TephraNet: Wireless Self-Organizing Network Platform for Environmental Sensing

By

Andrew J. Wheeler

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ABSTRACT

The growing number of threats to the Earth's environment necessitates the gathering of fine-grained environmental sensor data to deepen our understanding of endangered species and assist in their protection. Traditional techniques for gathering environmental data, such as periodic field studies or satellite imaging, do not produce adequately detailed or persistent information. Self-organizing wireless networking provides an ideal way to quickly deploy and gather data from sensor networks in the field. The design of a practical, low-cost, and self-organizing wireless sensor network, TephraNet, is examined. This thesis also explores an implementation and deployment of TephraNet in Hawaii Volcanoes National Park to learn about the endangered ground plant *Silene hawaiiensis.*

Thesis Supervisor: Michael J. Hawley
Title: Assistant Professor of Media Arts and Sciences

Acknowledgements

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Table of Contents

Table of Figures

Chapter 1 Overview

1.1 Introduction

Researchers at the University of Hawaii Botany Department would love to understand the ecology of the rare *Silene hawaiiensis* plant. Existing only in a tiny microclimate region at the edge of a volcano crater in Hawaii Volcanoes National Park, little is known about this plant or its habitat. In an age of satellites and weather stations everywhere, it is hard to believe that so little could be known about the climate this plant lives in. The details of its habitat are too small to be noticed by satellites. The nearest weather station, a mere 3.5 miles away, is in a rainforest, while the *Silene* plant appears to be growing in a desert.

Little is known about the hardy Silene *plant. It is found only in one microclimate zone on the Big Island of Hawaii.*

Photo by Kim Bridges

Figure 1.1 *Silene hawaiiensis* in Hawaii

The lack of knowledge about the *Silene* plant and its habitat is just one example of a much broader problem. The environment of the earth is under siege. Pollution from industrial processes are reaching even the most remote points of the earth and affecting the complex ecosystem in ways that are barely understood. We have no time lapse view of the earth's environment. Tools that can capture a fine grained picture must be developed — and must be self-maintaining if there is to be any hope of blanketing the earth with them. The TephraNet system provides one example of a tool that can be used to assist in gathering long term sensory

data. This thesis describes the TephraNet system in detail and overviews the deployment in the *Silene's* native environment.

TephraNet weather station disguised as a rock (center), silently gathers data about the Silene's *environment.*

Photo by Michael Hawley

Figure 1.2 TephraNet Weather Rock

The TephraNet system described in this thesis consists of around 100 miniature weather stations designed to capture ecodata and relay it back for analysis. Due to the terrain covered by the *Silene* habitat, and the need for a fast deployment, the system was wireless and self-organizing. The system, disguised as rocks and tree branches was sprinkled around the *Silene* habitat. Each weather rock or branch is both a data gathering device and a relay point for other weather stations. The system organizes itself into a network and passes the data back to collection point.

1.2 Motivation

In addition to the desire to create an environmental monitoring system to aid in the study of endangered species, this thesis is motivated by several additional goals.

1.2.1 Platform for the study of Self-Organizing Wireless Networks

The relatively young field of self-organizing wireless networks has focused much of its effort on the use of simulators, such as NS-2 [NS01], for development and testing of algorithms. While simulators are valuable for getting a rough idea of how a particular algorithm performs, the current simulator technology either requires vast resources to be accurate, or does not capture many of the details of a real-world, resource constrained environment [Heidemann00].

TephraNet aims to provide a reference platform for environmental sensing and self-organizing network research.

Since simulators alone are not adequate for detailed testing of self-organizing wireless networks, a standard physical platform is needed to complete the testing suite used. The few testing platforms that have been built to date are primarily high cost and therefore prohibitive for research on large networks [Cerpa01] [Rockwell01]. This suggests the need for a low-cost, readily manufactured platform to serve as a standard testing environment for self-organizing wireless networks.

1.2.2 Proof of concept for self-organizing wireless networks applied to environmental sensing

An additional goal of this thesis is to demonstrate the viability of self-organizing wireless networks as a tool for use in environmental sensing. Current approaches, which are detailed below in Chapter 2, often yield only a brief snapshot of an area, or a high level view that misses out on important micro-climate details. Self-organizing wireless networks offer one possible approach towards filling in the gap in the current set of tools. The wireless and self-organizing network approach to these tools offers potential advantages in setup and maintenance costs over traditional wired approaches. Through the field deployment of a TephraNet system, this thesis aims to show the usefulness of this technology as an environmental research tool.

1.2.3 Validation of GRAd Routing Algorithm

The development of the TephraNet system was inspired in part by previous work in the Personal Information Architecture group at the MIT Media Laboratory on Hyphos and GRAd, by Dr. Robert Poor [Poor01]. The routing algorithms proposed by that research received preliminary testing in a real-world system, ArborNet, but were not fully implemented for that revision. One motivation for this thesis is the testing of a complete implementation of the GRAd routing algorithm in a physical installation.

ArborNet was the precursor to TephraNet and provided many useful design lessons.

Photo by Charlotte

Figure 1.3 ArborNet

1.2.4 Scope

The scope of this thesis includes the goals stated in this section, primarily focusing on the design of the TephraNet system. This thesis does not focus on the analysis or interpretation of environmental data, but rather on the system to gather that data.

1.3 Thesis Structure

The remainder of this thesis is comprised of four chapters. Chapter 2 provides a short background on traditional environmental sensing as well as a review of prior work in self-organizing wireless networks.

The design goals and high level design of the Tephranet system are presented in Chapter 3. The section begins with the design requirements and constraints, and follows with a view of the hardware and software systems that comprise TephraNet.

A prime motivation for this work is a field-deployment of the platform to test out the design in a non-laboratory environment. Chapter 4 contains a description of the field-deployment in Hawaii Volcanoes National Park. Beginning with the design of deployment-specific portions of the system, the section concludes with details about the study site and the field test.

The test of the system in Hawaii uncovered interesting findings relating to the networking algorithms used in the system design. Chapter 5 discusses these results, how well the system attained its goals, and future directions for work in this area.

Chapter 2 Background Research and Context

2.1 Existing Environmental Sensing Technologies

A review of the existing methods used for the collection of environmental data for scientific research reveals a gap in the selection of tools that motivated the design of the TephraNet system.

Existing methods for gathering environmental data about a study area fall primarily into two categories. The first is what could be termed traditional field measurement techniques, including scientists in the field, and individual sensor devices, such as weather stations. The second primary category is satellite imagery.

Traditional field research involves manual gathering of information in the field.

Photo by Michael Hawley

Figure 2.1 Gathering Data in the Field

Traditional field measurement techniques rely on researchers in the field using hand-held and portable instrumentation to gather data about a specific site. This works well for isolated or small regions, and for measurements that do not need to be taken with frequency. However, once a measurement is required with a frequency greater than weeks or days, scientists usually turn to automated equipment, such as remote weather probes.

Remote weather probes, such as this one at Everest Base camp, capture a pinpoint view of the weather at a place.

Photo by Matthew Lau

Figure 2.2 Everest Weather Probe

Remote weather probes, such as the Everest Weather Probe, developed at the MIT Media Lab, can autonomously measure weather conditions every hour and report them via a satellite connection [Lau98]. These measurements give a clear picture of the weather at a particular point on Everest, but fail to show what the weather is like on the whole mountain. Both hand measurement and remote instrumentation often lack the ability to provide the detailed view of what is going on. For example, on the Big Island of Hawaii, many micro-climate zones exist. A weather station located in a rainforest may not be able to provide any information about the desert immediately next to it.

Satellite images provide great big-pictures views, but often miss important details.

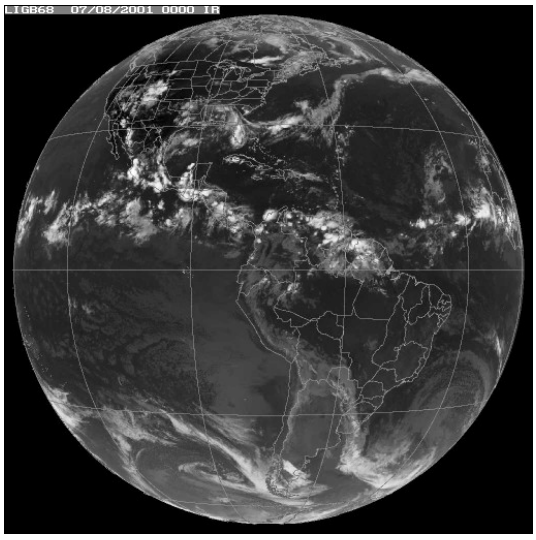


Figure 2.3 Satellite Weather Map

Satellite imaging provides the ultimate big-picture view of an environment, often able to take in a whole continent or hemisphere at a time. This

overview image is useful for capturing geographically large trends, such as the movements of a large storm. What satellite imagery is often lacking is the fine grained detail that can captures the most important events or trends in a small environment. A botanist wishing to learn about the pollination mechanisms for a particular flower may wish to know the wind characteristics right next to the plant- a level of detail beyond what a weather satellite captures.

A new type of observation tool is required that can measure and record detailed and long term information about an environment in a cost effective manner. Consider the scenario where an animal researcher wishes to learn what sort of sounds a particular animal makes when a very rare even occurs. Traditional observation techniques such as a few hidden microphones or a researcher in the field may take an unacceptable amount of time or money to record the sound. If the habitat of the animal could be blanketed with miniature sound recorders in a cost effective manner, then the answer could be heard sooner.

2.2 Self-Organizing Wireless Network Research

Self-organizing wireless network research presents an ideal match for many of the needs of the environmental sensing community.

One field of research in the networking and defense communities has great potential for application to the environmental sensing problem. Self-organizing (or ad-hoc) wireless sensor networking is an area that until recently existed almost entirely in simulation. The research in this field centers on the development of routing algorithms that allow a random collection of wireless nodes to form a data network. Each node in the network is not only a potential sensor or data source, but also a relay node. The network is like a bucket brigade, where messages are passed along from neighbor to neighbor on the way to the final destination.

These networks offer many advantages over traditional wireless networking, including spatial frequency reuse, increased reliability, and low setup and maintenance overhead. [Poor01] presents a good overview of the advantages of this type of networking. An overview of the types of routing algorithms present in the research field can be found in [Broch98] and [Johansson99]. Readers interested in a comparison of the GRAd routing algorithm used in the TephraNet implementation and other more mainstream algorithms, such as AODV and DSR, should refer to [Wheeler00].

The ad-hoc networking research community needs a hardware platform to compliment the currently used software simulators.

To date, most of the research in the field has been performed in simulators, most notably in NS-2 (network simulator 2) [NS01]. While network simulation provides a reasonable first pass at simulating the characteristics of an algorithm, it does not capture many real world characteristics of wireless networks. In particular, the NS-2 simulator does not provide a particularly accurate wireless simulation environment. It is missing key elements such as simulation of external interference and changing noise floors. An evaluation of the make up a self-organizing sensor network beyond the routing algorithms is difficult to do without a physical platform. A few university and military research groups, notably [Cerpa01] and [Rockwell01] have created physical platforms for ad-hoc networking research. These platforms have not been scaled to large numbers, primarily because of prohibitive cost, and are not common between the various groups, making result comparison difficult. A low cost sensor platform, COTS SmartDust, suitable for field deployment is presented in [Hollar01]. Although this platform is low cost and has been released to the community, it has very limited computing and memory resources, and runs a custom operating system, making it unlikely to be a good general purpose research platform.

Current platforms for sensor network study tend to either be prohibitively expensive or very resource constrained.

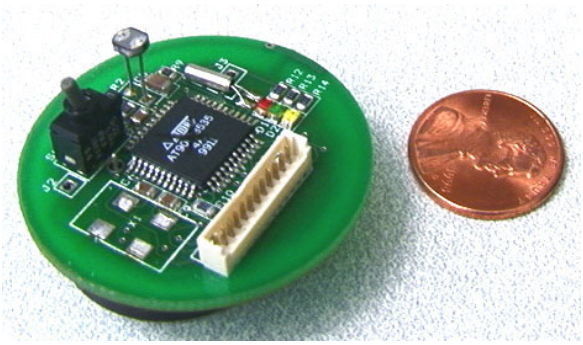


Photo from Seth Hollar

Figure 2.4 COTS SmartDust Platform

The TephraNet platform, described in detail in the next chapter, provides a solution for both environmental sensing and self-organizing wireless network research. It provides environmental researchers with a prototype sensing platform, while also providing ad-hoc networking researchers a common physical platform on which to test out algorithms.

Chapter 3 TephraNet System Design

3.1 Functional Description

The TephraNet platform consists of a number of the basic building blocks – TephraNodes. These nodes may be used both as a sensor network to gather environmental data, as discussed in the previous sections, or as the basic components of a network algorithm test bed.

TephraNodes awaiting programming and deployment.

Photo by Michael Hawley

Figure 3.1 TephraNodes

3.1.1 TephraNet as Sensor Network Demonstration

In the context of the TephraNet platform as a platform for environmental sensor data gathering, each TephraNet consists of two basic pieces: TephraNodes with sensors, and gateway nodes to collect data. In order to construct a complete data gathering solution, a number of TephraNodes are placed around a target observation area. The nodes, using the service discovery and network routing services, form an ad-hoc network as described in Chapter 2. Once formed, each node in the network can both relay packets for their neighbors, as well as gather sensor data. The TephraNodes can perform local processing on the data before determining to send reports to the data collection points within the network.

3.1.2 TephraNet as Networking Algorithm Testbed

In order to ensure that the TephraNet platform can also be used as a general network routing algorithm test bed, the software pertaining to the networking routing must be replaceable with another network routing

algorithm. The hardware and software that makes up TephraNet must contain enough expansion abilities to be amenable to hosting both software and hardware peripherals that would be desired for the testing of other network routing algorithms.

3.2 Design Goals

TephraNet is designed with manufacturability, low power and ease of use in mind.

TephraNet has several design goals that are presented in this section. These goals derive from the thesis goals of creating TephraNet as a platform for both environmental field work and for testing wireless networking algorithms.

3.2.1 Manufacturability

The goal of using the TephraNet platform as a common hardware system to test networking algorithms dictates that the components used in the design are easily procurable in research lab quantities and ideally manufacturable and serviceable in a standard academic laboratory environment. Since the TephraNet system was to be field deployed during the course of the thesis research, the designed platform had to be manufacturable within a short time schedule. This required using off-the-shelf and readily available components where possible and ensuring that the system could be tested easily.

3.2.2 Low Power

In order for the TephraNet system to be useful for most field research, the system has to function for at least a month on available power. This requirement dictates that all the hardware designed into the platform is as generally low power as possible and have special low-power or sleep modes where possible. A software power management system is required in addition to the hardware both of which will effectively control the low power modes of the hardware in order to extract maximum battery life.

3.2.3 Ease of Development and Software Flexibility

A major goal of the TephraNet platform is ease of development, both for hardware components and software components. Due to the short development and manufacturing schedules, the amount of custom component design required (i.e. custom chips, custom software) should be minimized. Design environments for the hardware and software are important beyond the development of the initial platform. Developing

additional software and hardware components for the finished system should be easy. Those who wish to use TephraNet as an environmental platform should have to do minimal work to add sensors and configure reporting characteristics, while those who use TephraNet as a test platform should have a well designed and open software environment in which to test their algorithms.

3.2.4 Autonomous

The TephraNet system needs to be autonomous and easy to use in order to cater to people not familia with the field of networking. Beyond the ability of the system to route data without configuration, this includes the setup and on-going maintenance of the network. As new nodes are placed into the network during initial deployment and any future expansions, they should integrate with a minimum of effort. The network should also be able to automatically adjust to new services and data collection points placed into the network.

3.3 Hardware Platform Description

This section presents a high level view of the hardware, showing block diagrams of the system and noting rationale for specific hardware component choices. Readers interested in obtaining detailed schematics and parts listings should refer to Appendix A: Hardware Design.

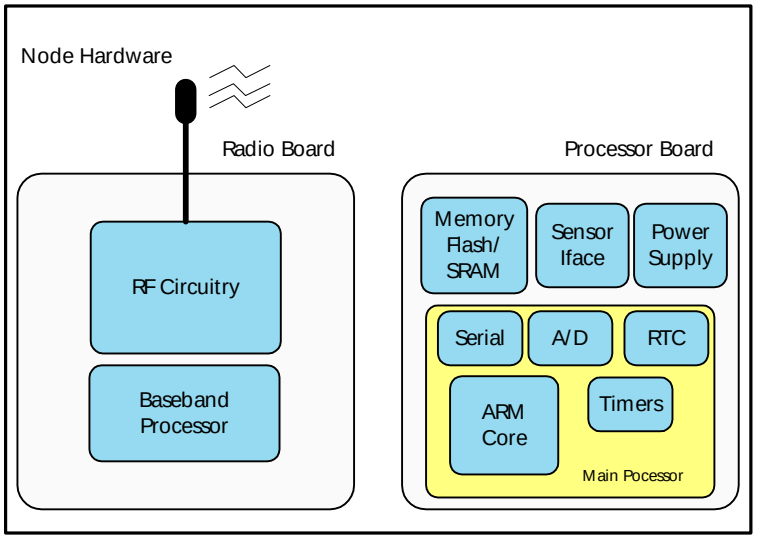


Figure 3.2 TephraNode Hardware

Each of the basic hardware blocks is shown in Figure 3.2. Early in the design process, the blocks comprising the radio were placed on a second board. This separation eased the simultaneous development of the analog RF board and the digital processor board. The size of the two boards is the same in order to facilitate an easy mechanical interconnect. The size is the minimal optimal size to act as a good groundplane for a ¼ wave commercially available "whip" antenna for the radio. The completed board stack can be seen in Figure 3.3. The specific motivation behind the choice of each component is presented below. The overall motivation is for a low-cost flexible platform.

TephraNode hardware: the radio is on top, the processor on bottom.

