Design and Evaluation of a Body Temperature Controlled Air-conditioning System

By

Stuart Wild

A Thesis submitted to Murdoch University

To fulfil the requirements of

Industrial Computer Systems Engineering

Author's Declaration

I declare that this thesis is my own account of my research and contains as its main content work which has not previously been submitted for a degree at any tertiary education institution.

Stuart Wild

Acknowledgements

Thanks go to Associate Professor Graeme Cole, Dr. Gareth Lee and Professor Parisa Arabzadeh Bahri, I do appreciate all the input that you have given me. Privately I wish to thank Jillian Goll (why haven't you left me already?), Ali Kharrazi and Elizabeth Aisbett (God rest her soul) and anyone else who has given me the time of day when it wasn't explicitly required from them or in their interest.

Abstract

While remote sensing technologies for airconditioners have been available for some time, no research has been done on airconditioner remote sensing of the body. This thesis looks at the opportunities for remotely sensing body temperature from the wrist. The goal of this report was to evaluate any potential energy savings to be had for airconditioners by utilising this measure of the body. A prototype was designed emphasising factors such as size, weight and energy consumption/battery life. The prototype was then evaluated for success by comparison with baseline energy use and the observance of a reduction in the coefficient of determination between outside air temperature and energy use. While dramatic energy savings were not realised due to the simplistic nature of the prototype, a saving of almost a kilowatt hour for sub 35ºC days was able to be achieved. These results show the promise that body temperature sensing offers.

Table of Contents

Index of Tables

Illustration Index

Introduction

Even the most sceptical among us agree that climate change is an issue that needs to be addressed, if not by us, then the burden will be passed on to our children. The cumulative nature of carbon emissions means that solutions that provide immediate reductions in emissions provide the greatest reward (Rhys 2011). A dynamic life cycle assessment of the entire solar industry suggests that, as of yet with the rate that new solar panels are being installed with respect to their carbon payback period, not a single gram of CO2 equivalent emissions has been saved by the industry (De Decker 2015).In this vein, technologies that provide retrofits to existing technologies and systems that encourage better usage of appliances, either by encouraging behaviour change or via automation, will provide the greatest benefit.

In Australia heating and cooling energy use accounted for 41% of all domestic energy usage, with 18% of heating provided by reverse cycle airconditioning (“4614.0.55.002 - Energy in Focus: Energy Efficiency of Australian Homes, Apr 2010” 2010). With average temperatures increasing this risks a positive feedback loop of greater emissions being caused by greater emissions. Additionally, the middle class of countries such a China and India continue to swell (“Middle Class Growth in Emerging Markets - China and India: Tomorrow’s Middle Classes - EY - Global” 2016) which will result in many more airconditioners being installed. The growth rate of airconditioning for cooling and it's large energy usage provide an opportunity for large savings of emissions.

Many currently installed window airconditioners have their temperature sensors mounted within their bodies, precariously close to the outside air. Knowing that older heating technologies such as the hot water bottle provided heat only where it was needed, it was desired to do the same with cooling. Air temperature is also not an indicator of thermal comfort, as anyone who has chopped wood in winter can tell you.

This thesis shall design a device that will control an existing airconditioner's compressor based upon the temperature of an occupant, not of the air close to the airconditioner itself. The prototype will be tested to see if any energy savings can be gained and its effectiveness shall be weighed against its embodied energy. Temperature measurements are desired to be taken from the underside of the wrist as this would be a convenient measurement place for a consumer device based upon this thesis. In wanting to create a system that could achieve widespread adoption, parts will be selected to minimise the physical size of the device as well as to ensure a long battery life for convenience.

An argument may be made that adjusting room temperature based upon one person's wrist temperature will make others uncomfortable. But would not the temperature of another human being still be a better measure than the temperature of the air immediately in front of the airconditioner, given these people otherwise share the same environment? Especially considering that the human body even across the sexes has an average temperature of 36.8ºC with a standard deviation of only 0.4ºC (Elert 2016)

Background

Commercial Offerings

A number of commercial offerings exist to augment additional sensing onto existing airconditioning systems. Manufacturers include Honeywell, Google, Ecobee and Ambiclimate.

The Honeywell Lyric, Google Nest and Ecobee are intelligent Thermostats designed to be used with whole house HVAC (heating, ventilation and airconditioning) systems(“Honeywell Lyric Thermostat Installation Process” 2015) (“Meet the Nest Thermostat | Nest” 2015) (“Smart WiFi Thermostats by Ecobee |” 2015). Energy savings are achieved by scheduling temperature changes based upon historical use, allowing the temperature to creep up or down in periods that a lack of user input indicates an acceptable temperature. A mobile application provides the ability for the temperature to be adjusted based upon the mobile phone's distance from the house. To provide repeatability these devices include a number of sensors such as temperature and humidity. Additionally, the Ecobee is able to communicate with other sensors through mediums such as Zigbee (“Smart WiFi Thermostats by Ecobee |” 2015).

The closest a commercial offering has come to achieving the aims of this thesis is the Ambiclimate. The Ambiclimate contains the features of other commercial offerings but is not a replacement for a whole house thermostat, it is able to communicate with an airconditioner via infrared (“How Ambi Climate Works” 2015).

ASHRAE Thermal Sensation Scale

The American Society of Heating, Refrigeration and Air-Conditioning Engineers Thermal sensation scale is a value that reflects subjective temperature comfort as given in Table 1(“About ASHRAE | Ashrae.org” 2016) (“Predicted Mean Vote Index (PMV)” 2015):

Table 1: ASHRAE Thermal Sensation Scale (“Predicted Mean Vote Index (PMV)” 2015)

ASHRAE Sensation Scale Value	Sensation
-3	Cold
-2	Cool
-1	Slightly Cool
0	Neutral
1	Slightly Warm
2	Warm
3	Hot

An understanding of the ASHRAE scale is important as the body of literature uses this scale for the self reported sensations of its test subjects.

Predicted Mean Vote Index

The predicted mean vote index gives a measure of the mean response of a large group of people to a given set of thermal conditions and is given in the ASHRAE thermal sensation scale (“Predicted Mean Vote Index (PMV)” 2015). It's exact formula is as follows:

$PMV=\left(0.303\,e^{(-0.036M)}+0.028\right)L$ (“Prediction of Thermal Comfort” 2016)

Where M is the metabolic rate and L is “the difference between the internal heat production and the heat loss to the actual environment for a person hypothetically kept at comfort values of skin temperature and evaporative heat loss by sweating at the actual activity level.”(“Prediction of Thermal Comfort” 2016).

Two sample T-test

An understanding of the paired two sample t-test is important for an interpretation of the existing works in this area. The paired to two sample t-test is used to determine if the means of two samples of paired data, such as before and after measurements of the same subjects, are in fact the same (Shier 2004). The P value given out correlates to the chance that the null hypothesis has been incorrectly rejected, typically a less than 5% chance is deemed significant (“P Values (Calculated Probability) and Hypothesis Testing” 2016).

Belkin Conserve Insight

The energy monitor used was a Belkin Conserve Insight. Energy usage shall be determined via the usage of its cost mode. In the cost mode the Conserve Insight will display a 30 day cost for operation of the connected device, based upon an entered price per kWh(“Conserve Insight Energy Use Monitor User Guide” 2016). This cost of operation is based upon a cumulative average of power since the unit was connected(“Conserve Insight Energy Use Monitor User Guide” 2016). The cumulative nature of the average was also confirmed by observation, the fluctuation of the predicted cost decreases the longer the energy meter has been plugged in. Confirmation was required of this because an “x-point” moving average would not provide an accurate measure of power consumption during a prolonged period of compressor action or inaction.

DS18B20

The DS18B20 is a digital temperature sensor available in both through-hole and smd (surface mount device) packages(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015). It's accuracy is ±0.5ºC with a maximum resolution 0.0625ºC (“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015). The temperature range supported is -55ºC to 125ºC(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015). Its 1-Wire communications are achieved by the master (in this case our microcontroller) pulling the line low for signalling and the DS18B20 doing the same with its open drain input(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015).

Writing bits

For the master to write a “1” the line is pulled low for at least 1us and then must return to a high voltage within 15us of the start of pulling the line low(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015). Then the line is held high for the remainder of the 60us period of the write operation(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015). There is a 1 second recovery needed between each write operation(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015). To write a “0” the line is simply held low for the entire 60us duration(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015).

Reading bits

To read a bit the master must pull the line low for 1us and then the

DS18B20 will transmit either a 1 or a 0 for the rest of the 60us read period(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015). There must be a 1us recovery time between read operations(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015).

Communication with the DS18B20 is achieved with a sequence of three commands that must be executed in order(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015). They are an initialisation command, a ROM command and a Function Command(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015).

Initialisation Command

The initialisation command consists the master pulling the 1-Wire bus low for 480us and then after 15 to 60us the DS18B20 will pull the bus low itself for 0 to 240us while the master enters into receive mode for 480us(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015).

