Acute Node Failure Detection in Wireless Sensor Networks

Final Proposal
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Executive Summary

The Air Force Research Laboratory has proposed a project for solving an open-ended problem of developing a diagnostic to best determine the health of a wireless sensor network. The main objective of the project is to scientifically determine the best set of metrics that indicate that a node is about to malfunction, is malfunctioning, and has malfunctioned. In order to accomplish this objective a wireless sensor network must be configured to collect metrics about the environment being monitored as well as metrics about the sensor nodes themselves.

Contents

1. Introduction

Wireless sensor networks are commonly used to monitor important environmental information such as temperature or light level which may alert users of hazardous conditions for themselves or machinery. However, wireless sensors typically have very limited power and memory and as a result node failure or malfunction is common. A network of largely malfunctioning nodes can mislead users analyzing the data of the nodes and may lead to dire consequences. Thus, it is very important to monitor the health of the nodes in the network in order to ensure they are properly functioning. The number of properly functioning nodes has a direct impact on the health of the wireless sensor network.

This project consists configuring wireless sensor network and monitoring a few external parameters such as environmental metrics like light, temperature, and humidity as well as internal network parameters such as node current, voltage, received signal strength, RF transmission power and channel availability. After recording these metrics, the ones most vital to the network health must be determined. Determining the best metrics to monitor the health of a wireless sensor network is a problem of particular interest to the United States Air Force.

2. Background

The Air Force has used wireless sensor networks for many years, but has just recently been examining ways to better monitor the health of their networks. Their work on developing a health diagnostic for wireless sensor networks did not lead to a definitive solution which led them to create an open design project for senior capstone teams. They worked with multiple sensor networks of Sun SPOT and Crossbow sensor nodes organized in a mesh network topology as shown in Figure 1. In a mesh network topology each node must be able to collect and distribute its own data and serve as a relay for other nodes in order to propagate the data throughout the network. The main advantage of this topology includes its robustness to failing nodes, but a drawback is that the nodes consume large amounts of power in order to propagate data around the network. Once the network was implemented the Air Force needed to detect anomalies tracked by collecting metrics about the network. In order to detect anomalies identifying failing nodes, the Air Force used a number of algorithms including side-channel analysis and thresholding. Side-channel analysis consists of using information obtained from the status of the sensors themselves to correlate parameters and determine the interconnected metrics that contribute to sensor failure. Training-based and thresholding algorithms work by tracking sensor data over time to make projections based on past data and comparing those projections against incoming data. While the Air Force was not able to come to any major conclusions there has also been a lot of work done with sensor network health in industry and other branches of government.

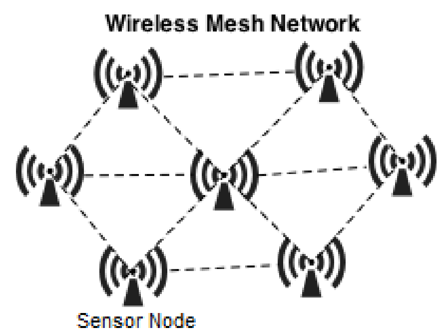

Figure 1 - Diagram of a wireless mesh network topology.

Upon further research, NASA's Ames Research Center also addressed the creation of intelligent wireless sensor networks.[1] "Intelligence is defined as the capability for supporting dynamic ad-hoc self-configuring real-time sensor networks able to adapt to faults while maintaining measurement accuracy and temporal integrity." They developed an ad-hoc sensor network that integrated additional sensors for specific health monitoring functions. They also created a custom software application that was able easily display node status as well as the environmental conditions being tracked. They periodically polled the sensor network for the data in order to dynamically display the data collected from network in real-time. The proposed design solution will utilize some of this background knowledge to aid in the rapid deployment of a wireless sensor network and development of new algorithms.

3. Design Specification

A. Mission Statement

The purpose of this design project is to research which metrics should be used to monitor the health of a sensor network. The end result will consist of a set of metrics that best indicate that a sensor node is about to malfunction, is malfunctioning, or has malfunctioned.