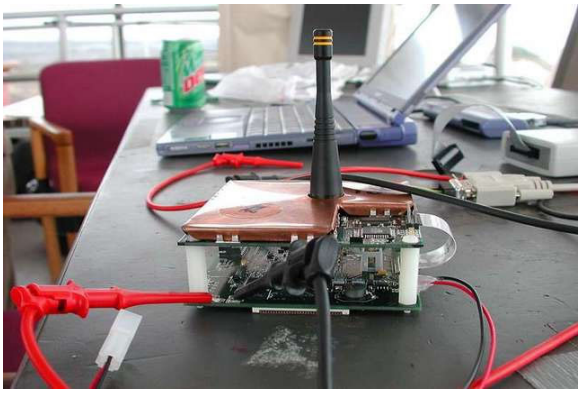


Photo by Michael Hawley

Figure 3.3 TephraNode Hardware

3.3.1 Radio

The radio was selected to operate in a license free band and be frequency agile.

Several factors motivated the choice of radio for this design. First is the need to operate in an unlicensed band (also known as an ISM band- Industrial, Scientific, and Medical). The regulatory issues surrounding licensed bands, as well as the lack of tightly integrated RF components for bands other than SM or cellular bands, dictated the choice of an ISM band system. The ArborNet system [Poor01], which provided several design lessons used in this design, was build around an ISM band 915MHz single channel radio. Having only a single channel simplifies design, although it is desirable to be frequency agile in order to avoid interference. Most RF systems operating in unlicensed bands (or ISM bands) use some spread spectrum technique in order to comply with FCC Part 15 regulations. The ability to use a spread spectrum technique was therefore also a consideration in the design of the radio. Also, since some networking algorithms make use of received signal strength indicator (RSSI) to determine link quality and also adjust output power, an RSSI output and adjustable transmit power are required. Some commercial RF systems, such as 802.11 meet these requirements, although their power consumption is too high for use in the TephraNet system given the lifetime required.

The radio module is designed around the Texas Instruments TRF6900 ISM band transceiver. This IC contains much of the circuitry required to produce a radio module, which simplifies design and minimizes size. It also has substantially lower power consumption than other available radio IC's, as well as all of the features required above. The radio module is designed to operate at a raw channel data rate of 100kbps in the 902-936MHz band. Transmit power is controllable between approximately -20dBm and +4.5dBm. The radio module is attached to a ¼ wave whip antenna manufactured by Lynx Technologies, selected for its good performance, reasonable size, and low cost. The module has a measured range of approximately 150-300ft in open space.

One unusual feature in the radio design is its low cost crystal reference. Traditionally, highly accurate, expensive frequency references are required for RF systems. Since this radio is frequency agile, the software compensates for any inaccuracy in the crystal by adjusting the PLL in the radio based on a stored measurement of the crystal frequency from

testing. Mechanisms are in place to allow software compensation of frequency drift due to temperature fluctuations as well. Readers interested in the details of the design of the radio modules can refer to Appendix A.

3.3.2 Radio Baseband Processor

The baseband processor controls the radio module. It configures the radio, controls the power, transmit/receive state, formats the data correctly for transmission, as well as decodes received data. While it is common for a baseband processor to be implemented as a custom piece of hardware (as in 802.11 or Bluetooth RF systems), the design cycle for such a device was beyond the available time for the design. Because of the relatively low data rates involved, the TephraNet design uses a microcontroller processor to implement the baseband. Using a microcontroller also allows the baseband to be changed by future users of TephraNet.

Several low-power and low-cost microcontrollers were evaluated, including the PIC series from Microchip, and the AVR series from Atmel. The most important factor in the choice was the amount of available memory. Previous designs such as ArborNet encountered development difficulty due to lack of RAM space within the microcontroller to act as buffer space for incoming and outgoing packets. The Atmel AT90S8535 was chosen due to its large amount of RAM (512 bytes). The Atmel chip also contains an A/D converter, which is used to sample the analog RSSI output of the radio, a counter which can be used as a real time clock, and low power modes that allow power to be minimized. The implementation of the baseband features using the Atmel chip is discussed below in Section 3.4.2.

3.3.3 Main Microprocessor

The main processor is an ARM7TDMI, offering the best MIPS/watt ratio available today.

The processor chosen for the main system microprocessor is the Samsung S3C3410X, which is based on an Advanced RISC Machines ARM7TDMI 32bit processor core. The ARM7TDMI core was selected early in the design process as the main core for several reasons. First, the ARM7TDMI core is one of the most power efficient 32bit core in common use. Its widespread use in industry ensured that it had a significant amount of development tool support. Although a 32bit chip seems like potential overkill for this application, it ensures that time is not wasted attempting to squeeze code into a resource constrained part.

The Samsung chip was chosen out of the many chips designed around the ARM7TDMI core for its high level of integration and availability. Targeted at MP3 players and handheld devices, this chip integrates many essential peripherals, such as serial ports, memory controllers, a real time clock, and a high resolution (10 bit), high speed (500K samples/sec) A/D converter. The chip also contains several useful reduced power modes, including sleep and reduced speed. The high level of integration also ensures a more power efficient design than using separate chips to implement each function [Samsung01].

3.3.4 Memory

The TephraNet design ensures that there is a reasonable amount of memory to work with for the same reasons that a 32bit processor was chosen. Both program space as well as data space are maximized to avoid wasting development effort on minimizing resource use and to allow debug status to be maintained. Flash memory was selected as the memory technology for the program space since it can be programmed by the processor without the high voltage requirements of standard EEPROM and does not have the current draw or mechanical parts a hard drive would. SRAM is the choice for system memory technology because of its static nature. No power is used to refresh the memory, and SRAM can retain data even while the system is asleep.

The original design specified the use of an Intel stacked chip SRAM and flash component that combined 256KB SRAM and 2MB flash components into a single chip. However, subsequent availability problems led to the selection of separate 512KB Toshiba SRAM and a 4MB Intel flash chips. Unfortunately, availability also dictated the choice of a uBGA packaged for the Intel flash chips, which proved to be a large hurdle in manufacturing. Many smaller manufacturers and most academic labs are not set up for this miniature package, and future revisions should select a more standard package.

3.3.5 Expansion I/O

The TephraNode processor board contains over 100 pins of I/O, listed in Table 3.1.

Serial Port	4 pins	Standard RS232 port, primarily for debugging

JTAG Connector	20 pins	Used for programming and debugging the processor
Radio Interface	18 pins	Synchronous serial data and radio control signals
Analog Sensor Port	20 pins	Provided access to 5 A/D ports
Memory Bus Connector	60 pins	Access to memory and data bus of processor

Table 3.1 TephraNode I/O

The analog sensor port connects internally to an array of resistor pads that can be configured to attach to a large family of analog sensors without additional external hardware (all resistive or voltage out sensors). The memory bus connector allows more complicated modules to be added onto the TephraNode that provide additional services or features not in the base system. For example, a digital camera or high speed radio (such as 802.11) could make use of this port. All of the I/O ports mentioned are discussed in further detail in Appendix A.

3.3.6 Power Supply

A power supply was placed on the TephraNode to reduce the number of boards, although this could potentially reduce the flexibility of the system by forcing the user to use only certain battery configurations. The power supply can be bypassed to minimize this problem. The power supply is based on the Maxim MAX639 switching power supply controller IC. This controller was selected primarily for its very low (~10uA) quiescent current (current drawn when no load is present) and high efficiency (>90%) [Maxim97]. The low quiescent current simplifies the design significantly by allowing the power supply to stand alone without a special sleep control signal from the processor. A low dropout voltage and high efficiency ensure maximum utilization of the power stored in the power source.

3.4 Software Overview

The software running on the TephraNet system provides numerous services related to forming and maintaining a network, sending and receiving data, and managing power consumption at nodes. A diagram showing the various software components present in TephraNet is shown in Figure 3.4. This section presents a functional view of the software in the TephraNet system. Implementation details are located in Appendix B: Source Code Listing.

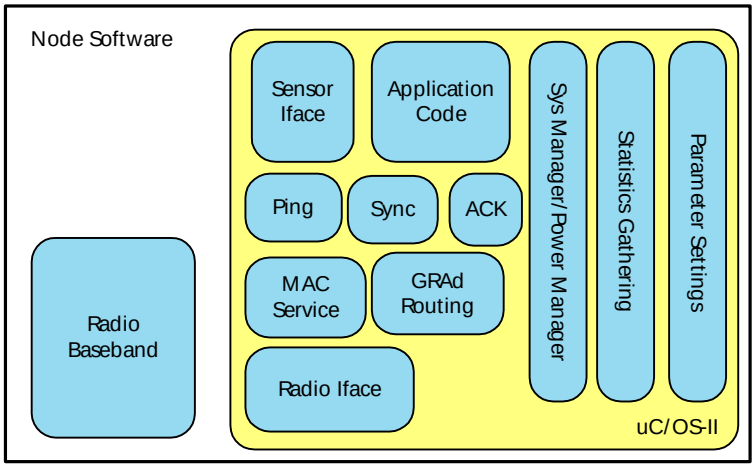


Figure 3.4 TephraNode Software

3.4.1 Node Lifecycle

After bootup, nodes alternate between an awake mode, where they can operate fully, and a low-power asleep mode, where all components are off except a clock.

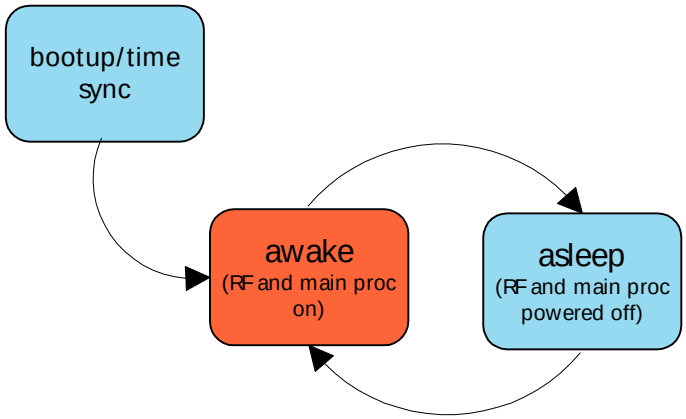


Figure 3.5 Node Lifecycle

A TephraNode progresses through several states during its lifecycle. When a node starts up, it goes through a bootup phase. During this period of time, the operating system is booted, and hardware peripherals are configured. The node then enters a synchronization period, where it attempts to synchronize its network time with any neighbor nodes that may be present. Once synchronization has been obtained, the node enters normal operation. During this period of time, the node alternates between being awake, and being asleep. All nodes in a TephraNet follow the same waking and sleeping schedule due to their synchronization. While awake, a node can run application level software which can generate and receive packets from the network, or it can simply act as a repeater. The node

can also forward on packets for other nodes. While asleep, the node powers down all peripherals and the processor in order to conserve power.

3.4.2 Radio Baseband Software

The software running on the Atmel AT90S8535 chip forms the baseband processing system for the radio module. The tasks of the radio baseband are shown in Figure 3.6. The majority of the software written for this section was written in Atmel AVR assembly code. The precise timing requirements required for data transmission and reception precluded the use of a higher-level language. A partial listing of source code can be found in Appendix B.

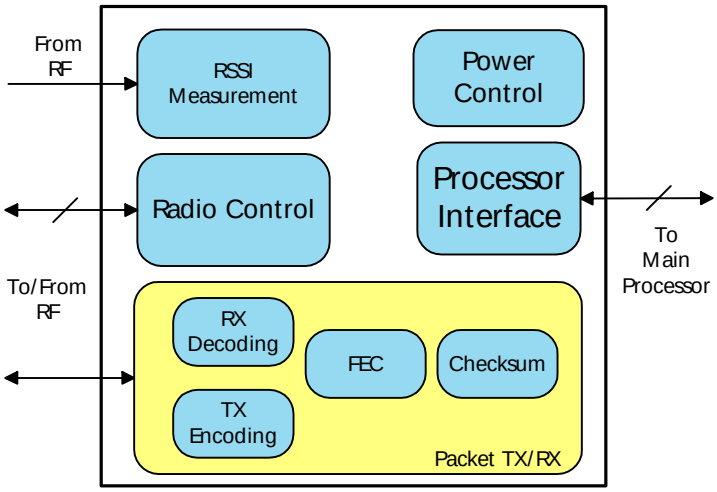


Figure 3.6 Baseband Functions

3.4.2.1 Power Control

The baseband software provides power down control of the RF section of the circuit as well as the baseband processor. When instructed to do so by the main processor, the baseband software can power down the RF section of the circuit and then suspend its own operation. Operation continues upon reception of the proper signal from the main processor.

3.4.2.2 Processor Interface

The baseband software controls the interface to the main system processor. This interface consists of signals that allow each processor to send an interrupt signal to the other. Packet and configuration data is exchanged over a synchronous serial port. The interface to the main processor is detailed further in Section 3.4.4.3 as well as Appendix A.

3.4.2.3 Packet Transmission and Reception

The primary job of the baseband processor is to provide the mechanism by which packets are exchanged “over the air”. During transmission, the baseband processor takes a packet from the main processor, prepends the RF level header (composed of a synchronization sequence and start symbol), and sends the data in a DC balanced format. The final version of the code utilized Manchester encoding, which uses 2 bits per symbol to ensure a DC balance [Rappaport96]. The transmission also includes a simple forward error correcting code (FEC). When in receive mode, the processor monitors the incoming data stream watching for valid packet data, which is decoded and checked for validity before transmission to the system processor.

3.4.3 Operating System

The software running on the Samsung ARM7TDMI (main) processor requires an operating system in order to ease development for those wishing to use TephraNet as a platform. uC/OS-II was selected as the operating system after evaluating several commercial and free embedded operating systems. uC/OS-II is open source, well documented, and provides all the services that are required for development. Other operating systems evaluated required licensing fees that are prohibitive for most academic environments. Many others contain features considered unnecessary, increasing the code size with no benefit, and were not as well documented as uC/OS-II. Additionally, this OS had previously been ported to a close relative of the Samsung chip used as the main processor in TephraNet, easing the job of porting the operating system to the TephraNode hardware. Details about uC/OS-II can be found in [Labrosse99].

3.4.4 Packet Transmission and Reception

3.4.4.1 Packet Types

During normal waking operation, the node constantly waits for incoming packets. When a packet is received, it is examined to discover what types of data are contained within. Packet types are shown in Table 3.2. Multiple segments of different types can be contained within a single “over the air” packet. Each segment is sent off to the corresponding “handler” for that type. For example, all packets that contain a GRAd routing header

are handed over to the GRAd service (described below) for routing. Many of the packet types here are related to services described in subsequent sections.

Packet Type	Description
SYNC	Contains current time of sender
GRAD	GRAd routing header type
DISCO	GRAd route discovery packet
PING	Ping packet
PONG	Reply to a ping packet
ARQ	Request the whole packet be acknowledged
ACK	Packet acknowledgement
NEIGHBOR_REQUEST	Request a node to discover all its neighbors
NEIGHBOR_REPORT	Report of who the senders 1 hop neighbors are
LINK_REQUEST	Request a link state report from a node
LINK_REPORT	Report of the senders link strength to a neighbor
PARAM_SET	Sets the parameters in a node
PARAM_REQUEST	Requests the current node parameters
PARAM_REPORT	Report of the current parameters
STATS_RESET	Resets all statistics to startup values
STATS_REQUEST	Requests a statistics report from a node
STATS_REPORT	Report of the current statistics values in a node
APPX_REPORT	Sensor value report
COST_TABLE	The GRAd routing table of the sender
BOOT_REPORT	Contains information about a nodes bootup
ENTER_TEST	Causes a node to enter a “sleepless” mode
EXIT_TEST	Exits the test mode above
START_ASYNC	Tells a node to wait for a specific node to wake up or come on-line and then to run a link strength test
STOP_ASYNC	Stops the above process

Table 3.2 Packet Segment Types

3.4.4.2 MAC Service

The MAC (Medium Access Control) service provides access control for the radio. This service regulates when packets are sent out over the radio interface. TephraNet implements an 802.11 style MAC layer, described in [IEEE99]. Since all packets sent are broadcast, the entire RTS/CTS system is not implemented. The MAC service implements only the broadcast portion of the 802.11 MAC specification. This service can be modified or replaced to examine the effect the MAC algorithm has on various routing algorithms.

3.4.4.3 Radio Interface

DMA allows packet transfers to occur in the background without processor attention.

The radio interface is the portion of the TephraNet code that communicates with the radio. A DMA-based (Direct Memory Access)

interface to the radio baseband was developed to ease the main processor overhead of processing incoming or outgoing packets. Normally, the radio module code sits idle, waiting for the radio baseband to indicate that a packet has been received. When the baseband receives a valid packet, it transfers the data via a synchronous serial port directly into the main processor memory space (using the DMA controller on the Samsung processor). The processor is then interrupted, and the radio module comes to the foreground to parse the packet. The parsed packet is then handed up to the routing service and the application software for processing.

When a software module is ready to transmit, it calls an access function in the radio module that sets up the transmission. First the radio baseband is interrupted to indicate the beginning of transmission. The radio baseband then uses the DMA interface to read the packet to send directly out of the processor memory without further main processor intervention. The packet is then sent by the baseband as described in Section 3.4.2.3.

3.4.5 GRAd Routing Service

TephraNet implemented the GRAd routing algorithm for this revision. In order to use TephraNet as a general network algorithm testbed, the GRAd algorithm can be replaced with another algorithm, such as AODV (Ad-hoc On-demand Distance Vector) or DSR (Dynamic Source Routing). All of the main GRAd feature set was implemented for this revision as described in [Poor01]. This implementation parameterized several GRAd settings. These are shown along with other parameterized system settings below in Table 3.3. These parameters can be adjusted during the course of network operation.

3.4.6 Synchronization Service and Power Management

The synchronization service is used to power manage the network by sleeping all nodes simultaneously.