ROM Commands

ROM commands are used in the identification of individual devices on the 1-wire bus according to their 64-bit ROM code(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015). Since we are only interested in a single device on the bus the only ROM command we are interested in is SkipRom which is transmitted as hexadecimal CC (“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015).

Function Commands

Function commands include asking the DS18B20 to retrieve the current temperature, and to read and write to an area of memory known as the Scratchpad(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015). The format of the Scratchpad is given in Table 2.

Table 2: Format of the DS18B20 Scratchpad

Byte	Function
0	Temperature least significant byte
1	Temperature most significant byte
2	High temperature alarm byte
3	Low temperature alarm byte
4	Configuration register
5	Reserved
6	Reserved
7	Reserved
8	Cyclic Redundancy Check

Bits 5 and 6 of the configuration register are used to set the resolution of the temperature sensor, default values on startup are 1 and 1 which gives the highest resolution available. All other bits in the configuration register are reserved(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015). The Alarm bytes can be written to and an internal alarm flag will be set upon either set point being reached (“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015).

The function commands used in this project are the ConvertT and ReadScratchpad commands. ConvertT (hexadecimal 44) reads the temperature and stores it within the two temperature bytes and takes a maximum of 750ms(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015). Conversion time can be reduced by reducing the resolution of the temperature reading. ReadScratchpad (hexadecimal BE) will return in sequence the entire contents of the Scratchpad (lsb first) and can be escaped by issuing a reset pulse(“DS18B20 Programmable Resolution 1-Wire Digital Thermometer” 2015).

Life Cycle Assessment

The ISO 14040 defines life cycle assessment as “the compiling and evaluation of the input and outputs and the potential environmental impacts of a product system during its lifetime” (Moore 2014). It involves the consideration of the input and outputs of a product during its production, use and end of life (Moore 2014). The phases of a life-cycle assessment include goal and scope definition, inventory analysis, impact assessment as well as interpretation as each stage (“UNEP Life Cycle Assessment” 2016).

Academic Background

The thesis of Muhammad Aftab is similar to this project in that both deal with moving the sensing of temperature away from the airconditioner proper. Chiefly the thesis was concerned with the development off an algorithm balancing the power usage of 4 remote sensors with the comfort of the room(Aftab 2013). Control schemes maintaining the temperature of all 4 temperature sensors as well as only one temperature sensor were developed (Aftab 2013). Of particular interest is that an almost 50% energy saving was achieved by controlling a single zone of interest rather than the entire room, suggesting that a control scheme based upon a single person's temperature may be effective(Aftab 2013).

Another network of temperature sensors is presented in *Opportunities for Wireless Sensors and Control for Building Operation* (Kintner-Meyer 2005). 30 wireless sensors were placed around an office building which enabled the building's cold water supply to be varied between 45ºF and 55 ºF based upon their average (Kintner-Meyer 2005). During the year of 2002 3500USD was saved on cooling (Kintner-Meyer 2005). The study also presented a comparison of various wireless technologies and their energy use (Kintner-Meyer 2005).

Few studies were found to discuss the usage of skin temperature as a measure of comfort. *Experimental Study on Skin Temperature and Thermal Comfort of the Human Body in a Recumbent Posture under Uniform Thermal Environments* measures the temperature of the skin at 16 different locations and then evaluates 14 methods using these measurements for their accuracy in reflecting the subject's mean skin temperature (Lian et al. 2007). These temperature measurements and the mean skin temperature are then compared to their local thermal sensation and overall thermal sensation respectively (Lian et al. 2007). *Investigation of human body skin temperatures as a bio-signal to indicate overall thermal sensations* evaluates the usefulness of ten regions of the body as individual measures of thermal comfort (Choi and Loftness 2012).

Yao et al. concludes that thermal sensation is governed by the parts of the body that experience the greatest extremes in temperature, that is the head and trunk for warm temperatures and the extremities for cool temperatures (Lian et al. 2007) Of the 14 methods analysed to determine mean skin temperature it is claimed that the 3 point Burton method for mean skin temperature determination shows no significant difference with the 13 other methods with $p > 0.25$ (Lian et al. 2007). This p value suggests that over 25 percent of studies would produce these observed differences between these 14 methods due to random sampling errors (“How to Correctly Interpret P Values” 2016). The study also demonstrates that idea of skin temperature as an indicator of thermal comfort is a valid one, with the lowest coefficient of determination between skin temperature and local thermal comfort (ASHRAE scale) being 0.89 for the calf implying that 89 percent of the variability in the data is explained by the linear model presented (Lian et al. 2007) (“Regression Analysis: How Do I Interpret R-Squared and Assess the Goodness-of-Fit?” 2016). The point was also made that women feel cool more easily with women rating themselves at a mean thermal comfort of -2.1 while men rated themselves -1.9 for an environment at 21ºC (Lian et al. 2007).

Choi and Loftness evaluate individual sites of the body for their usefulness as a measure of comfort. Of particular interest is their data on the wrist which due to the nature of the device being designed is one of the few places suitable for comfortable 24 hour measurement. The study concluded that for the wrist it was difficult to differentiate between slighty cool, neutral and slightly warm sensations. However, the two sample t-test presented between neutral and slightly warm suggests that the means for these two samples of people are different, enabling the identification between these two states (Choi and Loftness 2012).

In observing the mean temperatures presented by Choi and Loftness and the differentiation apparent for the wrist between neutral sensation, an initial control scheme was developed. A temperature crossing point of 32ºC was defined as the signal to issue an on or off control to the airconditioner. This temperature is well outside of 95 percent of the sample means possible for a neutral sensation, given the 95 percent confidence interval shown(Choi and Loftness 2012). Unfortunately it is over the mean for the slightly warm sensation but below that of the warm sensation, meaning that some people may not be as adequately chilled as they would like. Provision has been made within the code for more fine grained control than a whole number temperature in the future.

Choi and Loftness also investigate the temperature gradients of the body. Gradient measurements were taken between 180 second intervals as a smaller interval did not allow for a significant enough change in temperature to be detected (Choi and Loftness 2012). It was noted that for the wrist a neutral sensation occurred at a zero temperature gradient (Choi and Loftness 2012). Given that at a neutral sensation there may be an inflection point which would imply that we have moved from the neutral sensation, but is in fact simply just a slight variation which will correct itself, it was proposed to use the square of the gradient to eliminate this effect (Choi and Loftness 2012). Given the small confidence interval about the mean of the square of the gradient(Choi and Loftness 2012), this allows for the possibility of a controller based upon this measure.

Opportunities for improvement and further investigation are numerous. The work of Yao et al. produced a finding that would not typically be considered significant (“P Values (Calculated Probability) and Hypothesis Testing” 2016). The work also is limited in that it considers only the recumbent position whereas it is desired to develop a system for everyday life. This thesis extends upon both that of Aftab and Kintner-Meyer by taking localised temperature sensing to its extreme and making it personalised temperature sensing. The work of Choi and Loftness is most influential on this thesis, which can be thought of as evaluating their findings as well as extending upon them to create a practical system.

The Airconditioner

The airconditioner being controlled is a Teco LK0776Y. It is a non-inverting single phase window mount with a rated power consumption of 672W. Its cooling capacity is 1.85kW. The modes of operation supported by the LK0776Y are Cool, Dry and Fan only. The Speed of the fan can be set to high, low or automatic, automatic adjusting “to achieve the optimum air flow for peak performance” (“Room Air Conditioner (vertical Type) Operating, Maintainence and Installation Instructions to Suit Models: LK0776Y (Wireless Remote Model)” 2009). Through 7 years of observation it has been found that the high fan speed setting results in the best performance, circulating the cool air throughout the room at an effective rate. Low fan speed is used to give the air a greater contact time with the cool fins of the airconditioner, resulting in greater dehumidification.

The Cool mode of operation of the airconditioner uses what appears to be bang-bang control to achieve the user entered temperature setting. While this mode may achieve the desired temperature at the temperature sensor located within the airconditioner, that does not necessarily reflect that comfort has been achieved within the room. On hot days the airconditioner appears to over compress, resulting in user intervention being needed to increase the temperature setting of the air conditioner. This indicates that an automated system would be able to both improve comfort and reduce energy usage.

Dry mode of operation is used for dehumidification and cycles the airconditioner on and off at a 50% duty cycle over 6 minutes. Fan mode simply does not use the compressor at all.

The remote control included is a simplistic model that issues commands to change the state stored within the airconditioner proper. Temperature is displayed upon a pair of 7 segment displays on the airconditioner body. A consequence of the state being internal to the airconditioner is that a device controlling the airconditioner has no idea what the current settings are, and that a missed transmission from the remote control is completely lost. This is in contrast to remotes with displays that store the state internal in the remote, such that the next successful transmission will synchronise the state known by the remote with that within the airconditioner by transmission of the entire state as the payload (Aftab, Chau, and Armstrong 2013). Fortunately as well, when issued on/off commands by the remote control the airconditioner remembers its state, while if turned off via the built in controls its state is set to a default.