B. Design Criteria

To successfully accomplish the task of understanding how metrics of a sensor node react to failure of a sensor or complete node, a wireless sensor network must be configured and specific metrics must be monitored in correlation to failure. Criteria that must be satisfied include configuring a wireless sensor network that keeps track of metrics of the system. Along with this, according to the customer, these nodes must be low power, have a consistent and easily useable communication protocol, and be able to measure external and internal metrics reliably. For a design to be deemed feasible the network must also be easy to set-up, a graphical user interface must be created, and sensor data must be transmitted accurately.

<u>Must be satisfied</u>:

1) **Configuring the wireless sensor network:** To begin on the project, a wireless sensor network must be established. This includes sensor nodes that monitor external and internal measurements, a cluster head, and communication between the nodes over an established protocol. Also a network topology must be decided. This parameter of the project is absolutely necessary.

2) **Low power:** A node must be able last sufficiently long while deployed which includes tasks such as collecting accurate data and transmitting a high fidelity signal to the cluster head. In order to accomplish these tasks for a long period of time the node must be low powered. Sensor nodes with long lifetime will decrease collection errors and ultimately allow for greater accuracy in nodal failure detection. This parameter is very important.

3) **Communication protocol:** For the sensor nodes to communicate with the cluster head and the cluster head to the mainframe computer a communication protocol is needed. Additionally, one that is consistent, easy to use, and secure will allow for greatest accuracy in failure detection. Ease of use adds more to the feasibility of the design, but is also a parameter very important to the customer.

4) **Metric measurement system:** The sensor node must be able to communicate not only accurately, but with reliable data. This includes external metrics such as temperature, light, humidity, etc., but also internal metrics about the nodes, such as current, voltage drop, signal strength, etc. These metrics will monitor the environment the network is deployed in and also track relevant data about the health of each sensor itself. These metrics were are the crux of the project goal and are a crucial design parameter.

Increase desirability:

For a design to be deemed feasible, there were a number of additional features necessary.

1) **Ease of setup of network:** It is particularly desirable to choose a network design that is easy to setup and configure. A network that can scale up to handle more sensor nodes is another desirable feature. This will allow the customer to customize a network at any point during its lifetime. Having this ease of setting up and adjusting a network is an important part of the project and very desirable to the customer.

2) **Graphical user interface:** A visually appealing graphical user interface that displays the data obtained from the sensor network should be developed to allow an operator to quickly solve problems when they arise. A graphical user interface will make it easier to pin point what is going on in the network at all times. This will help when trying to identify failing nodes. This part of the project isn't necessarily required, since most data can be easily pulled off of the cluster head, however having a nice visual would significantly increase the desirability. A diagnostic is only as good as how it is displayed to the user and a graphical user interface is very important to an operator attempting to diagnose a problem with the network.

3) **Signal accuracy:** To assist in determining if a node or sensor is failing, the data that is retrieved by the cluster head and analyzed in the mainframe computer must be accurate. Signal accuracy is a combination of signal transmission power, received signal strength, and communication protocol. Every design considered had comparable signal accuracy that would be sufficient for communicating data of a wireless sensor network. Data fidelity is highly important in order to develop metrics that diagnose the health of the network.