The synchronization service (SYNC) is responsible for ensuring that the time at each node in the network is uniform. This plays a central role in power management. The largest source of power consumption in a low power network is the power used for reception [Wheeler00]. Although high power radios consume far more power during transmission than reception (due to the power amplifier), current low transmit power radios consume the same or more power during receive than transmit. A major goal for minimizing power consumption is reducing the amount of time the receiver

is on. In traditional base-station architectures where a single high power base station can communicate with all nodes (such as in a cellular network), the receiver at each node can be controlled by the base station, who schedules all network traffic. In an ad-hoc network, one approach to distributed synchronization, with the goal of being able to turn off radio receivers, is presented in [Xu00].

The basic description of the synchronization system is that a packet describing a node's current time is sent out periodically. Every node receiving this packet averages their internal time with the time heard. In this way, the time across all the nodes in the network converges to a common time. This system is based on the distributed synchronization system proposed by Poor in [Poor01].

This basic concept was implemented in the TephraNet system, with some modifications. The first is a bootup phase. During this period of time, they do not send any packets indicating their current time. Instead, they listen to all incoming timing packets and set their time to the network time they hear. This assumes that the network time has already previously settled. If no packets are heard during this period, or if times vary widely, then the node enters normal operation with the time it currently has set.

Once in a steady state, the network has a duty cycle of awake and asleep that can be adjusted to control the average power consumed by the network. The timing used in TephraNet is nine minutes asleep followed by one minute of awake time. While the network is awake, each node broadcasts a timing packet approximately every four to six seconds. When a node is asleep, it wakes up approximately every thirty seconds and sends out a timing packet to help nodes that are far off the network time (i.e. awake when they should be asleep) converge to the correct time.

3.4.7 Network Configuration and Statistics Gathering

The PARAM module stores TephraNet system settings that can be altered during network operation. These parameters are meant to provide an easy way to change the way the network operates and behaves without having to recompile and reinstall software on each of the nodes. Alterable settings are shown in Table 3.3.

Parameter	Description
PING_SEARCH_COUNT	Number of pings to send when searching

	for neighbors
PING_LINK_TEST_COUNT	Number of pings sent in a link test
PING_LINK_TEST_DELAY	Time to wait between pings
ARQ_DELAY	Timeout while waiting for an ACK
ARQ_RETRY	Number of time to resend a packet
COST_TTL	Lifetime of a GRAd routing cost table entry
COST_AGE_QUANTUM	How often routing table is purged
GRAD_DISCOVERY_COUNT	How large the initial GRAd discovery cost is
GRAD_ENABLE_RELAY	Enables relaying by this node
MAC_TICKS_PER_BACKOFF	Quantization of MAC backoff timer
AWAKE_TIME	How long to stay awake for in a cycle
SLEEP_TIME	How long to sleep for in a cycle
BASESTATION_ADDR	Address of node that is the current gateway
ARQ_REPORTS	Indicates sensor reports should be ack'd

Table 3.3 Parameters in a TephraNode

The STATS module provides a repository for network and node performance statistics. During normal operation, each TephraNode records information about internal statistics (shown in Table 3.4). Summary information is routinely sent to the gateway node for display and processing.

Statistic	**Description**
maxTimeDiffThisPeriod	Largest difference between internal time and received time broadcasts this waking cycle
uptime	Uptime of node in OS scheduling ticks
badPackets	Number of corrupted packets seen by radio
goodPackets	Number of valid packets seen by radio
duplicatePackets	Number of duplicate packets seen
gradOriginated	Number of routed packets (not ping or timing) originated by this node
gradFlooded	Number of route discovery floods from this node
gradRelayed	Number of packets relayed for other nodes
arqPktsSent	Number of packets sent with an ack requested
arqPktsRcvd	Number of ACKs received
arqPktsDropped	Number of packets that never got an ack

Table 3.4 Statistics Gathered

3.5 Summary

This chapter described the goals and design of the TephraNet system. Further design and implementation details are available in the various appendices. The next chapter shows the additional elements added to the TephraNet system that are specific to the Hawaii deployments. The deployments are also reviewed.

Chapter 4 Implementation and Deployment

Photo by Michael Hawley

Figure 4.1 Joint Project

The TephraNet system design was motivated in large part by the desire to use the system in an actual field deployment for detailed environmental sensing. In collaboration with the Botany department of the University of Hawaii, Manoa campus, the TephraNet system was deployed in Hawaii to study environmental conditions. This section describes the joint project.

4.1 Problem Background

Nene birds, the state bird of Hawaii, are just one of many endangered species living in Hawaii Volcanoes National Park.

Photo by Michael Hawley

Figure 4.2 Nene Birds

Hawaii Volcanoes National Park on the Big Island of Hawaii contains numerous micro-climate zones. In the space of several miles, the climate zone can change from rainforest to desert. These steep weather gradients are home to many endangered plant and animal species, such as the endangered Nene bird, Hawaii's state bird. One of the goals of the deployment is the measurement of one of these gradients.

Hawaii Volcanoes National Park (dotted region on map) contains numerous microclimate zones, home to many endangered species.

Photo by Michael Hawley

Figure 4.3 Hawaii Volcanoes National Park

In one of these microclimate zones, near the crater of Halemaumau, is an area known as the Southwest Rift Zone. The Southwest Rift Zone is thought to be the fastest moving piece of land on the planet. This desert-like zone is home to the *Silene hawaiiensis*, a diminutive endangered plant, usually not taller than half a meter [Bridges01]. Little is known about this plant, or its habitat. Only a few pictures exist of its flowers, and its flowering schedule is unknown. The plant is considered an endangered species.

The Silene plant in its native habitat.

Photo by Michael Hawley

Figure 4.4 *Silene hawaiiensis* in SW Rift Zone

A detailed picture of the plants' habitat is needed in order to understand their reproductive mechanisms and lifecycle. Knowledge of details about wind speed and patterns can give clues about pollination vectors. For example, if the area is subjected to high winds 24 hours a day, then insects can be ruled out as the pollination mechanism. Data about the amount of rainfall and moisture in the air can help uncover how the plant acquires water. Although the area is thought to be a desert (defined as less than 15" of rainfall a year), this has yet to be confirmed [Bridges01].

The nearest weather station is only 3.5 miles away, but it is in a rainforest and provides little useful information about the climate these plants exist in.

This particular situation presents an ideal example of environmental measurement where TephraNet is needed. The weather patterns in the Southwest Rift Zone require samples at intervals on the order of a few hundred feet in order to gain a useful understanding of how those patterns act on the *Silene hawaiiensis*. Traditional measurement such as periodic weather stations can not capture this detailed information, and constant human observation is both prohibitively expensive and lacks the granularity required. A dense network of weather stations which will observe the area and continuously report their findings back to botanists studying the area is the ideal solution.

4.2 Deployment Specific System Design

In order to deploy the TephraNet system as a weather gathering network in the Southwest Rift Zone several additional hardware and packaging components had to be designed.

4.2.1 Sensors

The sensors added to the TephraNet system transform the generic platform into the weather stations necessary for this research. This section discusses the main characteristics of each sensor. Details on the settings used on the TephraNode board analog inputs and any additional hardware used to attach the sensors can be found in the Hardware Design Appendix A.

4.2.1.1 Temperature

The temperature sensor used was a RL1005, manufactured by Thermometrics [Thermometrics01]. It has the ability to measure temperature with 1 degree accuracy from 0 to 150 degrees Celsius. The sensor is of the thermistor class of temperature sensors. The sensor appears as a resistor whose resistance varies inversely with the ambient temperature.

4.2.1.2 Humidity

The humidity sensors can help determine how the Silene obtains water, and if the SW Rift Zone is a desert.

Photo by Michael Hawley

Figure 4.5 Humidity Sensor in Rock

Humidity was measured by a capacitive humidity sensor from Panametrics, the MC-2 [Panametrics01]. The sensor can measure from 0% to 100% relative humidity with approximately 15% accuracy uncalibrated. This sensor appears as a capacitor whose capacitance varies with humidity. Because the basic TephraNet sensor interface only provides the ability to measure analog voltages or resistive values, this sensor required additional hardware to convert the capacitive variance into an analog signal (see Appendix A for details). The humidity level provides an important indicator about the region and can point to the how the Silene obtains water.

4.2.1.3 Wind speed

Localized wind speed is an important factor in pinpointing pollination vectors.

Photo by Michael Hawley

Figure 4.6 Wind Sensor showing sail

Wind speed was measured by using a flex sensor from Abrams Gentile Entertainment [Abrams]. The sensor, originally used in toys, is a force sensitive resistor that changes value with the degree of deflection. The

sensor was modified to measure wind by attaching a small sail to the end of it (see Figure 4.6). The flex sensor is resistive; its resistance changes with the degree of flex. Wind pushes the sail and causes the flex sensor to bend. This novel sensor design was developed by the University of Hawaii and tested in the SW Rift Zone prior to the main deployment.

Sensors blend into the surface of the fake rocks, and are hardly noticeable.

Photo by Michael Hawley

Figure 4.7 Light Sensor Embedded in Fake Rock

4.2.1.4 Light level

The light level was measured using a standard photoresistor. This sensor varies resistance proportionally with the amount of light incident on it. This sensor allowed researchers to determine when the area was overcast, and the time of sunrise and sunset.

4.2.2 Power Source

The lifetime goal for the deployment was six weeks between battery changes. Using a relatively conservative estimate of the nodes power consumption and alkaline battery power, a four D cell configuration was chosen. This configuration was specified to operate clearly within the six week goal.

4.2.3 Gateway Node Antenna

The gateway node for the network was located in a high observation tower, and was out of the range of the standard antennas selected during the design of the TephraNodes. A directional high gain Yagi antenna was selected to compensate for the distance. Details about the selected antenna can be found in Appendix A, hardware design.

4.2.4 Enclosures

The National Park Service does not permit exposed scientific equipment to be left out in the Southwest Rift Zone. This necessitated the design of camouflaged enclosures to hide the TephraNodes. Mike Lurvey at the University of Hawaii designed fake rocks and tree branches to place the nodes in.

4.2.4.1 Lava Rocks

The TephraNode sits on top of the batteries for maximum antenna elevation.

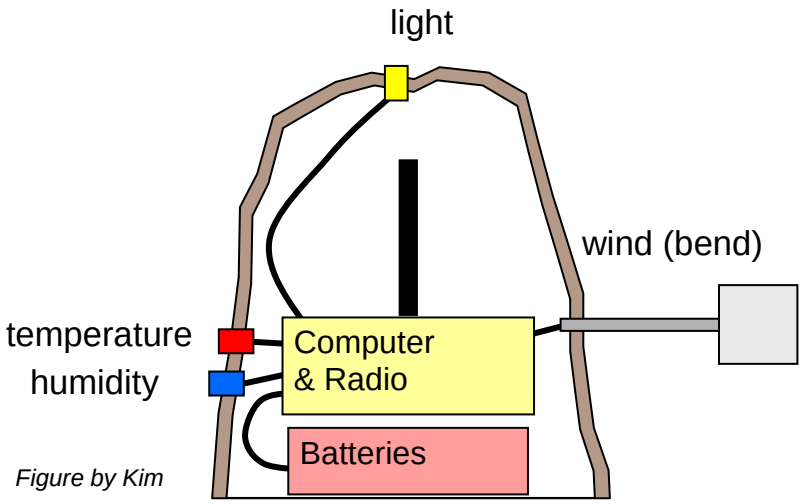


Figure by Kim

Figure 4.8 Rock Enclosure Drawing

The majority of the weather stations were enclosed in fake rocks. The study area had many rocks on the order of one foot in diameter. Samples of these rocks were taken from the study area and plaster casts were taken of them. The fake rocks were then constructed out of tinted Bondo and finished by hand-painting (see Figure 4.9). Each of the rocks had sensors mounted into the surface (see Figure 4.7 above). Figure 4.8 shows the placement of the TephraNode within the fake rock.

Photo by Kim Bridges

Figure 4.9 Rocks at U of Hawaii Awaiting Deployment

4.2.4.2 Ohia Tree Branches

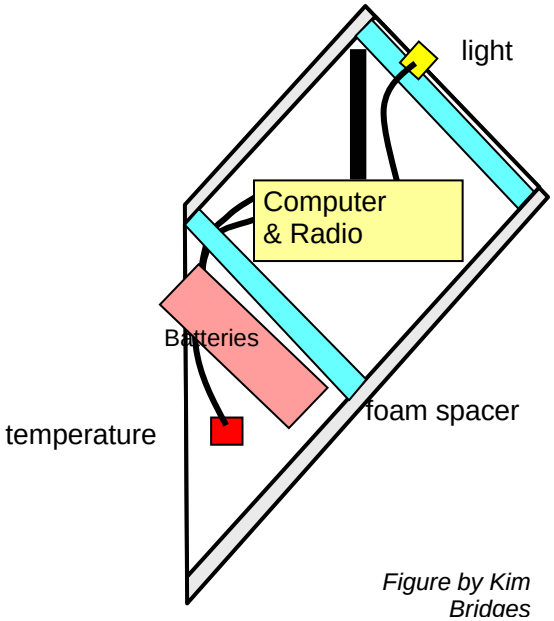


Figure by Kim Bridges

Figure 4.10 Ohia Branch Assembly

The Ohia tree is a native Hawaiian tree that is found near the study area. The fake tree branches were constructed from PVC tubing. The exterior was covered with a printout of bark pattern of the Ohia tree and sprayed with a waterproof coating. A top cap was constructed out of Bondo and color matched. The bottom cap held the batteries and was constructed out of Styrofoam. The bottom cap could be inserted while in the field just prior to deployment. This design held only a temperature and light sensor. It was strapped into Ohia trees for deployment using plastic cinch straps.

Figure 4.10 shows the placement of TephraNode and batteries within the branch. Figure 4.11 shows a placed branch. Although it appears to be quite obvious, from any real distance it is no longer visible unless one is looking for it.

Although obvious up close, the Ohia branch enclosures are difficult to detect from a distance.

Photo by Michael Hawley

Figure 4.11 Ohia Branch Enclosure in Tree

4.2.5 Software

Several pieces of software were developed for the Hawaii Volcanoes Deployment. On the TephraNode level, a custom application takes sensor readings and sends packets out to a collection point. A gateway application was written that runs on a Linux PC which takes packets from the gateway node and makes them available on a web server. To assist in deployment, a "doctor mode" was added to TephraNode software that allows a computer to attach to a TephraNode and use it to communicate with the TephraNet. Finally, a data visualization suite was developed that displays the data collected from the network for visual analysis.

4.2.5.1 Sensor Application

Each of the TephraNodes includes software that gathers and reports sensor data. This piece of software averages ten successive readings from each of the sensors in order to filter out noise. The readings are then encapsulated in a packet and routed to the nearest data collection node. The basic packet types described in Section 3.4.4.1 are extended with an APPX_REPORT type that contains sensor readings. Details about this packet type can be found in the listing for appx.h in Appendix B. The collection interval defaulted to once every ten minutes, although this could be set through the network.

Each node includes software additions to the bootup code. This software runs on startup to run tests and broadcast messages to anyone within radio range about the bootup status. Immediately on boot, the System Manager begins the Synchronization (SYNC) service and broadcasts a message when the node has acquired sync with the network. If sync can not be obtained after some time, the software broadcasts an error message and proceeds. The boot software also listens for neighbors and runs link strength tests to assist in the placement of the node in the network. The results of these tests are broadcast out in informational packets.

4.2.5.2 Doctor Mode

In order to facilitate deployment, a special doctor mode was designed for the TephraNode software. A node placed into doctor mode communicates with a terminal (such as a Palm Pilot or a laptop) over a serial port, allowing the terminal to monitor information coming from the network and to communicate with nodes in the TephraNet.

Function	Description
Target Node	Selects a node in the network for tests
Collect Neighbors	Collects the single hop neighbors of the target node
Neighbor Strength	Tests link reliability between the target and another node
All Neighbor Strength	Tests link reliability between target and all its one hop neighbors
Test Mode	Causes a node to enter or exit a mode where it never sleeps
Async Ping	Runs a link test to a node the next time it wakes up
Node Existence	Checks if a node (even if asleep) is within radio range
Update Params	Updates the configurable parameters of the target node

Table 4.1 Doctor Mode Functions

Doctor mode contained several functions, listed in Table 4.1. Functions such as the async ping and the node existence tests rely on the fact that nodes send a time synchronization packet a few times a minute. During the period of time that the nodes send the synchronization packet, they wake up long enough to process pings. The ping and synchronization mechanisms are described in more detail in Section 3.4 and in Appendix

B. In addition to these functions, the doctor mode prints out messages from the boot sequence (such as a bootup packet, and time sync information) described in the previous section.

The author uses the doctor mode to log into a deployed rock and debug it.

Photo by Michael Hawley

Figure 4.12 Author Logs into a TephraNode

4.2.5.3 Gateway Software

A gateway mode was also written for the TephraNodes to allow a node to function as a network gateway. When placed into this mode, the node will print out packets to its serial port. A gateway application, running on a Linux computer, was developed to turn these packets into useful data. The gateway application parses the packet data out of the serial stream and logs it. Another part of the gateway software suite passes over the log file and gathers statistics from it. All of the information is made available through a web server and an HTML based interface. Gateway code can be found in the code listings in Appendix B.

4.3 Deployment Plan

The deployment plan was developed by the author with the University of Hawaii Botany team, led by Dr. Kim Bridges. The deployed system contains three primary components. The base station location contains the network gateway node, which connects the TephraNet network into the Internet. A line of nodes runs from the base station location to the study area, collecting information about the weather gradient and serving as a relay system. The bulk of the nodes in the network are spread out evenly over the study area. The role of each component is presented below with a procedural overview of the deployment.

4.3.1 Base Station

The gateway node was placed in the USGS Volcano Observatory that sits on the rim of the Halemaumau crater (shown in Figure 4.13). The observatory has a high speed Internet connection that allows the data to be reviewed in real time.

The Halemaumau crater is visible through the observatory window.

Photo by Kim Bridges

Figure 4.13 Author in Volcano Observatory

On the top of the observatory is a glass walled “situation” room that served as the headquarters of the deployment operation and also continues to house the base station. This room was used for the final programming of nodes and assembly of Ohia branches and rock packages before being taken into the field. A computer running the gateway software discussed above in Section 4.2.5.3 was located in the observatory. This base station computer allowed remote access to the network, facilitating both data retrieval as well as sending packets into the network.

