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DIOMEDES: An integrated automotive diagnostics system that is customizable, low-cost, and non-intrusive built on a wireless sensor network

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by

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Abstract

DIOMEDES: An integrated automotive diagnostics system that is customizable, low-cost, and non-intrusive built on a wireless sensor network

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All persons who interact with a vehicle (*e.g.* drivers, mechanics) require a unique set of data about its operation; diagnostics data. Drivers, for example, need to know that their cars are healthy and that they are not currently breaking any traffic laws; mechanics, on the other hand, need to know the current operational state of numerous components in the car, as well as a history of the car's performance, in order to do their jobs. Although the automotive industry has fully embraced the need for the "mass customization" of their vehicles, this trend does not extend to diagnostics displays. This leaves an open niche for third-party solutions. Unfortunately, the third-party solutions tend to be targeted at specific subsets of the problem and do not work in all cases. Our solution employs a wireless sensor network which results in a system which is integrated, customizable, low-cost, and non-intrusive. Wireless sensing nodes are small and are located close to the signals they are measuring. A base station aggregates the readings from the sensing nodes and then logs and displays them.

We describe the design and implementation of the system and evaluate it, showing that ultimately it is a feasible solution for low-rate, non-critical automotive diagnostics.

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Chapter 1

Introduction

. . . tu cum olfacies, deos rogabis
totum ut te faciant, Fabulle, nasum.[1]

G. Valerius Catullus, *carmen tredecim*

All people who interact with a vehicle require custom indicators of the vehicle's performance; custom diagnostics data. Drivers need to see that the vehicle has sufficient fuel and that the engine is not overheating; whereas mechanics require detailed readouts of all operational parameters. Though the automotive industry has recognized the need for options and customization in other aspects of their vehicles, such as paint colors and wheel designs; customizable diagnostics displays are seldom offered. When an original equipment manufacturer does provide diagnostics read-outs, they are typically insufficient for general uses, and are always limited in scope. Temperature gauges only read engine coolant temperature, when other engine temperatures, for example, the air temperature at the throttle intake, would also be valuable.

[1] . . . when you smell it, Fabullus, you will beg the gods to make you all nose.

This leaves a niche to be filled by third-party developers. Unfortunately, though third-party solutions greatly increase the flexibility of automotive diagnostics systems, they typically fail to provide all desired aspects: integration, customizability, low cost, and non-intrusiveness.

The system must be integrated into the car to such a degree that it can operate effectively whether the car is stationary or moving. Clearly, the goal is not to have the driver actively interacting with the system, but rather to allow data collection and display at all times. For troubleshooting, some conditions may only occur when the car is operating.

The system must be customizable in order to support the full range of expected, and unexpected uses. It must be able to collect and display data from any of the car's on-board sensors and it must additionally be capable of introducing additional sensors to measure previously unplanned parameters.

The system must be low-cost so that it is feasible to collect a large number of parameters from the operating vehicle while maintaining affordability. This system must support the needs of all users, from the home user interested in a little more feedback from his or her vehicle, to the well-established auto mechanic. While the mechanic may be able to afford another piece of expensive diagnostics equipment, the home user would likely not be able to.

Finally, the system must be non-intrusive. The system must not affect the operation of the car to which it is attached, and after it has been removed it must leave minimal evidence of its presence.

Taking these requirements into account, the question then becomes:

> *Can integrated diagnostics systems be built that are customizable, low-cost, and non-intrusive?*

We provide a solution to the problem, and probe the answer to this question, using the nodes of a wireless sensor network to read and relate diagnostics data to a central base station. The base station, either a notebook computer for a temporary system, or an integrated carputer for a more permanent solution, logs and displays the data in a coherent manner. By removing the wires which characterize traditional automotive diagnostics systems, we enable the system to be much more integrated, customizable, and non-intrusive. By utilizing sensor network nodes, which are projected to be inexpensive and ubiquitous in the future, we make the system low-cost.

After detailing the solution and giving its justification in relation to alternate approaches, we enumerate a series of requirements which an implementation must meet. Then we present the design and implementation of our prototype solution, which uses Crossbow Mica2 motes as the remote sensor nodes for the system and an Apple notebook computer as the base station. The Mica2 motes

are fitted with Crossbow MDA100CB prototyping boards, which include temperature and light sensors and provide a space to construct a signal conditioning circuit. The motes run a custom application built on top of TinyOS which handles the timing of all data acquisition and networking operations. The notebook computer has another Mica2 mote attached to it via RS-232 serial, which acts as a packet forwarder. It also runs a Java application which provides graphical displays of the data, as well as data logging capabilities.

The prototype is built and exercised in a real-world scenario. The data logs are reduced to statistics which are then evaluated. We also analyze the qualitative aspects of the system. Finally, we discuss which aspects of the system meet specifications, such as its integration and non-intrusiveness, and give ideas for how to improve other aspects, such as the overall packet reception rate and the customizability. We also review a body of related work, including other commercial diagnostics systems, wireless networking in cars, and general work on sensor networks.

The rest of this thesis is structured as follows. Chapter 2 states the problem being solved and gives some background on existing commercial solutions. Chapter 3 presents a solution to the problem, its justification, the challenges inherent in solving the problem, and then the requirements for any implementation of the solution to meet. Chapter 4 describes the design and implementation

of the prototype used to show the feasibility of this solution. Chapter 5 gives an evaluation of the prototype with respect to the problem. Chapter 6 reviews a body of related work. Finally, conclusions and potential elaboration are covered in Chapter 7.

Chapter 2

The State of the Art

2.1 Background

All people who interact with vehicles need feedback from the vehicles about how they are performing. Car owners lean towards increasingly elaborate displays of their vehicles' operational parameters (*e.g.* any *ad-hoc* survey of Toyota Prius owners will reveal how much their cars' advanced dashboard readouts influenced their purchase); car tuners need data on the parameters that they are tuning, during tuning operations in the shop and later during road testing; mechanics need to be able to measure a host of operational parameters for a car in the shop, and could benefit from historical 'debug' information about the state of the car when a problem occurred. All of these people have different needs for this feedback, or *diagnostics*, data.

The automobile industry is well aware of the need to cater to the diverse needs of its customers. Embracing the notion of mass customization[27, 37], companies offer hundreds of options in each of their models. Some manufacturers, notably MINI[22] and Scion[32], center their marketing campaigns on the customizability of their cars; they make statements that "over 10,000,000 possible configurations"[22] are available, or that no two cars are exactly alike. Everything can be customized, from engine sizes and transmissions to interior trim and wheel colors.

2.2 The Problem

Despite the displayed need for customized vehicle diagnostics displays, and the auto industry's espousal of mass customization in nearly every other facet of its production, the development of factory customization of diagnostics data is not keeping pace. It is left up to the third-party automotive test and modification industries to fill this need. For a third-party solution to completely fill the needs of all interested parties, it must achieve several high-level requirements: integration, customizability, low cost, and non-intrusiveness.

It must be integrated, offering diagnostics data as easily on the road as it does in the garage, with minimal modification. This is a requirement which is

not often seen in general-purpose diagnostics systems because most systems are built specifically for installation on static vehicles. For a system to be truly integrated it must require that its wiring be routed carefully around the vehicle or it must be wireless.

It must be customizable, allowing the collection of data from a variety of existing data sources on-board, as well as permitting the addition of data sources not previously envisioned by the original equipment manufacturer. Thus, it should be able to read the voltage from a temperature sensor already built into the engine of a vehicle, but it should also be able to read temperature in a region of the car which does not already have a temperature sensor in it. Typically systems either allow connection to existing signals or measurement of conditions (*e.g.* temperature) at arbitrary locations; to do both will require a more general measurement platform than is currently available. It should also be able to work on a variety of vehicle models and model years.

It must be low-cost, making it appropriate for home users as well as skilled mechanics. This requirement may seem at odds with the others, but it is essential that the system provide some utility to home users if it is to be truly general in scope.

Perhaps most importantly, it must be non-intrusive. The system should be capable of being attached to a vehicle, of taking data, and then of being removed

from the vehicle. During data collection the operation of the vehicle should not be negatively impacted, and afterwards there should be minimal evidence that the diagnostics system was ever installed. This is easy to achieve with a system which does not directly interface with the vehicle, but it becomes more difficult once electrical connections are made. This also implies that the system's components are small enough to fit in spaces existing in the vehicle, allowing all panels and doors to be left unmodified and safely closed during operation.

The range of existing diagnostics solutions is discussed in Section 6.2. Chapter 3 discusses our solution to this problem.

Chapter 3

A Solution

3.1 Architecture

3.1.1 Overview

The basic notion of this solution is to build an automotive diagnostics system utilizing a collection of wireless sensor nodes collecting data from the car. The sensor network is arranged in a static star topology surrounding a central base station which aggregates the data. The base station also provides display and logging functionality.

Figure 3.1 shows the architecture. The diagram illustrates a couple of important aspects of the system. First, the wireless sensing nodes are scattered around the car as close as possible to the signals which they are measuring, resulting in no wires more than a few inches long. Also, the base station is shown outside of the car to emphasize the flexibility of the architecture. Depending

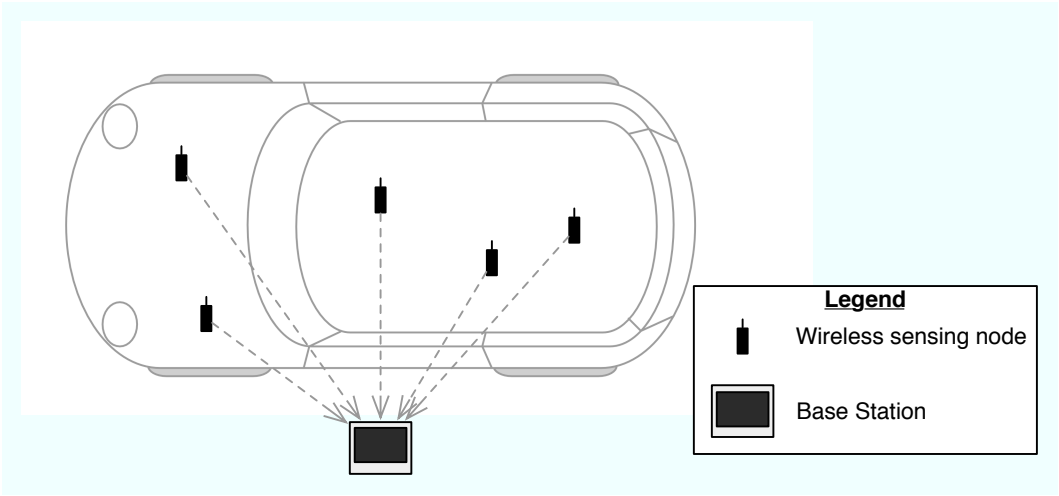


Figure 3.1: Solution Architecture

upon the need for the system, the base station could be a built-in *carputer* (*i.e.* a computer built into an automobile) for a permanent installation, or it could be a ruggedized laptop for a more temporary diagnostics system.

3.1.2 Justification

When approaching the architecture for a diagnostics system, an initial question is how to collect readings from disparate signals into a central place. Traditionally, this was done with long cables all connected to a central computing device. Wires either had to be routed through barriers, limiting the non-intrusiveness of the system, or routed externally to the car, limiting the system's integration. Making the system wireless adds significant flexibility.

Once wireless has been chosen as the medium of communication, we must examine the available protocols. Two prime choices are Bluetooth or low-power radio protocols such as ZigBee. Low power radios have numerous advantages over Bluetooth for large, customizable deployments. ZigBee networks can contain more nodes, they are typically more resilient and reliable, and consume much less power[3, 40]. Automotive applications of these protocols have been suggested[24], even as a complete data cable replacement[8], but only in a speculative fashion, and with a fair amount of trepidation with respect to using them in safety-critical instances. The nodes are also projected to be inexpensive and tools exist to make them easier to program, and less platform-specific, than if they were programmed directly in C or assembly.

The system can be expected to receive sufficient battery life for any reasonable temporary application, and more permanent applications could make use of the on-board, switched 12V available in a car. Also, the 'indoor' interference characteristics of Zigbee[9, 13], and other sensor network-specific low power radio standards, make it an excellent choice for the cluttered and potentially electromagnetically-noisy environment around a car's engine.

The system also aims to be non-intrusive, meaning that for a temporary application, it must be possible to clamp it onto a car, take measurements, remove the system, and have little in the way of evidence that it had ever been

present; the car should continue to perform as if the system is not, and has never been, attached. Sensor nodes are small and light and fulfill this aim well. Also, since they are wireless there is no need to carefully route wires between areas of the car. Ultimately, it is the wires, characteristic to most automotive diagnostics systems, that limit the non-intrusiveness of these systems.

We discuss related research in Section 6.3.

3.2 Challenges

Although inter-vehicular networking has been studied[12, 31], and intra-vehicular networking has been examined using Bluetooth[24, 10, 28, 17], there has been little empirical work with ZigBee and other low-power wireless radios in automotive applications. Because of this, there are expected to be several challenges to evaluate and overcome.

For one, the environment in a car is electromagnetically noisy, due in part to the presence of high voltage, high frequency signals (such as those running through the plug wires). Moreover, line-of-sight between wireless sensor nodes in a typical application is often broken by large sheets of steel. More than in other applications of low-power radios, it is expected that this application will experience significant interference and, consequently, packet loss. Thus, reliabil-

ity mechanisms will need to be employed to reach acceptable packet reception rate.

The environment is also inhospitable in other ways. Both vibration and high temperatures could cause problems for the system. Luckily, there is a history of sensor network solutions in far more extreme environments[20, 36], often achieved by insulating the sensor nodes, either physically, from vibrations, or thermally, from high temperatures.

Another source of challenge, common to any networking system, is coordination of network traffic. With a large number of wireless sensor nodes asynchronously transmitting samples to the base station, likely at different frequencies of transmission, the base station must be able to attribute the samples to the proper data source on the proper sensor node, order them relative to other messages sent from the same node, and determine which, if any, of the samples were corrupted. This will require an additional application-level protocol on top of any existing network-level protocols.

Finally, sensor node hardware is not well-suited to automotive signals. Signal voltage ranges are potentially wide and varied, voltage spikes can potentially damage analog to digital converters, and there can be significant noise. To handle all of these issues, the sensor nodes will require some signal conditioning in front of the analog to digital converter.

3.3 Requirements

At the high level, the solution must meet the requirements from Section 2.2; it must be integrated, customizable, low-cost, and non-intrusive. Beyond these high level requirements, however, lie the requirements on this particular solution in order to make it a viable system. These requirements can be divided by the component to which they pertain; they are either requirements for the wireless sensing nodes or for the base station.

The wireless sensing nodes need to collect data samples and forward them to the base station. The nodes should have a sensor package which allows them to measure environmental parameters without the support of existing sensors. They must also be able to clip onto existing wires in the vehicle, reading the voltage present without damaging themselves or the car. In order to be non-intrusive, they must also be small and light, and ought to be battery-powered with a reasonable battery life. Finally, they must be capable of completing all of their tasks while inside a vehicle.

The base station needs to receive samples from all of the wireless sensing nodes in the car, and then either display those samples in real-time or log them to secondary storage for post-processing. In the case where samples are being displayed, the base station would need a display device and a visual represen-

tation of each of the data sources, either as simple digital display or some more complex graphical representation. In the case where samples are being logged, the base station would require an interface to configure a logging session, and then a means to extract the completed log data.

Chapter 4 discusses a prototype implementation of this solution, then Chapter 5 evaluates the prototype against these requirements.

Chapter 4

A Prototype

4.1 Introduction

This chapter describes the prototype which we built to determine the feasibility of the solution. The prototype system is called DIOMEDES, which stands for: Diagnostics Implemented On Motes Expressly Designed for Engine Sensing[1]. It is built using Crossbow Mica2 *motes* for the sensor nodes, which are comprised of an Atmel ATMega128L microcontroller (with built-in 10bit analog to digital converter) and a Chipcon CC1000 900MHz low-power radio. Another Crossbow Mica2 mote is used as wireless interface for the base station, and an Apple notebook computer is the user interface to the system, connected to the base station mote with RS-232 serial. The architecture for the prototype is shown in Figure 4.1.

[1] Also a Greek hero from Homer's *Iliad*.

