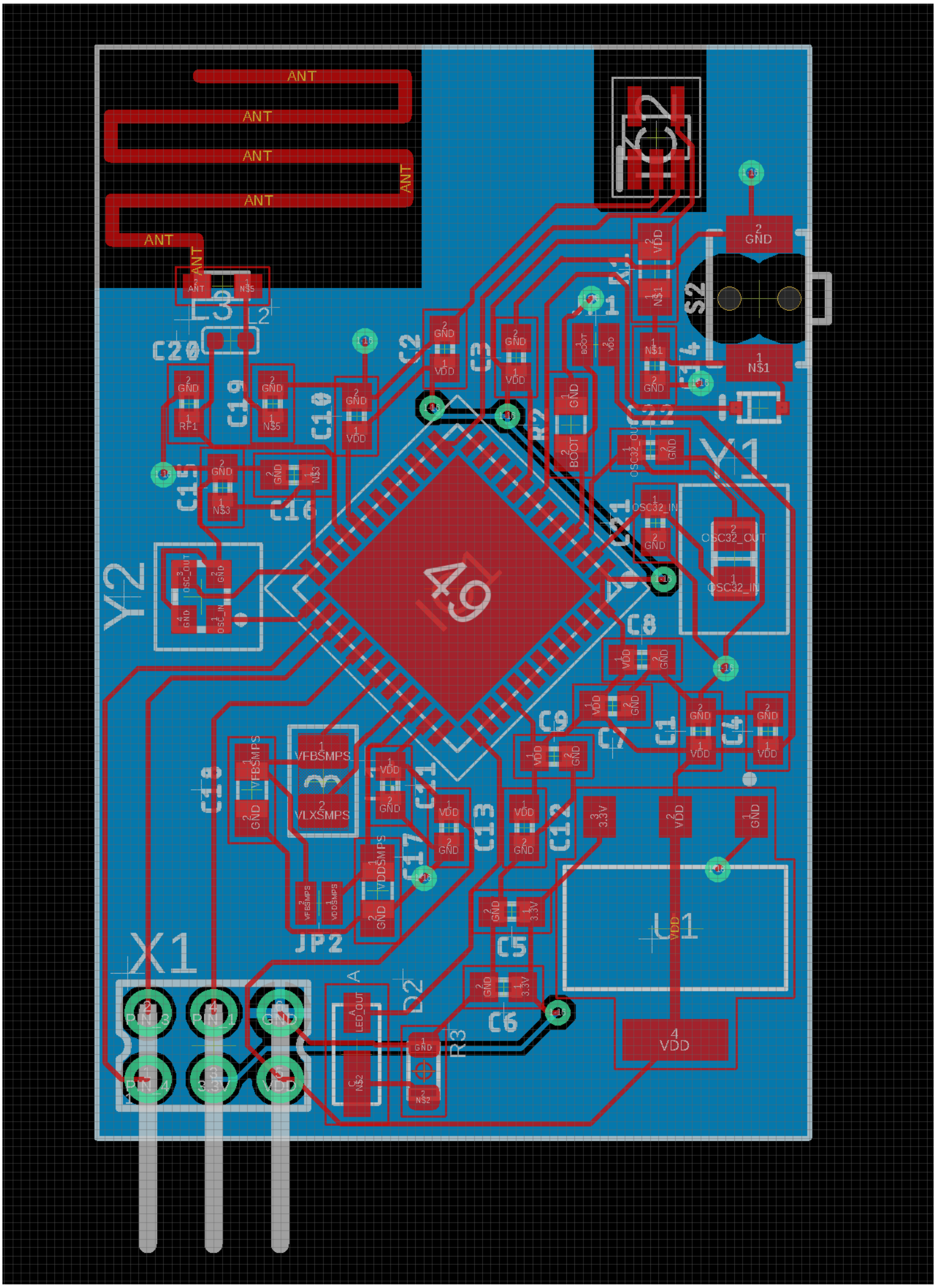

Figure 3: PCB layout of the data collection board

3.4.2 Battery Expansion Board

The battery board contains holder for two 18650 size lithium ion batteries, these batteries contain enough power to keep the data collection board operating for 4 weeks. The rest of the spare GPIO is routed out to five pins, with the GPIO, two USART and voltage out and the ground. This will allow the system it potentially allow other sensors to be added to the unit. The layout of this board is shown in Figure 4.