Photo by Michael Hawley

Figure 4.14 Ohia Branches Awaiting Deployment

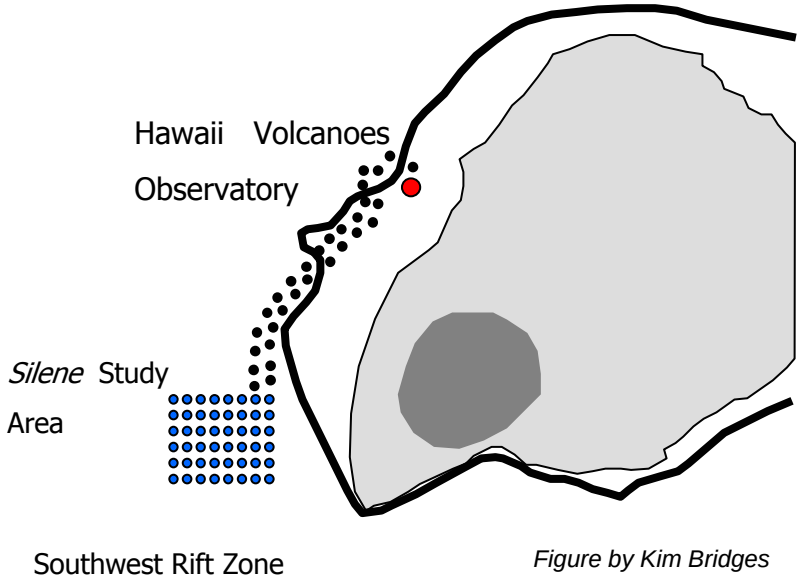


Figure by Kim Bridges

Figure 4.15 Node Placement Plan

4.3.2 Node Placement

Node deployment was planned in two forms- a long string from the observatory and a large field at the study area.

The Hawaiian Volcano Observatory is over a kilometer from the desired target area in the Southwest Rift Zone. A rough map of the planned deployment is shown in Figure 4.15. The size of the TephraNet was planned to be 80-100 nodes. The nodes are divided into two basic types. The first is a string of nodes running from the observatory to the study area. All of these nodes are housed in Ohia branch enclosures. This string of nodes captures the weather gradient from the observatory, which is often in the clouds, down to the area where the Silene grows, which is believed to be a desert. As the path nears the Silene habitat, the Ohia trees become sparser, and the trail of nodes switches to the rock housings. The plan for this section of the deployment was ensure the network was at least second order to provide redundancy (see Figure 4.16 for an explanation). This string of nodes also acts as the relay for the data coming from the study zone. The approximate spacing between nodes in the trees is 100-150 feet. This long string of nodes allowed the GRAd routing algorithm to be tested in a much larger diameter network than had been done previously.

Each node should be able to communicate with at least two nodes on either side for increased reliability.

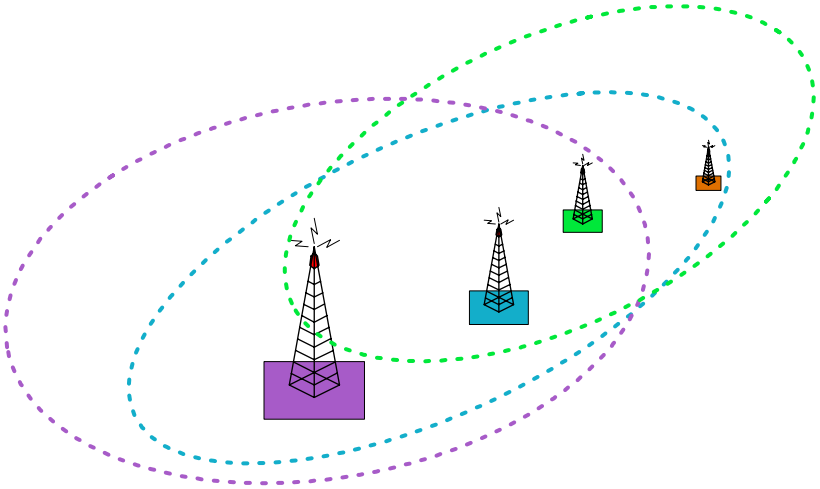


Figure 4.16 Overlapping Radio Ranges

The majority of the nodes are placed in the study area. Since the study area does not have any Ohia trees, all the nodes in this section of the network are in rock enclosures. In this area, the TephraNodes are positioned around 50 ft from each other. This is due primarily to the proximity of the antenna to the ground in the rock setup. RF does not propagate as well when in close proximity to the ground. The spacing plan in this area provides a large amount of redundancy in the network. This network arrangement also provided testing of a dense network configuration with much more opportunity for congestion.

4.4 Hawaii Deployment 1

4.4.1 Overview

The first deployment of the TephraNet system took place in March, 2001. This deployment was planned to be the sole deployment of the system. The intent was to deploy the nodes as described above, and let them run for 6 weeks, collecting data about the network and the environment. Unfortunately, this deployment did not go as planned, although several key lessons were learned in the process. In the week that was spent in Hawaii, the first four days were spent at the University of Hawaii, performing integration between the TephraNet system and the sensors

and software testing. The last three days were spent at the park performing layout planning for the node deployment and testing out nodes.

While in the field, the base station node was set up and the directional antenna was aimed out at the first outdoor node position. Three Ohia branch nodes were deployed into their planned positions, and radio performance was measured with these nodes. After encountering software problems in the nodes that were not correctable in the field most of the remaining time was spent surveying the site and determining the layout of nodes for a future deployment.

4.4.2 Problems Encountered

4.4.2.1 Software Reliability

The most difficult problem encountered during the Hawaii deployment centered on software reliability. On the first field deployment day four nodes were placed into the field. An unknown bug would cause the nodes to crash after forty five minutes to several hours. After eight hours all of the nodes were non-functioning. Due to the time necessary for the error to manifest, the error could not be corrected during the field trial.

Upon return from Hawaii, the node software was analyzed to uncover the source of the instability. The operating system port was found to be at fault. An obscure nested interrupt problem would caused the stack in the operating system to be corrupted when two particular interrupts (such as a packet arrival and a timer) occurred at the same time. The frequency of this occurrence was dependant on the amount of radio traffic. Under heavily loaded conditions, it would usually occur within two hours.

4.4.2.2 Hardware Problems

Several problems relating to the hardware also appeared during the deployment. The first was with the base station. As mentioned in the deployment plan, a directional Yagi antenna was used at the base station node in order to provide long range. Even with this antenna, the measured reliability of the link never exceeded 75% (roundtrip packet throughput), which was not reasonable performance. The best guess made in the field was that the antenna was not properly grounded (since it was in the tower room) or that temperature differentials from inside to outside were adversely affecting the radio. After the deployment exercise

completed, the problem was found to be the small AC power supply brick that had been substituted for the battery pack in this node. The power supply generated an extremely noisy power signal, and much of the noise passed through the voltage regulator and negatively affected RF performance.

The RF hardware also acted unreliably in the field, occasionally the radio would get stuck in a mode where it would not output any valid data. Further investigation revealed that human error in the field caused all the radio boards to be programmed repeatedly at a voltage nearly twice the specified programming voltage. Due to this error, the RF transceiver was permanently damaged, and a new run of radio boards were fabricated prior to performing a second deployment.

The power consumption of the hardware platform was also much higher than the expected consumption. Post-field-test examination of the system revealed an undocumented setting in the Atmel microcontroller which accounted for most of the difference between measured and expected power consumption.

4.4.2.3 Misc. Problems

Even in the medium volume of one hundred nodes, many little design issues become huge headaches. One such issue relates to the stacking of the boards. The radio and processor board are stacked and attached using nylon spacers and screws (see Figure 3.1). The design precluded inserting the programming header for the main processor when the boards are stacked. This added a prohibitive amount of assembly overhead in the field and made field corrections of software mistakes difficult. Requiring the boards to be screwed together also added hours of assembly overhead.

A final problem encountered was with the connectors between the battery packs and the TephraNode hardware. A mismatch in parts went undetected until assembly in Hawaii. The part problem required the power supply wires to be soldered directly to the nodes instead of using a connector.

4.4.3 What Went Right

Despite all of the problems encountered on the first deployment, several positive things came out of the experience. Perhaps the most valuable was the ability to verify that the pieces designed with each team interoperated. The sensors successfully attached to the TephraNodes and sensor readings were taken. The TephraNode hardware fit successfully within the rock and Ohia branch housings. The time in the field was also an excellent opportunity for the MIT and University of Hawaii teams to meet in person and communicate.

4.5 Hawaii Deployment 2

4.5.1 Overview

After the software stability issues were corrected and new radio hardware was manufactured, a second deployment was performed in June of 2001. This second deployment, although still not entirely successful, provided great insight into the performance of the GRAd routing algorithm and the usability of the TephraNet platform for field work.

The string of nodes headed toward the SW Rift Zone were deployed successfully.

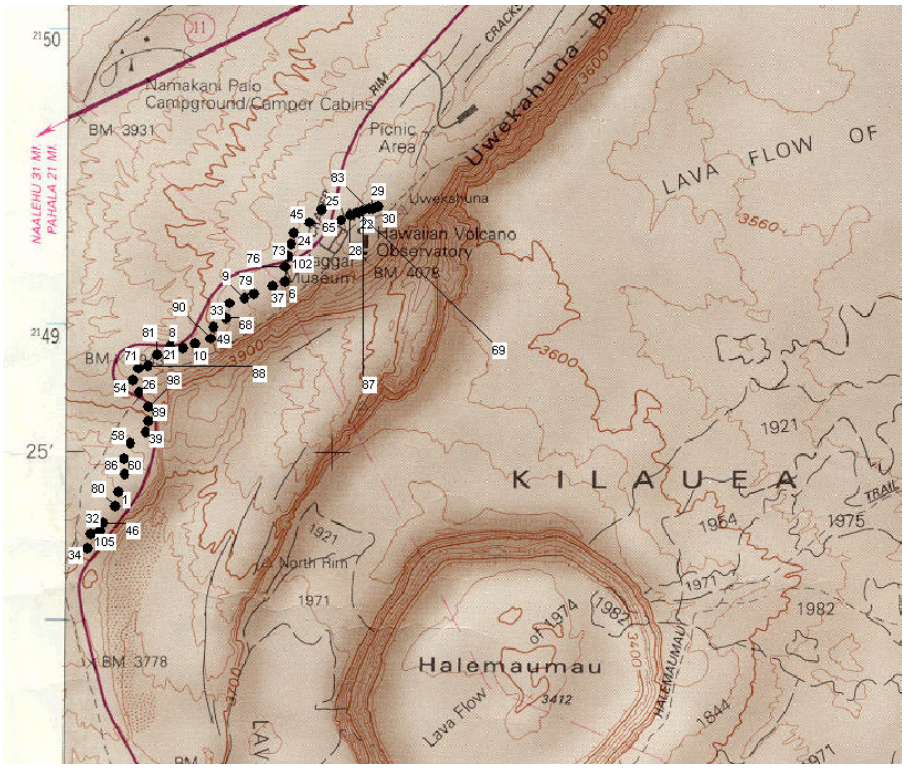


Figure 4.17 Deployed Node Positions

During this deployment, the entire line of nodes running out to the study site was deployed (see Figure 4.17). In addition, a *Silene hawaiiensis* population was discovered near the Volcano Observatory, off of the planned deployment track. The team decided to take advantage of this monitoring opportunity, and deployed the first TephraNodes in rock enclosures in this area. Around three days was spent in the park deploying both the nodes going to the study site, and those around the Observatory.

4.5.2 Problems Encountered

4.5.2.1 Power Supply Noise

Power supply noise negatively impacted radio performance.

As mentioned in the description of the first deployment, the link from the base station node out to the first outdoor node functioned poorly. Experimentation during the first day of the second deployment revealed that the source of the poor performance was noise generated from the power supply. It was replaced by a clean power supply. In addition to this problem, a problem with the power regulator on each node was also discovered after several nodes were deployed on the first day. The nodes demonstrated packet reliability on the order of 50% even over moderate distances. Experimentation uncovered noise in the power supply as the main problem. Work done in the laboratory had often bypassed the on-board power supply in favor of an external one that could source the current necessary for all the programmers, and so the problem was not detected prior to field work.

This problem was partially overcome by implementing a simple FEC (forward error correcting) code in the radio. An FEC achieves higher reliability at the expense of bandwidth by sending redundant information. The code used was a simple block code where each byte of data is sent three times, and the receiver uses the three bits received to vote on the value (i.e. if two zeros and a one arrive for a particular bit, the receiver decides that the bit is a zero). This technique improved the bit error rates to over 90% in the 100 ft distance range.

4.5.3 Ease of Deployment

One unanticipated problem faced during this deployment was the ease of deployment. The actual placement of the nodes took much longer than expected, and the correction of any errors once a node was placed was

difficult. Most nodes placed were of the Ohia branch type, which often involved climbing a tree with the branch and securing it with plastic zip-ties. Once a tree was identified as the node location, the node was powered up and the author stood by with a doctor mode system as described in Section 4.2.5.2 to watch the node boot. Obtaining link tests to neighbors to assure a reliable positioning consumed the majority of deployment time. The branch was often high in the tree, and someone had to hold the branch in place while the tests ran. Since deployed nodes were usually in their sleep cycle, and woke only every thirty seconds or so, running several link tests took minutes. Adjusting the branch slightly and running more tests was extremely time consuming. As a result of the difficulty of the deployment, nodes were often placed in sub-optimal locations and not enough time was available to deploy all nodes.

Mike Lurvey of the University of Hawaii places an Ohia branch node into a tree.

Photo by Michael Hawley

Figure 4.18 Placing Node in Ohia Tree

Another major issue surrounding the ease of deployment was the difficulty making any changes to the deployed system. Although a mechanism was present to change certain parameters of the deployed system, the main body of the software could not be modified without taking the nodes out of the trees, disassembling them, and reprogramming them by physically attaching to them. For an experimental system intended to be a testbed, this is not acceptable.

4.5.4 Synchronization and Routing Algorithm Problems

The TephraNet system suffered from several synchronization and routing problems after deployment. Once deployed, the system appeared to have major problems settling in on a common time. The time at each node determines when it is awake and asleep. If all the nodes in the network do

not wake up at the same time, a packet can not be relayed through the network. The time synchronization thus prevented packets from being routed successfully through the network. A complete analysis of the synchronization problem is provided below in Chapter 5.

The GRAd routing algorithm itself also suffered from performance issues. Data indicated that very few packets from further than 3 or 4 hops away was successfully reaching the base node, despite the fact that over 20 hops worth of nodes were deployed. This low reliability was seen even with end-to-end per-packet acknowledgements in place. A detailed analysis of the data collected relating to the routing problem is presented below in the analysis section.

Overall, these algorithmic problems prevented the deployment from being fully successful.

4.6 Summary

This section illustrated what was required to use the basic TephraNet platform in an environmental sensing application. The Hawaii Volcanoes specific implementation was detailed and a plan for deployment was presented. The two deployment activities in Hawaii were reviewed. The next section presents the lessons learned on the deployment and draws conclusions about how the project met its goals.

Chapter 5 Results and Conclusions

This chapter analyzes the data collected about network operation from the two field deployments. An evaluation of how well the TephraNet design met its stated design goals is also presented. Finally, future areas of work and the contributions of TephraNet are discussed.

5.1 Analysis

This section presents an analysis of the major problems found during the field tests. An analysis of how well the TephraNet system measured up to its stated goals is also presented.

5.1.1 Ease of Use- The End User Perspective

Ease of use from the end user's perspective is an important design consideration that was not stressed

The field tests revealed the importance of ease of use issues if a network platform is to become a routinely used environmental research tool. As mentioned in chapter two, most of the research in self-organizing networks has focused on routing algorithms. These self-configuring algorithms alleviate much of the pain of setting up a complex multi-hop wireless network. However, the network routing is only a small piece of the entire usage experience.

The design of the TephraNet system attempted to take ease of use into account. The system included tools for nodes that were intended to ease the deployment of a network, such as the doctor mode, which provided a deployment team with an easy way to view what was occurring in the network. However, a researcher faced with the reality of a steady strong wind twenty feet above the ground in a treetop, while holding too many things, quickly finds these tools clumsy and overly complicated. The delays in determining if a node was placed well — on the order of several minutes — became unacceptably long once in the field.

Holding nodes in position while link tests are obtained proved to be highly taxing.

Photo by Michael Hawley

Figure 5.1 Difficulty with Placement

Any design that is to succeed in a field such as environmental sensing must make deployment totally painless. An absolute minimum of knowledge should be required of the deployment team, or they will reject the new tool. The user should ideally be able to simply turn on a node, and view a green light if it is in a good position to join the network, or a red light if it is in a bad position. Multiple modes should be avoided at all costs unless switching between them is totally autonomous. Future work should examine the utilization of the system from the perspective of the targeted end user, and ensure that the system is as easy to use as is required.

5.1.2 Sensor Network Demonstration

As discussed in Chapter 4, the deployment of the system was not smooth. The problems encountered with the synchronization and routing algorithms (discussed below) prevented any useful amount of data from being gathered. The current deployment failed to collect information about the *Silene* environment, but did make a large step towards doing so. In order for the system to work as a sensor network demonstration, the synchronization and routing algorithms need to be fixed. Potential fixes for these algorithms are discussed in Section 5.1.5 and 5.1.6.

Feedback from the researchers at the University of Hawaii clearly indicates that this tool is both valuable and necessary to further the study of the environment. The current system already presented many of the characteristics required of such an environmental tool, and with further refinement, could be used widely for field research.

5.1.3 Network Algorithm Testbed

The other main goal of this thesis was to present a viable hardware platform on which to test self-organizing wireless network algorithms. The TephraNet platform successfully obtained this goal, acting as a platform that uncovered several interesting results about the GRAd routing algorithm that had not been obtained through analysis in simulation. Further refinements to the hardware could result in a system even more manufacturable and lower cost than the current design, giving researchers a platform that can be scaled to large numbers. The scalability and operation of network routing algorithms outside of simulation is important to test, and the TephraNet platform goes a long way toward providing a common platform on which to do those tests.