4. FAST Diagram

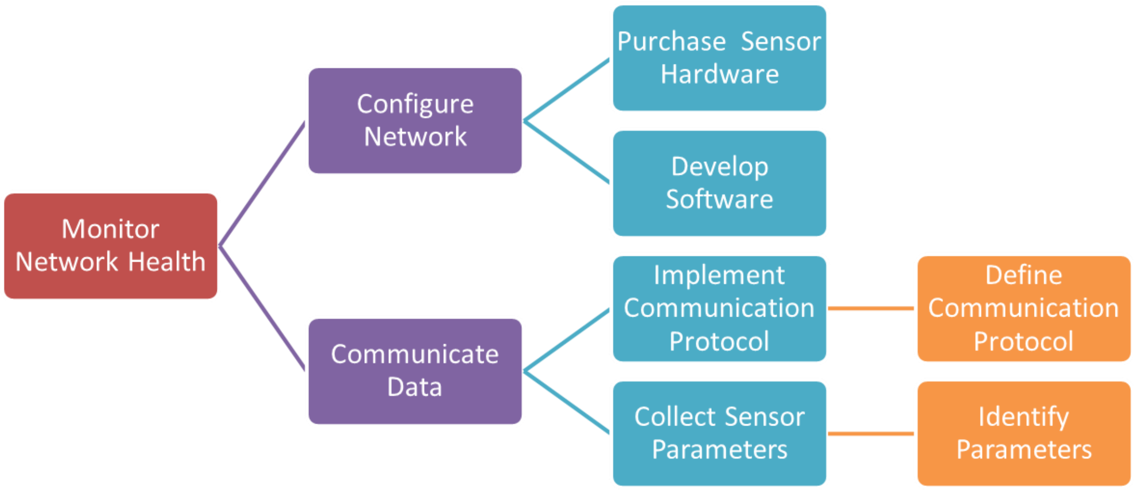

Figure 2 – A FAST diagram outlining the necessary steps to complete the project.

5. Conceptual Design Descriptions

The primary focus of this project is determining the metric(s) that best represents the networks health but in order to monitor the health of a network the network must be configured. A number of configuration options were considered for the design.

The first design under consideration was to build a sensor network from the ground up. This included a PCB design, attached sensors, and a system-on-chip with a built in ZigBee communication protocol. In addition to this, other components would be needed to measure current draw and voltage drop in the internal circuit at each individual node.

The next group of considerations was buying ZigBee communication network kit. This would require adding additional circuits for the sensors that are feed into the analog input/output port on each network node. Similarly, this group would need additional circuitry to determine internal metrics of the sensor node.

The last group of considerations was a full sensor development kit with an included ZigBee communication node and cluster head. These kits had built in sensors as well as analog input/output ports for additional sensor testing. In addition, the kits that were considered measured internal metrics already.

A. Feasibility Matrix

	Design and build sensor network	Communication kit with sensor configuration	Full sensor network development kit
Functionality	Highly dependent on quality of design in the given amount of time. Generally would not be as accurate because of the lack of time given and able to be put into the design. Lacked a cluster head design. Feasible (2/10)	Be effective in communicating easily between node and cluster head with simple analog signals. Still need a circuit design for internal metrics of sensor. Feasible (7/10)	Already measures internal and external metrics with easy programmable communication chip. All sensors are verified to factory specs, and internal node measurements are able to be tracked. Feasible (10/10)
Cost	With the necessary tools to program the System-On-Chip, the total cost was approximately: $100 for a node + $75 for a cluster head Feasible (9/10)	The communication kits would reduce what is needed circuit wise, however with a price of the cost of product. With this kit, only sensors are needed. Cost approximately: $300 for one development kit + $50 for all the sensors needed Feasible (8/10)	One of the full sensor development kits would fulfill all hardware requirements. Extra sensors for robust testing would be obtained. Cost is approximately: $1200 for development kit + $20 for extra sensors to test Feasible (6/10)
Time	Creating a complete, accurate sensor network would require a semester of work itself. Feasible (1/10)	Having this development kit would allow for less time setting up and more time determining the metrics that cause failure. Only extra time is configuring to send correct information from sensors. Feasible (9/10)	The full sensor kit would eliminate a lot of configuration time. Additional sensors could be added. Very easy to set up. Feasible (9/10)

As seen from the feasibility matrix shown above, using the full sensor development kit would provide with the most accuracy and functionality, with a good time frame of getting results. The decision was made to research more into this category mainly because of its completeness in the kits themselves, as well as the ease of use. The on board sensors for internal and external metric detection are very similar to what the Air Force is currently using, which can make are results more valuable to them. Similarly, the lack of needing to set up a network will allow for more time digging into the main focus of the project which is to determine the best metrics that can identify the health of the sensor network.