The Room

The room to be cooled is a 295 by 426cm bedroom with doors leading to the main room and bathroom of the apartment. Double Brick construction is used adding to the thermal mass of the room. Adjoining a bathroom increases the humidity in the room, while the room's north facing window is shielded from the sun, being located on a balcony. Within the room heat sources apart from up to 2 occupants include a 32 inch CRT (Cathode Ray Tube) display, a desktop computer, a xbox console used as a set top box, and up to 2 netbooks. To ensure even distribution of heat a 40 cm oscillating pedestal fan is used and to ensure a somewhat even level of humidity a “Damp-Rid” deliquescent dehumidifier is present. The highest heat load in the room would be produced when watching a programme being encoded on demand, utilising the desktop computer, xbox console and CRT tv.

IR Transmissions

Consumer Infrared covers a broad range of protocols used to control such things as televisions, stereos and in this case airconditioners. While infrared light has its own frequency we want immunity from noise hence the IR light is modulated by being switched at a given carrier frequency(“SB-Projects - IR Index” 2016). The most common carrier frequencies are 36kHz, 38kHz and 40kHz, followed by 56kHz and then 30, 33 and 455kHz which are very rare (“USB IR Toy – Infrared Carrier Frequency Review - AnalysIR Blog” 2016). Data itself is transmitted by switching this carrier frequency on and off (“Data Formats for IR Remote Control” 2013). The absence of transmission is known as a space while transmission of the carrier is known as a space (“SB-Projects - IR Index” 2016). While there are a number of common protocols for how this data is encoded we will have to capture the IR codes in order to identify the given protocol. This affords us the opportunity to skip analysis of the captured code and simply play it back.

802.15.4 Wireless

802.15.4 is a wireless standard maintained by the IEEE for low data rate and low power use applications(Selavo 2015). It operates on either the 868MHz, 915MHz or 2.4GHz frequency range(Selavo 2015). 16 separate channels are supported upon the 2.4GHz frequency range with a throughput of 250kbps (Selavo 2015). The 802.15.4 standard only specifies the Physical and (MAC) Media Access Control layers of the 7 layer OSI model so additional software is needed for the transmission of data(Gutierrez 2006).

Atmel LWMesh Framework

Atmel Lightweight Mesh is a software framework that provides the additional 5 layers of the OSI model. Features include the sending and receiving of data, acknowledgements, routing, security, transceiver power management, encryption, energy consumption measurement and random number generation (“Atmel AVR2130: Lightweight Mesh Developer Guide” 2014). Conceptually the framework is separated into Physical, Network and System layers. The Physical layer is responsible for providing access to the transceiver hardware, providing application level access to the setting of network parameters such as channel and network level access for requesting data to be sent and specifying handlers for the reception of data (“Atmel AVR2130: Lightweight Mesh Developer Guide” 2014). The network layer provides the core functionality of the stack while the application layer provides both the user program and facilities such as software timers for the network layer (“Atmel AVR2130: Lightweight Mesh Developer Guide” 2014).

Zigbee

Zigbee is a completed mesh networking framework to be used for 802.15.4 communications. So ubiquitous that its name is sometimes used synonymously with 802.15.4. In the methodology and design section an argument is presented for the choice of Atmel LWMesh over Zigbee.

Atmel Studio

Atmel Studio is the IDE (Integrated Development Environment) provided by Atmel. All programs developed for this thesis will use Atmel Studio and their project files will require it to be opened.

GCC

GCC is the GNU compiler collection (formerly the GNU C Compiler), which provides compilers for C, C++, Objective-C, Fortran, Java, Ada and Go (“GCC, the GNU Compiler Collection - GNU Project - Free Software Foundation (FSF)” 2016). It is a free and open-source compiler for a number of architectures including x86, x86-64 and AVR. Of not is that GCC is not specifically designed for embedded applications unlike the non-free IAR embedded workbench (“IAR Embedded Workbench” 2016).

Methodology and Design

To Zigbee or not to Zigbee?

Radio technology was of course needed for this project. The nature of a sensor mounted to the body requiring a reliable transmission of data at regular intervals requires a non line of sight technology. The decision to be made was one of which wireless technology.

The particular radio technology was chosen solely on the basis of availability and power usage. Data rate was not a concern as the sensor would only be sending a floating point or pair of integers representing the temperature.

802.15.4 wireless technology was selected. While ISM (industrial, scientific and medical) radios provide superior energy savings, they're not widely available or standardised. Standard hardware is required as it enables the project to be completed in good time and as an individual. 802.15.4 wireless includes a number of competing technologies including the ubiquitous Zigbee and Atmel's proprietary LWMesh.

Both Zigbee and LWMesh are supported by the ATMega256RFR2. The decision to choose LWMesh over Zigbee was made due to the maximum time between of the Zigbee standard being specified at 90 seconds(“LWMesh Not Zigbee - Why” 2015). LWMesh has no such limitations. The majority of energy use from a wireless sensor will be from the data transmission, with microcontrollers being able to enter a number of energy saving states between transmissions (Aftab 2013). This ruled out the simpler microcontroller and programming framework of Arduino as the Arduino board and hence framework did not include energy saving features at the time of selection as evidenced by the offering of a thesis project by Dr. Gareth Lee to develop these features. Additionally, the LWMesh framework had a much smaller “footprint” in both memory requirements and lines of code, this is beneficial to development as it provides a smaller code base to be comprehended.

Microcontroller Selection

The initial selection criteria for microcontrollers were a small physical size, a built in temperature sensor, low transmission and reception current draw, low supply voltage and the availability of an evaluation board. Additionally, cost was added as a constraint as after initial searches provided a number of suitable microcontrollers some of them had expensive licenses for their integrated development environments (IDEs) and some required additional hardware to be programmed over and above their development boards, which first appeared to have embedded debuggers. Table 3 illustrates the initial selection process.

Table 3:Microcontrollers initially evaluated

Device	Max Tx/Rx current draw?	Built in Temperature Sensor	Voltage required	Evaluation Board? Debug Interface?	Other
CC2538 (TI)	24mA (“CC2538 | ZigBee (IEEE 802.15.4 / ZigBee PRO) | Wireless Connectivity | Description & Parametrics” 2015)	Yes (“CC2538 | ZigBee (IEEE 802.15.4 / ZigBee PRO) | Wireless Connectivity | Description & Parametrics” 2015)	2-3.6V (“CC2538 | ZigBee (IEEE 802.15.4 / ZigBee PRO) | Wireless Connectivity | Description & Parametrics” 2015)	Yes (“CC2538 | ZigBee (IEEE 802.15.4 / ZigBee PRO) | Wireless Connectivity | Description & Parametrics” 2015), Yes (“SmartRF06 Evaluation Board - SMARTRF06EBK - TI Tool Folder” 2015)	Familiarity has already been gained with the TI IDE
ATMEGA2564RFR2 (ATMEL)	18.6mA (max) (“ATmega 2564RFR2 Datasheet” 2014)	Yes (“ATmega 2564RFR2 Datasheet” 2014)	1.8-3.6V (“ATmega 2564RFR2 Datasheet” 2014)	Yes (“ATmega256RFR2 Xplained Pro Evaluation Kit” 2015), Yes (“ATmega256RFR2 Xplained Pro Evaluation Kit” 2015)	Disqualified as the evaluation board is only available next April
88MZ100 (Marvell)	26mA (“Marvell 88MZ100 Zigbee SoC Solution for Home Automation and More Product Overview” 2014)	Yes (“Marvell 88MZ100 Zigbee SoC Solution for Home Automation and More Product Overview” 2014)	2-3.6V (“Marvell 88MZ100 Zigbee SoC Solution for Home Automation and More Product Overview” 2014)	Yes (“Marvell 88MZ100 Zigbee SoC Solution for Home Automation and More Product Overview” 2014), unknown	Have to sign a NDA for more information
ST32W108C8 (ST)	31mA (“STM32W108C8 High_performance, IEEE 802.15.4 Wireless System-on-Chip with 64-Kbyte Flash Memory” 2015)	No (“STM32W108C8 High_performance, IEEE 802.15.4 Wireless System-on-Chip with 64-Kbyte Flash Memory” 2015)	2.1-3.6V (“STM32W108C8 High_performance, IEEE 802.15.4 Wireless System-on-Chip with 64-Kbyte Flash Memory” 2015)	Yes (“CD00262415.pdf” 2015), Yes (“CD00262415.pdf” 2015)	Chip marked as not recommended for new designs, only 802.15.4 library mentioned is RF4CE (“STM32W Series - STMicroelectronics” 2015)

The initial controller selected was the Texas Instruments CC2538. The CC2538 is a system on a chip (SoC) containing both microcontroller and 802.15.4 wireless hardware within the same package. Texas Instruments was also favoured having previously been used for development. Unfortunately what was billed as an evaluation board also required either a separate PCB for programming (“CC2538 Development Kit - CC2538DK - TI Tool Folder” 2015).