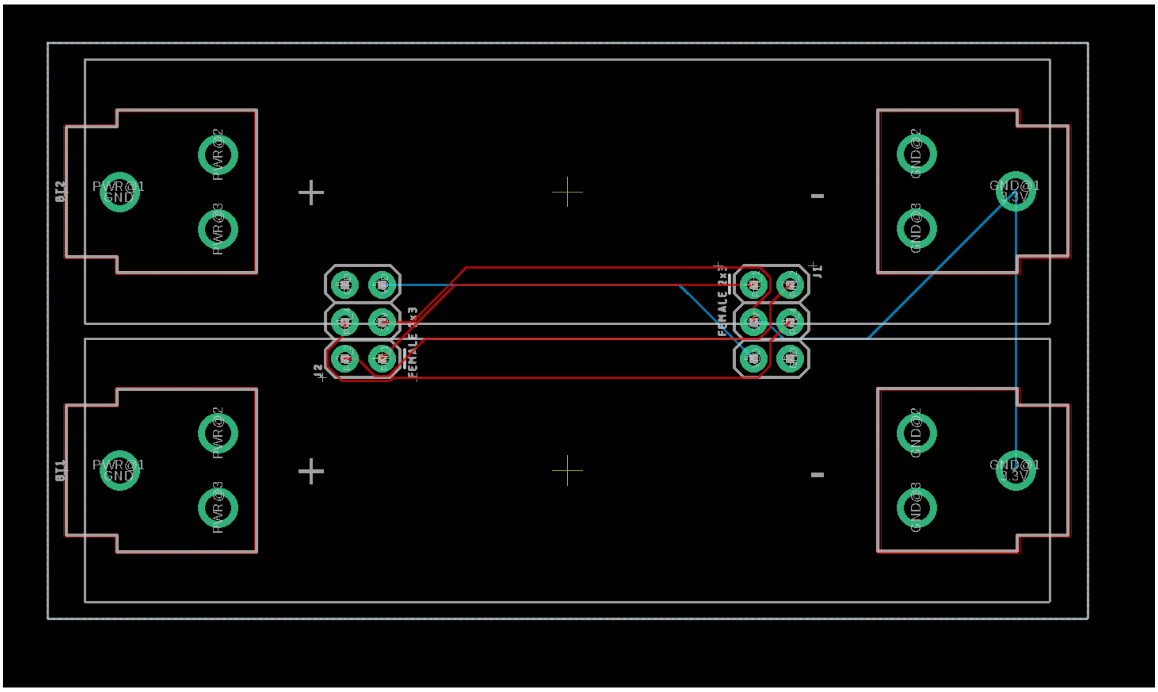

Figure 4: PCB layout to the battery expansion board

As shown in the figure above the board is keep as simple as possible, this is in an effort to keep the assembly and part costs down.

3.4.3 Base Station Expansion Board

This module is much more complicated than the battery board, this board uses a DC barrel jack to power it from the main supply. This board also contains an ESP32 module this module is integrated for the base station to allow WiFi connectivity. There is also EEPROM to allow for long term data storage on the board. The ESP32 is connected to the USART connections of the STM micro controller, in this configuration the STM will be running in a slave like manner, with is being used primarily as a transmitter for into the ZigBee network. The ESP32 will be running Amazon FreeRTOS this is based on the popular FreeRTOS platform. The schematic PCB layout for the base station expansion board is shown below in Figures 5 and 6.