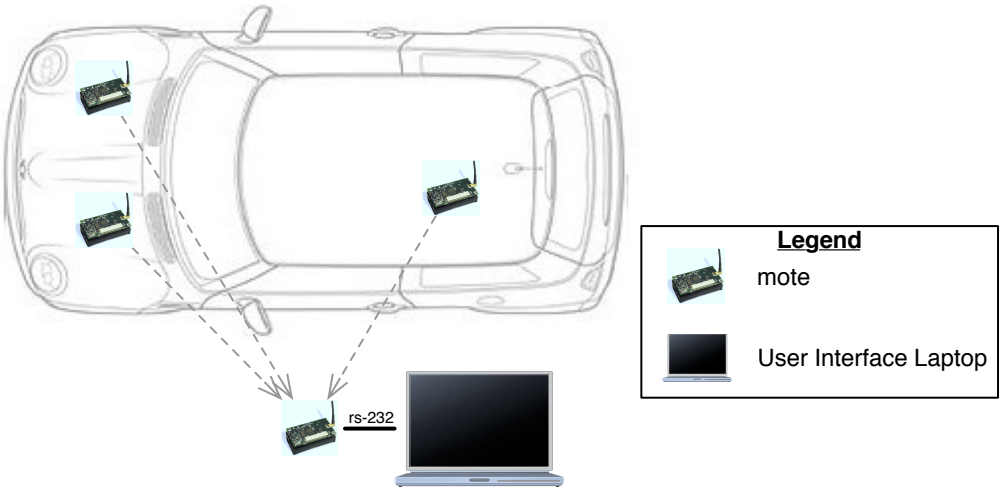


Figure 4.1: Prototype Architecture, DIOMEDES (Image of car courtesy of MINI USA[22]; image of motes courtesy of Crossbow[7])

The Mica2 motes were a good choice for wireless sensor nodes for a number of reasons. First, we had a number of them from previous experiments, so finding three sensors and a base station mote was not a problem. They also have sufficient on-board memory and processing capability to collect samples and transmit them via their built-in radios in a light, compact package. Also, Crossbow makes a prototyping board (MDA100) that connects to the Mica2's expansion port. This made it easy to experiment with our analog signal conditioning. The motes are battery-powered, as well, making them better suited for a testing environment.

The Mica2 motes were not without their downsides. The Mica2 uses a 900MHz radio, instead of the aforementioned 2.4GHz ZigBee radios. In this sense we sacrifice some accuracy in our prototype. With ZigBee's additional protocol features and its wideband radio, it is expected that replacing our prototypes with ones using ZigBee radios would have yielded better results in terms of reception rate, but slightly worse results in terms of range[29].

The software for the prototype system consists of three main components: software running on the sensor modes, software running on the base station mote, and software running on the user interface laptop. All of the sensor node software is written on top of TinyOS[11], a lightweight, event-driven operating system specifically designed for use with sensor networks. Components are written in a domain-specific version of the C programming language called NesC and compiled with TinyOS to create the device images. The base station software is the BaseStation module provided with TinyOS, while two components on the sensor nodes were written custom. There is a Java language package to interface between the network and the graphical user interface, which is also written in Java.

The rest of this chapter deals with the design, and then the implementation, of the DIOMEDES prototype.

4.2 Design

4.2.1 Sensor Package

Considering that we want to read an external signal with the mote, we need to interface with the Mica2's on-board analog-to-digital converter (ADC). The Mica2's Atmel ATMega128L has 8 ADC inputs. Since the first ADC input, ADC1, is already taken up by the built-in temperature and light sensors, we have to use ADC2. This is accomplished by connecting a probe wire directly to pin ADC2 on the Mica2 expansion connector (Figure 4.2), as in Figure 4.2, broken out on the prototyping board.

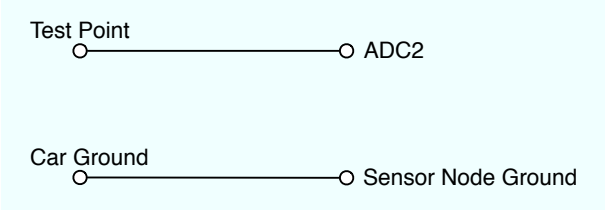


Figure 4.2: ADC2 signal conditioning

This simplistic design does not account for the variety of voltage ranges which could be present in the car. Because the ADC on the microcontroller only supports voltages in the range of 0-3V, it is necessary to add a voltage divider to the front end of the ADC, dividing the actual input voltage such that the maximum voltage that the sensor could 'see' does not exceed 3V. This is

accomplished with the circuit shown in Figure 4.3. The ratio of R1 and R2 determine the amount that the voltage is divided, according to the following formula:

$$V_2 = \frac{V_{TP} \cdot R_2}{R_1 + R_2} \tag{4.1}$$

Where V_{TP} is the voltage at the test point and V_2 is the voltage across R_2 (and, thus, the voltage that ADC2 'sees'). Because the effect of the measurement circuit on the car's electronics must be minimal, the total resistance, $R_1 + R_2$ should be as large as possible. At the same time, the total resistance should be several orders of magnitude lower than the input resistance of the ADC, which is $10M\Omega$. Thus, the value of R_2 was fixed at $50K\Omega$, and R_1 is subsequently sized according to the desired maximum test point voltage as follows, solving Eqn 4.1 for R_1:

$$R_1 = R_2 \cdot \frac{V_{TP}}{V_2} - R_2 \tag{4.2}$$

And inserting our known quantities for R_2 and the maximum V_2:

$$R_1 = 50,000\Omega \cdot \frac{V_{TP}}{3.0V} - 50,000\Omega \tag{4.3}$$

Which means that, given a desired maximum test point voltage, V_{TP}, we can size R_1 using Table 4.1.

maximum V_{TP}	R_1
3.0V	0Ω
5.0V	$33,333.33\Omega$
6.0V	$50,000\Omega$
10.0V	$116,666.67\Omega$
12.0V	$150,000\Omega$
15.0V	$200,000\Omega$
...	...

Table 4.1: Sizing R_1 of the ADC front end circuit

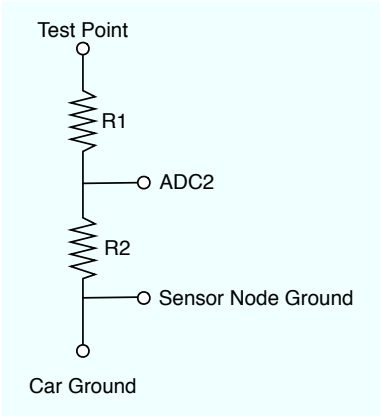


Figure 4.3: ADC2 signal conditioning - w/ Voltage Divider

In order to filter out spikes and noise from the input signal, this circuit needs a capacitor across the lower resistor (Figure 4.4). This creates a simple RC filter. Now we must properly size C_1 in order that our low-pass filter's cutoff frequency can be properly adjusted. The Nyquist frequency of our 10Hz sample rate is 5Hz. Thus, we want to size the filter such that the cutoff frequency is less than or equal to 5Hz. This ensures that we are able to sample the highest frequencies

which pass through our filter. So, given the relation of cutoff frequency in terms of R and C:

$$f = \frac{1}{2\pi RC} < 5Hz \tag{4.4}$$

We can solve for C:

$$C > \frac{1}{10\pi R} \tag{4.5}$$

In this case, R is equal to the equivalent resistance of R_1 parallel to R_2, which is $20,000\Omega$, assuming $R_1 = 33,333\Omega$ for a voltage range of $0 - 5V$ across V_{TP}. So,

$$C > \frac{1}{10\pi \cdot 20,000\Omega} \tag{4.6}$$

$$C > 1.59\mu F \tag{4.7}$$

Finally, we must protect the mote from unexpectedly-large voltages. Although the resistors are large enough that reasonably large voltages would not pull sufficient current to damage the microcontroller, as an added protective measure a 3.0V Zener diode is placed across R_2 (Figure 4.5)[2].

[2]Analog design tips from electronics-minded colleagues James and Brian were instrumental in getting to this point in the sensor package design

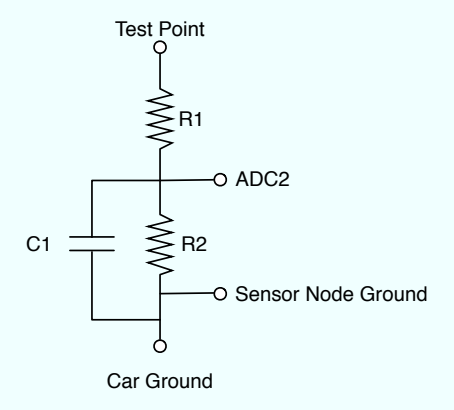


Figure 4.4: ADC2 signal conditioning - w/ Filter

4.2.2 Mote Software

The mote software consists of two custom components and several unmodified TinyOS components. One of the custom components is the abstraction of the sensor board, which provides management of the ADCs, as well as any associated hardware I/O necessary. The other is the main application, `DiomedesApp`, which must manage the timer, coordinate ADC reads, and initiate the sending of messages via the radio. Both components run on top of the TinyOS operating system, making use of its ADC and Radio abstractions, among others. The whole mote software architecture is shown in Figure 4.6.

A sequence diagram of the basic operation of the mote software is shown in Figure 4.7. Essentially, during operation the mote need only wait on a timer event and then kick off an ADC read from whichever of the three available

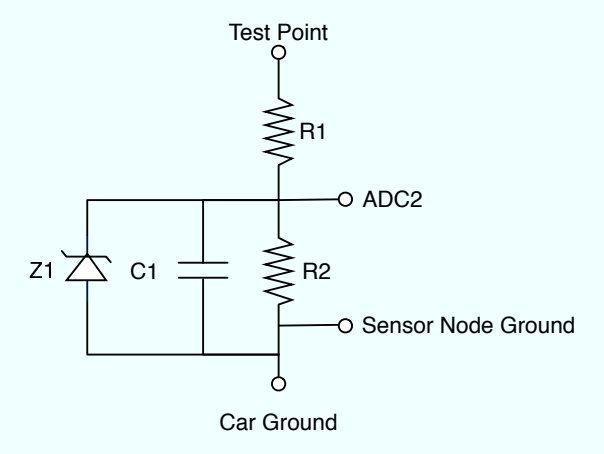


Figure 4.5: ADC2 signal conditioning - w/ Protection Diode

channels is chosen. When the ADC read completes it needs to format the data into a message and pass the message to the Mote Radio for transmission.

Additional reliability mechanics are not shown. These involve an 'ACK' mechanism for each packet sent, checked at the sensor node before another packet is sent, and a CRC check for each packet, checked at the base station.

4.2.3 User Interface Software

The operation of the user interface software is based upon the receipt and processing of messages from the distributed sensors. For this reason, most of the classes in the design of the software implement a simple interface called `SampleHander`, which defines a method called `handleSample(...)`, as shown in

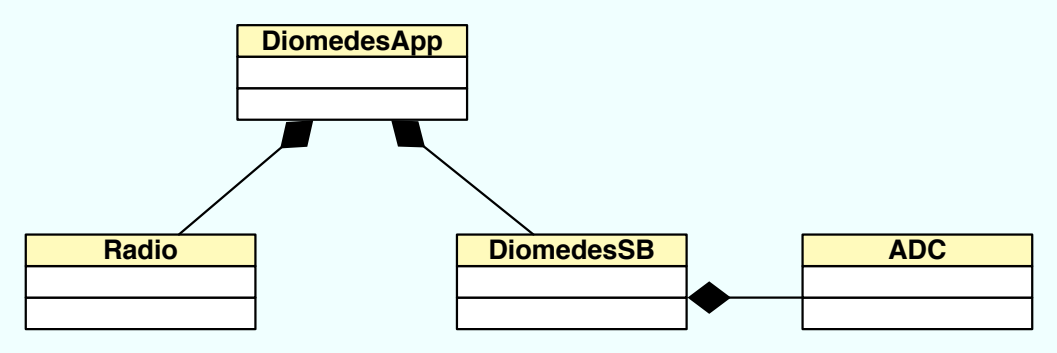


Figure 4.6: Mote Software Architecture

the high-level Class Diagram (Figure 4.8). This diagram also elucidates the "has a" relationships present in the system, which will be discussed shortly.

The unmodified TinyOS class `MoteIF` handles all of the communication with the base station mote. To abstract the concept of the network and its components, we introduce classes `WirelessSensorNetwork`, `Mote`, and `Channel`. The user interface also uses classes `SampleLogger` and `Gauge`.

Class `WirelessSensorNetwork` receives the incoming `DiomedesTLMMsg` messages from `MoteIF`. Its job is threefold. First, it must decode the packet into a `Sample` of the appropriate type, based upon what kind of data it contains. Next, it must dispatch the `Sample` to the proper `Mote` class. Finally, it must pass the `Sample` to any other registered handlers, typically implementers of the `SampleLogger` interface which can log the samples to file, among other projected uses.

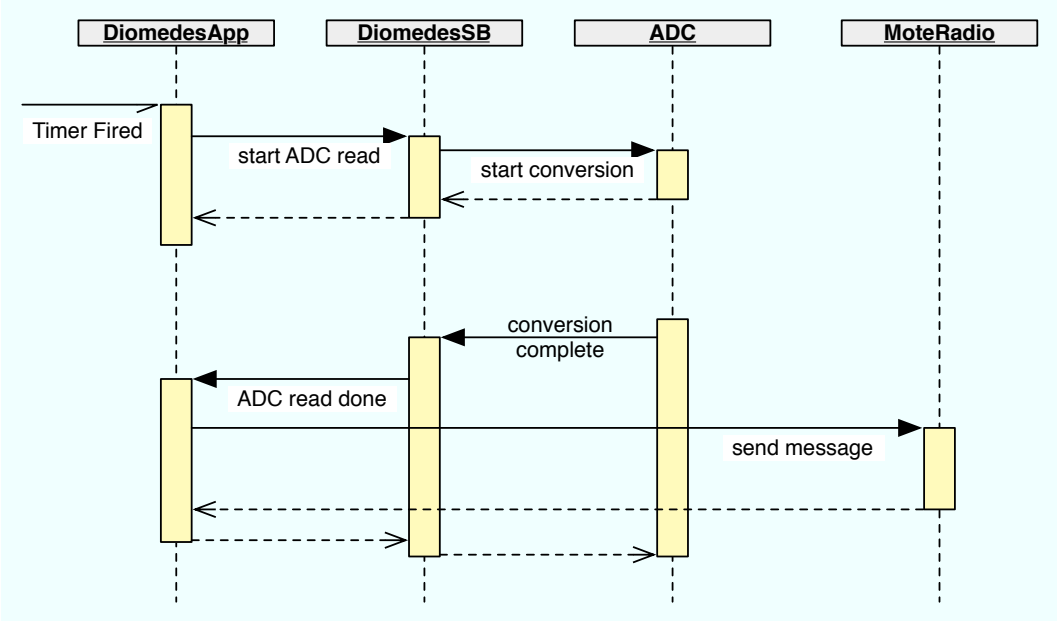


Figure 4.7: Sequence Diagram of the mote software

Class `Mote` accepts objects of type `Sample` from the `WirelessSensorNetwork` class and must dispatch them to the proper registered `Channel` class.

Channels in this case represent potential sources of data from the mote; in the current prototype, these are `TempChannel`, `LightChannel`, and `ADCChannel`, for temperature, light, and general voltage data, respectively. The channels encapsulate the type of data coming in from a particular mote, and must therefore also provide conversion from raw ADC readings into the appropriate engineering units. When a `Sample` is passed to a `Channel`, the `Channel` must register itself with the `Sample` so that, later, the `Sample`'s engineering units can be expediently

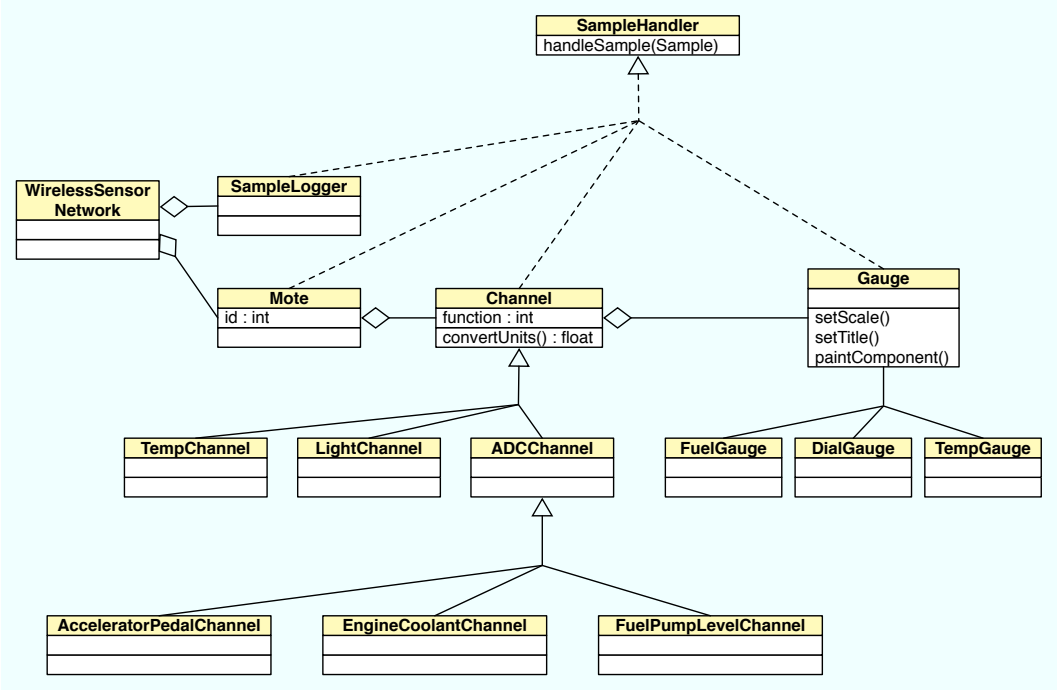


Figure 4.8: Class Diagram for Sample Handler children

extracted. The final job of the `Channel` is to pass the `Sample` to any registered handlers, typically subclasses of the abstract class `Gauge`.