5.1.4 System Goal Analysis

The TephraNet system was designed with several design goals in mind, presented in Section 3.2. Each of these goals was met with varying degrees of success.

5.1.4.1 Manufacturability

The TephraNet system proved to have several manufacturability issues that should be corrected in future revisions. One is the presence of the uBGA package Intel flash chip. This package requires feature sizes on the board below standard sizes (5 mils) and special handling during assembly. This increases the cost of manufacturing significantly. The other problem was the calibration required at the RF level. The radios require tuning and measurement of several parameters, which should either be eliminated or automated since it is prohibitively time consuming.

5.1.4.2 Low Power

TephraNet met its low power goal well. The system consumes a minimum amount of power (both running and asleep) for the feature set it incorporates, due to careful component selection and design. To further optimize power consumption, a more efficient RF design can be considered and more rigorous power management at the software level can be developed.

5.1.4.3 Ease of Development and Software Flexibility

The ease of software development goal was met adequately. The choice of a standard operating system is a major factor in easing development. The interfaces between the various software modules in TephraNet can be improved, so that new software can be more readily integrated. The ease with which the system is programmed also needs improvement. Currently the system requires disassembly for programming. Ideally, the system would support in-network programming and a simpler out-of-network programming system than is currently in place.

5.1.4.4 Autonomous

Although the system was designed with this goal in mind, and tools were put in place to meet this goal, the system did not perform as well as required. As mentioned above, the system required too much user intervention to be truly easy to use. The failure of the synchronization system also significantly lowers the autonomy of the system.

5.1.5 Routing Algorithm Performance Analysis

Analysis of the TephraNet's network performance revealed two primary points of algorithmic failure.

The first error encountered was related to the non-ideal link reliability characteristics. During network operation, not many packets originating from nodes beyond three or four hops away from the base station node ever reached the base station. The GRAd algorithm relies on end-to-end acknowledgements of packets to verify receipt. If a node does not receive an acknowledgement to a sent packet, it resends up to a maximum number of retries (six times in the Hawaii deployment). Figure 5.4 below shows an average scenario of link reliability observed in the field. A basic, first order calculation of the probability of a packet reaching its destination in the GRAd network is simply p^n, where p is the probability of successfully going a single hop, and n is the number of hops. As the graph in Figure 5.2 shows, this probability quickly approaches an unacceptably low number. Even accounting for retries and second order effects (lower, but non-zero probabilities of going through a 2^{nd} degree neighbor directly), the probabilities are still well below reasonable levels.

Probability of a successful multi-hop transmission without per-hop acknowledgements rapidly decreases with number of hops.

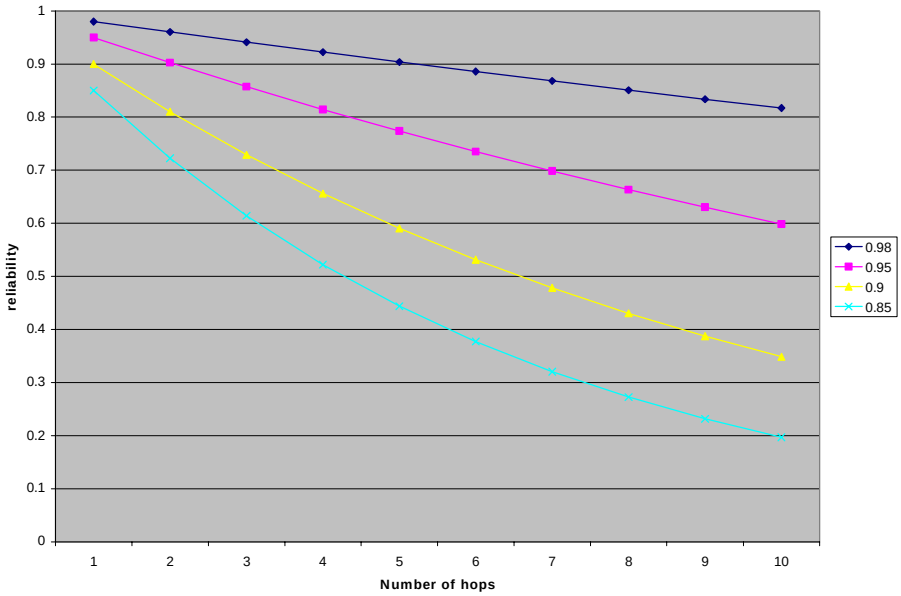


Figure 5.2 Probability of Multi-hop Success

In a network of unreliable links, a pure broadcast end-to-end approach, such as that advocated by the original GRAd algorithm is not ideal. Other routing algorithms, such as AODV and DSR route data through specific nodes. As shown in [Wheeler00], this selection of specific neighbors for transmission often requires additional routing overhead and algorithmic complexity. One possible solution that would not require much additional overhead is the use of a "passive per-hop acknowledgement." With this system, a node which relays a packet waits to see if it hears another node relay the same packet at a lower advertised cost. If none is heard within a timeout period, the packet can be resent. If this is used through the whole chain of nodes, it has the potential to significantly increase the reliability of the network.

Abnormal RF propagation prevented normal network operation due to an algorithmic deficiency.

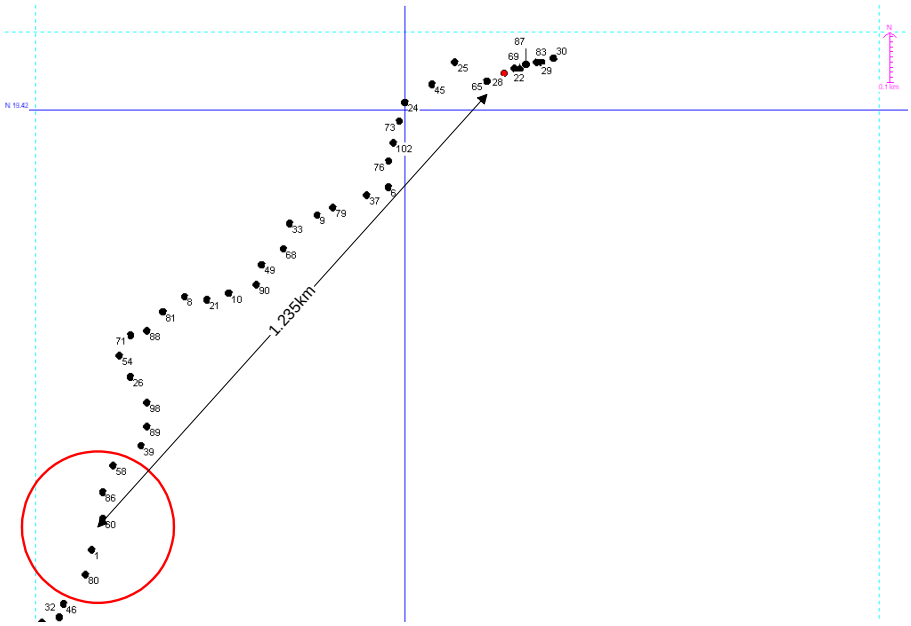


Figure 5.3 Long Distance RF Communcations

The second observed behavior within the network was the occasional receipt of packets from a cluster of nodes far from the base station node (see Figure 5.3). This node cluster was over a kilometer from the Volcano Observatory tower, although one of the nodes could occasionally get a packet through the link. Several of the surrounding nodes occasionally reported data back to the Observatory using this highly unreliable link. A related occurrence was several nodes near the base station only sending packets through short-hop count, but highly unreliable links, even though a longer, more reliable path existed (see Figure 5.4).

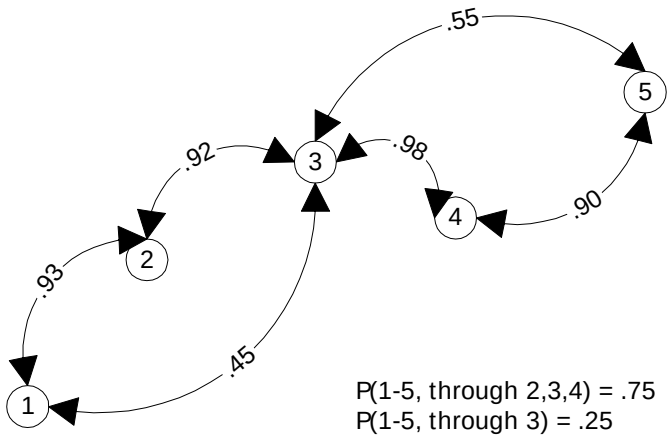


Figure 5.4 Unreliable Link Selection

Both of these occurrences are related to the same underlying problem. GRAd, and most other ad-hoc networking algorithms use a hop count as the sole metric for determining the distance of a route through a network. In the case of the Hawaii TephraNet deployment, the unreliable links caused the network to resend packets many times. Probabilistically, every once in a while a packet will traverse the shorter, less reliable link. When this occurs, an artificially low distance is recorded by the algorithm. When the nodes attempt to communicate again, they will specify the low hop-count path as the distance, and the packets will almost certainly fail to arrive at the destination.

This problem affects not only the GRAd algorithm, but the entire class of algorithms that use only hop count as the metric for route selection. Several possibilities exist for correcting this problem. One is to weight the hop count by some factor that takes into account link reliability. This requires that some method of measuring link reliability be found. Sending explicit ping packets could work, but would add a large amount of overhead to the network operation. One possibility would be to use the RSSI (received signal strength indicator) to judge the approximate RF quality of the link. Most radio systems, including the TephraNet system, have this output available.

5.1.6 Synchronization System Review

The synchronization system (described in Section 3.4.6) was responsible for keeping network time consistent through the network. The time in turn controlled sleeping and waking cycles in the system for power management purposes. Analysis of the exact causes of the failure of the synchronization system is difficult because detailed timing data was not sent back to the base station node through the network *and* when the synchronization system failed, the whole network often failed. Observation of the system revealed several problems that were corrected in the field, and point to a further problem that was not corrected.

Early revisions implemented the algorithm exactly as proposed by Poor in [Poor01]. This quickly proved to require a large settling time and had a hard time recovering from the constant addition of new nodes to the network (each of them injected a new time that had to be averaged in). A startup period was added that listened to timing packets and simply set the internal time to the time heard instead of averaging. This alleviated most of the settling time issues.

The next problem encountered was that the sleep cycle of a node has nine times as much sleeping time as waking time. If a node somehow is off of the network time enough that its waking time is while the other nodes are asleep, the node never hears the correct time, and cannot recover. This was fixed by causing each node to wake up briefly several times during its sleeping time to broadcast a timing packet.

Even with the above corrections, the network appeared to get into situations where synchronization was lost. Analysis of the data reveals that even with the broadcast of timing packets while asleep, the system did not recover once a node was no longer awake when other nodes were. Since the degree of connectivity in the network was poor, the settling time of the network was large— each node only averaged time with a neighbor or two on each side. Once timing is off, a situation can arise where a node is directly between its two neighbors in time, but far enough away in timing that it is never awake at the same time as either of its neighbors. When this happens the node in the center does not actually adjust its time at all, and the nodes on the side will take many sleep cycles to adjust their time, and may also fail to adjust it meaningfully.

These stability problems with the algorithm indicate it is not appropriate for use in a network like TephraNet. Previous simulation of the algorithm failed to simulate static networks and networks that alternate between a sleeping and waking period.

5.2 Future work

The work started in TephraNet made a large step forward in establishing self-organizing wireless networks as a valuable research tool for environmental research, and toward establishing a common platform on which to test these network algorithms. However, much additional work remains to improve on what has been started.

5.2.1 Redesign of Hardware Platform

The hardware platform should be redesigned in order to increase its manufacturability. The current platform contains certain components, such as the uBGA packaged flash chip that significantly increase the complexity and cost of the system. The 2 board design should also be revisited, either finding a new stacking method, or condensing onto a single board. This will ease the programmability and handling of the platform in the field.

5.2.2 Long Term Deployment and Other Deployments

In order to fully prove the usefulness of this technology in the field of environmental research, a long term deployment should be done. Additional information about the performance of the routing algorithms and system could potentially be uncovered if tested for a longer time period. The TephraNet system should also be deployed into other areas besides the Hawaii Volcanoes site to determine its general usefulness.

5.2.3 Use as a Test Platform

In order to further evaluate the usefulness of the TephraNet platform as a test bed for network routing algorithms, more of these algorithms should be implemented on the system. Continued detailed analysis of the differences between results seen in simulation and on the platform should be conducted to uncover potential problems in the design of the platform or the simulator.

5.2.4 Software Toolkit Refinements

The software portion of the TephraNet system can benefit from several additional features. In order for the system to be a viable test platform, it should be easy to gather data about the operating network and to make changes to the running code. This points to the need for software on the platform to be interchangeable with a minimum amount of effort. Ideally, this could be done directly through the network and also through a back-channel, such as a wired network attached to each node.

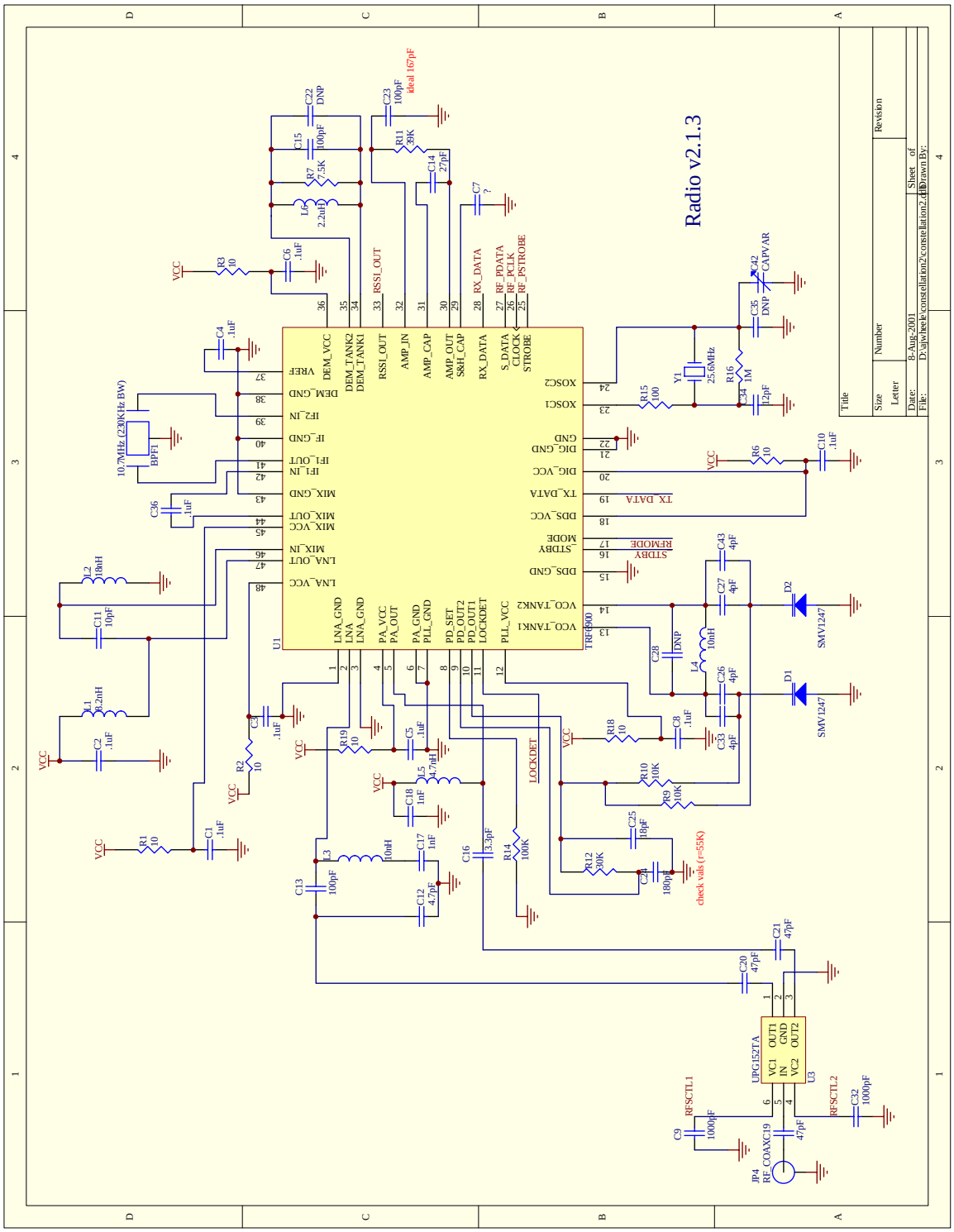
5.2.5 Refinement of Software Algorithms

The synchronization and routing algorithms play key roles in the operation of TephraNet for environmental sensing. Since these two components did not function correctly, they should be reworked. The suggestions posed in the analysis (Section 5.1.5) should be tested out as possible solutions to the algorithmic problems.