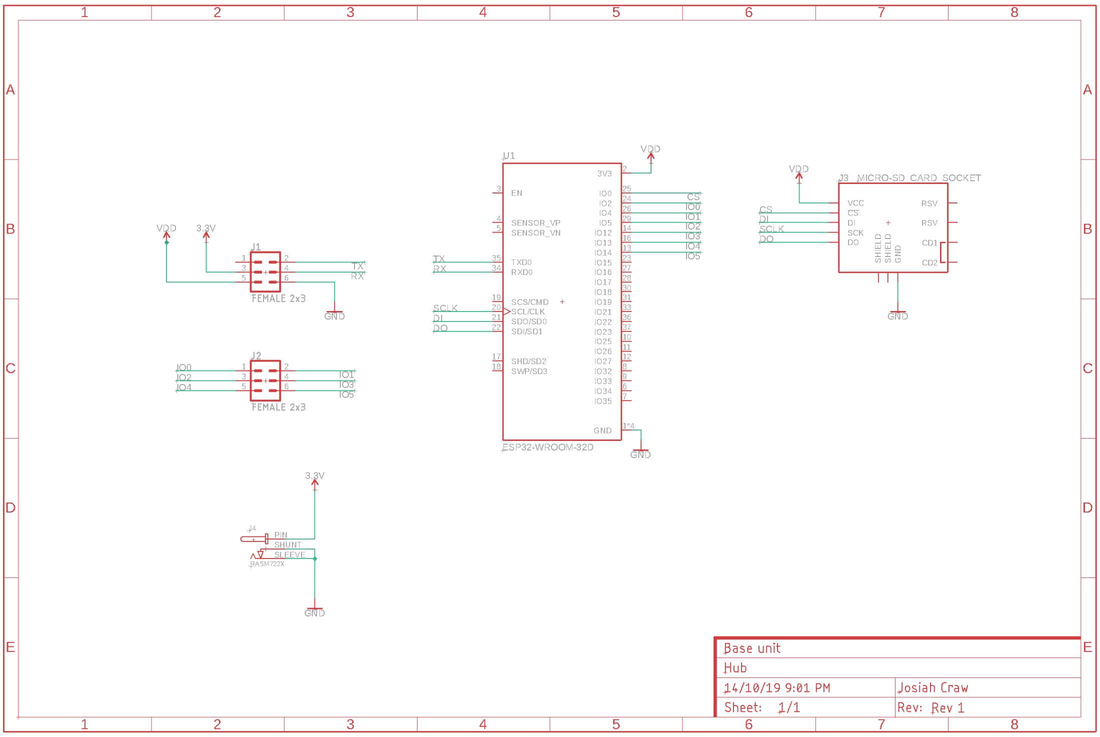

Figure 5: Base station module schematic

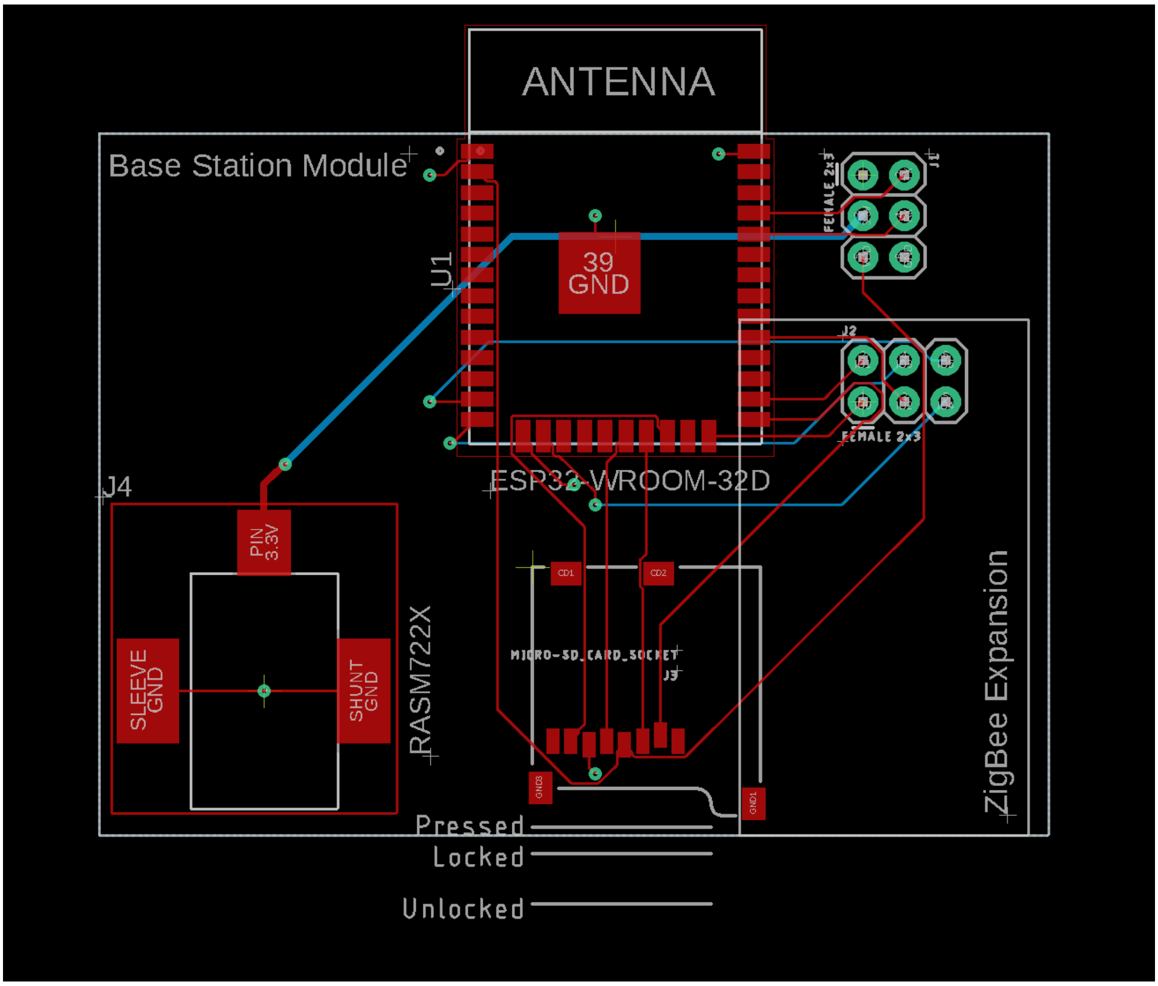

Figure 6: Base station module PCB layout

4 Firmware

As the system has two different modes, the first external sensor node and the second base station mode. These modes will be implemented as separate software on the two devices, this will reduces the computational complexity on each device, reducing power consumption. This however has the trade off that the devices will have to be flashed with the correct software and changed when hardware expansions are made.

4.1 Node

The first firmware component is on the wireless node. This firmware is optimised to reduce power consumption for the device. The firmware will use the feature of the micro controller allowing the system to be woken from deep sleep by a network interrupt. The device will then add its unique ID to the data. The completed data is then sent through the mesh network to the base station. The goal was to keep as little of the processing as possible on the nodes themselves. This was to aid in their battery life.