A `Gauge` represents a UI element which displays the readings from a particular `Channel`. It could be as simple as a text box showing the rapidly changing values or as complex as a graph of the previous data history or a graphical representation of a car's gauge.

The typical sequence of operations when a message is received from the sensor network is showing in Figure 4.9. If at any point in this sequence the sample is

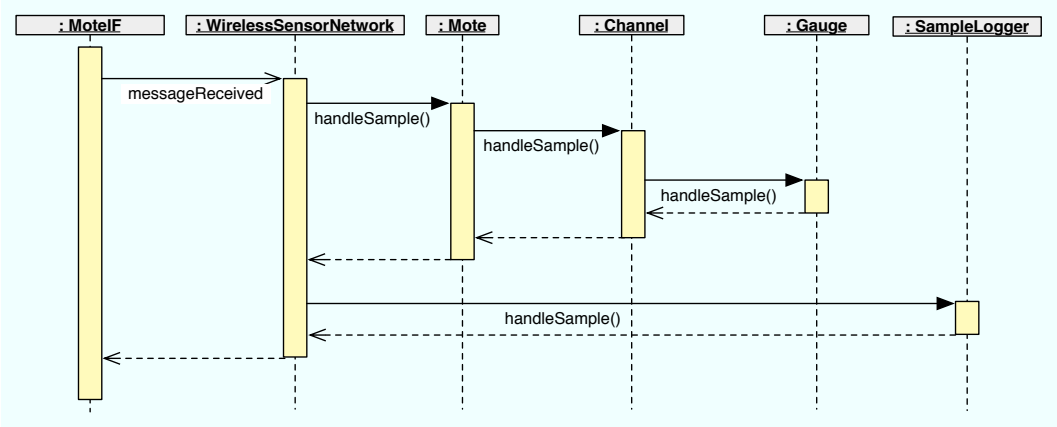


Figure 4.9: Sensor network message handling Sequence Diagram

found to be invalid (*e.g.* impossible readings, nonexistent channels or motes), an exception is thrown and all processing on that sample is halted.

4.3 Implementation

4.3.1 Introduction

This section describes the physical construction of the custom software and hardware, focusing especially on the places where the ideal assumptions of the design diverged from the reality of implementation.

4.3.2 Sensor Board

The reality of hardware implementation typically provides a disconnect from the ideals of hardware design. Where, in design, it is possible to pick any resistor value desired and have it be exact, in reality there are only very particular resistor values available, and those with tolerances upwards of 10-20%. The closest resistor value available to the ideal $50K\Omega$ R_2 resistor is a $49.9K\Omega$ resistor. To compensate, R_1 had to be sized as in Table 4.2 in order to achieve the desired voltage division.

maximum V_{TP}	R_1
3.0V	0Ω
5.0V	$34K\Omega$
6.0V	$49.9K\Omega$
12.0V	$150K\Omega$
20.0V	$280K\Omega$

Table 4.2: Sizing R_1 of the ADC front end circuit, actual values

All of these resistances take into account the tolerance of 1% in the resistance of metal film resistors, since we would prefer to have the maximum voltage across R_2 be less than 3.0V, as opposed to greater than 3.0V. This translates into larger resistances than would ideally be required.

The Zener diodes also proved to be a problem. They were sized to have a 3.0V breakdown voltage, but they appeared to be flowing too much current at lower voltages, affecting the ADC reading. It was determined that the Zener

diodes had leakage current at lower voltages which rivaled the typical current flowing through the circuit. This resulted in hugely affected readings. The only solution was to remove the Zener diodes and rely on the current limiting of the resistors to protect the microcontroller. There was no reason to believe that this would not be sufficient. It would be possible, in the future, to purchase Zener diodes with more agreeable leakage characteristics.

The capacitors also caused issues. The original construction of the sensor board used $3.3\mu F$ electrolytic capacitors, assuming a sampling rate of 10Hz. As will be shown in the Section 5.3.1, the target sampling rate of 10Hz was not always met, making this capacitor slightly undersized. The $3.3\mu F$ electrolytic capacitors were replaced with $22\mu F$ tantalum capacitors. The change in capacitor type was necessary because larger electrolytic capacitors would not have fit easily on the board; tantalum capacitors are significantly smaller in footprint.

The circuit was constructed on top of a Crossbow MDA100 prototyping sensor board. The board provides built-in temperature and light sensors, both connected to the ADC1 pin on the microcontroller. Each of these built-in sensors has a general-purpose digital input/output (GPIO) pin used to enable and disable it. The MDA100 also gives a break-out panel giving solder points corresponding to most of the pins on the expansion module interface, including the needed ADC2 pin, where we connect our signal conditioning and arbitrary volt-

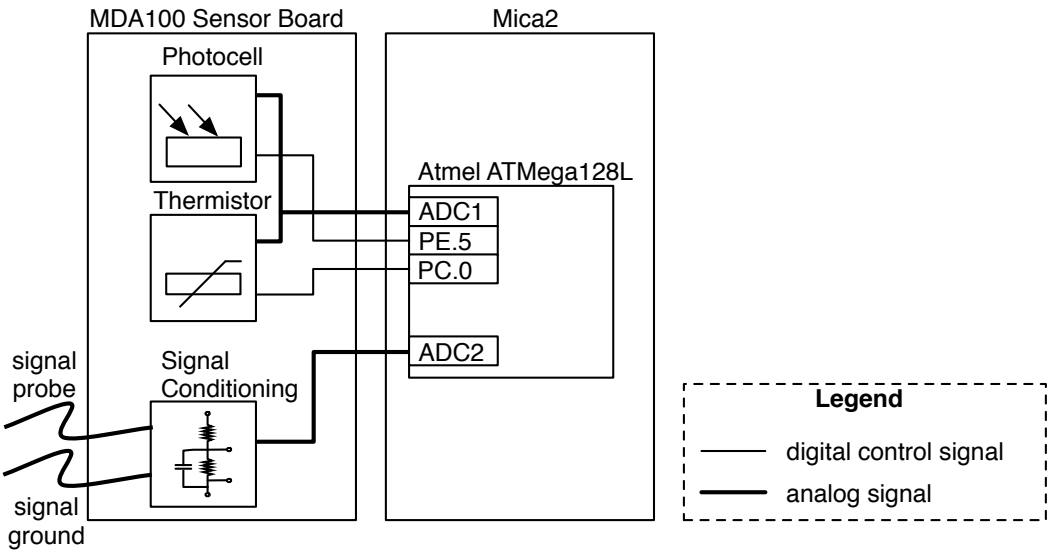


Figure 4.10: Mica2 and sensor board block diagram

age probe wires. The voltage probe wires are connected to the signals of interest in the car. A block diagram of the Mica2 with the sensor board is shown in Figure 4.10.

The final result, with green wires forming jumpers, is shown in Figure 4.11. The resistors are 1% metal film and the capacitor is a 6.3V tantalum. The leads for the sensor board are a pair of 18AWG wires with 0.250" insulated male disconnects crimped onto the ends, with their other ends soldered to the sensor board and strain-relieved with 50lb. nylon monofilament. Connecting the sensor board to a signal wire becomes a matter of crimping a Female T-Tap disconnect onto the wire and slipping on the sensor board leads.

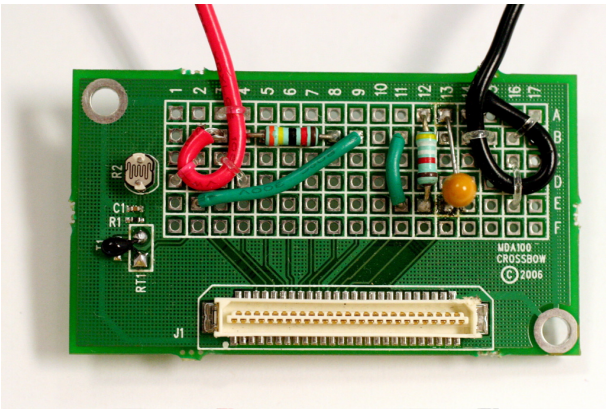


Figure 4.11: Sensor Board Implementation

4.3.3 Mote Software

The software for the motes was written in NesC for the TinyOS operating system. The details of the code can be found in Appendix B, which is the `nesdoc` output. There are two main components, the Diomedes Sensorboard and the Diomedes Application.

Diomedes Sensorboard

The Diomedes Sensorboard was based, at least philosophically, on the standard SensorMts300 sensor board provided with TinyOS. The component provides three `Read<uint16_t>` interfaces called `Light`, `Temp`, and `ADC2`. Depending on which `read()` command is called, the software enables the appropriate sensor,

waits for it to warm up, starts the conversion, and then, when the conversion is done, it posts the result in an event.

For `ADC2`, the act of enabling the sensor is trivial; it basically ensures that the other sensors are disabled. `Temp` and `Light` share the same ADC channel, so it is necessary to enable the proper sensor. This is done by setting the corresponding digital output pin on the microcontroller (Port E pin 5 for the `Light` sensor, Port C pin 0 for the `Temp` sensor).

Diomedes Application

The Diomedes Application uses three `Read<uint16_t>` interfaces (those corresponding to the interfaces provided by the Diomedes Sensorboard), the `AMSend` interface, the `Timer<TMilli>` interface, and the `PacketAcknowledgements` interface.

Once the software has initialized it starts a periodic timer (10Hz, typical), and goes to sleep. When it receives a timer event, if the previous packet has not been acknowledged, it is retransmitted and the software goes to sleep. Otherwise it calls `read()` on the appropriate `Read` interface and goes to sleep.

When the software receives a `readdone()` event, it builds a message containing the data sample, the mote's ID, packet number (an ever-increasing counter), and the type of data being sent. Then an acknowledge for the message is re-

quested and it is sent. If the send ever fails or the message is not ACK'd before the following timer event, then the same message is sent again until it succeeds.

4.3.4 User Interface

The user interface software is built in Java, making use of the existing java packages (`net.tinyos.*`) for connecting to the base station mote through a serial port and getting its messages. The graphical user interface code is written using Java Swing. The details of the code can be found in Appendix A, the `javadoc` of the code.

The classes in the application directly mirror those laid out in Section 4.2.3. Every message received from the `MoteIF` is converted to a `Sample` and passed through the hierarchy of `SampleHandlers`. If at any time the `Sample` object is deemed to be invalid, a `WSNException` is thrown and its handling is stopped.

The UI of the application provides gauges and controls, as shown in Figure 4.12.

The gauges are subclasses of the class `Gauge`, which extend the standard Swing class `javax.swing.JPanel`. Most of them are images with transparent portions wherein simple vector art can be drawn to indicate the current value of the mote's channel. Gauges which look like thermometers, car dial gauges, car fuel gauges, simple digital readouts, and stripcharts have been constructed.

The controls on the application serve a few additional functions. They allow logging to be started and stopped. When logging is started a standard Java file dialog asks the user to choose a location for the logfile. After that, until the Stop Logging button is pressed, every reading which comes from the `MoteIF`, and is not deemed to be invalid, is logged to that file. There is also a Quit button, to do the obvious.

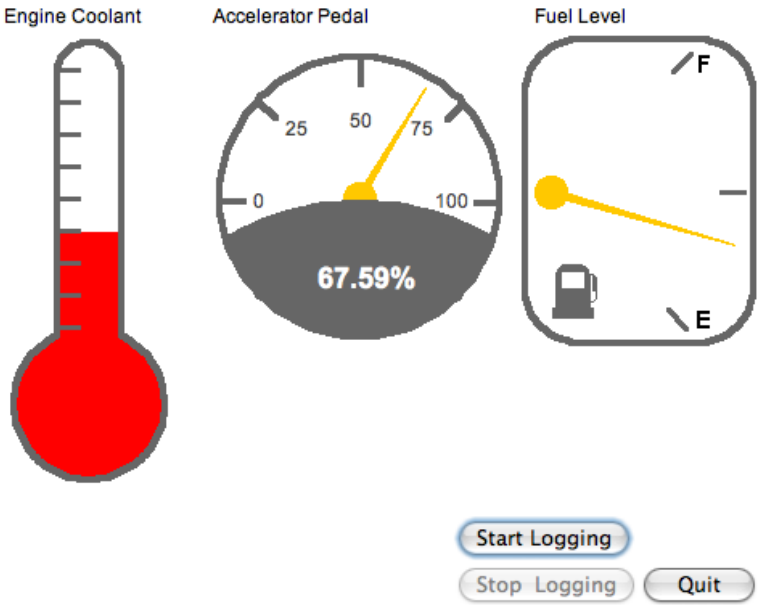


Figure 4.12: User Interface

Chapter 5

System Evaluation

5.1 Criteria for Evaluation

Because the goal of this project is to build a system which is integrated, customizable, low-cost, and non-intrusive clearly it must be shown that this solution meets these overarching criteria. Also inherent in the construction of an automotive diagnostics system is showing that the device can, indeed, be used as an automotive diagnostics system. It must be capable of reading a variety of signals with sufficient resolution, and presenting them to the user in a sane way. This implies a reasonable minimum update rate per type of channel. For example, temperatures need not be read as often as throttle pedal position, because temperatures change slowly and throttle pedal position can change quickly. This partly depends on the rate of collection at the motes, themselves, and partly on the networking.

For a wireless application, update rate translates into a few parameters. Most important are the ultimate packet throughput and the reception rate. Also important is what is happening to the packets that do not make it to the front-end application intact. Are they lost? Are they corrupted? Packets which are lost might be able to be resent whereas corruption of packets might be hard to detect without more sophisticated packet integrity check mechanisms.

5.2 Evaluation Methodology

5.2.1 Calibration

Before data in engineering units could be collected from the sensors, each sensor had to be calibrated. When the calibration was complete, the conversions between raw ADC readings (DN) to engineering units (EU) were placed in the user interface classes corresponding to each sensor.

The two built-in sensors on the MDA100 have generic calibration profiles packaged with them. For the thermistor temperature sensor, Equation 5.1 converts from a raw ADC reading (DN) to Temperature in Kelvins. This is taken directly from the datasheet[23].

$$EU = \frac{1}{0.001010024 + 0.000242127 \cdot \ln(R_{thr}) + 0.000000146 \cdot [\ln(R_{thr})]^3} \quad (5.1)$$

where $R_{thr} = \frac{10{,}000 \cdot (1023 - \mathrm{DN})}{\mathrm{DN}}$.

The light sensor measures a simple intensity, 0-100, and the conversion is shown in Equation 5.2.

$$EU = \frac{100 \cdot DN}{1023} \quad (5.2)$$

The engine coolant sensor was calibrated by recording raw readings from startup until the engine reached operating temperature (mid-way on the car's temperature gauge). The raw data were then scaled so that they corresponded to the appropriate gauge readings, with the bottom of the gauge being 0 and the top of the gauge being 100. The final conversion is shown in Equation 5.3.

$$EU = 65.820313 - 0.09765625 \cdot DN \quad (5.3)$$

The throttle pedal position sensor was calibrated by taking a reading with the pedal untouched and then taking a reading with the pedal on the floor. These values were scaled to read 0% to 100%, with the conversion shown in Equation 5.4.

$$EU = 0.30864198 \cdot DN - 22.839506 \tag{5.4}$$

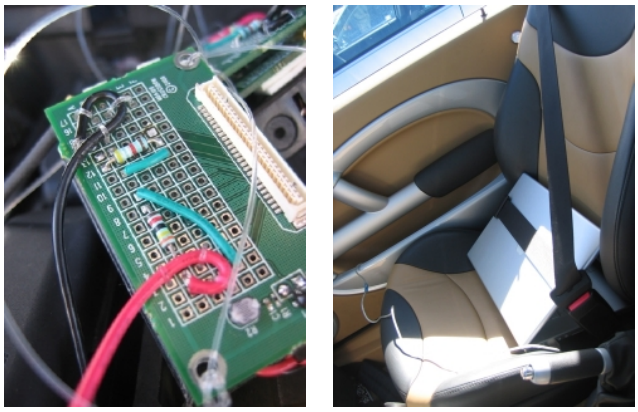
Finally, the fuel level sensor was calibrated by taking a reading at full gas tank and then taking a reading at half gas tank, scaling these values to read from 0% fuel to 100% fuel. The final conversion is shown in Equation 5.5.

$$EU = 0.01082908 \cdot DN \tag{5.5}$$

While the units of throttle pedal position calibration are percents (%), which is appropriate for a throttle value, the other two sensors could only be decoded into units of some arbitrary range (0 - 100 was chosen), not their true engineering units (*i.e.* gallons for fuel, degrees Fahrenheit for coolant temperature). This is ultimately acceptable since the goal is to mirror the physical gauges, and they are unit-less.

5.2.2 Data Collection

Once the system was complete, it had to be tested in a real data collection scenario. A typical data collection experiment involves clamping three of the motes into the test car, a 2004 MINI Cooper S, at interesting test points, strapping a laptop into the passenger seat (Figure 5.1), and then driving around Santa Barbara for an hour.