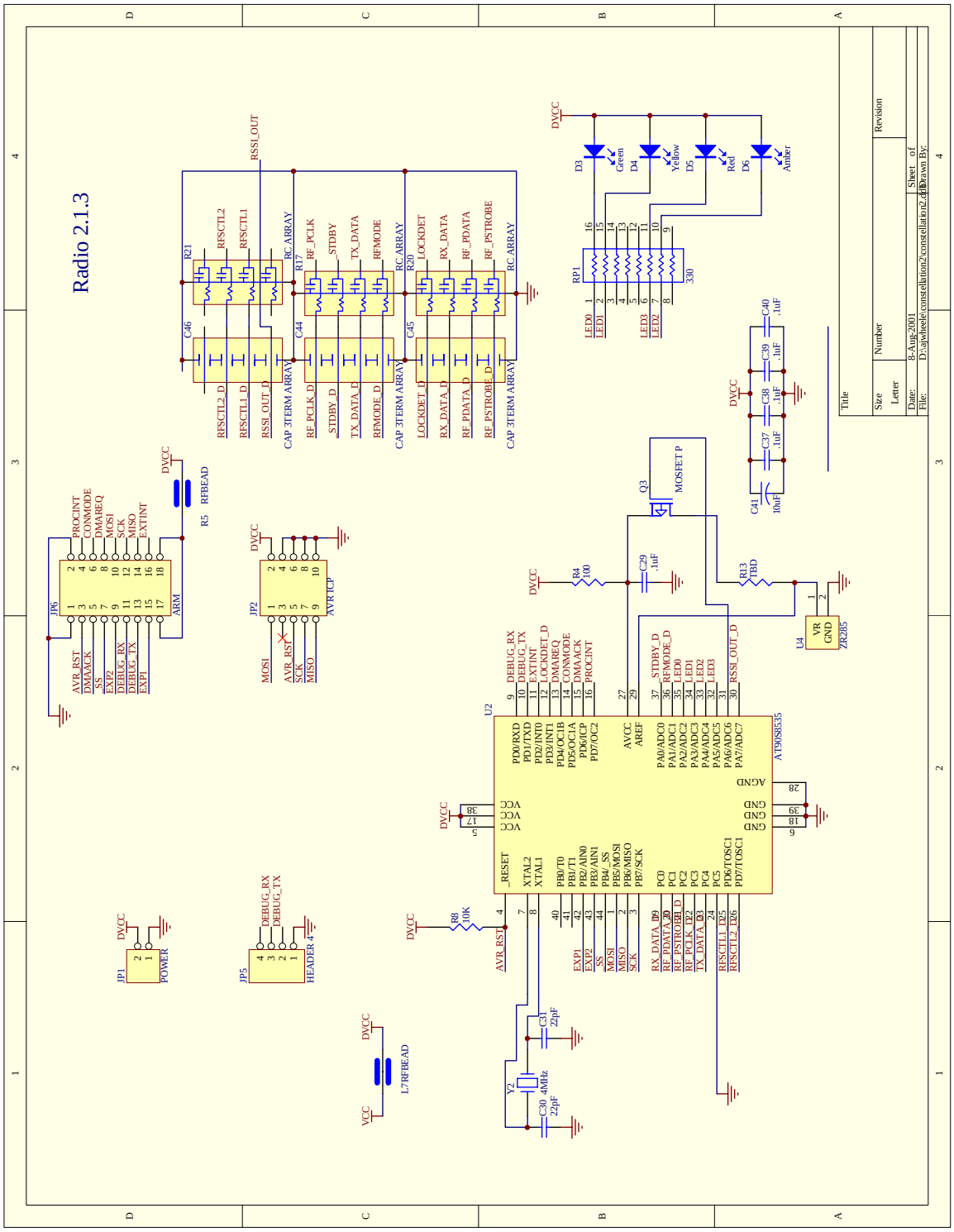
5.3 Contributions and Conclusions

The TephraNet system made several contributions to the areas of self-organizing network research and to environmental sensing tools. The TephraNet system introduced self-organizing networks as a tool for environmental research and made a significant step towards demonstrating a working system for that application. The system also presents a first revision of a common hardware and software toolkit for both environmental sensing and the testing of ad-hoc network routing algorithms. Significant problems with the current formulation of both GRAd and other hop-count based algorithms were also uncovered. Future work with the TephraNet platform should help advance both the fields of environmental sensing and ad-hoc wireless networking.

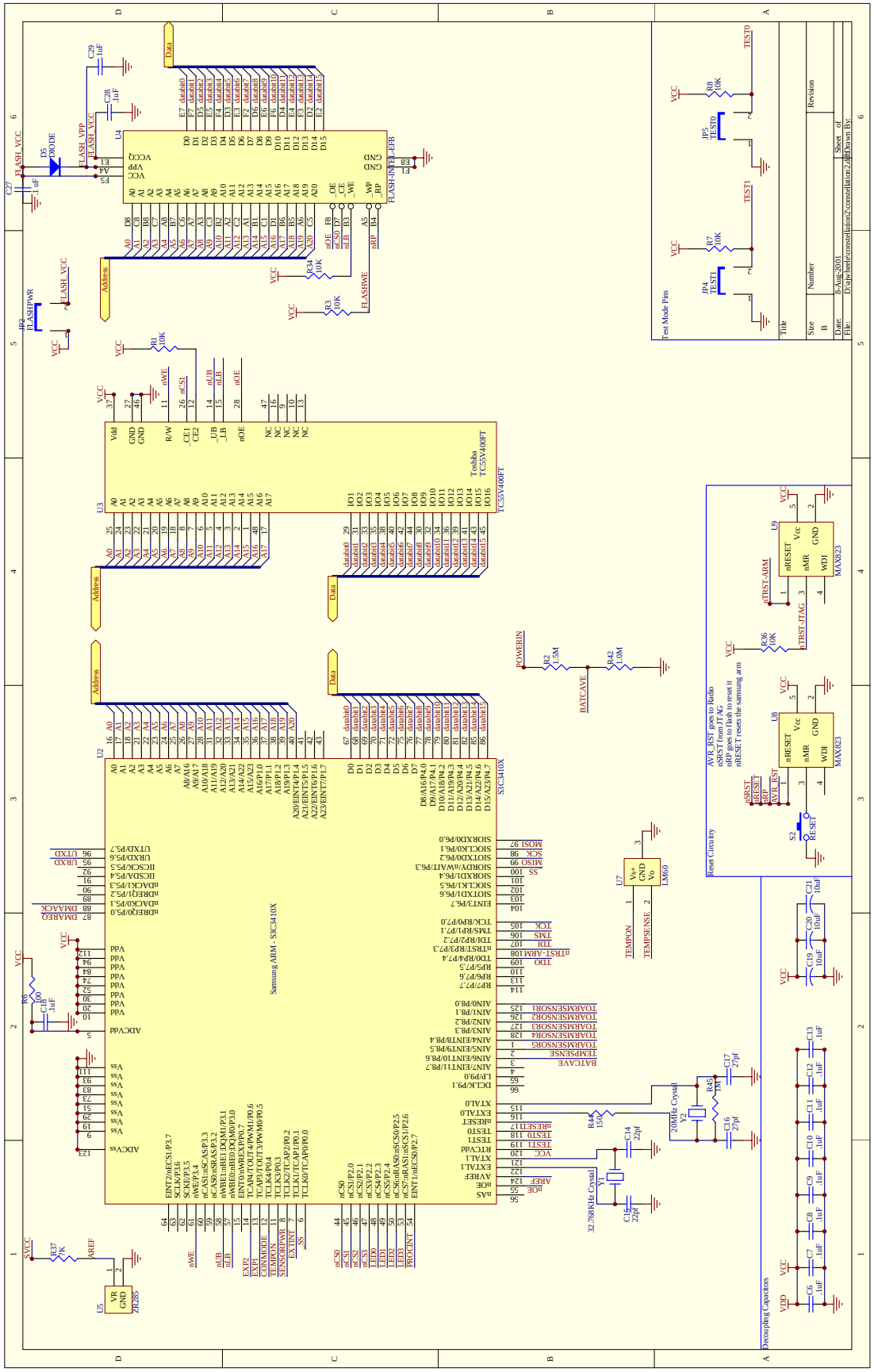
Appendix A: Hardware Design



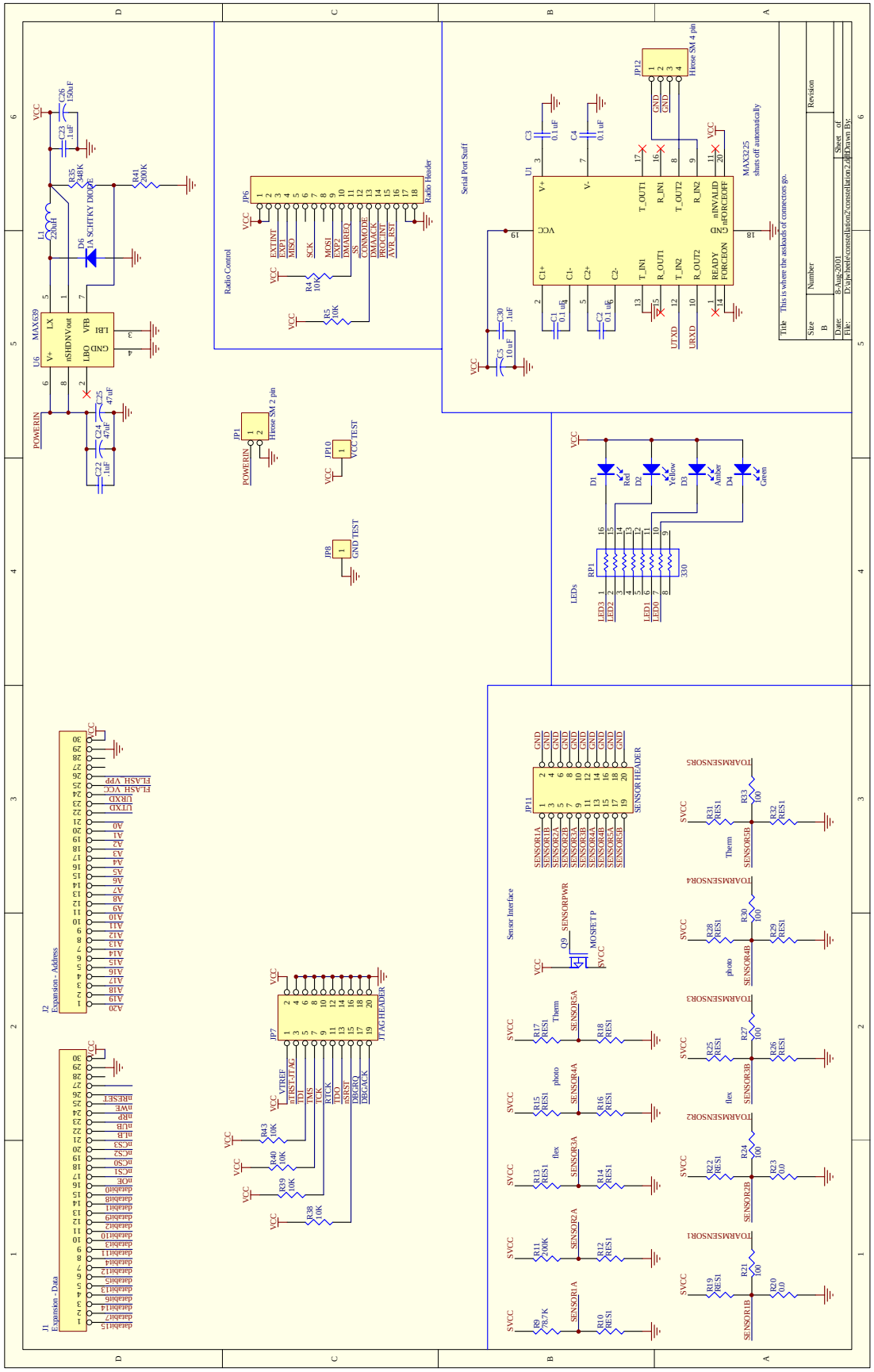
Radio Schematic, part 1/2



Radio Schematic, page 2/2



Processor Schematic, page 1/2



Processor Schematic, page 2/2

Designator(s)	Num/Board	Part Type	Footprint	Packaging Notes	Manufacturer	Part Num	Description	Substitution	Distributor	Dist. Part Num	
BPF1	0	10.7MHz (180KHz BW)	EFO-S	**DNP**	Toko	SK107M2N-AO-20	FM 180KHz 10.7MHz IF filter	contact first	Digkey	TK2306-ND	
C1-6,C8,C10,C29,C36-39,C40	14	.1uF	0603C	reel	*	*	*	*	*	*	
C7	1	5600pF	0603C	reel	*	*	*	*	*	*	
C11	1	10pF	0603C	reel	*	*	*	*	*	*	
C12	1	5pF	0603C	reel	*	*	*	*	*	*	
C13,C15	2	100pF	0603C	reel	*	*	*	*	*	*	
C9,C17,C18,C32	4	1000pF	0603C	reel	*	*	*	*	*	*	
C16,C26,C27	3	3pF	0603C	reel	*	*	*	*	*	*	
C33,C43	2	.5pF	0603C	reel	*	*	*	*	*	*	
C19,C20,C21,C25,C34,C35	6	47pF	0603C	reel	*	*	*	*	*	*	
C23	1	150pF	0603C	reel							
C24	1	470pF	0603C	reel	*	*	*	*	*	*	
C14	1	56pF	0603C	reel	*	*	*	*	*	*	
C30,C31	2	22pF	0603C	reel	*	*	*	*	*	*	
C41	1	4.7uF	EIA-A	reel	*	*	*	*	*	*	
D1,D2	2	SMV1247	SC-79	reel	Alpha Industries	SMV1247-079	varactor	no substitute	www.compdist.com	*	
D3,D6	2	Amber	1206-LED	reel	Lite-On	LTST-C150AKT	amber LED	other color	Digikey	160-1166-2	
D4	1	Yellow	1206-LED	reel	Lite-On	LTST-C150YKT	yellow LED	other color	Digikey	160-1170-2	
D5	1	Green	1206-LED	reel	Lite-On	LTST-C150GKT	green LED	other color	Digikey	160-1169-2	
R1-3,R6,R18,R19	6	10 Ohm	0603C	reel	*	*	*	*	*	*	
R4,R15	2	100 Ohm	0603C	reel	*	*	*	*	*	*	
R5,L7	2	RFBEAD	0805	reel	TBD	*	*	*	*	*	
R7	1	12K	0603C	reel	*	*	*	*	*	*	
R8,R9,R10	3	10K	0603C	reel	*	*	*	*	*	*	
R11	1	39K	0603C	reel	*	*	*	*	*	*	
R12	1	19.6K	0603C	reel	Panasonic ECG	ERJ-3EKF1742V	1% Resistor	*	Digikey	P17.4KHCT-ND	
R13	1	5.6K	0603C	reel	*	*	*	*	*	*	
R14	1	100K	0603C	reel	*	*	*	*	*	*	
R16	3	1M	0603C	reel	*	*	*	*	*	*	
RP1	1	220 Ohm	CTS742-16	reel	CTS Corp	742C163221JTR	220 res pack	742C163331JTR (330 Ohm)	Digikey	742C163221JTR	
JP1	1	POWER	HDR1X2	loose - in bag	any	*	.1" 2pin header	*	*	*	
JP2	1	AVR ICP	HDR2X5	loose - in bag	any	*	.1" 2 row 10 pin header	*	*	*	
JP4	1	RF_COAX	LINX ANT VERTICAL	bulk- bagged individually	Linx Technologies	CONREVSMA001	rSMA connector	no substitute	Linx	*	
JP5	0	HEADER 4	HDR1X4	**DNP**	any	*	.1" 4 pin header	*	*	*	
JP6	1	ARM	HIROSE 1MM 18PIN	in tubes	Hirose	FH10A-18S-1SH	18pin 1mm flex	no substitute	Digikey	HFE18F-ND	
L1	1	8.2nH	0603C	cut tape (>36" extra)	Toko	*	PTL type inductor	*	*	*	
L2	1	18nH	0603C	cut tape (>36" extra)	Toko	*	PTL type inductor	*	*	*	
L3,L4	2	10nH	0603C	reel	Murata	*	5% wirewound	*	*	*	
L5	1	4.7nH	0603C	cut tape (>36" extra)	Toko		PTL type inductor	*	Digikey	TKS2341CT	
L6	1	2.2uH	1812C	reel	API Delevan	*	5% wirewound	*	*	*	
MISC2-MISC24	23	shield clips	free pad	reel	Autosplice	7-V2004-125AA	RF shield clip	no substitute	Quest		
MISC1	1	test clip	free pad	reel							
U1	1	TRF6900	SQFP7X7-48(N)	tray	TI	TRF6900PT	900MHz transceiver	TRF6900APT	Wyle	*	
U2	1	AT90S8535	QFP10X10-44(N)	tray	Atmel	AT90LS8535	AVR RISC processor	AT90S8535	*	*	
U3	1	UPG152TA	SOT-26	cut tape (>36" extra)	NEC	UPG152TA	microwave switch	no substitute	Digikey	*	
U4	1	ZR285	SOT-23	reel	Zetex	ZR285F03TA	micropower 2.5V reference	contact first	Digikey	ZR285F03CT	
Y1	1	25.6MHz	HC-45-GW	loose - in bag	International Crystal	865842	25.6MHz gull-wing crystal	26MHz gull-wing	ICM	*	
Y2	1	4MHz	ECS-CSM-12	cut tape (>36" extra)	ECS	ECS-40-20-18-TR	4MHz 20pF crystal	no substitute	Digikey	XC587CT-ND	
Q3	1	transistor .3Ohm	SOT-23	reel							
C44,C45,C46	3	CAP 3TERM ARRAY	RESARRAY	cut tape (>36" extra)	Panasonic						
R17,R20,R21	3	RC ARRAY		cut tape (>36" extra)	Panasonic						
Board Revision 2.1.4 BOM Revision 1.3 4/2/2000 Andy Wheeler ajw@media.mit.edu											