B. Selection Matrix

Ratings: Strong = 9 (◊) Moderate = 3 (○) Weak = 1 (□)	**Selection Matrix (Conceptual Design Rankings)**				
Product / Features	**Importance (1-5)**	**Sun SPOT (Rev8)[2]**	**Crossbow(MTS400)[3]**	**Powercast (P2210-Eval-01)[4]**	**National Instruments Wireless Sensor Network Starter Kit[5]**
Development Kit	4	Complete Wireless Sensor Network	Sensor Board	Complete Wireless Sensor Network	Complete Wireless Sensor Network
		Rating: ◊	Rating: □	Rating: ◊	Rating: ◊
Cost($)	2	400.00	395.00	1295.00	1999.00
		Rating: ◊	Rating: ◊	Rating: ○	Rating: □
Programming Language	4	JAVA	LabVIEW	C Programming	LabVIEW
		Rating: □	Rating: ○	Rating: ◊	Rating: □
Type of Sensors	2	Temperature, Light, Accelerometer	Temperature, Humidity, Barometric Pressure, Light, Acceleration and Optional GPS	Temperature, Humidity, Light and Voltage	Temperature and Voltage
		Rating: ○	Rating: ◊	Rating: ◊	Rating: □
Power	5	Battery	Battery	Wireless(RF to DC)	Battery
		Rating: ○	Rating: ○	Rating: ◊	Rating: ○
Totals		94	57	141	59

The table below displays the rankings of our conceptual designs based on the ratings from the selection matrix.

Design	Powercast (P2210-Eval-01)	Sun SPOT (Rev 8)	National Instruments WSN Starter Kit	Crossbow (MTS 400)
Ranking: 1 – Best 4 - Worst	1	2	3	4

6. Proposed Design Solution

A. Hardware Selection

The proposed design solution uses the Powercast Lifetime Power Energy Harvesting Development Kit (P2110-EVAL-01)[4] for the hardware of the wireless sensor network. The development kit is jointly developed by Powercast and Microchip. The kit consists of three main components; the transmitter, the sensor board and the radio access point. Figure 3 outlines network communication and power flow of a configured development kit. The transmitter broadcasts RF power (915MHz) to the sensor boards. The sensor board consists of a receiver and a collection of sensors. A block diagram of the sensor board is shown in Figure 4. The Powercast receiver converts RF energy into regulated DC power which powers the PIC microcontroller sensor board. The sensor information (temperature, humidity and light) is read by the XLP PIC MCU and converted into a packet. The packet is sent by Microchip's MRF 24J40 radio using an IEEE 802.15.4 communication protocol. The radio access point connected to the computer by USB then collects the packets and allows the data to be read by the user.

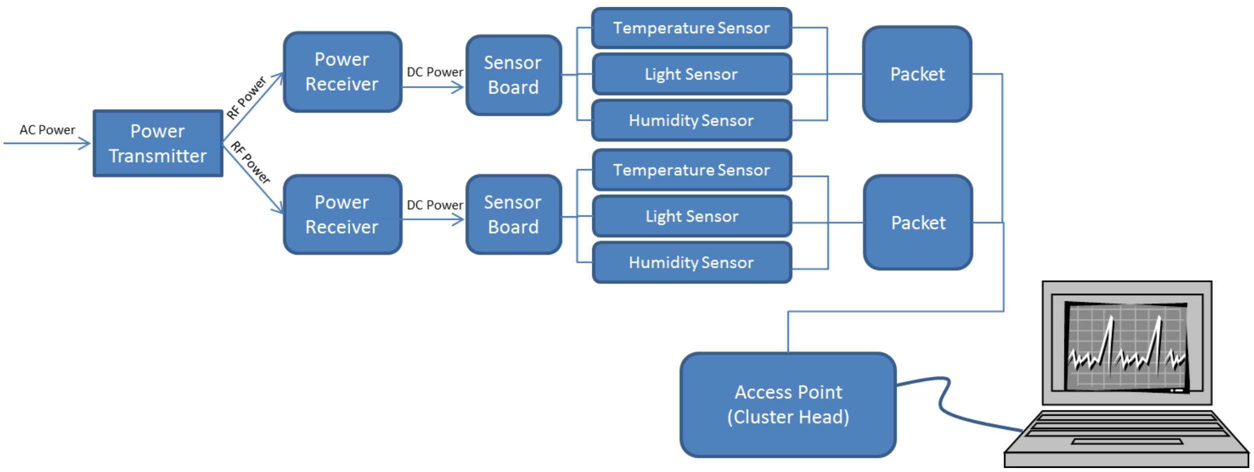

Figure 3 - Powercast P2110-EVAL-01 sensor network flow.