After discovering that the initial microcontroller selection was invalid more controllers were evaluated this time with an enhanced emphasis on completeness of their evaluation kits as well as cost. Two alternatives were considered the Anaren CC2530 booster pack and the Atmel Atmega256RFR2. The Anaren CC2530 booster pack is an add-on kit for the Stellaris Launchpad series of evaluation boards (“BoosterPack for ZigBee Standard Applications from Anaren” 2015). This would have been an economical option as a pair of Stellaris Launchpad boards were available, but this was abandoned as the physical size of two PCBs stacked upon each other would have been too large for an experimental setup.

The final microcontroller chosen was the ATMega2564RFR2. It fulfils the initial criteria for microcontroller selection as well as providing a free IDE and multiple wireless software stacks (“ATmega256RFR2” 2015).

IR Hardware

The IR transmission hardware is a simple common emitter BJT amplifier. It was assumed that the maximum carrier frequency of 40kHz would be too low to be effected by BJT saturation, which has been validated by successful IR data transmission. The collector current was selected as 300mA, being bounded by the board being able to be powered by USB which itself is limited to 500mA (“Powering Electronics from the USB Port” 2005). 300mA is above the rated current of the IR LED used but it is common practice for large intermittent currents of approximately 1A to be used to increase transmission range (“LIRC - Serial Port Transmitters” 2016). The supply voltage of the amplifier is 3.3V as well as the input voltage.

IR reception was achieved using a BRM-15S8-11 IR receiver module. This part was chosen for local availability and its wide supply tolerance requiring no voltage level shifting to be able to be used as it supports a voltage input between 2.7 and 5.5V (“Datasheet Device Number: BRM-15S8-11” 2008). This aids the design criteria of achieving minimum size and energy usage. The 38kHz centre frequency of the device puts it in the middle of the most common carrier frequencies of remotes (“USB IR Toy – Infrared Carrier Frequency Review - AnalysIR Blog” 2016). The attenuation for 36 and 40kHz was assumed to be small enough that transmissions would still be effectively received.

Program overview

Three programs are used within the regular operations of this project, along with numerous others developed as “unit tests” along the way.

IR Capture

IR capture is a simple program for the acquisition of the marks and spaces of a given IR transmission. It does so via the polling of the output pin of an appropriately selected IR demodulator such as the BRM-15S8-11 at 20us intervals. Each mark and space couplet is then saved into an array. The timeout for a missed transmission is set at 65ms. This was corrected from the Arduino program that this program is a port of, which mistaken due to the 20us delays present multiplying the maximum timeout by approximately 20 (assuming that loop time is dominated by the 20us delay with respect to the execution time of other instructions) (“Tutorials:learn:sensors:ir.html [AdaWiki]” 2016).

Terminal output is supplied over a USB virtual COM port provided by the embedded debugger. Code for this was developed based upon the datasheet of the ATMega2564RFR2 as well as the ATMega2564RFR2 Xplained Pro user guide, which in conjunction allowed for the identification of the UART which passes data through the embedded debugger.

LWMesh Sensor

The program for the wireless sensor was developed from the LWMesh developer guide and a tutorial by Bruce E. Hall entitled *Build a Dual – Temperature Maxim DS18B20 Thermometer.* Approximately every six minutes the program polls a DS18B20 digital temperature sensor. The 6 minute polling time was chosen based upon the time for the completion of one on/off compression cycle of the dehumidification programme on the airconditioner.

Figure 1 shows the initialisation of the timer function provided by the

LWMesh framework. AppTimer is a SYS_Timer_t structure defined by the framework whose mode can be SYS_TIMER_PERIODIC_MODE or SYS_TIMER_INTERVAL_MODE for repeating or one shot timers respectively. Experimental measurement found that while the timer interval is specified as milliseconds in the documentation that it does not work this way in reality.

```
static void startTimer(void)
{
    appTimer.interval = 90000; //in atmel funbucks time, 75000 is approximately 5 minutes, 2000 is roughly 8 seconds
    appTimer.mode = SYS_TIMER_PERIODIC_MODE;
    appTimer.handler = appTimerHandler;
    SYS_TimerStart(&appTimer);
}
```

Figure 1: LWMesh framework timer initialisation method

Figure 2 shows the method that is launched when the timer is executed. “appMsg” is an arbitrary structure chosen to bundle the data for transmission, as the data is transmitted as an array of 8 bit unsigned integers. Additional data can be transmitted by adding additional members to the structure as needed.

```
static void appTimerHandler(SYS_Timer_t *timer)
{
    therm_ReadTemp();
    appMsg.Temp.whole=temperature.whole;
    appMsg.Temp.decimal=temperature.decimal;
    send();
}
```

Figure 2: Function called upon timer expiration

```
typedef struct temp_t {
    int16_t whole;
    uint16_t decimal;
} temp_t;

static NWK_DataReq_t nwkDataReq;
volatile temp_t temperature;

typedef struct AppMessage_t { //from WSNDemo, simply add more members to this struct as appropriate
    temp_t Temp;
} AppMessage_t;

static AppMessage_t appMsg;
```

Figure 3: structure definition of appMsg

For the transmission of data a structure of the type NWK_DataReq_t must be created. This data structure specifies the destination address, destination and source endpoints (analogous to sockets in standard network programming), if security or an acknowledgement is required, a pointer to the message to be sent, the size of the message and a method to be called when confirmation is received from the recipient (“Atmel AVR2130: Lightweight Mesh Developer Guide” 2014). Destination and source endpoints are a number specified from 1 to 15 allowing the devices to perform multiple different transmission streams in a way that seems parallel to the user(“Atmel AVR2130: Lightweight Mesh Developer Guide” 2014). For transmission an unused source endpoint is required while for reception the destination endpoint specified must match that which the receiver is listening on. The method that actually sends the data requires the message to be sent to be an unsigned 8 bit integer (“Atmel AVR2130: Lightweight Mesh Developer Guide” 2014). This is achieved by casting our appMsg structure as the required unsigned value which can be seen in figure 4. A method to resend the data if no confirmation is received is not required as the chipset itself will issue 3 retries(“Retries in LwMesh | AVR Freaks” 2016). While no special programming is required for the implementation of retries, care must be ensured that only one NWKDataReq is called before a reply is received and processed (“Atmel AVR2130: Lightweight Mesh Developer Guide” 2014). This is achieved through a simple two state state-machine, defining the enumerated type known as appState, which blocks the issuing of additional data requests until the confirmation callback method has been executed.

```
static void sendFrame(void)
{
    nwkDataReq.dstAddr = 0;
    nwkDataReq.dstEndpoint = 1;
    nwkDataReq.srcEndpoint = 1;
    nwkDataReq.options = NWK_OPT_ACK_REQUEST | NWK_OPT_ENABLE_SECURITY;
    nwkDataReq.data = (uint8_t *)&appMsg;
    nwkDataReq.size = sizeof(appMsg);
    nwkDataReq.confirm = appDataConf;
    NWK_DataReq(&nwkDataReq);
}

void send(void) {
    if(appState==APP_STATE_SEND) {
        sendFrame();
        appState=APP_STATE_PENDING;
    }
}
```

Figure 4: The data sending method and state-machine interlock

LWMesh Receiver

The complete name of the final receiver program is “LWMesh Receiver with delays”. The name refers to the exact implementation of the IR modulation within the program.

Reception of data is achieved via the registration of an endpoint indication callback (“Atmel AVR2130: Lightweight Mesh Developer Guide” 2014). A method is defined that will be called upon the reception of data to the specific endpoint. The method called is one that casts the raw 8 bit unsigned integer data back into an AppMessage_t structure, allowing the data to be retrieved. It is highly important that the AppMessage_t type is maintained between or else garbage data will be returned, the LWMesh sensor network example includes the code for both the receiver and sender being only differentiated by their network address for this reason. This data is then evaluated against previously received data to determine if the specified 32ºC threshold has been crossed. If this crossing has occurred a flag is set which will enable an IR transmission during the next run of the program's main loop. Since the sensor only sends raw temperature data and the decision to turn on and off the airconditioner remains on the receiver side, if a transmission is missed and a temperature threshold is passed, the next transmission will send a value that either still passes the threshold or will indicate that the occupant has reduced in temperature by themselves.