(*a*) (*b*)

Figure 5.1: Data Collection Photos
(a) Sensorboard closeup affixed to the engine (b) Laptop strapped (safely) into the car

Three sensors were chosen for the experiment: Engine Coolant Temperature, Throttle Pedal Position, and Fuel Level. The location of the sensors and the correct signal wires were collected from the Bentley Publishing MINI Cooper Service Manual[21].

Engine Coolant should mirror exactly the readout on the dashboard 'temperature' gauge. This signal from this sensor is accessible where it meets the Electronics Control Module (ECM) under the car's bonnet.

Throttle Pedal Position is also available under the bonnet at the ECM. For a drive-by-wire vehicle, this is the desired throttle position, transferred from a sensor the gas pedal in the passenger compartment. This is an attractive sensor

to monitor because it is easy for the experimenter (*i.e.* the driver) to interactively affect.

Finally, the Fuel Level sensor was chosen as it differs from the other two sensors in several ways. First, this signal is not available in the engine compartment with the other two. The only way to access this signal is to remove the rear seats and place the sensor node directly on the fuel pump enclosure; this varied the relative locations of the motes. Second, while the other two sensors are well described in the service manual, this signal was poorly documented. The output could be a simple voltage level proportional to the amount of fuel in the tank–which was the preferred outcome–or it could be something entirely different. The MINI has a two-lobed gas tank, equalized with a syphon pump between the two lobes[21], with two independent fuel level sensors. It was assumed that one of the sensors would, typically, read half of the total fuel in the vehicle.

So, with two motes secured under the hood, a mote sitting on the fuel pump under the rear seats, and a laptop strapped securely into the passenger seat, the car was driven and data was collected. There were also data collection sessions wherein the motes were laid out at a workstation. These typically provided baseline information, giving an idea of what to expect from the in-car experiments.

The particular data collection session used in the following evaluation took place over an hour of a variety of driving conditions. It began at UC Santa Barbara, went out to Cathedral Oaks Road, east to Old San Marcos Road, back down highway 154 to 101, and then back to campus. This provided slow city traffic, rough and twisty hills, and relatively quick highway driving. All three motes were programmed to collect and transmit data at a maximum rate of 20Hz.

5.2.3 Data Processing and Evaluation

The datafiles collected with the front-end's logging facility were fed through a series of `bash` and `awk` scripts which rendered them down to statistics and graphs. Parameters extracted from the data, second-by-second, are:

- number of packets received - count of the number of seconds with the same timestamp, to the precision of the second
- number of packets lost - count of packets missing during a particular second, as determined by missing 'packet numbers'
- total packets - sum of packets received and packets lost
- reception rate - ratio of packets received to total packets, expressed as a percent

If a particular second of the experiment is found to not have packets associated with it, it is recorded appropriately to show instances of 0 packet reception.

The scripts also extract the data samples themselves as per-second averages. This made it possible to generate graphs of the fuel level, engine coolant temperature, and throttle position throughout the experiment. Sanity checks were performed on these data to see if they properly reflect the operation of the car. Another helpful form of sanity check is to look at the laptop while the car is operating to compare the digital gauges with the physical ones. Ultimately, they should match. Clearly this is dangerous if performed by the driver, so these kinds of evaluations were limited to instances in controlled driving conditions or with copilots.

The evaluation of these data rests on two parameters, the effective throughput (Section 5.3.1), or the number of packets per second, and the reception rate (Section 5.3.2). Another parameter of the system which is worth evaluating is the *resolution* of the measurements. This can be calculated directly and is covered in Section 5.3.3.

5.2.4 Qualitative Evaluation

Other criteria cannot be quantitatively evaluated. The integration, for example, is a purely qualitative measurement. It can be described and compared

with alternatives, but the decision must be left up to the reader as to whether these criteria are met.

We must qualitatively examine the parameters set forth in the thesis question:

- integration - can the system be used in the service bay as easily as it can be used in the field or even on the road?
- customizability - are a diverse range of modes of operation supported which can support conceivable automotive applications?
- cost - is the final system relatively inexpensive?
- non-intrusiveness - does the presence of the system affect operation of the vehicle or does the system leave any evidence of its installation?

5.3 Results

5.3.1 Effective Throughput

The CDF of the effective throughput for an hour-long run of the system is shown in Figure 5.2. Each line represents a single mote in the system. The graph is fairly straightforward. For example, for the Coolant Temperature mote, 10% of the time the system achieves 6 or less readings per second. In contrast, the Fuel Level mote achieves roughly 10 or less readings per second 10% of

the time and the Accelerator Pedal mote achieves 8 or less readings per second 10% of the time. Another way of looking at this is that 90% of the time, the Coolant Temperature mote achieves rates higher than 6 readings per second, the Fuel Level mote achieves rates of higher than 10 packets per second, and the Accelerator Pedal mote achieves more than 8 readings per second.

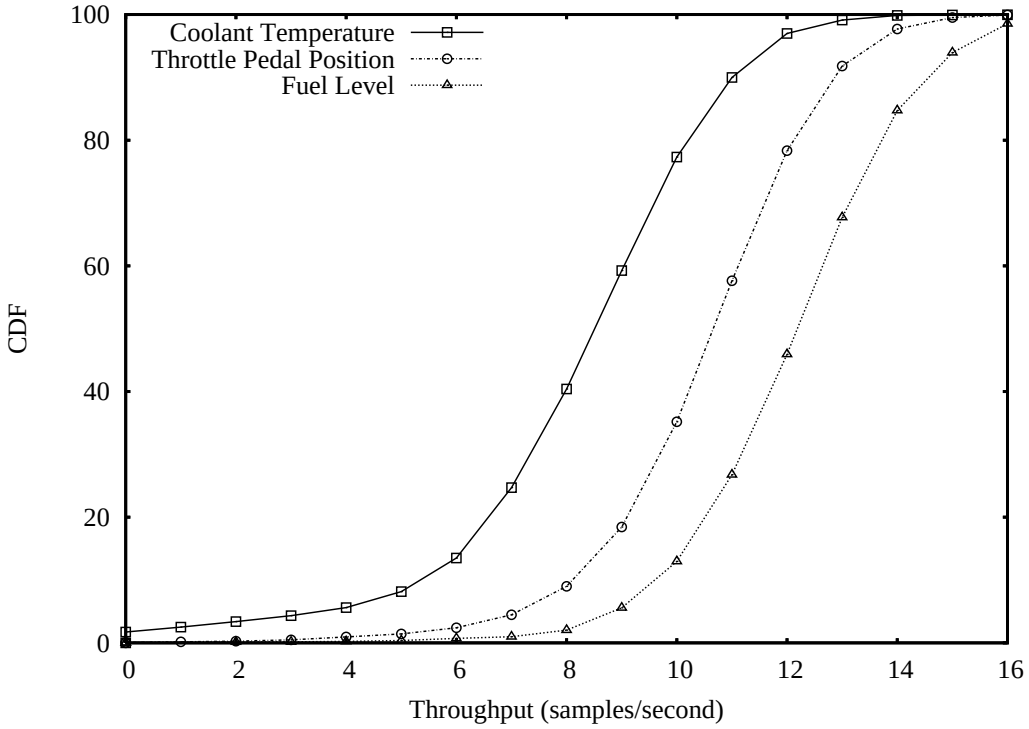


Figure 5.2: Effective Throughput CDF

Since all three motes are running the same software and all had new batteries installed prior to the test, the variation in rates must be explained by something environmental, by either the relative positioning of the motes to the base station,

by the amount of occluding material, or simply by the activity of the motes' radio protocol. We can rule out the simple explanation of the amount of occluding material because the Temperature and Pedal motes were collocated; yet they showed different throughputs. Physical orientation could have been a factor. Previous studies have shown that sensor network mote radios are very sensitive to placement and orientation[39].

5.3.2 Reception Rate

The CDF for reception rate for an hour-long run of the system is shown in Figure 5.3. Each line represents a single mote in the system. Again, like Figure 5.2, the graph is pretty straightforward. For both the fuel level and throttle pedal motes, 90% of the time each had 90% or better reception rate. This is in marked contrast to the coolant temperature mote which achieves 90% or better reception rate only 60% of the time.

Again, the motes were all running the same software, so the variation between the reception rates must be something more environmental. The mote connected to the fuel pump was fully surrounded in the metal of the car's body with what can only be described as a metal blast shield screwed down on top of it. It was in cramped quarters, squeezed down next to the fuel pump, and its antenna was in a peculiar orientation. This almost certainly negatively impacted its reception

rate. And yet, it is the coolant temperature mote, sitting physically next to the throttle pedal mote, which achieves the worst performance. It is doubtful that electrical and physical interference alone are to blame since, again, the throttle pedal position mote was directly next to the poorly-performing coolant temperature mote. This may be a case where the previously documented mis-calibrations of Mica2 radios comes into play[34]. It may be that the coolant temperature mote inherently performs worse than the other two motes.

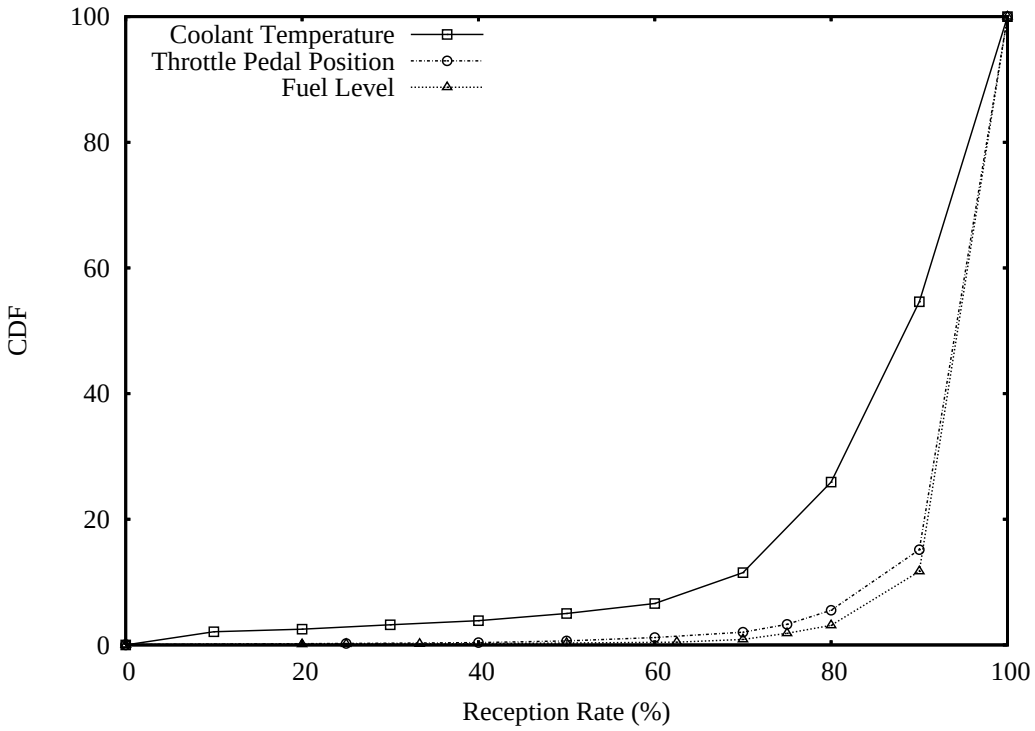


Figure 5.3: Reception Rate CDF

5.3.3 Measurement Resolution

The key to understanding the resolution of our measurements is that the ADCs on the Mica2 mote have 10 bits of resolution. For a voltage connected directly to the ADC input, with its 0-3V range, this equates to a resolution of about 3mV, as shown in Equation 5.6. In other words, the difference between a measurement and the next highest measurement is 3mV, due to the discrete nature of ADCs.

$$\frac{3.0V}{2^{10}} = 0.00293V \tag{5.6}$$

With linear relationships in hand which convert raw ADC readings into reasonable units for the light sensor (Equation 5.2), engine coolant temperature (Equation 5.3), throttle pedal position (Equation 5.4), and fuel level (Equation 5.5), it is a simple matter to determine the resolution of each measurement. Unfortunately, with all of these readings being unit-less the resultant resolution is also unit-less. Nevertheless, Table 5.1 shows the resolution of each of the measurements; all sensors but the temperature sensor have a unit-less range of 0-100.

The only measurement which has real engineering units is the built-in temperature sensor on the MDA100 board. The default calibration curve (Equation 5.1) for this thermistor is not linear, so it is impossible to give a single resolution for

measurement	range	resolution
temperature sensor	0-50°C	$\sim 0.1°C$
light sensor	0-100	0.0978
engine coolant temperature sensor	0-100	0.0977
throttle pedal position sensor	0-100%	0.309%
fuel level sensor	0-100	0.0108

Table 5.1: Measurement ranges and resolutions

the measurement. Rather, since the curve is nominally valid over the range 0°C to 50°C, it is possible to calculate the average resolution by determining the ADC reading corresponding to 0°C and 50°C and calculating the slope of the linear fit between those points. The result is also shown in Table 5.1.

5.3.4 Integration

When examining the criterion of integration, it is necessary to consider how easily the system translates from operation in a static deployment (*e.g.* in a garage) to another location, or even on the road in-between. Many existing systems fail this criterion because they are designed specifically to be used on an immobile vehicle. This system was designed with integration in mind and proves successful in this regard. Because all of the components of the system are modular and relatively decoupled, it proved simple to take the instrumented car on the road. The only additional work required was to secure the motes to their locations (using, in this case, 50 lb. test fishing line) and the laptop to the

passenger seat. Beyond those minor fixes, the system operated identically in the garage as it did on the road.

5.3.5 Customizability

Another important criterion for this system was customizability. The system needs to be capable of not only reading a variety of signals in the electrical system of the car, but it needs to be capable of reading additional channels of data which the user might want to see. Like any similar diagnostics system, this one works well for connecting to existing signals. The front-end to the ADC can be configured, through a minor hardware change (sizing a resistor), to read a variety of voltage ranges. The series resistance of the front-end also limits the current to the ADC input, thus protecting the micro-controller from out-of-range voltages. The front-end software can also be modified to perform conversions of these data into appropriate engineering units.

What this system also enables is the ability to read additional channels. Currently, the software of the motes can be configured to read from the built-in temperature and light sensors; all of the infrastructure exists to make these measurements. In future revisions of the sensor board, additional built-in sensors could be added to further expand its customizability.

Without the wires of traditional diagnostics systems, installing the motes becomes a simple prospect. The most difficult aspect is finding the signal wire which is to be read. This wire is then tapped with a t-tap, a small, ubiquitous connector requiring only a pair of pliers. Once the wire is tapped the mote can be connected to the tap and secured in-place. Because the motes are small, they can easily be placed anywhere on the car. With no wires to route, the mote is now turned-on and the data immediately stream to the laptop, whether it be outside of the car or, in our test case, on the passenger seat.

Right now the customization of the system requires changing the source code in several places, but it has been abstracted to be straightforward. The infrastructure also exists for the front-end software to detect new motes in the system and to automatically allow the user to customize its data channel(s).

5.3.6 Cost

Much of the work on sensor networks does so with the assumption that, in the future, the sensor nodes will be ubiquitous and inexpensive[40, 30]. Although each node in this prototype cost about $250 in materials per unit, it is projected that sensor nodes could cost less than $1 per node. In this future, this whole system will be very inexpensive to build. The motes are off-the-shelf with minimal analog front-ends consisting of a few passive components. Combine this

inexpensive mote hardware with an equally inexpensive serial packet-forwarding base station, already a mainstay of sensor network design, and the total hardware cost is projected to be minimal.

5.3.7 Non-intrusiveness

There are two aspects of non-intrusiveness worth evaluating: physical and electrical. Physically, the motes are small and light and easily fit wherever they needed to fit. Also, the probes were connected with t-taps, which remove easily, leaving behind almost no trace of their previous installation. Electrically, the total resistance of the whole sensor package is very high, which allows very little current to flow. Consequently, the motes are nearly invisible to the car's electronics.

5.4 Analysis

5.4.1 What worked?

Ultimately, the system works to its requirements. Even with packet losses, the rates are reasonable for monitoring and some post-processing. All the readings have sufficient resolution, and could conceivably be made even better with a better knowledge of the signals being read. The system is integrated, customiz-

able, and relatively cheap. Certain mechanisms proved especially useful in the system's construction.

Filtering, in both hardware and software, did much to clean up the signals received from the motes. The addition of the hardware filter (Figure 4.4) in front of the analog to digital converter cleaned up most of the huge, periodic voltage spikes common to automotive applications. Basic filtering in software, by throwing out corrupted messages, as detected by a CRC check at the base station, removes many of the packets which we can only assume are damaged during transmission.

Also, making use of the built-in packet acknowledgment system in TinyOS active messaging also did much to increase packet reception rates.

Of the three sensor positions chosen for this study, the throttle position and temperature proved to be good choices. Both gave deterministic readings.

5.4.2 What didn't work?

Not everything went perfectly in the system's development. Some of the more notable problems and less-conclusive results are described below.