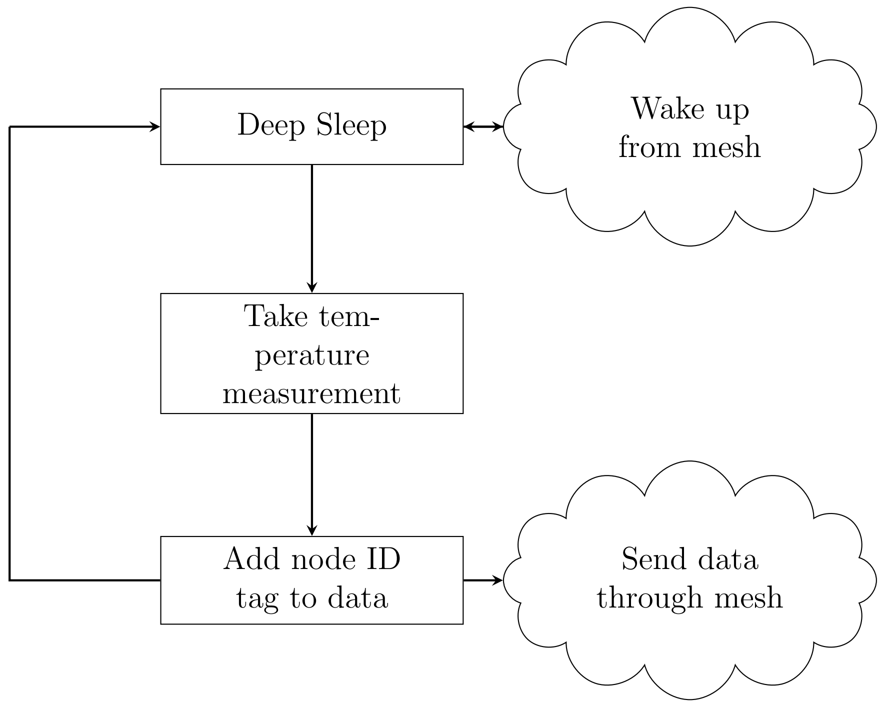

Figure 7: Individual node firmware block diagram

As a part of the over the air update system the firmware will have to include protocols to allow remote updates from the base station. This will require integration between the base station firmware and the firmware on the nodes. This feature is included on the chosen processors, making the development much simpler.

4.2 Base Station

The base station firmware, shown in Figure 8 below shows the operation of the base station module. The main routine is for the module to send an interrupt to the mesh every five minutes. This is used to offload the timing processing to the central base station. The other main use of this centralised timing system is to ensure that the intervals are synchronised. Also this means that tagging the temperature readings with a time is done universally, reducing the load and therefore the power consumption of the remote nodes.

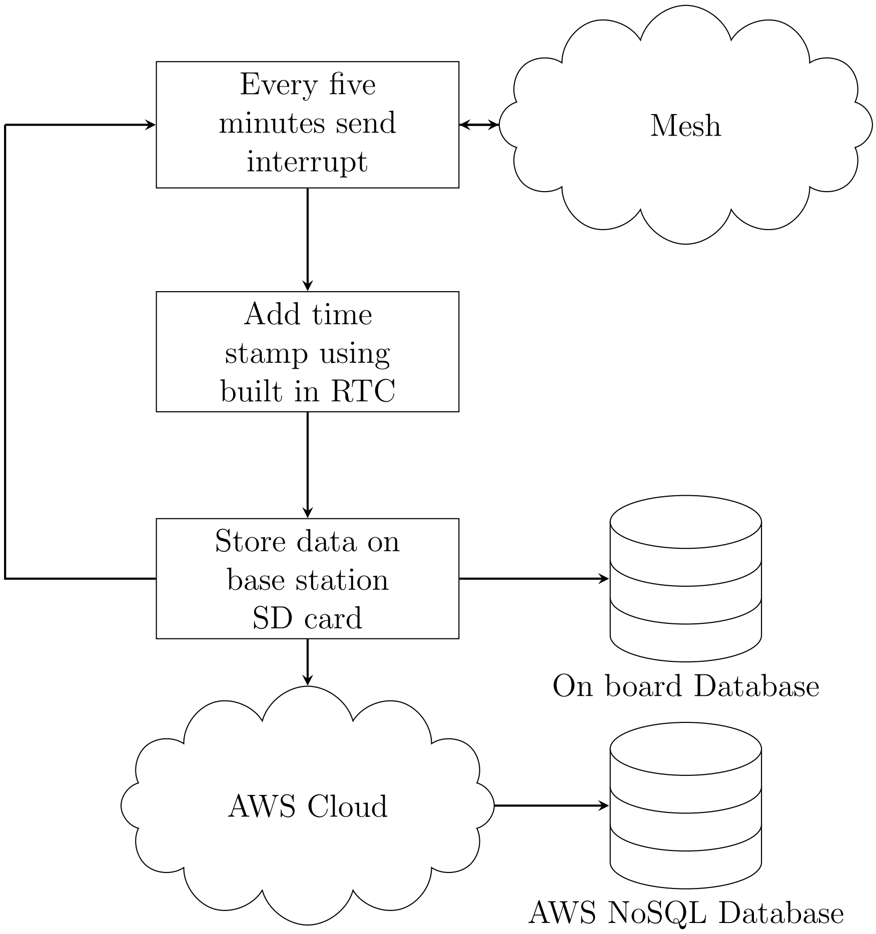

Figure 8: Base station firmware block diagram

5 Cloud System

The cloud system key component of the IoT platform and must be implemented securely, and seamlessly to aid in ease of use, the system must also meet the cost constraints as to ensure the product is competitive in price while still being able to offer a complete experience to the user. For these reasons the Amazon Web Services (AWS) platform has been chosen for the cloud platform due to the cost as AWS operates on a 'pay as you go' model with competitive prices allowing the project to require no investment in compute hardware infrastructure.