The 32ºC set point was chosen based upon the temperature data gathered by Choi and Loftness. 31.6988ºC was given as the mean temperature of the neutral-warm sensation, so as an over estimation and simplification 32ºC was used (Choi and Loftness 2012). While not being used for comparison, the full 12 bit decimal resolution is transmitted to enable further development. Temperature data is transmitted as a separate whole and decimal number to ease the complexity of performing comparisons with floating point numbers.

```
static bool appDataInd(NWK_DataInd_t *ind) {

    PINB |= (1<<PINB4); //toggle light
    AppMessage_t *msg = (AppMessage_t *)ind->data; //cast raw data back to the struct is was originally

    int16_t currWhole = msg->Temp.whole;
    uint16_t currDecimal = msg->Temp.decimal;

    if((currWhole>=32) && (prevWhole<32))
        blastflag=true;

    if((currWhole<32) && (prevWhole>=32))
        blastflag=true;

    prevWhole=currWhole;
    prevDecimal=currDecimal;
    NWK_SetAckControl(NWK_SUCCESS_STATUS);
    return true;
}
```

Figure 5:The method called upon reception of a data packet

Infrared transmission is achieved through the appropriately timed enabling and disabling of a consumer IR frequency carrier wave. This carrier wave is generated by a hardware interrupt which toggles the state of a pin upon reaching a specified value. This carrier wave is then modulated by setting its toggle pin as either an input or an output. Equation 1 shows the formula used to determine the value to be set in register OCR1A to toggle the pin at the required rate ("Atmel AVR2130: Lightweight Mesh Developer Guide" 2014). In our case the frequency required is double that of the carrier frequency as each wavelength contains a low and high section.

$$OCR1A = \frac{F_{CPU}}{F_{required} * 2 * (CPU\ frequency\ prescaler)} - 1$$

Equation 1: Determining OCR1A for a required toggling frequency ("Atmel AVR2130: Lightweight Mesh Developer Guide" 2014)

The timings for modulating this carrier are stored within an array of on/off timing pairs. The program iterates through these pairs setting or resetting the toggled pin as output and then waiting the length of the timing specified. These waits are provided by a microsecond delay method. This loop contains a delay of 20us, reducing any possible overhead of calling this delay that could be incurred by calling a 1us delay repeatedly. 20us was chosen as that was the resolution that the timing data was captured at. Figure 6 below shows the section responsible for achieving this. Interrupts are disabled globally, lest the timings are corrupted and transmission is not achieved.

```
    sreg=SREG; //save interrupt flags
    cli(); //clear interrupts

    uint8_t ilength=sizeof(timings)/sizeof(timings[0]);

    for(i=0;i<ilength;i++) {
        for(j=0;j<2;j++) { //will always be two because marks and spaces are given in couplets
            if(j==0) {
                DDRB &= ~(1<<DDRB5);
                delayus(timings[i][j]);

            }
            if (j==1) {
                DDRB |= (1<<DDRB5);
                delayus(timings[i][j]);
            }
        }
    }

    DDRB &= ~(1<<DDRB5);
    SREG=sreg; //restore flags
    sei(); //set interrupts
}
```

Figure 6: Code snippet showing the algorithm responsible for IR modulation

Measurement Methodology

Measurements were taken from 4pm to 4pm the next day. This was to try to capture within one measurement period the main heat of the day. Taking a temperature reading from 12 pm to 12pm would result in significant components of the energy use being influenced by the peak temperatures of two separate days, stopping us from being able to perform a regression between peak temperature and the airconditioner's energy use. Temperature data was sourced from the Australian Bureau of Meteorology. Care was made to ensure that the closest weather observation data was used, Perth CBD, while the experiment was performed in South Perth.

To validate the results a regression between temperature and energy will be performed. As exterior temperature is not able to be controlled or predicted regression is used, to show the decoupling between peak temperature and energy that should be apparent with this system.

Problems Encountered

A number of implementation problems were encountered during this project. These problems can be broadly divided into two categories; problems due to incomplete knowledge and experience and problems that were unpredictable.

This section is provided to document the pitfalls encountered when programming with the Atmel LWMesh framework, to provide documentation that it is absent but required for the creation of your own programs based upon it.

The first major stumbling block was an optimisation problem with the GNU C compiler. Between regular execution and interrupt service routines (ISR) shared variables are cached, a register assigned for each, allowing for an improvement in execution speed (“Guidelines for Handling Volatile Variables | Embedded” 2016). During the initial development of an IR transmitter an ISR that set a flag to transmit a “mark” was used. This value being stored in a different register for the main execution thread and the ISR means that the value is never changed as far as the main execution thread is concerned. Unfortunately the GNU C compiler being predominantly used on desktops does not provide warnings or terminal output that this kind of optimisation has been used, even though having an ISR modify a variable is a common operation in embedded systems programming. This problem consumed a number of weeks until the “volatile” keyword was discovered through an Internet search (“Avr Gcc - Changing a Global Variable in C - Stack Overflow” 2016). The volatile keyword used before the declaration of a variable ensures that the variable will not be cached, preventing a variable from not being updated by an ISR (“Guidelines for Handling Volatile Variables | Embedded” 2016b). As the vast majority of documentation for GCC is based upon programming for desktop applications and this error provides compilable code this error was completely unanticipated.

Unfortunately, the successful development of a highly accurate interrupt based IR transmission scheme was not even used, as the LWMesh framework has reserved all ISR vectors, to be initialised by an incompletely documented method. The function prototype void tc_set_compa_interrupt_callback(volatile void *tc, tc_callback_t callback) is given but inadequate information is given on the possible values of tc and the form of the tc_callback_t type (“ASF Source Code Documentation” 2016). Given the time wasted on interrupt based IR transmission and the lack of documentation for integrating it within an LWMesh application the decision was made to implement a simple delay based IR transmission scheme under the assumption that it would be accurate enough for our purposes. The lack of documentation has hampered the majority of this project and is typified by the link for documentation within Atmel Studio returning a 404 error (“Atmel Software Framework Group_common_hw_timer_group” 2016).

Additionally, problems were encountered when trying to establish an initial wireless connection. While the example program “WSN_Demo” included the appropriate code to initialise the interrupts required by the wireless framework, templates for writing your own program that include the LWMesh stack do not. The changes required have been commented in the code.

Initial tests of the IR transmitter revealed an extremely short range necessitation the placement of the IR LED mere centimetres in front of the airconditioner's sensor. This is both impractical for mounting and interferes with reception of the airconditioner's regular remote. While the BRM-15S8-11 IR demodulator used to record the airconditioner remote's had a wide enough bandwidth for proper reception it appears that the centre frequency and bandwidth of the airconditioner's IR receiver are smaller, resulting in the reduced range due to greater attenuation. The next common IR carrier frequency down from the initial 38kHz, 36kHz was used, increasing the range of IR transmission to a couple of metres.

During initial testing of the fully integrated programs and hardware it became apparent that control was lost relatively quickly after turning on the microcontroller. It became apparent that only the first infrared transmission was being received correctly with all subsequent transmissions not being received. An observation of the IR emitter was made with the help of a mobile phone camera which enables infrared light to be seen with the eye. IR transmissions were able to be seen at the appropriate transmission times but were unable to actuate the airconditioner. After much experimentation it was found that within the delay based infrared code that after the first IR transmission the subsequent transmission were not being modulated with the 36kHz carrier. The version of the code use for the production of results disables interrupts around the code that generates marks and spaces, in an effort to increase timing accuracy. Of course on closer inspection this should stop the IR carrier interrupt but it does not, the IR carrier interrupt only ceases after the marks and spaces modulation has completed. The work around for this is to reinitialise the carrier after each IR transmission. This should be considered for revision in future works.

An unpredictable failure occurred with reading the DS18b20. During testing it was found that the sensor would read a value of -127ºC. Of course this indicates a condition of line high for an application expecting an 8-bit signed integer. The code was reviewed many times and no errors were found. It appears that there is a hardware/noise flaw with the DS18b20, this behaviour appears when the sensor is attached to a microcontroller running at “high” frequencies such as 12MHz(“DS18B20 – Cristian COPCEA” 2016) and the 16MHz the project was originally running at. By applying a clock divisor and running the microcontroller at 2MHz successful 1-wire communication was achieved.

Results and Analysis

The final form of the device is shown in Figure 7. Top is the battery pack for the sensor board, lower left is the sensor board with attached DS18b20 protoboard and lower right is the receiver board with attached IR blaster. Not pictured is the plug pack that provides power for the receiver board. Figure 8 shows the experiment set up and monitoring temperature. The bandages wrap both the sensor board and battery pack to the arm with another bandage laid underneath for comfort. The temperature sensor is attached beneath the wrist with a bandaid and is unobstructed by the bandages as when wrapped the protoboard proved uncomfortable.