Bill of Materials for Radio

Designator	# per board	Part Type	Footprint	Notes	Manufacturer	Part #	Description	Substitution	Distributor	Distrib #
C14, C15	2	22pf	0603C		*	*	22pf Capacitor		Digikey	PCC220ACVCT-ND
C1-4, C6-C13, C18, C22, C23, C27-C30	19	.1uF	0603C		*	*	.1 uF Capacitor		Digikey	PCC1788CT-ND
C16, C17	2	27pf	0603C		*	*	27 pf capacitor		Digikey	311-1063-1-ND
C5, C19-21	4	10uF	EIA-A		*	*	*		*	*
C24, C25	2	47uF	PANASONIC TE CAP D		Panasonic - ECG	ECS-T1AD476R	47uF Cap 10V Tantalum		Digikey	PCS2476CT-ND
C26	1	150uF	PANASONIC UE CAP		Panasonic - ECG	EEF-UE0J151R	150uF Cap 6.3V Spec Polymer		Digikey	PCE3269CT-ND
D1	1	Red	1206-LED		Lite-on	LTST-C230CKT	red led 1206 footprint		Digikey	160-1186-1
D2	1	Yellow	1206-LED		Lite-On	LTST-C190EKT	orange LED 1206 footprint		Digikey	160-1182-1
D3	1	Amber	1206-LED		Lite-On	LTST-C230AKT	Amber LED 1206 footprint		Digikey	160-1185-1
D4	1	Green	1206-LED		Lite-On	LTST-C230GKT	Green LED 1206 footprint		digikey	160-1188-1
D5	1	DIODE	SC-70		*	*	*		*	*
D6	1	1A SCHTKY DIODE	SMA		Diodes, Inc	B130-13	1A Schottky Diode, 30 V SMA		Digikey	B130DICT-ND
J1, J2	2	Expansion - Data/Addr	HIROSE 1MM 30PIN FLEX		hirose	fh10a-30s-1sh	1mm 30 pin flex ribbon cable header		digikey	HFE30F-ND
JP1	1	Hirose SM 2 pin	HIROSE SM RA 2PIN		HIROSE	df3-2p-2h (20)	2 pin right angle 2mm header		digikey	H2127-ND
JP11	1	SENSOR HEADER	HIROSE 20PIN 2MM RA HDR		hirose	df11something	*		Digikey	*
JP12	1	Hirose SM 4 pin	HIROSE SM RA 4PIN		hirose	df3-4p-2h (20)	4 pin right angle 2mm header		Digikey	H2129-ND
JP2, JP4, JP5	3	JUMPERS	RAD0.1		any	*	.1 inch header 1x2		Digikey	WM4000-ND
JP6	1	Radio Header	HIROSE 1MM 18PIN FLEX		hirose	fh10a-18s-1sh	1mm 18 pin flexible ribbon cable header		digikey	hfe18f-nd
JP7	1	JTAG HEADER	LOGIC ANALYZER HEADER		3M		.05 inch header 2x10		Digkey	MHB20K-ND
JP8	1	GND TEST	IRON		Keystone Elec	PC test point	*		Digikey	5016KCT-ND
L1	1	220uH	DT3316		Coilcraft	DT3316	220 uH inductor		Coilcraft	DT3316
Q9	1	MOSFET P	SOT-23-T		Fairchild	NDS356P	pfet		Digikey	NDS356PCT
R1, R3-R5, R7, R8, R34, R36, R38, R39, R40, R43	12	10K	0603C		*	*	*		Digikey	P10KGCT-ND
R11	1	200K	0603C	ordered 200 arr 2.5.01	Phycomp	9C06031A2003FKHFT	RES 200K OHM 1/16W 1% 0603		Digikey	311-200KHCT-ND
R2	1	1.5M	0603C			*	1.50M OHM 1% 0603		Digikey	P1.50MHCT-ND
R20, R23	2	0	0603C		*	*	0.0 Ohm 1/16W		Digikey	311-0.0GCT-ND
R21, R24, R27, R30, R33	5	100	0603C	ordered 1000 arr 2.5.01	Phycomp	9C06031A1000JLHFT	100 OHM 5% 0603		digikey	311-100GCT-ND
R35	1	348K	805		*	*	348K 0805 Resistor		Digikey	P348KCCT-ND
R41	1	200K	805		*	*	200K 0805 Resistor		Digikey	P200KCCT-ND
R42, R45	2	1.0M	0603C		*	*	Resistor 1.00 ohm 1% 0603		Digikey	311-1.00MHCT-ND
R44	1	150	0603C		*	*	*		Digikey	P150GCT-ND
R6	1	100	0603C		*	*	*		Digikey	*
R9	1	78.7K	0603C	ordered 200 arr2.5.01	Phycomp	9C06031A7872FKHFT	RES 78.7K OHM 1/16W 1% 0603 SMD		Digikey	311-78.7KHCT-ND
RP1	1	330	CTS742-16		CTS	742c163331j	8 resistor pack 330 ohm		Digikey	742c163331jct-ND
S2	1	RESET	PUSHSWITCH-P8058S-ND		Panasonic	EVQPJB04K	momentary push button switch		Digikey	P8058S-ND
U1	1	MAX3225	MAX3225CAP	ordered 30 arr 2.5.01	Maxim	max3225cap	maxim rs232 converter		maxim	MAX639CAP
U2	1	S3C3410X	S3C3410X		Samsung	S3C3410X	Samsung 32bit ARM processor		HarborTech	*
U3	1	TC55V400FT	TC55V400FT		Toshiba	TC55V400FT	256K x 16bit SRAM low power		Caltech electronics	*
U4	1	FLASH-INTEL-EFB	28F320C3 UBGA		Intel	RD28F320C3	Intel Flash uBGA .75mm		Intel	*
U5	1	ZR285	SOT-23		Zetek	ZR285F03TA	IC voltage REF 2.5V SMD sot-23		digikey	ZR285F03CT-ND
U6	1	MAX639	SO-8		Maxim	MAX639CSA	step down DC-DC switching converter		Maxim	MAX639CSA
U7	1	LM60	SOT-23		National	LM60CIM3	2.7V SOT-23 Temperature Sensor		Newark Electronics	92F317
U8, U9	2	MAX823	SOT23-5		Maxim	MAX823TEUK-T	5 pin Microprocessor Supervisory Circuit		SemiXchange	MAX823TEUK
Y1	1	32.768KHz Crystal	CM202_XTAL		Citizen	CM202-32.768KDZFT	32.728 KHz crystal		Digikey	300-1006-2-ND
Y2	1	20MHz Crystal	XC620_XTAL		ECS	ECS-200-20-20A	20 MHz crystal		digikey	XC620CT
JP10	1	DO NOT PLACE	IRON	DO NOT PLACE	Keystone Elec	PC test point			Digikey	5016KCT-ND
R10	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R12	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R13	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R14	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R15	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R16	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R17	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R18	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R19	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R22	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R25	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R26	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R28	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R29	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R31	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R32	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*
R37	1	TBD	0603C	DO NOT PLACE	*	*	*		*	*

Bill of Materials for Processor

Appendix B: Source Code Listings

This appendix contains a partial listing of the source code for the TephraNet system. The code contained here implements most of the important functionality in the system. The following code is not listed here: code running on radio baseband controller, bootloader for node, testing and programming code for node, code running on base station computers, and operating system port for node. Also not listed is “helper code” implementation- i.e. code that does not provide major functionality. For those files, only the header is listed. Readers interested in code not listed here, or obtaining the following code in electronic form should contact the author. Code is listed header file first, followed by c file. Tephra is listed first, which is the boot code. Subsequent files are in alphabetical order. See the software description in Chapter 3 for an explanation of the various modules.

tephra.h

```
// File: tephra.h
// Description: General header file for the Tephra system
// Author(s):   Andrew Wheeler <ajw@media.mit.edu>
//              Robert Poor <r@media.mit.edu>
//
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// warranty.

#ifndef TEPHRA_H
#define TEPHRA_H
// Global definitions for the tephra system.

#include "types.h"

// Task IDs and priorities.  In the uCos system, each task has a
// unique prioritiy, which also serves as a task ID.  The lowest
// numbered task runs with the highest priority.

#define SER_RCV_TASK_ID       5         // monitor and process serial input
#define RTC_TASK_ID     6       // blinks lights for sync DEBUGGING ONLY
#define RAD_RCV_TASK_ID       10        // receive packets from the radio
#define MAC_TASK_ID 15        // send packets to the radio
#define APPR_TASK_ID          20        // process packets at application level
#define APPX_TASK_ID          25        // generate packets to transmit
#define BEACON_TASK_ID  26      // testing routine that discovers devices
#define ARQ_TASK_ID 30        // automatic retry/retransmit
#define PING_NEIGHBORS_TASK_ID 31 // task id for discovering neighbors
#define LINK_REQUEST_TASK_ID   32
#define COST_TASK_ID    33      // prunes cost tables
#define SYNC_TASK_ID    34      // sends sync packets out
#define STAT_TASK_ID    35      // sends statistics packets out
#define BOOT_TASK_ID    36
#define SYS_TASK_ID     37      // system manager/background
#define BASE_TASK_ID          38        // initialization task (perhaps should be
high)

// stack sizes for each of the above tasks
#define SER_RCV_TASK_STACK_SIZE         256
#define RAD_RCV_TASK_STACK_SIZE         256
#define MAC_TASK_STACK_SIZE   256
#define RTC_TASK_STACK_SIZE     256
#define APPR_TASK_STACK_SIZE  256
#define APPX_TASK_STACK_SIZE  256
#define ARQ_TASK_STACK_SIZE   256
#define BASE_TASK_STACK_SIZE  256
#define PING_NEIGHBORS_STACK_SIZE 256
#define LINK_REQUEST_STACK_SIZE 256
#define SYNC_TASK_STACK_SIZE    256
#define STAT_TASK_STACK_SIZE    256
#define COST_TASK_STACK_SIZE    256
#define SYS_TASK_STACK_SIZE     256
#define BEACON_STACK_SIZE       256
#define BOOT_TASK_STACK_SIZE         256

#define TEPHRA_BAUD_RATE        19200

// payload for entering operational mode
```

```
typedef struct
{
  uint8_t unused; // c doesn't like empty structures
} setOperationalPayload;

/*void SetOperationalMode( bool );
bool GetOperationalMode( void );
void SetSleeplessMode(bool val);
*/
#endif
```

tephra.c

```
// File: tephra.c
// Description: main() and main processing thread for Tephra system.
// Author(s):   Andrew Wheeler <ajw@media.mit.edu>
//
//
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// warranty.

#include "tephra.h"
#include "types.h"
#include "includes.h"
#include "rad.h"
#include "mac.h"
#include "pseg.h"
#include "param.h"
#include "appr.h"
#include "appx.h"
#include "ping.h"
#include "sync.h"
#include "grad.h"
#include "rtc.h"
#include "cost.h"
#include "arq.h"
#include "util.h"
#include "serial.h"
#include "stats.h"
#include "sysmanager.h"
#include <stdlib.h>

#ifndef BIT
#define BIT(x)      (1 << (x))
#endif

// tephra.c defines the main() routine, including any one-time
// initialization (TephraInit()) and the main processing thread
// (TephraMain()).  The main processing thread runs at the lowest
// priority.

static unsigned int _mainStack[BASE_TASK_STACK_SIZE];
//static bool _systemAsleep;
//static bool _sleeplessMode;   // set to true if the system should not sleep
//static bool _operationalMode;   // set to true of the system is in operation

void tephraSWI(int);
extern void ResetHandler( void );

static void TephraInit() {
#ifdef DEBUG_BUFFER
  debug_buffer(1);
#endif

  // cold-start initialization of hardware and software.

  LED_1_OFF();
  LED_2_OFF();
  LED_3_OFF();
  LED_4_OFF();

  ParamInit();
  SysInit();
  StatsInit();
  RTCInit();
  RadInit();
  PSegInit();
  MACInit();
  AppRInit();
  AppXInit();
  PingInit();
  SyncInit();
  CostInit();
  ARQInit();
  SerialInit();


  // starts the OS timer... should be last thing in this function...
  StartSystemTimer();
}

static void _TephraMain(void *args)
{
  TephraInit();
  OSTimeDly(OS_TICKS_PER_SEC);

  // start the system manager and then exit
  SysStart();

  OSTaskDel(BASE_TASK_ID);
```

```
}

int main()
{
#ifdef DEBUG_BUFFER
    debug_buffer(3);
#endif
    // NOTE: when we reach here, all I/O directions are already setup (init.s)

    // low level peripheral inits
    //    Delay(0);  //calibrate Delay()

    Uart_Init(TEPHRA_BAUD_RATE);
    // begin target initialization
    ARMTargetInit();

    ISR_SWI = (unsigned)tephraSWI;
    ISR_UNDEF = (unsigned)HaltUndef;
    ISR_PABORT = (unsigned)HaltPabort;
    ISR_DABORT = (unsigned)HaltDabort;

    // initialize uCOS
    OSInit();
    OSTimeSet(0);

    // create the system task
    OSTaskCreate(_TephraMain, NULL,
                    (void *)&_mainStack[BASE_TASK_STACK_SIZE-1], BASE_TASK_ID);

    // start the OS...
    OSStart();
    // never reached

    return 0;
}



void tephraSWI(int swiNum)
{
#ifdef DEBUG_BUFFER
    debug_buffer(8);
#endif
    INTPND = 0;

    while (true)
      {
          Uart_Printf("SWI: %d\n", swiNum);
          Delay(10000);
      }
/*      _rebooted = true; */
/*      Uart_Printf("got bad interrupt, restarting\n"); */
/*      ResetHandler(); */
}
```

appr.h

```
// File: appr.h
// Description: Application-level support for incoming packets
// Author(s):   Andrew Wheeler <ajw@media.mit.edu>
//              Robert Poor <r@media.mit.edu>
//
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// warranty.

#ifndef APPR_H
#define APPR_H

#include "types.h"
#include "pseg.h"

// The application receive task accepts packets from the high priority
// radio receive task and processes each incoming packet, dispatching
// it to appropriate software modules according to the contents of
// each packet segment.

#define APPR_QUEUE_SIZE 20
// Sets the maximum number of packets that can be installed in the
// application receive queue.  Above this number, the oldest packets
// will be discarded.

void AppRInit(void);
// cold-start initialization

void AppRReset(void);
// wake-up reinitialization

void AppRStart(void);
// Start the application receive thread

void AppRReceivePkt(pseg_t *pkt);
// Install a packet in the application receive queue and notify
// the receive task.

bool AppRGetIsPrinting(void);
void AppRSetIsPrinting(bool b);
// get/set the state of packet printing.  When true, every packet
// received is printed (in hex) to serial output.

#endif
```

appr.c

```
// File: appr.c
// Description: Application-level support for incoming packets
// Author(s):   Andrew Wheeler <ajw@media.mit.edu>
//              Robert Poor <r@media.mit.edu>
//
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// warranty.

#include "appr.h"
#include "appx.h"
#include "arq.h"
#include "cost.h"
#include "grad.h"
#include "param.h"
#include "ping.h"
#include "pseg.h"
#include "serial.h"
#include "sync.h"
#include "tephra.h"
#include "types.h"
#include "vector.h"
#include "includes.h"
#include "stats.h"
#include "sysmanager.h"

// stack for the appr task
static unsigned int _apprStack[APPR_TASK_STACK_SIZE];

// Define the raw storage for the receive queue
static DEFINE_VECTOR(_apprQueue, APPR_QUEUE_SIZE);

// when true, prints out the contents of each received packet.
static bool _isPrinting;

static void _AppRTask(void *args);
static void _AppRServicePkt(pseg_t *pkt, pseg_t *gradSeg);


void AppRInit(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(12);
#endif
    // initialize the receive queue
    VectorInit(VECTOR(_apprQueue), APPR_QUEUE_SIZE);
    AppRSetIsPrinting(false);
}

void AppRReset(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(13);
#endif
    // launch the application receive task.  Called from INIT_TASK.
    VectorClear(VECTOR(_apprQueue));
}

void AppRStart(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(14);
#endif
    OSTaskCreate(_AppRTask, NULL, (void *)&_apprStack[APPR_TASK_STACK_SIZE-1],
                 APPR_TASK_ID);
}

void AppRReceivePkt(pseg_t *pkt)
{
#ifdef DEBUG_BUFFER
    debug_buffer(15);
#endif
    // install a packet in the receive queue and notify the receive thread.
    // If the queue filled up as a result of enqueuing a new packet, remove
    // and free the oldest.
    PSegFree(VectorShove(VECTOR(_apprQueue), pkt));
    OSTaskResume(APPR_TASK_ID);
}

bool AppRGetIsPrinting(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(16);
#endif
    return _isPrinting;
}

void AppRSetIsPrinting(bool b)
{
#ifdef DEBUG_BUFFER
    debug_buffer(17);
#endif
    _isPrinting = b;
}

static void _AppRTask(void *args) {
    // Application Receive Task.  Wait for a packet to come available,
    // then dispactch according to packet segment types.
    pseg_t* pkt;
```

```
    pseg_t* gradSeg;

    while (true)
    {
#ifdef DEBUG_BUFFER
          debug_buffer(18);
#endif

          //        Uart_Printf("AppRTask\n");
          while ((pkt = (pseg_t *)VectorDequeue(VECTOR(_apprQueue))) == NULL)
          {
              OSTaskSuspend(APPR_TASK_ID);
          }

          // pkt now refers to a successfully dequeued packet.  Look for a
          // grad header segment.
          gradSeg = GRAdFindSegment(pkt);

          if (gradSeg == NULL)
          {
              // No grad routing header found.  Unconditionally process and
              // free the packet.
              _AppRServicePkt(pkt, NULL);
              PSegFree(pkt);

          }
          else if (!CostUpdate(gradSeg))
          {
            // pkt has already been seen - check if it is for us and has an ACK
            if (GRAdIsForMe(gradSeg) && (ARQFindSegment(pkt) != NULL)) {
              // an ACK must not have gone through earlier- send one now
              ARQServiceARQ(ARQFindSegment(pkt), gradSeg);
            }
            /*        Uart_Printf("  grad dropping stale packet dst %d, src %d, seq
%d\n",
                        ((gradPayload *)PSegPayload(gradSeg))->fDestination,
                        ((gradPayload *)PSegPayload(gradSeg))->fOriginator,
                        ((gradPayload *)PSegPayload(gradSeg))->fSequence);*/
            PSegFree(pkt);
          }
          else
          {
              // pkt has a valid GRAd routing header.  Process it locally
              // if destined for this node.
              if (GRAdIsForMe(gradSeg))
              {
                    _AppRServicePkt(pkt, gradSeg);

                    /*                    Uart_Printf("  grad processing my packet
dst %d, src %d, seq %d\n",
                      ((gradPayload *)PSegPayload(gradSeg))->fDestination,
                      ((gradPayload *)PSegPayload(gradSeg))->fOriginator,
                      ((gradPayload *)PSegPayload(gradSeg))->fSequence);*/
                    GRAdRelayIfNeeded(pkt, gradSeg);
              }
              else
              {
                    // relay the message if needed, free it regardless.
                /*
                      Uart_Printf("  grad checking relay dst %d, src %d, seq %d\n",
                      ((gradPayload *)PSegPayload(gradSeg))->fDestination,
                      ((gradPayload *)PSegPayload(gradSeg))->fOriginator,
                      ((gradPayload *)PSegPayload(gradSeg))->fSequence);
                */
                    GRAdRelayIfNeeded(pkt, gradSeg);
                }
              }
          }
    }

void _AppRServicePkt(pseg_t *pkt, pseg_t *gradSeg)
{
    pseg_t *seg = pkt;

#ifdef DEBUG_BUFFER
    debug_buffer(19);
#endif
    if (AppRGetIsPrinting() && SerialGatewayMode())
    {
          PSegPrint(pkt);
    }

  // dispactch according to each segment type
    while (seg != NULL)
    {
          switch (PSegType(seg))
          {
          case PSEG_TYPE_EOP:
            break;
          case PSEG_TYPE_SYNC:          // inter-node synchronization info
            SyncServicePkt(seg);
            PingCheckSync(seg);
            SerialCheckSync(seg);
            break;
          case PSEG_TYPE_GRAD:          // gradient routing info
            break;
          case PSEG_TYPE_DISCO:         // discovery routing request
            break;
          case PSEG_TYPE_PING:          // ping packet, request for pong
            PingServicePing(seg, gradSeg);
            break;
          case PSEG_TYPE_PONG:          // reply to a ping
            PingServicePong(seg);
            break;
          case PSEG_TYPE_ARQ:           // received and ARQ: send and ACK
            ARQServiceARQ(seg, gradSeg);
            break;
          case PSEG_TYPE_ACK:           // received and ACK: prune retry queue
            ARQServiceACK(seg);
            break;
          case PSEG_TYPE_PARAM_SET:     // set parameters from payload
            ParamServiceSet(seg);
            break;
          case PSEG_TYPE_PARAM_REQUEST: // request current parameters
            ParamServiceRequest(gradSeg);
            break;
          case PSEG_TYPE_PARAM_REPORT: // here are my current parameters
            break;
          case PSEG_TYPE_STATS_RESET:   // clear current logging stats
            StatsClearData();
            break;
          case PSEG_TYPE_STATS_REQUEST: // request logging statistics
            SendStatsPkt(gradSeg);
            break;
          case PSEG_TYPE_STATS_REPORT_A: // here are my logging statistics
            break;
```

```
        case PSEG_TYPE_STATS_REPORT_B: // here are my logging statistics
          break;
        case PSEG_TYPE_APPX_REPORT: // receive a report..?
          break;
        case PSEG_TYPE_NEIGHBOR_REPORT: // a neighbor report has arrived (doctor)
          SerialServiceNeighborReport(seg);
          break;
        case PSEG_TYPE_LINK_REPORT:
          SerialServiceNeighborLinkReport(seg);
          break;
        case PSEG_TYPE_NEIGHBOR_REQUEST:
          PingServiceNeighborsRequest(seg, gradSeg);
          break;
        case PSEG_TYPE_LINK_REQUEST:
          PingServiceLinkRequest(seg, gradSeg);
          break;
        case PSEG_TYPE_SET_IN_OPERATION:
          //        SetOperationalMode(TRUE);
          break;
        case PSEG_TYPE_SDP_REQUEST:
          //SDPServiceRequest(seg, gradSeg);
          break;
        case PSEG_TYPE_SDP_REPLY:
          //SDPServiceReply(seg, gradSeg);
          break;
        case PSEG_TYPE_BOOT_REPORT:
          SerialServiceBootReport(seg);
          break;
        case PSEG_TYPE_ENTER_TEST:
          Uart_Printf(" enter test pkt\n");
          SysSetTestMode(true);
          break;
        case PSEG_TYPE_EXIT_TEST:
          Uart_Printf(" exit test pkt\n");
          // sets a keepalive
          SysRequestNoSleep(500);
          SysSetTestMode(false);
          break;
        case PSEG_TYPE_START_ASYNC:
          OSTaskDel(BOOT_TASK_ID);
          SysSetTestMode(true);
          PingStartAsyncLinkTest();
          break;
        case PSEG_TYPE_STOP_ASYNC:
          PingStopAsyncLinkTest();
          OSTaskDel(BOOT_TASK_ID);
          SysSetTestMode(false);
          break;
        default:
          break;
        }
        seg = PSegNext(seg);
    }
}
```