For one, the protection diode was unusable due to its leakage current. One of the assumptions is that the current leaking through the zener diode before its breakdown voltage is minimal, at least compared with the total current flowing

through the circuit. Because the circuit was designed with large resistors, the nominal current flow was already very small. With the zener diodes that we chose, the leakage current was sufficient to negatively impact the voltage readings. Luckily we were able to rely on the total resistance of the circuit to protect the microcontroller. Still, it would be worthwhile to investigate zener diodes with less leakage current.

Also, the default active message protocol in TinyOS needs to be bolstered with additional mechanisms in order to guarantee more reliable communication. Retransmissions and CRC checks were not able to protect the system from packet loss; there was inevitably at least one node in the system which experienced noticeable packet loss.

While the packet reception rates may be sufficient for monitoring, they are not sufficient for higher-rate data or for critical parameters. For example, under normal operation, the throttle pedal position sensor proves difficult to analyze at 8Hz. The standard rule of thumb says that sampling ought to be done at twice the frequency of the signal being sampled. Parameters such as temperature change very slowly, so a couple of samples per second would be sufficient, but one could imagine that the position of a pedal under one's foot could have much higher-frequency components to its position. An order of magnitude faster sam-

pling, infeasible with this system's sample-and-send scheme, would be required to better understand signals like this, with higher frequency components.

Finally, the fuel level sensor proved to be something of a mystery. When the car started up, our measured value could be transformed into a reliable reflection of the true fuel level gauge. However, several minutes into running the system the readings from the fuel level sensor grew erratic and difficult to fathom. Again, higher-rate sampling may reveal the problem with our readings, but for now this sensor is only useful for the packet reception statistics, not as a reflection of the fuel level.

5.4.3 Generalization

Now that this particular prototype has been evaluated, how will these results generalize into other instantiations? We expect that, with the use of commodity components and expandable technologies, this solution could work in numerous situations; harsher conditions might require modification.

First, the hardware is off-the-shelf with only minor additions. The Crossbow Mica series of motes are a standard in wireless sensor networking research. The only modifications made were to add a few inexpensive passive components. This design could be easily duplicated elsewhere.

Second, the software systems are all largely cross-platform. The user interface is written in Java and the mote software is written in cross-platform NesC code, with the exception of the digital I/O controls used to enable and disable the on-board sensors.

Finally, the technologies employed would make it simple to expand the system into tens or even hundreds of nodes. Changing from the Mica2 base to one using ZigBee radios would allow for 64k addressable nodes. Also, while the particular vehicle used with this prototype is arguably smaller than the average, there would be nothing stopping the introduction of multi-hop networking into the system. This would allow the sensor nodes to communicate across much larger vehicles.

One situation which might require a redesign for the system is a more extreme environment. Currently, the sensor nodes would not be able to operate exposed to the elements. Encasing the nodes in weatherproof casings would enable them to work as well outside of the vehicle as inside. There is also a history of running sensor networks in much more extreme environments (*e.g.* volcanos)[36], so we do not anticipate this being a problem.

Chapter 6

Related Work

6.1 Overview

This chapter discusses work related to this thesis in several fields. Related to the thesis question are current commercial automotive diagnostics systems, as well as research in the realms of wireless sensor networks, wireless networking in vehicles, and wireless automotive diagnostics systems.

6.2 Existing Diagnostics Solutions

Numerous products have been developed to fill the need for diagnostics data. They can be broken into the rough categories of: OEM offerings, on-board diagnostics readers, wired clamp-on devices, and after-market gauges. As we will show, the offerings tend to be targeted towards a particular need and no individual solution fills all needs.

Original equipment manufacturers have made initial strides towards customizable diagnostics for car owners. Aside from the standard cluster of gauges available on most cars, manufacturers typically offer additional on-board readouts. These can range from simple offerings, like additional gauge clusters and single, multifunction LED displays, to the elaborate systems employed in models like the aforementioned Toyota Prius[35]. These options are very integrated, in that they are permanent components in the car, and they are very easy to use as they blend into the standard user interface of the vehicle. Unfortunately, options such as these are typically expensive for the end-user. They also fail to meet the full customizability requirement, restricting the user to a small set of predefined data sources, often only displaying one at a time.

Another class of diagnostics solutions involves the standard On-board Diagnostics II (OBD II) port, installed on all production automobiles since the mid-1990's [25]. The OBD II port gives access to a selection of data sources, a standard set of fault codes, and the standard on-board data busses. These data busses, such as the Controller Area Network Bus (CANbus or ISO 11898-1[15]) or the K-bus (ISO 9141[14]), provide digital interfaces between peripherals and the central computer of a car. Companies such as AutoTap[25] and Snap-On[33] market products which connect to the OBD II port and provide a display of engine parameters and fault codes. These devices are very easy to use and can

often operate while the vehicle is driving, making them well integrated. Their prices are reasonable. They are also completely non-intrusive since they plug into existing ports on the vehicles made expressly for this purpose. Again, though, they fail to meet the customizability requirement in that they can only read data sources which have been predetermined. They can read engine coolant temperature, for example, but not the temperature in the undercarriage next to the fuel tank. They are also not available on vehicles older than 1994, so a mechanic or tuner looking to operate on an older-model car must find a different solution.

The third class of diagnostics options are wired clamp-on devices. These are general purpose diagnostics systems employing collections of cables that can be attached to arbitrary test points within the vehicle. They come from companies such as Pico Technology[26] and Snap-On[33] and are targeted mainly at auto mechanics. These systems are relatively easy to use, though they require more knowledge of the operation of the vehicle than other options. They fail to meet the integration and non-intrusive requirements as bundles of wires must be run to each test point, a complicated and potentially impossible prospect. They are also the most expensive of these options. Last, the customizability requirement is still not completely fulfilled. Although these systems can read a large number of existing voltages within the car, they cannot introduce new sensors out-of-the-box.

Finally, there are aftermarket gauges and gauge clusters, perhaps most notably those made by Auto Meter[2]. These are additional gauges which are installed in the passenger compartment to monitor small numbers of parameters and are targeted at tuners. These gauges are extremely customizable, capable of measuring any conceivable signal in a car, as well as adding additional sensors where appropriate. They are also very inexpensive. Like the original equipment manufacturer gauge clusters, these gauges install permanently in the vehicle, making integration a given. Still, they too have their downside. The installation of these gauges can be a difficult undertaking, requiring the routing of wires through inaccessible paths. They also often require modification of the vehicle, whether by perforating the firewall or installing mounting hardware, and thus are not non-intrusive.

None of these solutions fully solves the problem stated in Section 2.2.

6.3 Related Research

Recent research in wireless sensor networks covers significant breadth[1], from the early discussions of TinyOS[11] to discussions of habitat monitoring[18, 19] and acoustic target tracking[38]. Still, there is little to find about the empiri-

cal application of these low-power, wirelessly networked devices in automotive applications.

This is not the first paper to make a case for using wireless networking in automotive applications, with many applications involving inter-vehicular communications. One such application is Internet connectivity[6, 4]. Also, the idea of vehicular sensor networks is not new. Still, work on the subject has often focussed on the large-scale, inter-vehicle sensor networks[12, 31], without application of wireless sensor networks within the vehicle. Even connecting diagnostics data to the wide area has been proposed, but its data source was the factory OBD-II port[16].

There have been some discussions of entirely intra-vehicle wireless networks and often the subject of the discussion is Bluetooth (802.15.1)[24, 10]. It has been suggested as a choice for a partial replacement for cable bundles[5], with the bluetooth nodes acting as wireless bridges between disparate on-board wired networks, such as CANbus; the large number of bluetooth radio units required for a complete replacement is cited as cause for only partial replacement[10]. At Unicamp, Brazil, Bluetooth modules were used as the sensor nodes with the Bluetooth module acting as the central host[28]. Centralized wireless systems, where all data are taken directly from the car's electrical control module have been built[17]. Wireless sensor networks have even been recommended as a

complete data cable replacement[8], but only in a speculative fashion, and with a fair amount of trepidation with respect to using them in safety-critical instances.

Chapter 7

Conclusion and Potential Elaboration

If there's no one around
when the tour runs aground
and if you're still around
then we'll meet at the end of the tour

They Might Be Giants, *End of the Tour*

7.1 Conclusion

In this thesis we identified a problem in the automotive industry. Though users of automobiles require customized diagnostics data about their operating vehicles, and though the automotive manufacturers have fully embraced the idea of mass customization in other facets of their production, factory customized diagnostics displays are not forthcoming. This creates a niche for third-party manufacturers to fill. Unfortunately, third-party diagnostics systems fail to

meet all of the requirements of integration, customization, low-cost, and non-intrusiveness. Notably, they tend to trade off integration for customization.

As a solution to this problem we introduced a system architecture wherein the automobile is instrumented with a wireless sensor network. The nodes in the wireless sensor network transmit their readings to a central base station, which displays the samples in real-time, and logs them for later analysis. We then detailed a prototype implementation of the system using Crossbow Mica2 motes for the wireless sensor nodes and an Apple notebook as the base station and user interface. We described the hardware signal conditioning and software components which had to be designed and implemented.

Finally, we described the steps taken to test the system and evaluate its performance. We showed that the resulting prototype successfully meets our requirements. Although packet loss was not negligible, we argued that for an application such as low-rate real-time monitoring, where the data are not being used to make critical decisions, some packet loss is completely acceptable. Ultimately, the solution and its prototype make strides towards filling the general-purpose automotive diagnostics niche.

While this prototype represents an acceptable proof of concept, there are certainly aspects which could be improved or elaborated upon. In the next, and final, section, we outline some of these aspects.

7.2 Potential Elaboration

There are many facets of this system which, given additional resources, would have been interesting to investigate. These items would make for potential elaboration on the system.

Already mentioned, additional work could be done in minimizing packet loss. The addition of trivial retransmissions already greatly improved the performance, and more sophisticated retransmission mechanisms could do much to increase message reception rate, at the expense of overall throughput. Building the system using ZigBee radios should also yield better reception rates.

Also, taking the system to its logical conclusion by allowing customization at run-time would be a valuable exercise. At present, the code must be recompiled to support different data sources than the three experimental sensors. Allowing a single mote to be used as a light, temperature, or voltage sensor, with a fully-customizable front-end display, would be a matter of taking advantage of mechanisms already available in the system framework, but not exposed to the user.

Another often discussed addition to the system would be driving physical gauges with readings from the wireless sensors. The idea would be to have a general-purpose gauge mounted on the car's dashboard, but to have its input

connected to the output of a computer-based voltage output card (digital-to-analog board). This would have the advantage of being able integrate the system more cleanly into a car while still supporting the full customization of the totally software display system.

A common question when pitching this system as a valid on-the-road data collection scheme is how security is handled. There are currently no measures taken to segregate packets from two nearby instances of the system. There is also no protection against sniffers collecting data about the system while it operates. In the future, sensor nodes should be paired with base stations so that base stations are able to filter out messages destined for them.

Finally, the hardware could be made more robust. Adding an external ADC could yield significantly higher measurement resolution, and having the readings referenced to a precision voltage reference instead of the (variable) battery voltage would increase repeatability of measurements. The quality of the passive components could also be increased, which would yield less effects from temperature swings and varying signal frequencies. All of these efforts would help to increase trust in the measurements.

Bibliography

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. Wireless sensor networks: a survey. *Computer Networks (Amsterdam, Netherlands: 1999)*, 38(4):393–422, 2002.

[2] Auto Meter. http://www.autometer.com.

[3] N. Baker. ZigBee and Bluetooth strengths and weaknesses for industrial applications. *Computing & Control Engineering Journal*, pages 20–25, 2005.

[4] V. Bychkovsky, B. Hull, A. K. Miu, H. Balakrishnan, and S. Madden. A Measurement Study of Vehicular Internet Access Using In Situ Wi-Fi Networks. In *12th ACM MOBICOM Conf.*, Los Angeles, CA, September 2006.

[5] Y. Chen and L. Chen. Using Bluetooth wireless technology in vehicles. In *IEEE International Conference on Vehicular Electronics and Safety*, pages 344–347, October 2005.

[6] M. Cilia, P. Hasselmeyer, and A. Buchmann. Profiling and internet connectivity in automotive environments. In *Proceedings of VLDB*, pages 1071–1074, 2002.

[7] Crossbow technology inc. http://www.xbow.com.

[8] T. ElBatt, C. Saraydar, M. Ames, and T. Talty. Potential for intra-vehicle wireless automotive sensor networks. In *2006 IEEE Sarnoff Symposium*, 2006.

[9] G. Ferrari, P. Medagliani, S. Di Piazza, and M. Martal. Wireless sensor networks: Performance analysis in indoor scenarios. *EURASIP Journal on Wireless Communications and Networking*, 2007:Article ID 81864, 14 pages, 2007. doi:10.1155/2007/81864.

[10] L.-B. Fredriksson. Bluetooth in automotive applications. In *Bluetooth '99*, London, UK, June 1999.

[11] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. E. Culler, and K. S. J. Pister. System architecture directions for networked sensors. In *Architectural Support for Programming Languages and Operating Systems*, pages 93–104, 2000.

[12] B. Hull, V. Bychkovsky, Y. Zhang, K. Chen, M. Goraczko, A. K. Miu, E. Shih, H. Balakrishnan, and S. Madden. CarTel: A Distributed Mobile Sensor Computing System. In *4th ACM SenSys*, Boulder, CO, November 2006.

[13] O. Hyncica, P. Kacz, P. Fiedler, Z. Bradac, P. Kucera, and R. Vrba. The ZigBee Experience. In *Proceedings of the 2nd International Symposium on Communications, Control, and Signal Processing*, March 2006.

[14] ISO 9141:1989, 1989. Road vehicles – Diagnostic systems – Requirements for interchange of digital information.

[15] ISO 11898-1:2003, 2003. Road vehicles – Controller area network (CAN) – Part 1: Data link layer and physical signalling.

[16] W. Jenkins, R. Lewis, G. Y. Lazarou, J. Picone, and Z. Rowland. Real-time vehicle performance monitoring using wireless networking. In *Communications, Internet, and Information Technology*, pages 375–380, 2004.

[17] D. La Clair. Auto analyzer a mobile based automotive diagnostics tool utilizing wireless communications and embedded Java technology. Master's thesis, Arizona State University East, December 2002.

[18] T. Liu, C. M. Sadler, P. Zhang, and M. Martonosi. Implementing software on resource-constrained mobile sensors: experiences with impala and zebranet. In *MobiSys '04: Proceedings of the 2nd international conference on Mobile systems, applications, and services*, pages 256–269, New York, NY, USA, 2004. ACM Press.

[19] A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler, and J. Anderson. Wireless sensor networks for habitat monitoring. In *ACM International Workshop on Wireless Sensor Networks and Applications (WSNA'02)*, Atlanta, GA, Sept. 2002.

[20] K. Martinez, P. Padhy, A. Elsaify, G. Zou, A. Riddoch, J. K. Hart, and H. L. R. Ong. Deploying a sensor network in an extreme environment.

In *SUTC '06: Proceedings of the IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing - Vol 1 (SUTC'06)*, pages 186–193, Washington, DC, USA, 2006. IEEE Computer Society.

[21] *MINI Cooper Service Manual*. Bentley Publishers, 2004.

[22] MINI USA. http://www.miniusa.com.

[23] MTS/MDA Sensor Board User's Manual. Crossbow Doc. # 7430-0020-04 Rev. B.

[24] T. Nolte, H. Hansson, and L. L. Bello. Automotive communications - past, current and future. In *10th IEEE Conference on Emerging Technologies and Factory Automation*, 2005.

[25] OBD II. http://www.obdii.com.

[26] Pico Technology. http://www.picotech.com/auto/.

[27] B. J. Pine. *Mass Customization: The New Frontier in Business Competition*. Harvard Business School Press, 1993.

[28] J. Polar, D. Silva, A. Fortunato, L. Almeida, and C. Dos Reis Filho. Bluetooth sensor network for remote diagnostics in vehicles. In *2003 IEEE International Symposium on Industrial Electronics*, volume 1, pages 481–484, June 2003.

[29] J. Polastre, R. Szewczyk, and D. Culler. Telos: enabling ultra-low power wireless research. In *IPSN '05: Proceedings of the 4th international symposium on Information processing in sensor networks*, page 48, Piscataway, NJ, USA, 2005. IEEE Press.

[30] J. Rabaey, J. Ammer, J. L. da Silva Jr., and D. Patel. Picoradio: Adhoc wireless networking of ubiquitous low-energy sensor/monitor nodes. In *WVLSI '00: Proceedings of the IEEE Computer Society Annual Workshop on VLSI (WVLSI'00)*, page 9, Washington, DC, USA, 2000. IEEE Computer Society.

[31] H. Sawant, J. Tan, and Q. Yang. A sensor networked approach for intelligent transportation systems. In *(IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2004.*, pages 1796–1801 vol.2, October 2004.

[32] Scion. http://www.scion.com.

[33] Snap-on. http://www.snapondiag.com/.

[34] K. Srinivasan and P. Levis. Rssi is under appreciated. In *Proceedings of the Third Workshop on Embedded Networked Sensors (EmNets), 2006.*, 2006.