5.1 Amazon FreeRTOS

One of the key features provided by AWS for this project is the Amazon FreeRTOS. Amazon FreeRTOS is a real time operating system (RTOS) based on the open source FreeRTOS project. This software runs natively on the ESP32 used in the base station and allows the system to connect to the internet simply and securely. The main features of this is the secure connections to the AWS platform, using the MQTT platform for secure messaging to communicate with the AWS IoTCore product. This is provided in the AWS platform to manage and control devices. Another major feature for the system is the built in API for over the air (OTA) firmware updates. This is a powerful feature as it is very important for IoT devices to be able to be upgraded and features and security patches are essential to maintain a competitive IoT product.

5.2 Data Management and Security

The next key feature of AWS is the data management as using the AWS global platform allows the product to scale beyond one country with out increased cost and infrastructure upgrades. The security is also an important feature of the platform as maintaining data security can be expensive and as this is all contained within the cost of AWS this further reduces the cost of developing an in house system. The global system also allows the data to be made redundant across several data centres ensure potential customers data is not lost. All of the aspects combined show make the AWS platform a good option for the project as it significantly reduces cost compared to developing and maintaining the software and hardware support in house.

5.3 Over the Air updates (OTA)

Over the air updates are a key component of IoT devices as it allows engineers to fix security flaws as well as add feature sets while enabling non technical users to have simple update methods for their devices. The ESP32 running Amazon FreeRTOS supports built in over the air updates. This allows the project a method of updating from outside the network. The STM32WBxx series processors also support over the air updates through both the BLE and ZigBee radios. This means that the development process for this feature will be simple as only a bridge between the updates to the base station on to the mesh network needs to be implemented.

5.4 Data Analysis and Big data applications

Finally, AWS provides cost effective compute systems, this means that the collected users data can be efficiently processed and evaluated to provide insights into the user and may be informative for the user such as a heat map for their house and a simple animation demonstrating the temperature of their house and rooms over the course of a day or month. This information may assist users in finding the issue in their homes thermal management eg. If one room in the home was getting cold with all the other room cooling after, the first room is most likely the culprit for the thermal issues in the home.

The computed data provided by many customers in a area could provide a effective data set for many applications such as potential power consumption statistics and room occupancy during different time based on the temperature within the room. This data could be analyzed in cloud to provide insights into the habits of customers. However despite the potential research and informational value of the data, user privacy and security would have to be maintained. This could be done by stripping any identifying information for the data before it is computed and added to a larger set of users data. This could be achieved in the cloud by extracting the users general data from their storage and processing it automatically before processing it in the main data processing system.

6 Sustainability

7 Future Expansion

Due to both the hardware modularity and software modularity with over the air updates, the design can be expanded and upgraded simply thorough either pushing updates to the software and firmware or providing add in modules. This allows the system to provide continuing support for features, keeping the users in the platform and potentially funding the ongoing costs of the cloud systems.

7.1 Humidity Sensors

A future module could be installed using the spare GPIO available on the data collection board expansion connector.

7.2 Power Efficiency increases

In the future the battery life of the module could be increased by periodically turning off the 802.15.4 radio, conserving power. This could be very efficient as the processing Cortex M4 can operate on 600nA in standby mode, with 32kB of RAM and the real time clock functional. This could be used to pull the device out of standby mode at regular intervals. All the node could be turned on then send then all return to standby until the next period.