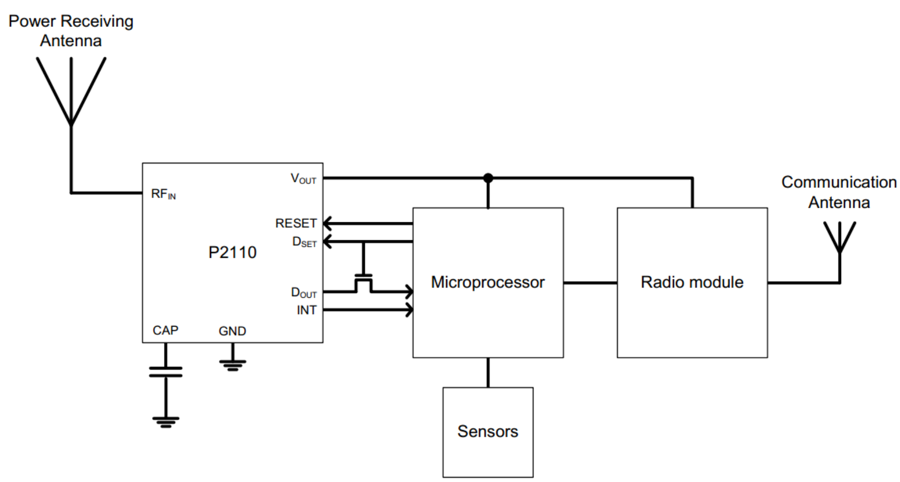

Figure 4 - A block diagram of the Powercast sensor boards

B. Design Methodology

I. Sensor Architecture

To make the sensors valuable, each sensor node must be tracking external conditions, but to make these sensors detect malfunctioning and signs of failure internal metrics must be measured as well. The proposed development kit makes this very simple, as it has three on board sensors detecting temperature, light, and humidity with easily adaptable analog input/output ports for additional sensors to detect external conditions. Accompanying this is a multitude of on board measurement systems for internal metrics such as voltage, current, and signal strength. The analog to digital converters that are attached the kit makes it simple to get the information to a digital signal and sent wirelessly to the cluster head. Additionally, these development kits are equipped with a USB interface to easily program the on board microcontroller to obtain and send the information desired.

II. Network Architecture

For simplicity of a semester long project, the chosen development kit comes with two nodes and a cluster head that will be used in a star topology. Star topology simply means that the nodes will only be communicating with the cluster head instead of communicating to each other as shown in Figure 5. This will ensure higher data accuracy and less collision within the data. The development kit is also already equipped with a ZigBee communication protocol interface, making it very simple to set up to communicate within the network. Another large benefactor of using ZigBee communication is its low power, which yields high importance when using wireless sensors. The final part of the network architecture is the mainframe computing device. This is mainly a computer hooked up either wired or wirelessly to the cluster head that will take in all of the digital data and calculate the results using the comparison algorithms and failure detecting sequences. Finally, this data will be displayed on a graphical user interface (GUI) which will allow ease of user interaction.

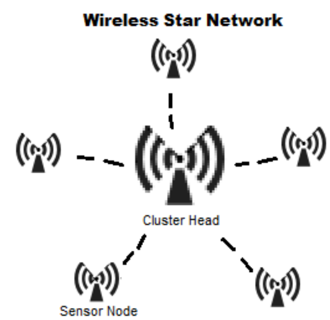

Figure 5 - Diagram of a wireless star network topology.

III. Technical Approach

In order to properly determine the health of the sensor nodes and the network, internal and external metrics must be accurately and consistently monitored. The chosen development kit tracks external metrics such as temperature, relative humidity, and light. This kit can also track signal strength, time differential between packets, sensor IDs, packets numbers, current, and voltage. All of the network stream data will allow for determining how the network itself is working in a sense of signals and communication. The other internal metrics could sense states such as high unexpected current draw or similarly low current draw, found from either open or short circuit as when a sensor has failed or broken. In order to scientifically determine the best set of metrics that indicate that a node is malfunctioning or about to malfunction, a set of algorithms will be tested which include, but are not limited to:

- Majority voting
    - A group of sensors will be sampled in the same sector at the same time and compared against its peers for irregularities.