[35] Toyota prius. http://www.toyota.com/prius/.

[36] Volcano sensorweb. http://sensorwebs.jpl.nasa.gov/.

[37] F. von Corswant and P. Fredriksson. Sourcing trends in the car industry: A survey of car manufacturers' and suppliers' strategies and relations. *International Journal of Operations & Production Management*, 22:741–758, 2002.

[38] Q. Wang, W.-P. Chen, R. Zheng, K. Lee, and L. Sha. Acoustic target tracking using tiny wireless sensor devices. In *Proc. of the 2nd International Workshop on Information Processing in Sensor Networks (IPSN'03)*, 2003.

[39] M. Yarvis, W. Conner, L. Krishnamurthy, J. Chhabra, B. Elliott, and A. Mainwaring. Real-world experiences with an interactive ad hoc sensor network. In *International Conference on Parallel Processing*, pages 143–151, 2002.

[40] ZigBee Alliance. www.zigbee.org.

Appendices

Appendix A

javadoc

A.1 Package org.ucsb.mayhem.diomedes

Package Contents *Page*

Interfaces

Classes

A.1.1 Interface SampleHandler

Sample Handler. Interface for any class capable of receiving samples.

Declaration

public interface SampleHandler

All known subinterfaces

TempGauge (in A.1.28, page 117), TempChannel (in A.1.27, page 116), SampleLogger (in A.1.2, page 76), Mote (in A.1.24, page 109), LightChannel (in A.1.21, page 107), GraphGauge (in A.1.20, page 106), Gauge (in A.1.19, page 103), FuelPumpLevelChannel (in A.1.18, page 102), FuelGauge (in A.1.17, page 101), FileSampleLogger (in A.1.16, page 99), EngineCoolantTempChannel (in A.1.15, page 98), DigitalGauge (in A.1.11, page 87), DialGauge (in A.1.10, page 86), ConsoleSampleLogger (in A.1.7, page 83), Channel (in A.1.6, page 79), ADCChannel (in A.1.4, page 77), AcceleratorPedalChannel (in A.1.3, page 76)

All classes known to implement interface

Mote (in A.1.24, page 109), Gauge (in A.1.19, page 103), Channel (in A.1.6, page 79)

Method summary

handleSample(Sample)

Methods

- **handleSample**
  `void` **handleSample**`( Sample s ) throws org.ucsb.mayhem.diomedes.WSNException`

A.1.2 Interface SampleLogger

Sample Logger. Parent interface for all logger classes.

Declaration

public interface SampleLogger
extends SampleHandler

All known subinterfaces

FileSampleLogger (in A.1.16, page 99), ConsoleSampleLogger (in A.1.7, page 83)

All classes known to implement interface

FileSampleLogger (in A.1.16, page 99), ConsoleSampleLogger (in A.1.7, page 83)

A.1.3 Class AcceleratorPedalChannel

Accelerator Pedal Channel. Represents the data coming from the 'requested throttle position' signal in a MINI Cooper S.

Declaration

public class AcceleratorPedalChannel
extends org.ucsb.mayhem.diomedes.ADCChannel (in A.1.4, page 77)

Constructor summary

AcceleratorPedalChannel() Default Constructor.

Method summary

convertUnits(Sample) Convert Units.

Constructors

- **AcceleratorPedalChannel**
  `public` **AcceleratorPedalChannel**`( )`

– **Description**
Default Constructor. Constructs the channel with known R1 and R2 values, as measured on the existing system.

Methods

- **convertUnits**
`public double` **convertUnits**`( Sample samp )`
  – **Description**
  Convert Units. Converts from a raw sample to the position of the accelerator pedal.
  – **Parameters**
    * `samp` – Sample to convert.
  – **Returns** – Pedal Position (0-100, w/ 100 = pedal to the metal)

A.1.4 Class ADCChannel

ADC Channel. Handles samples from ADC channels, converting them to Volts based on the values of R1 and R2 (resistor values in the circuit).

Declaration

public class ADCChannel
extends org.ucsb.mayhem.diomedes.Channel (in A.1.6, page 79)

All known subclasses

FuelPumpLevelChannel (in A.1.18, page 102), EngineCoolantTempChannel (in A.1.15, page 98), AcceleratorPedalChannel (in A.1.3, page 76)

Constructor summary

ADCChannel(int) Constructor.

Method summary

convertUnits(Sample) Convert Units.
getMaxV() Get Maximum Voltage.
setR1(long) Set Resistor 1.
setR2(long) Set Resistor 2.

Constructors

- **ADCChannel**
  `public` **ADCChannel**`( int ch )`
  - **Description**
    Constructor. Creates an ADC Channel handling the given ADC channel number.
  - **Parameters**
    - `ch` – ADC channel to handle (currently only FUNCTION_ADC2)

Methods

- **convertUnits**
  `public double` **convertUnits**`( Sample samp )`
  - **Description**
    Convert Units. Converts the reading into volts, based on the value of the sample and the resistors in the divider network.
  - **Parameters**
    - `samp` – Sample to convert
- **getMaxV**
  `public double` **getMaxV**`( )`
  - **Description**
    Get Maximum Voltage. Returns the maximum voltage reading, based upon the resistors in the voltage divider circuit.
  - **Returns** – max voltage
- **setR1**
  `public void` **setR1**`( long newR1 )`

- **Description**
  Set Resistor 1. Set the value of R1.
- **Parameters**
  - `newR1` – new value of R1

- **setR2**
  `public void` **setR2**`( long` **newR2** `)`
  - **Description**
    Set Resistor 2. Set the value of R2.
  - **Parameters**
    - `newR2` – new value of R2

A.1.5 Class ADCSample

ADC Sample. Represents a sample from an ADC channel.

Declaration

public class ADCSample
extends org.ucsb.mayhem.diomedes.Sample (in A.1.26, page 112)

Constructor summary

ADCSample(DiomedesTLMMsg)

Constructors

- **ADCSample**
  `public` **ADCSample**`( DiomedesTLMMsg` **m** `)`

A.1.6 Class Channel

Channel. Abstracts the concept of a data stream from a single mote.

Declaration

public abstract class Channel
extends java.lang.Object
implements SampleHandler

All known subclasses

TempChannel (in A.1.27, page 116), LightChannel (in A.1.21, page 107), FuelPumpLevelChannel (in A.1.18, page 102), EngineCoolantTempChannel (in A.1.15, page 98), ADCChannel (in A.1.4, page 77), AcceleratorPedalChannel (in A.1.3, page 76)

Field summary

function
handlers
units
unitsName

Constructor summary

Channel(int) Constructor.

Method summary

addHandler(SampleHandler) Add Handler.
convertUnits(Sample) Convert Units.
getFunction() Get Function.
getUnits() Get Units.
getUnitsName() Get Units Name.
handleSample(Sample) Handle Sample.
setUnits(String) Set Units.
setUnitsName(String) Set Units Name.

Fields

- protected int **function**
- protected java.util.Vector **handlers**
- protected java.lang.String **units**
- protected java.lang.String **unitsName**

Constructors

- **Channel**
  `public` **Channel**`( int` **newfunc** `)`
  - **Description**
    Constructor. Creates a new `Channel` with the given function.
  - **Parameters**
    - `newfunc` – The function that this `Channel` should handle.

Methods

- **addHandler**
  `public void` **addHandler**`( SampleHandler` **hand** `)`
  - **Description**
    Add Handler. Registers a Handler with the `Channel`. Typically used with `Gauge`s.
  - **Parameters**
    - `hand` – Handler to register.
- **convertUnits**
  `public abstract double` **convertUnits**`( Sample` **samp** `)`
  - **Description**
    Convert Units. Method which all children must implement that converts from a raw ADC sample into engineering units.
  - **Parameters**
    - `samp` – sample to convert to EU.
- **getFunction**
  `public int` **getFunction**`( )`
  - **Description**
    Get Function. Returns the function of the `Channel`
  - **Returns** – The function of the `Channel`
- **getUnits**
  `public java.lang.String` **getUnits**`( )`

- **Description**
  Get Units. Returns the abbreviation of the `Channel`'s units.
- **Returns** – The abbreviation of the units of the `Channel` (e.g. V for Volts)

- **getUnitsName**
  `public java.lang.String` **getUnitsName**`( )`
  - **Description**
    Get Units Name. Gets the full name of the units of the `Channel`.
  - **Returns** – The full name of the units of the `Channel`. (e.g. "Volts" for Volts).

- **handleSample**
  `public void` **handleSample**`( Sample` **samp** `) throws org.ucsb.mayhem.diomedes.WSNException`
  - **Description**
    Handle Sample. Pass the sample to all registered handlers.
  - **Parameters**
    - `samp` – Sample to handle.
  - **Throws**
    - `org.ucsb.mayhem.diomedes.WSNException` – Sample is not handled within `Channel`.

- **setUnits**
  `public void` **setUnits**`( java.lang.String` **newunits** `)`
  - **Description**
    Set Units. Sets the abbreviation of the `Channel`'s units.
  - **Parameters**
    - `newunits` – The new abbreviation of the `Channel`'s units (e.g. "V" for Volts)

- **setUnitsName**
  `public void` **setUnitsName**`( java.lang.String` **newname** `)`
  - **Description**
    Set Units Name. Sets the full name of the units of the `Channel`.

- **Parameters**
  - `newname` – The full name of the units of the `Channel` (e.g. "Volts" for Volts)

A.1.7 Class ConsoleSampleLogger

Console Sample Logger. Logs all samples to stdout, instead of a file.

Declaration

public class ConsoleSampleLogger
extends java.lang.Object
implements SampleLogger

Constructor summary

ConsoleSampleLogger()

Method summary

handleSample(Sample)

Constructors

- **ConsoleSampleLogger**
  `public` **ConsoleSampleLogger**`( )`

Methods

- **handleSample**
  `public synchronized void` **handleSample**`( Sample s ) throws org.ucsb.mayhem.diomedes.WSNException`

A.1.8 Class consoletest

Console Test. Jumping-off point for Diomedes. Accepts command line arguments and constructs the system.

Declaration

public class consoletest
extends java.lang.Object

Constructor summary

consoletest()

Method summary

main(String[]) Main.

Constructors

- **consoletest**
  `public` **consoletest**`( )`

Methods

- **main**
  `public static void` **main**`( java.lang.String[] args )`
  - **Description**
    Main. Console entry point. Parses the command line, constructs the network, and builds the GUI.
  - **Parameters**
    - `args` – Command line arguments.

A.1.9 Class Constants

Declaration

public class Constants
extends java.lang.Object

Field summary

AM_DIOMEDESTLMMSG
FUNCTION_ADC0
FUNCTION_ADC1

FUNCTION_ADC2
FUNCTION_ADC3
FUNCTION_ADC4
FUNCTION_ADC5
FUNCTION_ADC6
FUNCTION_ADC7
FUNCTION_LIGHT
FUNCTION_TEMP

Constructor summary

Constants()

Fields

- public static final byte **FUNCTION_ADC2**
- public static final byte **FUNCTION_ADC5**
- public static final short **FUNCTION_LIGHT**
- public static final short **FUNCTION_ADC7**
- public static final byte **AM_DIOMEDESTLMMSG**
- public static final byte **FUNCTION_ADC6**
- public static final short **FUNCTION_TEMP**
- public static final byte **FUNCTION_ADC3**
- public static final byte **FUNCTION_ADC4**
- public static final byte **FUNCTION_ADC1**
- public static final byte **FUNCTION_ADC0**

Constructors

- **Constants**
  `public` **Constants**`( )`

A.1.10 Class DialGauge

Dial Gauge. Creates a generic Dial Gauge.

Declaration

public class DialGauge
extends org.ucsb.mayhem.diomedes.Gauge (in A.1.19, page 103)

Constructor summary

DialGauge(boolean) Constructor.

Method summary

handleSample(Sample) Handle Sample.
paintComponent(Graphics) Paint Component.

Constructors

- **DialGauge**
  `public` **DialGauge**`( boolean` **floating** `)`
  - **Description**
    Constructor. Construct a Dial Gauge and detatch it if requested.
  - **Parameters**
    - `floating` – Whether or not to detatch the frame.

Methods

- **handleSample**
  `public void` **handleSample**`( Sample` **samp** `) throws org.ucsb.mayhem.diomedes.WSNException`
  - **Description**
    Handle Sample. Stores the sample and calls `repaint()`.
  - **Parameters**
    - `samp` – Sample to handle.
  - **Throws**
    - `org.ucsb.mayhem.diomedes.WSNException` –

- **paintComponent**
  `protected void` **paintComponent**`( java.awt.Graphics g )`
  - **Description**
    Paint Component. Place the gauge image and render a needle in the correct direction.

A.1.11 Class DigitalGauge

Digital Gauge. A digital readout which displays the readings as text in a textbox.

Declaration

public class DigitalGauge
extends org.ucsb.mayhem.diomedes.Gauge (in A.1.19, page 103)

Constructor summary

DigitalGauge(boolean) Constructor.

Method summary

handleSample(Sample) Handle Sample.
paintComponent(Graphics) Paint Component.

Constructors

- **DigitalGauge**
  `public` **DigitalGauge**`( boolean` **floating** `)`
  - **Description**
    Constructor. Constructs a Digital gauge, detatching it if requested.
  - **Parameters**
    * `floating` – Whether or not to detatch the frame.

Methods

- **handleSample**
  `public void` **handleSample**`( Sample` **samp** `) throws org.ucsb.mayhem.diomedes.WSNException`
  - **Description**
    Handle Sample. Store the value of the sample and call `repaint()`
  - **Parameters**
    * `samp` – The sample to handle.
  - **Throws**
    * `org.ucsb.mayhem.diomedes.WSNException` –
- **paintComponent**
  `protected void` **paintComponent**`( java.awt.Graphics g )`
  - **Description**
    Paint Component. Write the sample to the text box.

A.1.12 Class DiomedesTLMMsg

Declaration

public class DiomedesTLMMsg
extends net.tinyos.message.Message

Field summary

AM_TYPE The Active Message type associated with this message.
DEFAULT_MESSAGE_SIZE The default size of this message type in bytes.

Constructor summary

DiomedesTLMMsg() Create a new DiomedesTLMMsg of size 7.
DiomedesTLMMsg(byte[]) Create a new DiomedesTLMMsg using the given byte array as backing store.
DiomedesTLMMsg(byte[], int) Create a new DiomedesTLMMsg using the given byte array as backing store, with the given base offset.

DiomedesTLMMsg(byte[], int, int) Create a new DiomedesTLMMsg using the given byte array as backing store, with the given base offset and data length.

DiomedesTLMMsg(int) Create a new DiomedesTLMMsg of the given data_length.

DiomedesTLMMsg(int, int) Create a new DiomedesTLMMsg with the given data_length and base offset.

DiomedesTLMMsg(Message, int) Create a new DiomedesTLMMsg embedded in the given message at the given base offset.

DiomedesTLMMsg(Message, int, int) Create a new DiomedesTLMMsg embedded in the given message at the given base offset and length.

Method summary

get_function() Return the value (as a int) of the field 'function'

get_packetnum() Return the value (as a int) of the field 'packetnum'

get_sample() Return the value (as a int) of the field 'sample'

get_source() Return the value (as a short) of the field 'source'

isArray_function() Return whether the field 'function' is an array (false).

isArray_packetnum() Return whether the field 'packetnum' is an array (false).

isArray_sample() Return whether the field 'sample' is an array (false).

isArray_source() Return whether the field 'source' is an array (false).

isSigned_function() Return whether the field 'function' is signed (false).

isSigned_packetnum() Return whether the field 'packetnum' is signed (false).

isSigned_sample() Return whether the field 'sample' is signed (false).

isSigned_source() Return whether the field 'source' is signed (false).

offset_function() Return the offset (in bytes) of the field 'function'

offset_packetnum() Return the offset (in bytes) of the field 'packetnum'

offset_sample() Return the offset (in bytes) of the field 'sample'

offset_source() Return the offset (in bytes) of the field 'source'

offsetBits_function() Return the offset (in bits) of the field 'function'

offsetBits_packetnum() Return the offset (in bits) of the field 'packetnum'
offsetBits_sample() Return the offset (in bits) of the field 'sample'
offsetBits_source() Return the offset (in bits) of the field 'source'
set_function(int) Set the value of the field 'function'
set_packetnum(int) Set the value of the field 'packetnum'
set_sample(int) Set the value of the field 'sample'
set_source(short) Set the value of the field 'source'
size_function() Return the size, in bytes, of the field 'function'
size_packetnum() Return the size, in bytes, of the field 'packetnum'
size_sample() Return the size, in bytes, of the field 'sample'
size_source() Return the size, in bytes, of the field 'source'
sizeBits_function() Return the size, in bits, of the field 'function'
sizeBits_packetnum() Return the size, in bits, of the field 'packetnum'
sizeBits_sample() Return the size, in bits, of the field 'sample'
sizeBits_source() Return the size, in bits, of the field 'source'
toString()

Fields

- public static final int **DEFAULT_MESSAGE_SIZE**
  - The default size of this message type in bytes.
- public static final int **AM_TYPE**
  - The Active Message type associated with this message.