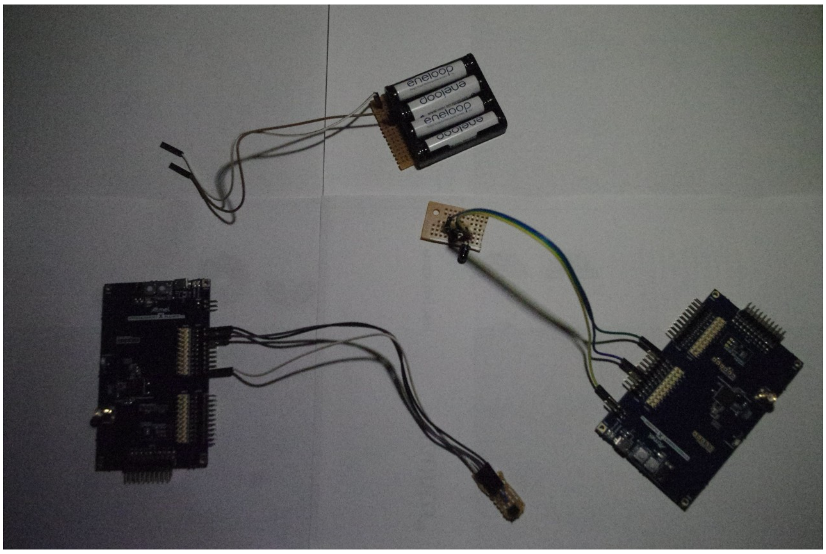

Figure 7: Hardware inventory

Figure 8:Test setup

The baseline airconditioner energy use versus temperature is given in Table 4 and Figure 9. Temperature data is provided by the Australian Bureau of Meteorology's Perth Metro weather station which is located 6.8km away from the experiment site. The temperature setting used was 23°C as that is the temperature required to ensure adequate dehumidification for comfort. The temperature measurements for the period ending the 28th had to be discarded as a breaker tripped wiping the averaged data.

Table 4: Predicted energy use vs. temperature with no controller

Date Ending Xth December 2015	Maximum External Temperature	Humidity at 9am	Predicted 30 day cost ($)	Predicted 30 day energy use (kWh)	Predicted daily energy use (kWh)
22	38.7	34	64.58	273.6440677966	9.1214689266
23	40.5	40	58.36	247.2881355932	8.2429378531
24	25.8	60	40.23	170.4661016949	5.6822033898
25	28	49	36.69	155.4661016949	5.1822033898
26	33.2	38	44.59	188.9406779661	6.2980225989
27	38.5	19	59.19	250.8050847458	8.3601694915
29	41.6	33	67.27	285.0423728814	9.5014124294

The predicted 30 day cost given in table 4 is the moving average value given out by the Belkin Conserve Insight. It is based upon a user input value of 0.236$/kWh. Predicted 30 day energy usage is derived from this figure by cancelling out the user input cost per kWh. Daily energy usage is simply the division of the predicted 30 day energy usage.

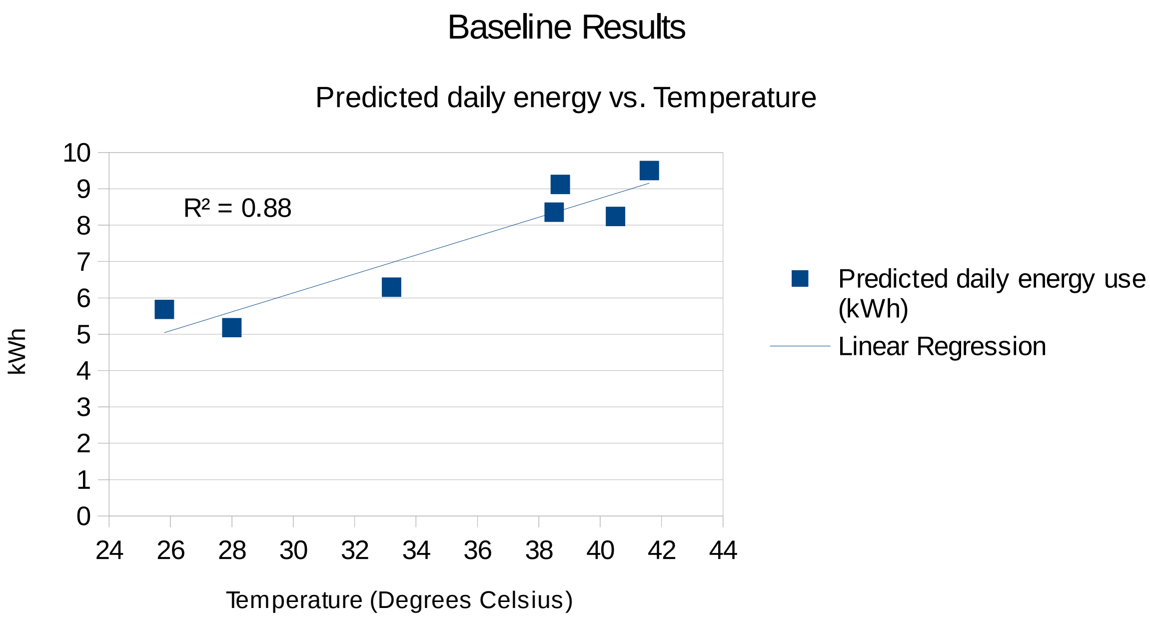

Figure 9: Predicted energy use vs. temperature with no controller

The baseline results are fairly unremarkable, with approximately 88 percent of the variability in the predicted daily energy use being caused by external temperature variation (“Regression Analysis: How Do I Interpret R-Squared and Assess the Goodness-of-Fit?” 2016). Of note is that the energy usage is highly coupled to temperature, with the 24th having a relative humidity of 60% but a low energy use according to its low temperature. This of course is due to the airconditioner only controlling for temperature. Again, the predicted cost for 30 days is the extrapolated value from the Belkin Conserve Insight based upon the moving average of power consumed since the device was plugged in.

Table 5:Predicted energy use vs. temperature with skin temperature controller

Date Ending	Maximum External Temperature	Humidity at 9am	Predicted 30 day cost ($)	Predicted 30 day energy use (kWh)	Predicted daily energy use (kWh)
25th Jan 2016	33.6	67	34.07	144.3644067797	4.8121468927
30th Jan 2016	27	39	78.64	333.2203389831	11.1073446328
3rd Feb 2016	31.5	50	24.68	104.5762711864	3.4858757062
4th Feb 2016	34.4	43	37.94	160.7627118644	5.3587570621
7th Feb 2016	40.4	45	59.73	253.093220339	8.436440678
8th Feb 2016	42.5	18	63.77	270.2118644068	9.0070621469
11th Feb 2016	33.7	63	64.82	274.6610169492	9.1553672316

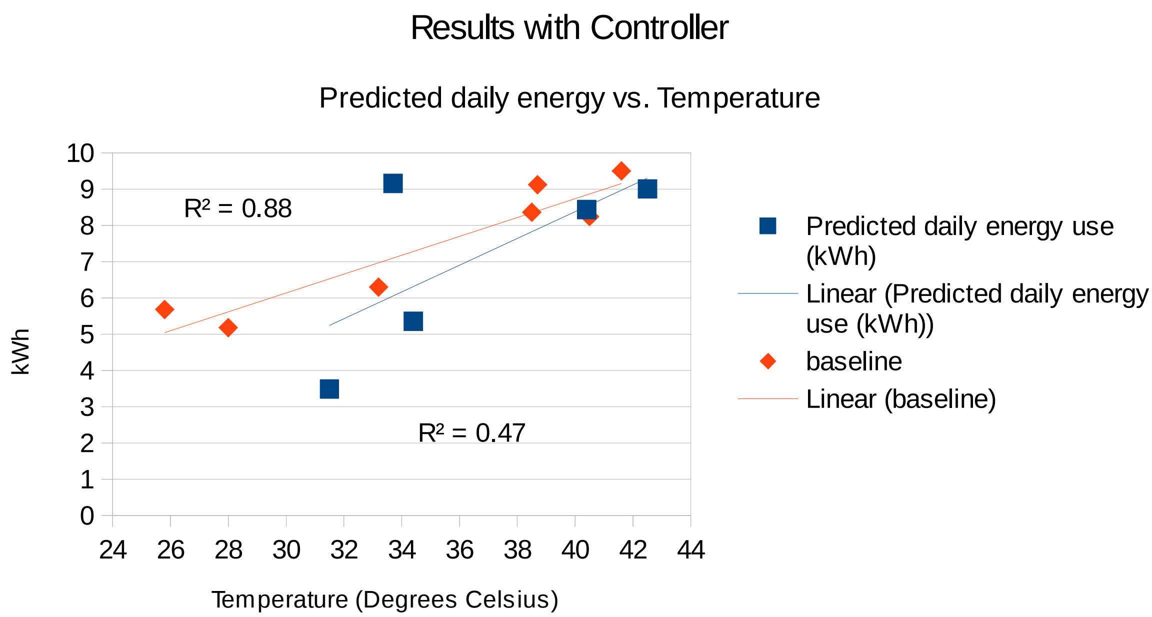

Figure 10: Predicted daily energy use vs. temperature with skin temperature controller

Table 5 shows the temperature and energy usage data temperature while compression was adjusted based upon occupant skin temperature. The highlighted lines within Table 5 indicate data that was compromised but was simply included for completeness. The measurements taken on the 25th are invalid due to only one successful IR transmission being completed due to the carrier wave re-initialisation error mentioned in the problems encountered section. On the 30th it was discovered that the initial 18ºC, high fan mode setting of the airconditioner would in fact use greater energy than utilising no controller at all. It is surmised that this is due to the inefficiency of turning the fan of the air-conditioner off when the compressor is desired to be off. This resulted in the cool radiator fins of the airconditioner drawing heat from its nearby surroundings, perhaps even from outside. All subsequent measurements relied on the air conditioner being set to dehumidify and a hi fan, producing a constant 50% duty cycle over six minutes, this necessitated a modification of the data sending code to have data sent at the same interval. These modifications made it so the maximum possible cooling could be extracted when the airconditioner is operating in dehumidify mode, as the compressor starts almost immediately from the off state, resulting in almost 3 minutes of fan only operation.