- Training based and thresholding
  - A sensor node will be tracked over time and will learn the approximate threshold compared to previous days, time of day, its data compared to other sensors, etc., and from this set determine irregularities.

IV. Interactive Graphical User Interface (GUI)

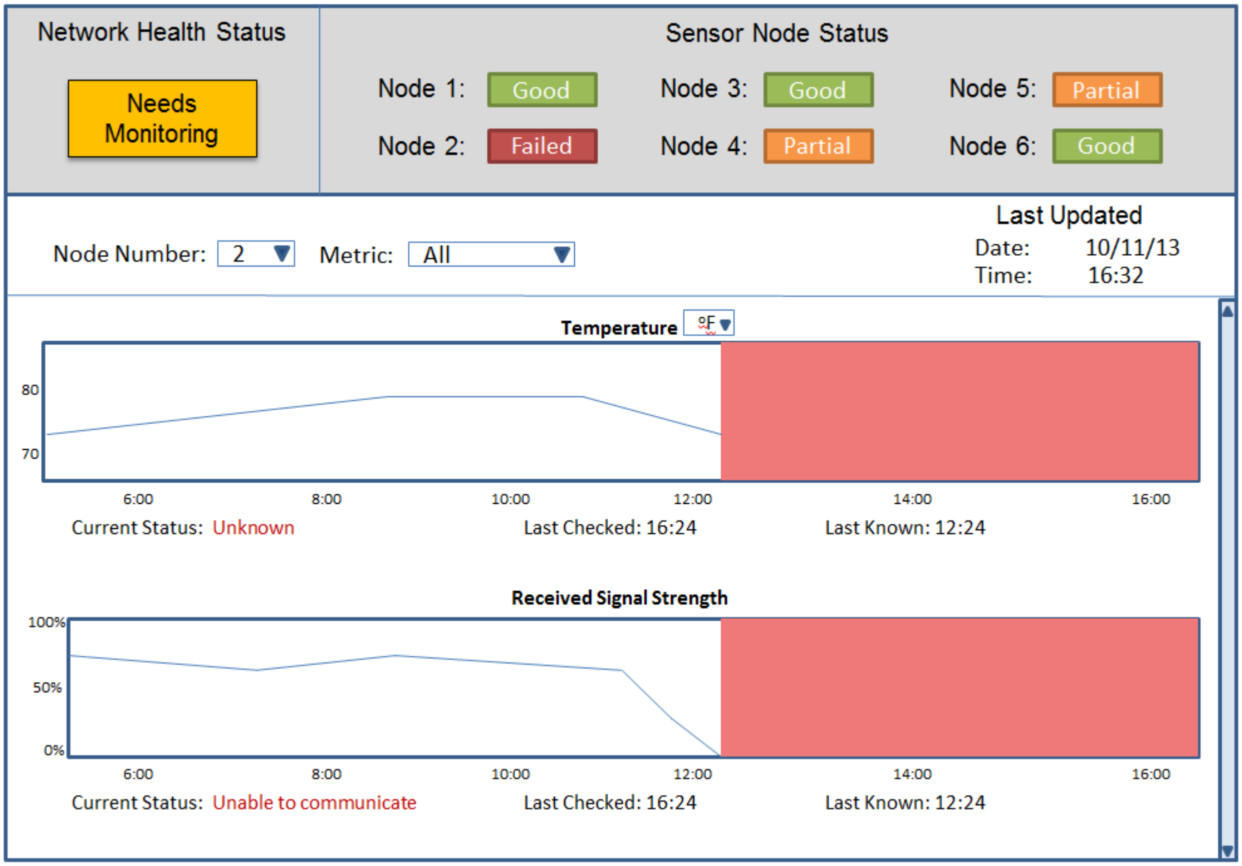

Figure 6 - A mockup of the graphical user interface (GUI).