Constructors

- **DiomedesTLMMsg**
  `public` **DiomedesTLMMsg**`( )`
  - **Description**
    Create a new DiomedesTLMMsg of size 7.
- **DiomedesTLMMsg**
  `public` **DiomedesTLMMsg**`( byte[] data )`
  - **Description**
    Create a new DiomedesTLMMsg using the given byte array as backing store.

- **DiomedesTLMMsg**
  `public` **DiomedesTLMMsg(** `byte[]` **data,** `int` **base_offset)**
  - **Description**
    Create a new DiomedesTLMMsg using the given byte array as backing store, with the given base offset.
- **DiomedesTLMMsg**
  `public` **DiomedesTLMMsg(** `byte[]` **data,** `int` **base_offset,** `int` **data_length)**
  - **Description**
    Create a new DiomedesTLMMsg using the given byte array as backing store, with the given base offset and data length.
- **DiomedesTLMMsg**
  `public` **DiomedesTLMMsg(** `int` **data_length)**
  - **Description**
    Create a new DiomedesTLMMsg of the given data_length.
- **DiomedesTLMMsg**
  `public` **DiomedesTLMMsg(** `int` **data_length,** `int` **base_offset)**
  - **Description**
    Create a new DiomedesTLMMsg with the given data_length and base offset.
- **DiomedesTLMMsg**
  `public` **DiomedesTLMMsg(** `net.tinyos.message.Message` **msg,** `int` **base_offset)**
  - **Description**
    Create a new DiomedesTLMMsg embedded in the given message at the given base offset.
- **DiomedesTLMMsg**
  `public` **DiomedesTLMMsg(** `net.tinyos.message.Message` **msg,** `int` **base_offset,** `int` **data_length)**
  - **Description**
    Create a new DiomedesTLMMsg embedded in the given message at the given base offset and length.

Methods

- **get_function**
  `public int` **get_function**`( )`
  - **Description**
    Return the value (as a int) of the field 'function'
- **get_packetnum**
  `public int` **get_packetnum**`( )`
  - **Description**
    Return the value (as a int) of the field 'packetnum'
- **get_sample**
  `public int` **get_sample**`( )`
  - **Description**
    Return the value (as a int) of the field 'sample'
- **get_source**
  `public short` **get_source**`( )`
  - **Description**
    Return the value (as a short) of the field 'source'
- **isArray_function**
  `public static boolean` **isArray_function**`( )`
  - **Description**
    Return whether the field 'function' is an array (false).
- **isArray_packetnum**
  `public static boolean` **isArray_packetnum**`( )`
  - **Description**
    Return whether the field 'packetnum' is an array (false).
- **isArray_sample**
  `public static boolean` **isArray_sample**`( )`
  - **Description**
    Return whether the field 'sample' is an array (false).

- **isArray_source**
  `public static boolean` **isArray_source**`( )`
  - **Description**
    Return whether the field 'source' is an array (false).
- **isSigned_function**
  `public static boolean` **isSigned_function**`( )`
  - **Description**
    Return whether the field 'function' is signed (false).
- **isSigned_packetnum**
  `public static boolean` **isSigned_packetnum**`( )`
  - **Description**
    Return whether the field 'packetnum' is signed (false).
- **isSigned_sample**
  `public static boolean` **isSigned_sample**`( )`
  - **Description**
    Return whether the field 'sample' is signed (false).
- **isSigned_source**
  `public static boolean` **isSigned_source**`( )`
  - **Description**
    Return whether the field 'source' is signed (false).
- **offset_function**
  `public static int` **offset_function**`( )`
  - **Description**
    Return the offset (in bytes) of the field 'function'
- **offset_packetnum**
  `public static int` **offset_packetnum**`( )`
  - **Description**
    Return the offset (in bytes) of the field 'packetnum'

- **offset_sample**
  `public static int` **offset_sample**`( )`
  - **Description**
    Return the offset (in bytes) of the field 'sample'
- **offset_source**
  `public static int` **offset_source**`( )`
  - **Description**
    Return the offset (in bytes) of the field 'source'
- **offsetBits_function**
  `public static int` **offsetBits_function**`( )`
  - **Description**
    Return the offset (in bits) of the field 'function'
- **offsetBits_packetnum**
  `public static int` **offsetBits_packetnum**`( )`
  - **Description**
    Return the offset (in bits) of the field 'packetnum'
- **offsetBits_sample**
  `public static int` **offsetBits_sample**`( )`
  - **Description**
    Return the offset (in bits) of the field 'sample'
- **offsetBits_source**
  `public static int` **offsetBits_source**`( )`
  - **Description**
    Return the offset (in bits) of the field 'source'
- **set_function**
  `public void` **set_function**`( int` **value** `)`
  - **Description**
    Set the value of the field 'function'

- **set_packetnum**
  `public void` **set_packetnum**`( int` **value** `)`
  - **Description**
    Set the value of the field 'packetnum'
- **set_sample**
  `public void` **set_sample**`( int` **value** `)`
  - **Description**
    Set the value of the field 'sample'
- **set_source**
  `public void` **set_source**`( short` **value** `)`
  - **Description**
    Set the value of the field 'source'
- **size_function**
  `public static int` **size_function**`( )`
  - **Description**
    Return the size, in bytes, of the field 'function'
- **size_packetnum**
  `public static int` **size_packetnum**`( )`
  - **Description**
    Return the size, in bytes, of the field 'packetnum'
- **size_sample**
  `public static int` **size_sample**`( )`
  - **Description**
    Return the size, in bytes, of the field 'sample'
- **size_source**
  `public static int` **size_source**`( )`
  - **Description**
    Return the size, in bytes, of the field 'source'

- **sizeBits_function**
  `public static int` **sizeBits_function**`( )`
  - **Description**
    Return the size, in bits, of the field 'function'
- **sizeBits_packetnum**
  `public static int` **sizeBits_packetnum**`( )`
  - **Description**
    Return the size, in bits, of the field 'packetnum'
- **sizeBits_sample**
  `public static int` **sizeBits_sample**`( )`
  - **Description**
    Return the size, in bits, of the field 'sample'
- **sizeBits_source**
  `public static int` **sizeBits_source**`( )`
  - **Description**
    Return the size, in bits, of the field 'source'
- **toString**
  `public java.lang.String` **toString**`( )`
  - **Description**

A.1.13 Class DummyMote

Dummy Mote. `Runnable` class to simulate the operation of a single mote in the system, for development.

Declaration

public class DummyMote
extends java.lang.Object
implements java.lang.Runnable

Constructor summary

DummyMote(short, short, double, WirelessSensorNetwork)
Constructor.

Method summary

run() Run.

Constructors

- **DummyMote**
  `public` **DummyMote(** `short` **newid,** `short` **newfunction,**
  `double` **freq,** `WirelessSensorNetwork` **wsn)**
  - **Description**
    Constructor. Creates a dummy mote with the given ID, function, data generation frequency, and network.
  - **Parameters**
    - `newid` – The ID of the mote.
    - `newfunction` – The function of the data to generate.
    - `freq` – The frequency to generate the data.
    - `wsn` – The associated WSN.

Methods

- **run**
  `public void` **run(** **)**
  - **Description**
    Run. Sleep based on the frequency and then wake up and generate some data.

A.1.14 Class DummyWirelessSensorNetwork

Dummy Wireless Sensor Network. A 'dummy' wsn which consists of three dummy motes generating data.

Declaration

public class DummyWirelessSensorNetwork
extends org.ucsb.mayhem.diomedes.WirelessSensorNetwork (in A.1.30, page 119)

Constructor summary

DummyWirelessSensorNetwork() Default Constructor.

Constructors

- **DummyWirelessSensorNetwork**
  `public` **DummyWirelessSensorNetwork**`( )`
  - **Description**
    Default Constructor. Create three dummy motes (1, 2, 3), all running at 10Hz.

A.1.15 Class EngineCoolantTempChannel

Engine Coolant Temp Channel. Channel which mirrors the operation of the MINI Cooper S engine coolant temperature gauge.

Declaration

public class EngineCoolantTempChannel
extends org.ucsb.mayhem.diomedes.ADCChannel (in A.1.4, page 77)

Constructor summary

EngineCoolantTempChannel() Default Constructor.

Method summary

convertUnits(Sample) Convert Units.

Constructors

- **EngineCoolantTempChannel**
  `public` **EngineCoolantTempChannel**`( )`

– **Description**

Default Constructor. Constructs an Engine Coolant Temperature Channel using the R1 and R2 values measured from the existing system.

Methods

- **convertUnits**
  `public double` **convertUnits**`( Sample samp )`
  - **Description**

    Convert Units. Converts raw sample into 0-100 value suitable for display.
  - **Parameters**
    - `samp` – The sample to convert
  - **Returns** – temp gauge reading (0-100(

A.1.16 Class FileSampleLogger

File Sample Logger. Writes samples to file for later analysis. Also presents appropriate GUI elements.

Declaration

public class FileSampleLogger
extends javax.swing.JPanel
implements SampleLogger, java.awt.event.ActionListener

Constructor summary

FileSampleLogger() Default Constructor.

Method summary

actionPerformed(ActionEvent) ActionPerformed.
handleSample(Sample) Handle Sample.
startLogging(String) Start Logging.
stopLogging() Stop Logging.
writeFileHeader() Write File Header.

Constructors

- **FileSampleLogger**
  `public` **FileSampleLogger**`( )`
  - **Description**
    Default Constructor. Construct a File Sample Logger, registering all button actions.

Methods

- **actionPerformed**
  `public void` **actionPerformed**`( java.awt.event.ActionEvent e )`
  - **Description**
    ActionPerformed. Handles Start and Stop button presses.
- **handleSample**
  `public synchronized void` **handleSample**`( Sample samp )`
  `throws org.ucsb.mayhem.diomedes.WSNException`
  - **Description**
    Handle Sample. If there is a valid file, write to it!
  - **Parameters**
    - `samp` – Sample to convert to a logfile line.
- **startLogging**
  `public void` **startLogging**`( java.lang.String fname )`
  - **Description**
    Start Logging. Starts logging to the filename given, if the file exists.
  - **Parameters**
    - `fname` – File to log to.
- **stopLogging**
  `public void` **stopLogging**`( )`
  - **Description**
    Stop Logging. Close the current logfile.
- **writeFileHeader**
  `public void` **writeFileHeader**`( )`

– **Description**
Write File Header. Start the logfile with the file header.

A.1.17 Class FuelGauge

Fuel Gauge. Gauge meant to mirror the MINI Cooper S's fuel gauge.

Declaration

public class FuelGauge
extends org.ucsb.mayhem.diomedes.Gauge (in A.1.19, page 103)

Constructor summary

FuelGauge(boolean) Constructor.

Method summary

handleSample(Sample) Handle Sample.
paintComponent(Graphics) Paint Component.

Constructors

- **FuelGauge**
`public` **FuelGauge**`( boolean` **floating** `)`
  - **Description**
    Constructor. Constructs a Fuel Gauge, either integrated or floating.
  - **Parameters**
    * `floating` – Whether or not to detach the frame.

Methods

- **handleSample**
`public void` **handleSample**`( Sample` **samp** `)`
`throws org.ucsb.mayhem.diomedes.WSNException`
  - **Description**
    Handle Sample. Stores the value of the sample and calls `repaint()`.
  - **Parameters**

* `samp` – Sample to handle.

– **Throws**

* `org.ucsb.mayhem.diomedes.WSNException` –

- **paintComponent**
  `protected void` **paintComponent**`( java.awt.Graphics g )`

  – **Description**

  Paint Component. Draws the gauge and renders a needle pointing to the appropriate place on the gauge.

A.1.18 Class FuelPumpLevelChannel

Fuel Pump Level Channel. Channel which converts the raw samples into a reading of fuel level on a MINI Cooper S.

Declaration

public class FuelPumpLevelChannel
extends org.ucsb.mayhem.diomedes.ADCChannel (in A.1.4, page 77)

Constructor summary

FuelPumpLevelChannel() Default Constructor.

Method summary

convertUnits(Sample) Convert Units.

Constructors

- **FuelPumpLevelChannel**
  `public` **FuelPumpLevelChannel**`( )`

  – **Description**

  Default Constructor. Constructs a fuel level channel assuming R1 and R2 values consistent measurements in the current system.

Methods

- **convertUnits**
  `public double` **convertUnits**`( Sample` **samp** `)`
  - **Description**
    Convert Units. Convert from raw samples to a 0-100 value meant to mirror the operation of the car's on-board fuel gauge.
  - **Parameters**
    * `samp` – Sample to convert.
  - **Returns** – fuel gauge reading (0-100)

A.1.19 Class Gauge

Gauge. Abstraction of a gauge, which embodies a sample-handling object and a GUI display.

Declaration

public abstract class Gauge
extends javax.swing.JPanel
implements SampleHandler

All known subclasses

TempGauge (in A.1.28, page 117), GraphGauge (in A.1.20, page 106), FuelGauge (in A.1.17, page 101), DigitalGauge (in A.1.11, page 87), DialGauge (in A.1.10, page 86)

Field summary

scaleMax Max and min displayed scale.
scaleMin Max and min displayed scale.
title Gauge title.
XOFFSET Internal graphical placement offsets.
YOFFSET Internal graphical placement offsets.

Constructor summary

Gauge() Default constructor.

Method summary

isScaleVisible() Is Scale Visible.
paintComponent(Graphics) Paint Component.
setScale(double, double) Set Scale.
setScaleVisible(boolean) Set Scale Visible.
setTitle(String) Set Title.
toFloat() To Float.

Fields

- protected double **scaleMax**
  - Max and min displayed scale.
- protected double **scaleMin**
  - Max and min displayed scale.
- protected java.lang.String **title**
  - Gauge title.
- protected static final int **XOFFSET**
  - Internal graphical placement offsets.
- protected static final int **YOFFSET**
  - Internal graphical placement offsets.

Constructors

- **Gauge**
  `public` **Gauge**`( )`
  - **Description**
    Default constructor. Constructs a `Gauge` with Arial as its title font.

Methods

- **isScaleVisible**
  `public boolean` **isScaleVisible**`( )`
  - **Description**
    Is Scale Visible. Checks the visibility of the scale.

  - **Returns** – Whether he scale numbering is visible (`true`: visible)

- **paintComponent**
  `protected void` **paintComponent**`( java.awt.Graphics g )`
  - **Description**
    Paint Component. Draws the title. Called by subclasses.
  - **Parameters**
    * `g` – `Graphics` context

- **setScale**
  `public void` **setScale**`( double` **min**`, double` **max** `)`
  - **Description**
    Set Scale. Adjusts the visible scale.
  - **Parameters**
    * `min` – Minimum value of the scale
    * `max` – Maximum value of the scale

- **setScaleVisible**
  `public void` **setScaleVisible**`( boolean` **val** `)`
  - **Description**
    Set Scale Visible. Changes whether the scale numbering is visible on the gauge.
  - **Parameters**
    * `val` – `true`: make visible; `false`: make invisible

- **setTitle**
  `public void` **setTitle**`( java.lang.String` **newTitle** `)`
  - **Description**
    Set Title. Sets the `String` title for the gauge.
  - **Parameters**
    * `newTitle` – The new value for the title.

- **toFloat**
  `protected void` **toFloat**`( )`
  - **Description**
    To Float. Causes the gauge to be rendered in a separate window, instead of the default mode as a child container.

A.1.20 Class GraphGauge

Graph Gauge. A gauge which graphs the data arriving at a `Channel`.

Declaration

public class GraphGauge
extends org.ucsb.mayhem.diomedes.Gauge (in A.1.19, page 103)
implements java.awt.event.ActionListener

Constructor summary

GraphGauge(boolean) Constructor.

Method summary

actionPerformed(ActionEvent) Action Performed.
handleSample(Sample) Handle Sample.
paintComponent(Graphics) Paint Component.

Constructors

- **GraphGauge**
  `public` **GraphGauge**`( boolean floating )`
  - **Description**
    Constructor. Constructs a Graph Gauge, displays buttons, and detatches the frame, if desired.
  - **Parameters**
    * `floating` – Whether or not to construct the frame detatched.

Methods

- **actionPerformed**
  `public void` **actionPerformed**`( java.awt.event.ActionEvent e )`
  - **Description**
    Action Performed. Handles the 'clear graph' button.
- **handleSample**
  `public void` **handleSample**`( Sample samp )`
  `throws org.ucsb.mayhem.diomedes.WSNException`

- **Description**
  Handle Sample. Adds the sample to the history array and fires off a `repaint()`
- **Parameters**
  - `samp` – The sample to add to the graph.
- **Throws**
  - `org.ucsb.mayhem.diomedes.WSNException` –

- **paintComponent**
  `protected void` **paintComponent**`( java.awt.Graphics g )`
  - **Description**
    Paint Component. Draw the graph based on the history array and the running max and min times.

A.1.21 Class LightChannel

Light Channel. Channel which handles onboard light sensor data.

Declaration

public class LightChannel
extends org.ucsb.mayhem.diomedes.Channel (in A.1.6, page 79)

Constructor summary

LightChannel()

Method summary

convertUnits(Sample) Convert Units.