7.3 Modular Expansion

With the breakouts for USART the main design is capable as operating as both a peripheral or supporting many different peripherals. This allows the design to be simply and cheaply expanded to support new modules within a smart home. Such modules could include a carbon monoxide or smoke sensor allowing extra functionality into the system. This support would allow continuing feature additions for users into the future. The over the air update compatibility for the system means that developers of the system could easily support additional hardware.

7.4 System API and existing system integration

A major feature for future implementation would be an API, this API could be used both on the external internet and on the internal users network. The API on the external network could be added using the AWS API Gateway. This would allow external API calls from systems that users use on the internet, allowing further development by other developers for the platform. Features the increase the value to consumers could be added, making this a valuable feature to implement. The internal API could be designed to run off of the ESP32 allowing the users other smart home products to interface with the system eg. A smart heating solution could interface with the product allowing the user to set heating thresholds and have the smart heater turn on when those limits are reached.

8 Conclusion

Appendices

A BOM

Part	Value	Device	Package	Description	DIGIKEY_PART_NO	MANUFACTURER	PRICE	PROD_ID	VALUE
C1	1.0uF	1.0UF-0402-16V-10%	402	1uF ceramic capacitors	GRM155R60G105ME01D-ND	Murata	0.0058	CAP-12417	1.0uF
C2	0.1uF	0.1UF-0402-16V-10%	402	0.1uF ceramic capacitors	1276-1004-2-ND	Samsung	0.00243	CAP-12416	0.1uF
C3	0.1uF	0.1UF-0402-16V-10%	402	0.1uF ceramic capacitors	1276-1004-2-ND	Samsung	0.00243	CAP-12416	0.1uF
C4	0.1uF	0.1UF-0402-16V-10%	402	0.1uF ceramic capacitors	1276-1004-2-ND	Samsung	0.00243	CAP-12416	0.1uF
C5	0.1uF	0.1UF-0402-16V-10%	402	0.1uF ceramic capacitors	1276-1004-2-ND	Samsung	0.00243	CAP-12416	0.1uF
C6	1.0uF	1.0UF-0402-16V-10%	402	1uF ceramic capacitors	GRM155R60G105ME01D-ND	Murata	0.0058	CAP-12417	1.0uF
C7	0.1uF	0.1UF-0402-16V-10%	402	0.1uF ceramic capacitors	1276-1004-2-ND	Samsung	0.00243	CAP-12416	0.1uF
C8	0.1uF	0.1UF-0402-16V-10%	402	0.1uF ceramic capacitors	1276-1004-2-ND	Samsung	0.00243	CAP-12416	0.1uF
C9	0.1uF	0.1UF-0402-16V-10%	402	0.1uF ceramic capacitors	1276-1004-2-ND	Samsung	0.00243	CAP-12416	0.1uF
C10	0.1uF	0.1UF-0402-16V-10%	402	0.1uF ceramic capacitors	1276-1004-2-ND	Samsung	0.00243	CAP-12416	0.1uF
C11	0.1uF	0.1UF-0402-16V-10%	402	0.1uF ceramic capacitors	1276-1004-2-ND	Samsung	0.00243	CAP-12416	0.1uF
C12	0.1uF	0.1UF-0402-16V-10%	402	0.1uF ceramic capacitors	1276-1004-2-ND	Samsung	0.00243	CAP-12416	0.1uF