On the 8th of February it should be noted that the batteries of the device failed approximately two hours before the end of the measurement period. It is believed that due to the elevated temperature being noticed only minutes before the end of the testing period that the effects on the result will be negligible. Additionally, the cumulative average performed by the Belkin Conserve Insight would have resulted in only a small disturbance being observed due to changes at the end of the measurement cycle.

The most interesting result is that of the 11th, which is the reason data for humidity has been included. The low coefficient of determination is caused by this measurement which would appear to be an outlier. Since the airconditioner's state is now determined by wrist temperature the measurement makes sense when one considers that a high humidity would prevent the body being able to lose heat as efficiently. Looking at a comparable humidity level in the baseline data would seem indicate that the controller has somewhat decoupled the effects of external temperature on energy use and exchanged it for a coupling to humidity. Perhaps another interpretation is that energy use has been successfully coupled to human comfort, which is a product of temperature and humidity, indicating that the work of Choi and Loftness is indeed valid, that wrist temperature can be used as a measure of human comfort. This is of course anecdotal evidence.

Given that external temperature is unable to be controlled it is hard to make an estimation of any energy savings. A qualitative comparison between 23rd of January and the 7th of February says that an additional 0.194kWh of energy will be consumed. An explanation for this arises from the fact that the current controller algorithm results in over compression when the test subject is in a sleeping position under the covering of a sheet. Upon waking it was discovered that the room was uncomfortably cold yet given that the sensor module was still powered and only a few meters away from receiver unit it is unlikely that multiple transmissions were missed leading to the conclusion that the wrist in the sleeping position is kept hotter than during the sitting position. Given that a small amount of additional power is consumed even when the airconditioner is kept in compression throughout the night, a large potential saving in power could be realised if this behaviour is corrected.

Looking at the 26th of December and the 4th of February suggests an energy saving of 0.940kWh is possible. It is worth noting that this is even with the 4th having a 1.2ºC higher temperature and a 5% higher relative humidity. Again due to the simplistic algorithm currently implemented, we have additional energy consumed overnight. A similar saving is noticed on other temperatures below 35ºC.

Figure 10 shows us the predicted energy usage versus the external temperature with the controller present. Looking at the trend lines of the energy usage with and without the controller it can be seen that at lower temperatures there is a divergence in energy usage, with the controller saving energy. This agrees with user experience, in that at cooler temperatures the airconditioner compresses greater than is needed, typically the airconditioner would be turned off periodically to achieve comfort.

In terms of comfort the system was able to adequately cool all occupants. Of course as the compressor was only adjusted based upon one occupants temperature occasionally other occupants would become uncomfortably cool, this was rectified with a sheet. It is suggested that if the system was to be used with multiple people present that the temperature sensor be attached to the person who feels the warmest, as it is fairly easy to warm yourself by the addition of insulation. It should be noted that in any room with multiple occupants tradeoffs will be made in the thermal comfort between them, this is not a product of the number of temperature sensing nodes in the system.

Data for calculating the embodied energy of the device is notoriously hard to come by. Nothing has been found on the Atmel website describing the energy use or kg of CO_2 equivalent nor the websites of similar companies. Texas

Instruments provides a measure for the average energy used to produce all of its devices, which would include analogue ICs, at 0.2kWh/kg (“ProductStewardship.pdf” 2016). An independent web article investigated the energy required to create an ATMega8 and found that their mid range results agreed with the “small IC” figure given in the EU ecodesign directive evaluation methodology, coming in at 0.117kWh and 0.071kWh respectively (“What Is the Embodied Energy of a Microcontroller?” 2016). There would be a greater level of complexity in the ATMega2564RFR2 owing to its greater internal memory and integrated radio chipset, however given the magnitude of embodied energy consumed and the savings that can be achieved over a single day this kind of technology will surely be able to lead to energy savings.

Comparisons to other studies within the field are difficult since this project seems somewhat novel and is interdisciplinary in nature. As mentioned earlier the small number of samples taken would seem to confirm the assertion by Choi and Loftness that the wrist is reflective of a subject's thermal comfort.

Future Work

It is hoped that this thesis and its associated source code will help students undertaking similar projects as this one to achieve their research goals in an expedient manner. While the timeline for this thesis has expired work will be undertaken to implement a complete algorithm based upon the findings of Choi and Loftness. Of course more results are desired to be taken, perhaps in controlled conditions, to prove the efficacy of the design.

The code could be verified particularly the behaviour of hardware interrupts and the interrupt flag in the status register as mentioned in the problems encountered section. An expansion could be made to vote on the temperature of multiple occupants. It is important to note however that this is for the sake of completeness, this interrupt behaviour only affects the successful transmission of IR commands, timing of when to transmit is controlled by the Atmel software framework's built in timing method. The successful transmission of these commands is confirmed with comfort able to be achieved by the person wearing the sensor.

It may be noticed that gaps are present in the experimental data while the controller was being utilised. These gaps are due to the necessities of the subject and the long measurement period undertaken. The testing set up is also uncomfortable to wear. A PCB is desired to be designed that will both make the testing more comfortable and more accurate. Care was taken in the measurement of results as it was possible for the bandages attaching the sensor module to the arm to interfere with readings. Readings of controller effectiveness were only able to be taken over intervals of two days as the current PCB design has a power indication LED that draws somewhere in the order of 20mA constantly. This must be rectified before any addition of power saving code utilising the energy saving features of the microcontroller is written, otherwise such work will be for naught. Fortunately a reference PCB including the dimensions of the radio frequency traces is available from Atmel, making such a design easily possible by an undergraduate.

Conclusion

This thesis has presented a prototype for a system to adjust the duty cycle of an airconditioner based upon the wrist temperature of one of the occupants within the room. Through regression analysis it is shown that energy usage of the airconditioner has been decoupled from the external temperature and provides anecdotal support for the report of Choi and Loftness. This decoupling saves almost one kilowatt hour of energy per day at sub 35ºC temperatures by ensuring the compressor is only run when absolutely needed. However, the simplistic and flawed algorithm ultimately hampered both night time comfort and energy savings but an improved algorithm based upon existing work, which better tracks human comfort is hoped to improve upon this.

References

“4614.0.55.002 - Energy in Focus: Energy Efficiency of Australian Homes, Apr 2010.” 2010. April 30. http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/4614.0.55.002Main+Features5Apr+2010.

“About ASHRAE | Ashrae.org.” 2016. Accessed February 2. https://www.ashrae.org/about-ashrae.

Aftab, Muhammad. 2013. “Thesis_Muhammad_Aftab.pdf.” *Engineering Wireless Sensor Networks for Smart Air-Conditioning Control - Thesis_Muhammad_Aftab.pdf*. June 30. http://web.mit.edu/parmstr/Public/aaReprints/Theses/Thesis_Muhammad_Aftab.pdf.

Aftab, Muhammad, Sid Chi-Kin Chau, and Peter Armstrong. 2013. “Smart Air-Conditioning Control by Wireless Sensors: An Online Optimization Approach.” In *Proceedings of the Fourth International Conference on Future Energy Systems*, 225–36. E-Energy ’13. New York, NY, USA: ACM. doi:10.1145/2487166.2487192.