C. Test Plan

Upon completion of setting up the network and achieving accurate data acquisition, testing must be done to determine when a failing node is present. Due to time constraints, running these sensors until they fail isn't a feasible solution to this problem since the lifetime of the sensors are very long. Therefore, failure must be systematically induced into the nodes. To implement this, instead of damaging the expensive sensor nodes bought in the development kit, additional sensors can be tampered with an attached to the nodes on an open port. This will require other sensors to be purchased and broken, then placed into the analog I/O ports then gather information based off of this.

There will be many factors associated with failures or misrepresented data, so a multitude of tests will be completed to ensure the greatest accuracy with metric to malfunctioning algorithms. These tests include, but are not limited to:

- Broken sensor testing
    - An example of a simply broken sensor is if some environmental factor causes a sensor to simply break, get cracked, smashed, etc., and cause a malfunction. To accomplish this task an external sensor will be broken then attached to an I/O port and gather data from this.
- Misrepresenting data
    - Misrepresentation of data could include a node in a family of sensors that is giving data not accurate to the rest, or majority voting. If this is the case the implemented algorithms should detect this accompanying other metrics to determine what is causing this, either an external factor causing its data to be different based on placement or actual failure. This is a testing of an algorithm, so multiple nodes will be placed in one area, then effect one node in ways such as putting more light on the sensor, and breathing on the device to cause higher temperature. The algorithms will then be tested to ensure that the data out of the norm is detected.
- Close to failure testing
    - While identifying when a sensor node has already failed is useful, the ability to detect when it is close to failure id even more useful. Thus, testing on sensors that are close to failing needs to be done. This is the most difficult testing since the time frame given does not allow for lifetime testing of some sensors. The plan is to research further into why a sensor would fail, and then cause this to happen to the sensor. For instance, if a thermocouple can reduce accuracy over time by separation in the two wires, separation can be induced to see metrics associated with this.

D. Evaluation Criteria

After doing testing a final set of metrics should be evaluated and gathered together to complete the algorithm sets that can detect certain failures within the network. To know that the design and correct metrics were determined the algorithms will have to pass the testing plan outlined above. Unfortunately because of timing constraints putting the design in real life situations over many years is out of the question, but getting the base metrics of the design is the scope of the project. If algorithms can detect the different types of failures such as a broken sensor, a sensor that is close to failure, or a sensor that is not giving accurate data because of some environmental factor without false alarms or missed failures then the design was successful.

7. Risk Analysis

With every design solution, there are concerns and challenges. Careful analysis of the purposed design solution brings about potential issues. The coding required for the network should not be an issue, but it could still bring about issue in translating current known programming languages into the code necessary to properly and effectively. Being able to systematically induce nodal failure within the network could be a challenge. Incorrectly receiving packet information within the network might be a potential issue. Without out gathering correct data, analysis on the metrics or parameters that determine nodal failure cannot be accurately obtained.

8. Project Management Plan

The schedule for the project is outlined in Appendix A. The table below lists the breakdown of tasks each team member is responsible for.

Personnel	**Non-Technical Task**	**Technical Task**
Stu Andrzejewski	Manager	Fault Determination and Systematic Failure of Nodes
Kelly Desmond	Document Prep	Sensor Network Configuration and Maintenance
David Rogers	Web Design	Graphical User Interface and Software Algorithm Development
Brad Garrod	Presentation Prep	Network Firmware Configuration and Software Algorithm Development

9. Budget

The total budget includes, but is not limited to:

Hardware/Components	**Price ($)**
Powercast P2110-EVAL-01 Development Kit [1]	1,250
Additional Sensors (Temperature, Light)	100
Additional Node	400
Engineering Shop Services Fees	250
Total	2,000

10. References

[1] Wireless Sensor Networks in Space, NASA Ames Research Center, March 2011
http://cenic2011.cenic.org/program/slides/cenic-2011-ZigBee-sensor-net_foster.pdf

[2] Sun SPOT (Rev8), Sun SPOT World, 2013,
http://www.sunspotworld.com/products/index.html

[3] Crossbow MTS 400, Crossbow Technology, 2007
http://www.eol.ucar.edu/isf/facilities/isa/internal/CrossBow/DataSheets/MTS400-420.pdf