C13	0.1uF	0.1UF-0402-16V-10%	402	0.1uF ceramic capacitors	1276-1004-2-ND	Samsung	0.00243	CAP-12416	0.1uF
C14	0.1uF	0.1UF-0402-16V-10%	402	0.1uF ceramic capacitors	1276-1004-2-ND	Samsung	0.00243	CAP-12416	0.1uF
C15	0.1uF	0.1UF-0402-16V-10%	402	0.1uF ceramic capacitors	1276-1004-2-ND	Samsung	0.00243	CAP-12416	0.1uF
C16	100PF	100PF-0402-50V-5%	402	100pF/0.1nF ceramic capacitors	311-1024-2-ND	Yageo	0.00346	CAP-13458	100PF
C17	4.7uF	4.7UF0603	603	4.7uF ceramic capacitors	1276-1907-2-ND	Samsung	0.01042	CAP-08280	4.7uF
C18	4.7uF	4.7UF0603	603	4.7uF ceramic capacitors	1276-1907-2-ND	Samsung	0.01042	CAP-08280	4.7uF
C19	0.8pF	0.8PF-0402-50V-0.1PF	402	0.8pF ceramic capacitors	490-6270-2-ND	Murata	0.0272	CAP-13456	0.8pF
C20	0.8pF	0.8PF-0402-50V-0.1PF	402	0.8pF ceramic capacitors	490-6270-2-ND	Murata	0.0272	CAP-13456	0.8pF
C21	4.3PF	100PF-0402-50V-5%	402	100pF/0.1nF ceramic capacitors	311-1024-2-ND	Yageo	0.00346	CAP-13458	100PF
C22	4.3PF	100PF-0402-50V-5%	402	100pF/0.1nF ceramic capacitors	311-1024-2-ND	Yageo	0.00346	CAP-13458	100PF
D1	120mA/40V/370mV	DIODE-SCHOTTKY-RB751S40	SOD-523	Schottky diode	RB751S40T1GOSTR-ND	ON Semiconductor	0.02805	DIO-11018	120mA/40V/370mV
D2	158301230	158301230	158301230	LED GREEN DIFFUSED 0603 SMD	732-12014-2-ND	Wurth Electronics Inc.	0.504		
IC1	STM32WB55CEU6	STM32WB55CEU6	QFN50P700X700X65-49N	STMICROELECTRONICS - STM32WB55CEU6 - MCU, 32BIT, 64MHZ	497-18490-ND	STMicroelectronics	3.76988		
L1	10UH-225MA	SMD-INDUCTOR-10UH-225MA-10%(0806)	L0806	303010042	490-4046-2-ND	Murata	0.11331		10UH-225MA
L2	LFB182G45SG9A213	LFB182G45SG9A213	INDC1608X95	Electromechanical Filter 2450MHz Freq. 2000MHz to 4000MHz	535-12208-2-ND	Abracon LLC	0.15		
L3	2.7NH	SMD-INDUCTOR-3.3NH-0.3NH-300MA(0402)	L0402	303010056	712-1416-2-ND	Johanson Technology	0.0153		3.3NH- 300MA
R1	10k	10KOHM-0603-1/10W-1%	603	10k resistor	RNCP0603FTD10K0TR-ND	Stackpole Electronics	0.00693	RES-00824	10k
R2	10k	10KOHM-0603-1/10W-1%	603	10k resistor	RNCP0603FTD10K0TR-ND	Stackpole Electronics	0.00693	RES-00824	10k
R3	RC0603JR-070RL	RC0603JR-070RL	RES_0603	RES SMD 0 OHM JUMPER 1/10W 0603	311-0.0GRTR-ND	Yageo	0.00213		
S2	MOMENTARY-SWITCH-SPST-SMD-RIGHT-ANGLE	MOMENTARY-SWITCH-SPST-SMD-RIGHT-ANGLE	TACTILE_SWITCH_SMD_RIGHT_ANGLE	Momentary Switch (Pushbutton) - SPST	P16767TR-ND	Panasonic	0.13471	COMP-12265	
U1	LD1117S33TR	LD1117S33TR	SOT-223	IC REG LINEAR 3.3V 800MA SOT223	497-1242-2-ND	STMicroelectronics	0.13558		
X1	332-06	332-06	332-06	6 Pin - 2mm Dual Row					
Y1	NX2012SA-32.768K-STD-MUB-1	NX2012SA-32.768K-STD-MUB-1	NX2012SA32768KSTDMUB1	NDK 32.76kHz Crystal Unit +/-20ppm SMD 2-Pin 2.05 x 1.2 x 0.55mm	644-1219-2-ND	NDK America Inc	0.4452		
Y2	NX2016SA-32M-EXS00A-CS06465	NX2016SA-32M-EXS00A-CS06465	NX2016SA32MEXS00ACS06465	CRYSTAL 32MHZ 10PF SMD	644-1301-2-ND	NDK America Inc	0.27985		
							5.71488		