"ASF Source Code Documentation." 2016. Accessed April 4. http://asf.atmel.com/docs/latest/thirdparty.wireless.avr2130_lwmesh.apps.wsndemo.atmega128rfa1_rcb/html/tc__megarf_8c.html#a2ebef10c9b3cac6a59d5b77e044311c2.
"ATmega 2564RFR2 Datasheet." 2014. http://www.atmel.com/Images/Atmel-42073-MCU_Wireless-ATmega2564RFR2-ATmega1284RFR2-ATmega644RFR2_Summary_Datasheet.pdf.
"ATmega256RFR2." 2015. Accessed September 18. http://www.atmel.com/devices/atmega256rfr2.aspx?tab=tools.
"ATmega256RFR2 Xplained Pro Evaluation Kit." 2015. Accessed August 7. http://www.atmel.com/tools/ATMEGA256RFR2-XPRO.aspx.
"Atmel AVR2130: Lightweight Mesh Developer Guide." 2014. http://www.atmel.com/Images/Atmel-42028-Lightweight-Mesh-Developer-Guide_Application-Note_AVR2130.pdf.
"Atmel Software Framework Group_common_hw_timer_group." 2016. Accessed April 4. http://asf.atmel.com/docs/3.28.1/mega/html/group__common__hw__timer__group.html.
"Avr Gcc - Changing a Global Variable in C - Stack Overflow." 2016. Accessed April 3. https://stackoverflow.com/questions/9228436/changing-a-global-variable-in-c.
"BoosterPack for ZigBee Standard Applications from Anaren." 2015. Accessed September 17. https://www.anaren.com/air/tv/videos/cc2530-boosterpack-zigbee-standard-applications-intro.
"CC2538 Development Kit - CC2538DK - TI Tool Folder." 2015. Accessed September 17. http://www.ti.com/tool/cc2538dk.
"CC2538 | ZigBee (IEEE 802.15.4 / ZigBee PRO) | Wireless Connectivity | Description & Parametrics." 2015. http://www.ti.com/product/cc2538?DCMP=lprf-cc2538&HQS=cc2538-pr.
"CD00262415.pdf." 2015. Accessed August 8. http://www.st.com/web/en/resource/technical/document/user_manual/CD00262415.pdf.
Choi, Joon-Ho, and Vivian Loftness. 2012. "Investigation of Human Body Skin Temperatures as a Bio-Signal to Indicate Overall Thermal Sensations." *Building and Environment* 58 (December): 258–69. doi:10.1016/j.buildenv.2012.07.003.
"Conserve Insight Energy Use Monitor User Guide." 2016. Accessed February 11. http://www.belkin.com/conserve/user-guide/WEB_F7C005_10MS041_ConserveInsight.pdf.
"Data Formats for IR Remote Control." 2013. August 13. http://www.vishay.com/docs/80071/dataform.pdf.
"Datasheet Device Number: BRM-15S8-11." 2008. August 27. http://download.altronics.com.au/files/datasheets_Z1611A.pdf.
De Decker, Kris. 2015. "LOW-TECH MAGAZINE: Solar PV Power: Why Location Matters." April 26. http://www.lowtechmagazine.com/2015/04/how-sustainable-is-pv-solar-power.html.
"DS18B20 – Cristian COPCEA." 2016. Accessed April 5. http://blog.copcea.ro/tag/ds18b20/.
"DS18B20 Programmable Resolution 1-Wire Digital Thermometer." 2015. *DS18B20 Programmable Resolution 1-Wire Digital Thermometer*. January. https://datasheets.maximintegrated.com/en/ds/DS18B20.pdf.
Elert, Glenn. 2016. "Temperature of a Healthy Human (Body Temperature)." Accessed

June 20. http://hypertextbook.com/facts/LenaWong.shtml.
“GCC, the GNU Compiler Collection - GNU Project - Free Software Foundation (FSF).” 2016. Accessed April 7. https://gcc.gnu.org/.
“Guidelines for Handling Volatile Variables | Embedded.” 2016a. Accessed April 3. http://www.embedded.com/design/programming-languages-and-tools/4415475/1/Guidelines-for-handling-volatile-variables.
———. 2016b. Accessed April 3. http://www.embedded.com/design/programming-languages-and-tools/4415475/1/Guidelines-for-handling-volatile-variables.
Gutierrez, Jose. 2006. “IEEE Std. 802.15.4 Enabling Pervasive Wireless Sensor Networks.” http://www.cs.berkeley.edu/~prabal/teaching/cs294-11-f05/slides/day21.pdf.
“Honeywell Lyric Thermostat Installation Process.” 2015. Accessed August 7. http://lyric.honeywell.com/getting-started/.
“How Ambi Climate Works.” 2015. Accessed August 7. http://www.ambiclimate.com/pages/how-it-works.
“How to Correctly Interpret P Values.” 2016. Accessed February 9. http://blog.minitab.com/blog/adventures-in-statistics/how-to-correctly-interpret-p-values.
“IAR Embedded Workbench.” 2016. Accessed April 7. https://www.iar.com/iar-embedded-workbench/.
Kintner-Meyer, Michael. 2005. “Opportunities of Wireless Sensors and Controls for Building Operation.” *Energy Engineering* 102 (5): 27–48. doi:10.1080/01998590509509441.
Lian, Zhiwei, Weiwei Liu, Qi Shen, and Ye Yao. 2007. “Experimental Study on Skin Temperature and Thermal Comfort of the Human Body in a Recumbent Posture under Uniform Thermal Environments.” *Indoor and Built Environment* 16 (6): 505+.
“LIRC - Serial Port Transmitters.” 2016. Accessed February 4. http://www.lirc.org/transmitters.html.
“LWMesh Not Zigbee - Why.” 2015. Accessed September 20. http://www.rayzig.com/manual/LWMeshnotZigbeewhy.html.
“Marvell 88MZ100 Zigbee SoC Solution for Home Automation and More Product Overview.” 2014. http://www.marvell.com/wireless/88MZ100/assets/Marvell_88MZ100_SoC-03_product_brief.pdf.
“Meet the Nest Thermostat | Nest.” 2015. Accessed August 7. https://nest.com/thermostat/meet-nest-thermostat/.
“Middle Class Growth in Emerging Markets - China and India: Tomorrow’s Middle Classes - EY - Global.” 2016. Accessed June 21. https://webforms.ey.com/GL/en/Issues/Driving-growth/Middle-class-growth-in-emerging-markets---China-and-India-tomorrow-s-middle-classes.
Moore, Andrew. 2014. “Introduction to Life Cycle Assessment & Life Cycle Thinking.” Murdoch University.
“Powering Electronics from the USB Port.” 2005. http://www.ti.com/lit/an/slyt118/slyt118.pdf.
“Predicted Mean Vote Index (PMV).” 2015. Accessed September 18. http://www.engineeringtoolbox.com/predicted-mean-vote-index-PMV-d_1631.html.
“Prediction of Thermal Comfort.” 2016. Accessed February 7. http://personal.cityu.edu.hk/~bsapplec/newpage315.htm.

“ProductStewardship.pdf.” 2016. Accessed April 7. https://www.ti.com/corp/docs/company/flipbooks/citizenship/ProductStewardship.pdf.

“P Values (Calculated Probability) and Hypothesis Testing.” 2016. http://www.statsdirect.com/help/default.htm#basics/p_values.htm.

“Regression Analysis: How Do I Interpret R-Squared and Assess the Goodness-of-Fit?” 2016. Accessed February 9. http://blog.minitab.com/blog/adventures-in-statistics/regression-analysis-how-do-i-interpret-r-squared-and-assess-the-goodness-of-fit.

“Retries in LwMesh | AVR Freaks.” 2016. Accessed April 2. http://community.atmel.com/forum/retries-lwmesh.

Rhys, John. 2011. “Cumulative Carbon Emissions and Climate Change: Has the Economics of Climate Policies Lost Contact with the Physics?” *Microsoft Word - EV_57.doc - EV-571.pdf*. July. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2011/07/EV-571.pdf.

“Room Air Conditioner (vertical Type) Operating, Maintainence and Installation Instructions to Suit Models: LK0776Y (Wireless Remote Model).” 2009. Teco.

“SB-Projects - IR Index.” 2016. February 6. http://www.sbprojects.com/knowledge/ir/index.php.

Selavo, Leo. 2015. “Zigbee_Intro_v5.ppt.” Accessed September 20. http://www.cs.virginia.edu/cs651-wsn/lectures/Zigbee_Intro_v5.ppt.

Shier, Rosie. 2004. “Statistics: 1.1 Paired T-Tests.” http://www.statstutor.ac.uk/resources/uploaded/paired-t-test.pdf.

“SmartRF06 Evaluation Board - SMARTRF06EBK - TI Tool Folder.” 2015. Accessed August 7. http://www.ti.com/tool/smartrf06ebk.

“Smart WiFi Thermostats by Ecobee |.” 2015. Accessed August 7. https://www.ecobee.com/.

“STM32W108C8 High_performance, IEEE 802.15.4 Wireless System-on-Chip with 64-Kbyte Flash Memory.” 2015. Accessed August 8. http://www.st.com/web/en/resource/technical/document/datasheet/DM00024653.pdf.

“STM32W Series - STMicroelectronics.” 2015. Accessed August 8. http://www.st.com/web/en/catalog/mmc/FM141/SC1169/SS1581.

“Tutorials:learn:sensors:ir.html [AdaWiki].” 2016. Accessed February 10. http://www.ladyada.net/wiki/tutorials/learn/sensors/ir.html#reading_ir_commands.

“UNEP Life Cycle Assessment.” 2016. Accessed June 22. http://www.unep.org/resourceefficiency/Consumption/StandardsandLabels/MeasuringSustainability/LifeCycleAssessment/tabid/101348/Default.aspx.

“USB IR Toy – Infrared Carrier Frequency Review - AnalysIR Blog.” 2016. Accessed February 6. http://www.analysir.com/blog/2014/01/10/usb-ir-toy-infrared-modulation-frequency-review/.

“What Is the Embodied Energy of a Microcontroller?” 2016. Accessed April 7. http://openenergymonitor.blogspot.com.au/2015/07/what-is-embodied-energy-of.html.