[4] Powercast P2210-Eval-01 User Manual, Powercast, 2013
http://www.Powercastco.com/PDF/P2110-EVAL-01-manual.pdf

[5] Wireless Sensor Network (WSN) Starter Kit, National Instruments, 2013
http://sine.ni.com/nips/cds/print/p/lang/en/nid/206916

Appendix A – Design Team Schedule

Task Name	Duration	Start	Finish	Predecessors	Resource Names	Deadline
Project Overview & Tasks	**9 days**	**Wed 9/4/13**	**Mon 9/16/13**			**NA**
First Group Meeting, Project Assignment & Initial Tasks	1 day	Wed 9/4/13	Wed 9/4/13		Brad,Stu,David,Kelly	Wed 9/4/13
Meeting Times & Scheduling	1 day	Wed 9/4/13	Wed 9/4/13		Brad,Stu,David,Kelly	NA
First Meeting w/Group Facilitator	1 day	Tue 9/10/13	Tue 9/10/13		Brad,Stu,David,Kelly	NA
Air Force Research Laboratory (AFRL) Proposal	7 days	Thu 9/5/13	Fri 9/13/13	2	Brad,Stu,David,Kelly	Fri 9/13/13
Submit AFRL Proposal	1 day	Mon 9/16/13	Mon 9/16/13	5	Stu	Mon 9/16/13
GNATT Chart	2 days	Mon 9/16/13	Tue 9/17/13		Stu	NA
Pre-Proposal Due	5 days	Mon 9/16/13	Fri 9/20/13		Stu,David,Brad,Kelly	NA
Team Webpage Started	6 days	Mon 9/16/13	Sun 9/22/13		David	NA
First Contact w/Sponsor	1 day	Wed 10/2/13	Wed 10/2/13	6	Stu,David,Brad,Kelly	Wed 10/2/13
Proposal	15 days	Mon 9/23/13	Fri 10/11/13	8	Stu,David,Brad,Kelly	NA
Configure Sensor Network & Verify Correct Sensor Readings	**16 days**	**Fri 10/4/13**	**Fri 10/25/13**	**6**	**Stu,David,Brad,Kelly**	**NA**
Research & Order Sensors/SOC	2 days	Fri 10/4/13	Mon 10/7/13		Brad	Mon 10/7/13
Study & Configuration of IEEE 802.15.4 (MiWi P2P Protocol)	7 days	Thu 10/10/13	Fri 10/18/13		David,Stu,Brad,Kelly	Fri 10/18/13
Verification of Correct Sensor Readings	6 days	Sat 10/19/13	Fri 10/25/13		Kelly	Fri 10/25/13
Design Day - Team Page Work	10 days	Mon 9/23/13	Fri 10/4/13		David,Kelly	NA

Oral Proposal Presentation Practice	10 days	Mon 9/23/13	Fri 10/4/13		Brad,Stu,David,Kelly	NA
Team Progress Report 1	5 days	Mon 10/28/13	Fri 11/1/13		Brad,Stu,David,Kelly	NA
Design Issues Paper	24 days	Tue 9/17/13	Fri 10/18/13		Brad,Stu,David,Kelly	NA
Team Progress Report 2 & Project Demonstration	5 days	Mon 11/18/13	Fri 11/22/13	18	Brad,Stu,David,Kelly	NA
Identify Simple Network Health Metrics	11 days	Sat 10/26/13	Fri 11/8/13	15	Brad,Stu,David,Kelly	Fri 11/8/13
Develop Graphical User Interface (GUI) for Configuring Sensor Nodes	11 days	Sat 11/9/13	Fri 11/22/13	21	Stu,Brad,David,Kelly	Fri 11/22/13
Confirm Health Diagnostics & Implement Network Security Functionality (If Time Allows)	7 days	Sat 11/23/13	Sun 12/1/13	22	Stu,Brad,David,Kelly	Sun 12/1/13
Final Reports			Wed 12/4/13		Brad,Stu,David,Kelly	NA
Design Day	1 day	Fri 12/6/13	Fri 12/6/13	23	Stu,David,Brad,Kelly	Fri 12/6/13