Constructors

- **LightChannel**
  `public` **LightChannel**`( )`

Methods

- **convertUnits**
  `public double` **convertUnits**`( Sample` **samp** `)`
  - **Description**
    Convert Units. Converts the raw binary reading into an 'intensity', that is percenta of full scale.
  - **Parameters**
    - `samp` – The sample to convert.
  - **Returns** – light sensor reading (0-100)

A.1.22 Class LightSample

Light Sample. A sample taken from an onboard light sensor.

Declaration

public class LightSample
extends org.ucsb.mayhem.diomedes.Sample (in A.1.26, page 112)

Constructor summary

LightSample(DiomedesTLMMsg)

Constructors

- **LightSample**
  `public` **LightSample**`( DiomedesTLMMsg` **m** `)`

A.1.23 Class LogfileFilter

Declaration

public class LogfileFilter
extends javax.swing.filechooser.FileFilter

Constructor summary

LogfileFilter()

Method summary

accept(File)
getDescription()
getExtension(File)

Constructors

- **LogfileFilter**
  `public` **LogfileFilter**`( )`

Methods

- **accept**
  `public abstract boolean` **accept**`( java.io.File` **arg0** `)`
- **getDescription**
  `public abstract java.lang.String` **getDescription**`( )`
- **getExtension**
  `public java.lang.String` **getExtension**`( java.io.File` **f** `)`

A.1.24 Class Mote

Mote. Abstracts the concept of a mote from the sensor network. Mainly used to organize channels and to funnel samples to them.

Declaration

public class Mote
extends java.lang.Object
implements SampleHandler

Constructor summary

Mote(int) Constructor, ID only.
Mote(int, String) Constructor, ID and Name.

Method summary

addHandler(int, SampleHandler) Add Handler.
getID() Get ID.
getName() Get Name.
handleSample(Sample) Handle Sample.

Constructors

- **Mote**
  `public` **Mote(** `int` **newid)**
  - **Description**
    Constructor, ID only. Constructs a `Mote` using only the ID. The name of the mote defaults to the modeID.
  - **Parameters**
    * `newid` – The ID of the `Mote` to construct
- **Mote**
  `public` **Mote(** `int` **newid,** `java.lang.String` **newname)**
  - **Description**
    Constructor, ID and Name. Constructs a `Mote` using both the supplied ID and name.
  - **Parameters**
    * `newid` – The ID of the `Mote` to construct
    * `newname` – The explicit name to assign to the `Mote`

Methods

- **addHandler**
  `public void` **addHandler(** `int` **function,** `SampleHandler` **hand)**
  - **Description**
    Add Handler. Registers a handler to this `Mote` on the given `function`. Typically for a `Channel`.
  - **Parameters**
    * `function` – The channel to register the handler to (defined in `Constants.java`).

        * `hand` – The handler to register.
    - **See also**
        * Constants.java

- **getID**
  `public int` **getID**`( )`
    - **Description**
      Get ID. Returns the ID of this `Mote`.
    - **Returns** – The ID of this `Mote`.

- **getName**
  `public java.lang.String` **getName**`( )`
    - **Description**
      Get Name. Returns the name of this `Mote`.
    - **Returns** – The name of this `Mote`.

- **handleSample**
  `public void` **handleSample**`( Sample s )`
  `throws org.ucsb.mayhem.diomedes.WSNException`
    - **Description**
      Handle Sample. Routes the `Sample` to the appropriate, registered `Channel`.
    - **Parameters**
        * `s` – The `Sample` to handle.
    - **Throws**
        * `org.ucsb.mayhem.diomedes.WSNException` – If the channel corresponding to the `Sample` is not found.

A.1.25 Class RealWirelessSensorNetwork

Real Wireless Sensor Network. Wireless Sensor Network which listens on the serial port for active messages from the TinyOS `Basestation` node.

Declaration

public class RealWirelessSensorNetwork
extends org.ucsb.mayhem.diomedes.WirelessSensorNetwork (in A.1.30, page 119)

Constructor summary

RealWirelessSensorNetwork()

Constructors

- **RealWirelessSensorNetwork**
  `public` **RealWirelessSensorNetwork**`( )`

A.1.26 Class Sample

Sample. Encapsulates message data, receive timestamp, and the information necessary to convert the message's sample to engineering units.

Declaration

public abstract class Sample
extends java.lang.Object

All known subclasses

TempSample (in A.1.29, page 118), LightSample (in A.1.22, page 108), ADCSample (in A.1.5, page 79)

Field summary

chan The associate `Channel`, for the purposes of EU conversion.
m The original `Message` object.
timestamp Time of sample receipt at the computer.

Constructor summary

Sample(DiomedesTLMMsg) Constructor.

Method summary

getFileHeader() Get File Header.
getFunction() Get Function.
getPacketNumber() Get Packet Number.
getRawSample() Get Raw Sample.
getSource() Get Source.

getTimestamp() Get Timestamp.
getTimestampInMillis() Get Timestamp in Milliseconds.
getTimestampInS() Get Timestamp in Seconds.
getUnits() Get Units.
getUnitsName() Get Units Name.
getValue() Get Value.
setChannel(Channel) Set Channel.
toLog() To Log.

Fields

- protected java.util.Calendar **timestamp**
  - Time of sample receipt at the computer.
- protected DiomedesTLMMsg **m**
  - The original `Message` object.
- protected Channel **chan**
  - The associate `Channel`, for the purposes of EU conversion.

Constructors

- **Sample**
  `public` **Sample**`( DiomedesTLMMsg` **newm** `)`
  - **Description**
    Constructor. Stores the message, timestamps, and returns.
  - **Parameters**
    - `newm` – `Message` to convert to a `Sample`

Methods

- **getFileHeader**
  `public static java.lang.String` **getFileHeader**`( )`
  - **Description**
    Get File Header.
  - **Returns** – The standard logfile header, in `String` format.

- **getFunction**
  `public int` **getFunction**`( )`
  - **Description**
    Get Function.
  - **Returns** – The function from the `Message`
- **getPacketNumber**
  `public int` **getPacketNumber**`( )`
  - **Description**
    Get Packet Number.
  - **Returns** – The packet number from the `Message`
- **getRawSample**
  `public int` **getRawSample**`( )`
  - **Description**
    Get Raw Sample.
  - **Returns** – The raw sample from the `Message`
- **getSource**
  `public int` **getSource**`( )`
  - **Description**
    Get Source.
  - **Returns** – The source mote from the `Message`
- **getTimestamp**
  `public java.lang.String` **getTimestamp**`( )`
  - **Description**
    Get Timestamp.
  - **Returns** – The timestamp of the receipt, in String format.
- **getTimestampInMillis**
  `public long` **getTimestampInMillis**`( )`
  - **Description**
    Get Timestamp in Milliseconds.

  - **Returns** – The timestamp of the receipt, in milliseconds since the epoch.

- **getTimestampInS**
  `public long` **getTimestampInS**`( )`
  - **Description**
    Get Timestamp in Seconds.
  - **Returns** – The timestamp of the receipt, in seconds since the epoch.

- **getUnits**
  `public java.lang.String` **getUnits**`( )`
  - **Description**
    Get Units. Returns a `String` containing the units of the value, suitable for concatenation to the end of the value in a display.
  - **Returns** – The abbreviation of the value's engineering units (e.g. V, km).

- **getUnitsName**
  `public java.lang.String` **getUnitsName**`( )`
  - **Description**
    Get Units Name. Returns the full name of the units of the value.
  - **Returns** – The full name of the value's engineering units (e.g. Volts, Kilometers).

- **getValue**
  `public double` **getValue**`( )`
  - **Description**
    Get Value. Converts the raw sample value into Engineering Units with the help of the associated `Channel`.
  - **Returns** – The value of the sample, in engineering units.

- **setChannel**
  `public void` **setChannel**`( Channel c )`
  - **Description**
    Set Channel. Associates a `Channel` with the `Sample`, allowing EU conversions.

- **Parameters**
  - `c` – The `Channel` to associate.

- **toLog**
  `public java.lang.String` **toLog**`( )`
  - **Description**
    To Log.
  - **Returns** – The `Sample` as a logfile line.

A.1.27 Class TempChannel

Temperature Channel. Converts raw binary readings from on-board temperature sensor into degrees Celcius.

Declaration

public class TempChannel
extends org.ucsb.mayhem.diomedes.Channel (in A.1.6, page 79)

Constructor summary

TempChannel() Default Constructor.

Method summary

convertUnits(Sample) Convert Units.

Constructors

- **TempChannel**
  `public` **TempChannel**`( )`
  - **Description**
    Default Constructor.

Methods

- **convertUnits**
  `public double` **convertUnits**`( Sample` **samp** `)`
  - **Description**
    Convert Units. Converts a sample into Celcius, based on the conversion curve found in the Crossbow documentation.
  - **Parameters**
    - `samp` – Sample to convert
  - **Returns** – sample in degrees Celcius

A.1.28 Class TempGauge

Temperature Gauge. Temperature gauge, consisting of a thermometer which displays the value with the level of a red indication 'fluid'.

Declaration

public class TempGauge
extends org.ucsb.mayhem.diomedes.Gauge (in A.1.19, page 103)

Constructor summary

TempGauge(boolean) Constructor.

Method summary

handleSample(Sample) Handle Sample.
paintComponent(Graphics) Paint Component.

Constructors

- **TempGauge**
  `public` **TempGauge**`( boolean` **floating** `)`
  - **Description**
    Constructor. Sets the size, loads the overlay image, initializes the container, and then spawns the floating frame, if desired.
  - **Parameters**

* `floating` – Whether to launch the gauge as floating.

Methods

- **handleSample**
  `public void` **handleSample**`( Sample` **samp** `)`
  `throws org.ucsb.mayhem.diomedes.WSNException`
  - **Description**
    Handle Sample. Saves the sample value and units and repaints.
- **paintComponent**
  `protected void` **paintComponent**`( java.awt.Graphics g )`
  - **Description**
    Paint Component. Draws the temperature gauge with the appropriate level.
  - **Parameters**
    * `g` – `Graphics` context.

A.1.29 Class TempSample

TempSample. Sample from a temperature sensor.

Declaration

public class TempSample
extends org.ucsb.mayhem.diomedes.Sample (in A.1.26, page 112)

Constructor summary

TempSample(DiomedesTLMMsg)

Constructors

- **TempSample**
  `public` **TempSample**`( DiomedesTLMMsg` **msg** `)`

A.1.30 Class WirelessSensorNetwork

Wireless Sensor Network. Encapsulates the first layer of packet handling from a WSN.

Declaration

public abstract class WirelessSensorNetwork
extends java.lang.Object
implements net.tinyos.message.MessageListener

All known subclasses

RealWirelessSensorNetwork (in A.1.25, page 111), DummyWirelessSensorNetwork (in A.1.14, page 97)

Field summary

handlers All first-level packet handlers (i.e.
motes Known motes in the network.

Constructor summary

WirelessSensorNetwork() Default constructor.

Method summary

addGlobalHandler(SampleHandler) Add Global Handler.
addHandler(int, int, SampleHandler) Add Handler.
messageReceived(int, Message) Message Received.

Fields

- protected java.util.Vector **handlers**
  - All first-level packet handlers (i.e. loggers).
- protected java.util.Vector **motes**
  - Known motes in the network.

Constructors

- **WirelessSensorNetwork**
  `public` **WirelessSensorNetwork**`( )`
  - **Description**
    Default constructor. Creates the wireless sensor network with three motes: 1, 2, 3.

Methods

- **addGlobalHandler**
  `public void` **addGlobalHandler**`( SampleHandler` **hand** `)`
  - **Description**
    Add Global Handler. Registers a handler which is called on all messages. This is typically a logging object.
  - **Parameters**
    - `hand` – The handler object to register.
- **addHandler**
  `public void` **addHandler**`( int` **moteID**`, int` **function**`,`
  `SampleHandler` **hand** `)`
  - **Description**
    Add Handler. Registers a `SamplerHandler` with the appropriate mote and on the proper channel.
  - **Parameters**
    - `moteID` – The id of the mote with which to register the handler
    - `function` – The function, or channel, of data to handle
    - `hand` – The handler object to register.
- **messageReceived**
  `public void` **messageReceived**`( int` **dest_addr**`,`
  `net.tinyos.message.Message` **msg** `)`
  - **Description**
    Message Received. Converts the message to a `Sample` and then passes it to the appropriate `Mote` and to any registered `SampleHandler`s.
  - **Parameters**

- `dest_addr` – The destination address of the packet (should always be '10')
- `msg` – The actual contents of the message

A.1.31 Exception WSNException

Wireless Sensor Network Exception. Thrown when errors are found in a packet received from the packetforwarder. Ceases all further processing of the packet.

Declaration

public class WSNException
extends java.lang.Exception

Constructor summary

WSNException(String)

Constructors

- **WSNException**
  `public` **WSNException**`( java.lang.String` **message** `)`

Appendix B

nesdoc

B.1 Diomedes Application

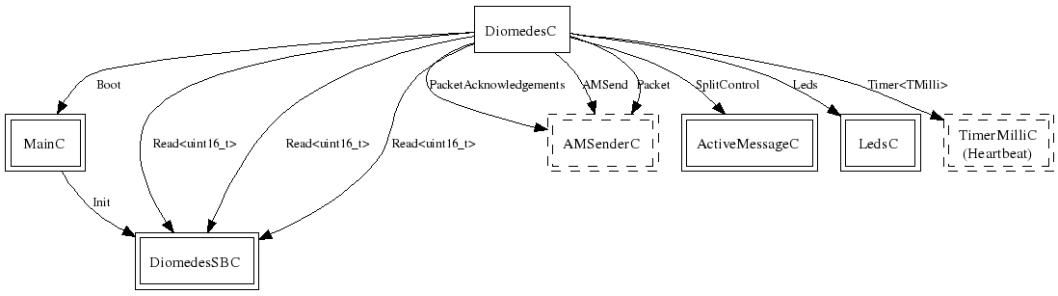


Figure B.1: DiomedesAppC Dependencies

B.1.1 DiomedesAppC

```
Configuration for the Diomedes Application.
Author: Erik Peterson
```

B.1.2 DiomedesC

```
Implementation for the Diomedes Application.
Author: Erik Peterson
```

Uses

- interface `PacketAcknowledgements` as `Acks`
- interface `Leds`
- interface `Read<uint16_t>` as `ADC2`
- interface `Timer<TMilli>` as `MilliTimer`
- interface `SplitControl` as `RadioControl`
- interface `Read<uint16_t>` as `Light`
- interface `Packet`
- interface `Read<uint16_t>` as `Temp`
- interface `AMSend`
- interface `Boot`

B.2 Diomedes Sensorboard

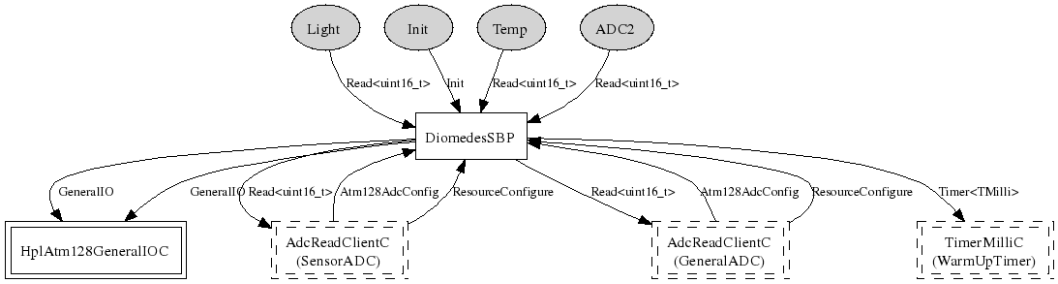


Figure B.2: DiomedesSB Dependencies

B.2.1 tos.sensorboards.diomedessb.DiomedesSBP

```
Implementation of the Diomedes Sensorboard software.

Author: Erik Peterson (wombatty@alumni.cs.ucsb.edu)
```

Uses

- interface `Timer<TMilli>` as `WarmUpTimer`
- interface `Read<uint16_t>` as `GeneralADC`
- interface `GeneralIO` as `TempPin`
- interface `GeneralIO` as `LightPin`
- interface `TaskBasic` as `getSample`
- interface `Read<uint16_t>` as `SensorADC`

Provides

- interface `ResourceConfigure` as `ADC2ResourceConfig`
- interface `ResourceConfigure` as `SensorADCResourceConfig`
- interface `Atm128AdcConfig` as `SensorADCAtm128AdcConfig`
- interface `Atm128AdcConfig` as `ADC2Atm128AdcConfig`
- interface `Read<uint16_t>` as `ADC2`
- interface `Read<uint16_t>` as `Light`
- interface `Read<uint16_t>` as `Temp`
- interface `Init`

B.2.2 tos.sensorboards.diomedessb.DiomedesSBC

```
Modified to work with the temp sensor on an MTS series board.
Author: Erik Peterson
```

Provides

- interface `Read<uint16_t>` as `Temp`
- interface `Init`
- interface `Read<uint16_t>` as `ADC2`
- interface `Read<uint16_t>` as `Light`