appx.h

```
// File: appx.h
// Description: Application-level support for incoming packets
// Author(s):   Andy Wheeler <ajwheele@mit.edu>
//
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// warranty.

#ifndef APPX_H
#define APPX_H

#include "types.h"
#include "pseg.h"

typedef struct {
  // need to decide what info is carried in APPX_REQUEST messages
  uint16_t fInternal_temperature;
  uint16_t fBattery;
  uint16_t fTemperature;
  uint16_t fLight;
  uint16_t fWind;
  uint16_t fHumidity;
} appXRequestPayload;

// The application transmit thread sits in a loop and periodically
// generates packets for transmission.  This can be thought of as
// a "push" model for sending data to a remote node.

void AppXInit(void);
// cold-start initialization

void AppXReset(void);
// wake-up reinitialization

void AppXStart(void);
// Start the application transmit thread

void AppXServiceRequest(pseg_t *seg, pseg_t *gradSeg);
// A segment of type PSEG_TYPE_APPX_REQUEST specifies what information
// the AppX thread should send, to whom, and how often.  This is the
// function that receives such a request packet (from the AppR module).

#endif
```

appx.c

```
// File: appx.c
// Description: Application-level support for incoming packets
// Author(s):   Andy Wheeler <ajwheele@mit.edu>
//              Ben Brown <texan@mit.edu>
//
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// warranty.

#include "appx.h"
#include "arq.h"
#include "grad.h"
#include "mac.h"
#include "param.h"
#include "pseg.h"
#include "tephra.h"
#include "types.h"
#include "vector.h"
#include "includes.h"
#include "ucos_ii.h"
#include <stdlib.h>

#ifndef BIT
#define BIT(x)      (1 << (x))
#endif

// stack for the appx task
static unsigned int _appxStack[APPX_TASK_STACK_SIZE];

static void _AppXTask(void *args);

void AppXInit(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(20);
#endif
}

void AppXReset(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(21);
#endif
}

void AppXStart(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(22);
#endif
    OSTaskCreate(_AppXTask,
                 NULL,
                 (void *)&_appxStack[APPX_TASK_STACK_SIZE-1],
                 APPX_TASK_ID);
}

void AppXServiceRequest(pseg_t *pkt, pseg_t *gradSeg) {
#ifdef DEBUG_BUFFER
    debug_buffer(23);
#endif
    // ## do something with the contents of pkt, then notify the
    // ## (presumably waiting) AppX task
    //  OSTaskResume(APPX_TASK_ID);
}


static void _AppXTask(void *args)
{
    uint16_t humidity_data[11];
    // Averaged data will be stored in array_data[10]
    uint16_t wind_data[11];
    uint16_t light_data[11];
    uint16_t temperature_data[11];
    uint16_t internal_temperature_data[11];
    uint16_t battery_data[11];
    uint16_t i;
    uint16_t min_data;
    uint16_t max_data;
    uint32_t array_total;
    pseg_t *pkt;
    appXRequestPayload *pp;
    // Application Transmit Task.

    //  if (ParamGet(PARAM_BASESTATION_ADDR) == BROADCAST_ID) {
    //    OSTaskDel(APPX_TASK_ID);
    //    return;     // Basestation address has not been initialized
    //  }

    while (true)
    {
#ifdef DEBUG_BUFFER
          debug_buffer(24);
#endif

          //        Uart_Printf("AppXTask\n");

          PDAT0 &= ~BIT(2);        // turns SENSORPWR on (inverse logic)
          PDAT0 |= BIT(3);         // turns TEMPON (internal temperature sensor)
                                   // on (positive logic)

          OSTimeDly(OS_TICKS_PER_SEC);
#ifdef DEBUG_BUFFER
```

```
        debug_buffer(198);
#endif

        for (i = 0; i < 10; i++)       // takes 10 readings from each sensor
        {
            ADCCON = ADCCON_AIN0         |
                     ADCCON_MCLK_DIV_16  |
                     ADCCON_10_BITS;
            OSTimeDly(1);
            ADCCON |= ADCCON_START;
            OSTimeDly(1);
#ifdef DEBUG_BUFFER
            debug_buffer(199);
#endif
            while (ADCCON_BUSY());
                humidity_data[i] = ADCDAT;

            ADCCON = ADCCON_AIN2         |
                     ADCCON_MCLK_DIV_16  |
                     ADCCON_10_BITS;
            OSTimeDly(1);
            ADCCON |= ADCCON_START;
            OSTimeDly(1);
#ifdef DEBUG_BUFFER
            debug_buffer(200);
#endif
            while (ADCCON_BUSY());
            wind_data[i] = ADCDAT;

            ADCCON = ADCCON_AIN3         |
                     ADCCON_MCLK_DIV_16  |
                     ADCCON_10_BITS;
            OSTimeDly(1);
            ADCCON |= ADCCON_START;
            OSTimeDly(1);
#ifdef DEBUG_BUFFER
            debug_buffer(201);
#endif
            while(ADCCON_BUSY());
            light_data[i] = ADCDAT;

            ADCCON = ADCCON_AIN4         |
                     ADCCON_MCLK_DIV_16  |
                     ADCCON_10_BITS;
            OSTimeDly(1);
            ADCCON |= ADCCON_START;
            OSTimeDly(1);
#ifdef DEBUG_BUFFER
            debug_buffer(202);
#endif
            while(ADCCON_BUSY());
            temperature_data[i] = ADCDAT;

            ADCCON = ADCCON_AIN5         |
                     ADCCON_MCLK_DIV_16  |
                     ADCCON_10_BITS;
            OSTimeDly(1);
            ADCCON |= ADCCON_START;
            OSTimeDly(1);
#ifdef DEBUG_BUFFER
            debug_buffer(203);
#endif
            while (ADCCON_BUSY());
            internal_temperature_data[i] = ADCDAT;

            ADCCON = ADCCON_AIN6         |
                     ADCCON_MCLK_DIV_16  |
                     ADCCON_10_BITS;
            OSTimeDly(1);
            ADCCON |= ADCCON_START;
            OSTimeDly(1);
#ifdef DEBUG_BUFFER
            debug_buffer(204);
#endif
            while (ADCCON_BUSY());
            battery_data[i] = ADCDAT;
        }

        // turn off ADC
        ADCCON = ADCCON_STANDBY_MODE;

        max_data = humidity_data[0];
        min_data = max_data;
        array_total = max_data;
        for (i = 1; i < 10; i++)
        {
            if (humidity_data[i] < min_data)
              min_data = humidity_data[i];
            else if (humidity_data[i] > max_data)
              max_data = humidity_data[i];
            array_total += humidity_data[i];
        }
        array_total = (array_total - min_data - max_data);
        humidity_data[10] = (uint16_t)(array_total / 8);
        array_total = 0;
#ifdef DEBUG_BUFFER
        debug_buffer(205);
#endif

        max_data = light_data[0];
        min_data = max_data;
        array_total = max_data;
        for (i = 1; i < 10; i++)
        {
            if (light_data[i] < min_data)
              min_data = light_data[i];
            else if (light_data[i] > max_data)
              max_data = light_data[i];
            array_total += light_data[i];
        }
        array_total = (array_total - min_data - max_data);
        light_data[10] = (uint16_t)(array_total / 8);
        array_total = 0;
#ifdef DEBUG_BUFFER
        debug_buffer(206);
#endif

        max_data = temperature_data[0];
        min_data = max_data;
        array_total = max_data;
        for (i = 1; i < 10; i++)
        {
            if (temperature_data[i] < min_data)
              min_data = temperature_data[i];
            else if (temperature_data[i] > max_data)
              max_data = temperature_data[i];
```

```
            array_total += temperature_data[i];
        }
        array_total = (array_total - min_data - max_data);
        temperature_data[10] = (uint16_t)(array_total / 8);
        array_total = 0;
#ifdef DEBUG_BUFFER
        debug_buffer(207);
#endif

        max_data = internal_temperature_data[0];
        min_data = max_data;
        array_total = max_data;
        for (i = 1; i < 10; i++)
        {
            if (internal_temperature_data[i] < min_data)
              min_data = internal_temperature_data[i];
            else if (internal_temperature_data[i] > max_data)
              max_data = internal_temperature_data[i];
            array_total += internal_temperature_data[i];
        }
        array_total = (array_total - min_data - max_data);
        internal_temperature_data[10] = (uint16_t)(array_total / 8);
        array_total = 0;
#ifdef DEBUG_BUFFER
        debug_buffer(208);
#endif

        max_data = battery_data[0];
        min_data = max_data;
        array_total = max_data;
        for (i = 1; i < 10; i++)
        {
            if (battery_data[i] < min_data)
              min_data = battery_data[i];
            else if (battery_data[i] > max_data)
              max_data = battery_data[i];
            array_total += battery_data[i];
        }
        array_total = (array_total - min_data - max_data);
        battery_data[10] = (uint16_t)(array_total / 8);
#ifdef DEBUG_BUFFER
        debug_buffer(209);
#endif

        max_data = wind_data[0];
        for (i = 1; i < 10; i++)
        {
            if (humidity_data[i] > max_data)
              max_data = humidity_data[i];
        }
        wind_data[10] = max_data;
#ifdef DEBUG_BUFFER
        debug_buffer(210);
#endif

        PDAT0 |= BIT(2);          // turns SENSORPWR off (inverse logic)
        PDAT0 &= ~BIT(3);         // turns TEMPON (internal temperature sensor)
                                  // off (positive logic)

        pkt = PSegAlloc(PSEG_TYPE_APPX_REPORT, sizeof(appXRequestPayload),
                        NULL);
        pp = PSegPayload(pkt);
        pp->fInternal_temperature = internal_temperature_data[10];
        pp->fBattery = battery_data[10];
        pp->fTemperature = temperature_data[10];
        pp->fLight = light_data[10];
        pp->fWind = wind_data[10];
        pp->fHumidity = humidity_data[10];

        LED_2_ON();
        OSTimeDly((OS_TICKS_PER_SEC*5) + (rand()%(OS_TICKS_PER_SEC*12)));
#ifdef DEBUG_BUFFER
        debug_buffer(211);
#endif
        // delay for between 3 and 15 seconds
        //  if (ParamGet(PARAM_ARQ_REPORTS)) {
        if (ParamGet(PARAM_BASESTATION_ADDR) != BROADCAST_ID)
        {

            MACXmitPkt(GRAdMakePkt(ARQMakeARQ(pkt),
                                   ParamGet(PARAM_BASESTATION_ADDR)));
        } else {
          PSegFree(pkt);
        }
        LED_2_OFF();
        OSTimeDly((OS_TICKS_PER_SEC * 120));
        /*  } else {
            //    while (1) {
            pkt2 = PSegCopy(pkt);                    // save a copy
            MACXmitPkt(GRAdMakePkt(pkt, ParamGet(PARAM_BASESTATION_ADDR)));
            // sends the packet
            OSTimeDly((OS_TICKS_PER_SEC*3) + (rand()%(OS_TICKS_PER_SEC*5)));
            pkt = pkt2;
            }
            }*/
    }
}
```

arq.h

```
// File: arq.h
// Description: support for Automatic Retry reQuest services
// Author(s):   Robert Poor <r@media.mit.edu>
//
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// warranty.

#ifndef ARQ_H
#define ARQ_H

#include "types.h"
#include "pseg.h"

// The Automatic Retry reQuest module keeps a copy of each
// outgoing packet and attempts periodic retransmission of
// the packet until it receives an acknowlegement that the
// packet has been received at the destination.

#define ARQ_QUEUE_SIZE 10
// Sets the maximum number of different packets that will
// be queued for retransmission.

typedef struct {
  uint8_t fReference;                   // reference number for the ack
  uint8_t fRetries;           // number of times we will attempt retransmit
} arqPayload;

typedef struct {
  uint8_t fReference;                   // reference number for the arq
} ackPayload;

void ARQInit(void);
// initialize the ARQ system

void ARQReset(void);
// warm restart

void ARQStart(void);
// Start the ARQ thread

void ARQDidXmit(pseg_t *pkt);
// Note that MAC layer sent a packet.  If it has an ARQ segment
// and the retry hasn't expired, queue a copy of the packet for
// subsequent retransmission.  Called from the MAC task.

pseg_t *ARQMakeARQ(pseg_t *pkt);
// Tack an ARQ segment on the front of this packet.  This has the
// effect that [1] a copy of the message will be queued for possible
// retransmission and [2] an ACK will be returned by the recipient.

void ARQServiceACK(pseg_t *seg);
// Handle an incoming ACK packet.  If there is a packet in the ARQ
// retry queue with matching reference number, delete it from the
// queue.

void ARQServiceARQ(pseg_t *arqSeg, pseg_t *gradSeg);
// Handle an incoming ARQ packet.  Respond by creating an ACK packet
// and returning it to the orginator of the ARQ.

pseg_t *ARQFindSegment(pseg_t *pkt);
// search for an ARQ segment and return it if found, otherwise return null
#endif
```

arq.c

```
// File: arq.c
// Description: support for Automatic Retry reQuest services
// Author(s):   Robert Poor <r@media.mit.edu>
//              Andrew Wheeler <ajw@media.mit.edu>
//
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// warranty.

#include "arq.h"
#include "grad.h"
#include "mac.h"
#include "node_id.h"
#include "param.h"
#include "pseg.h"
#include "tephra.h"
#include "types.h"
#include "vector.h"
#include "includes.h"
#include "stats.h"
#include "serial.h"

#undef ARQ_PRINTFS

static unsigned int _arqStack[ARQ_TASK_STACK_SIZE];
// stack area for arq task

static DEFINE_VECTOR(_retryQueue, ARQ_QUEUE_SIZE);
// Define the raw storage for the ARQ queue.

static void _ARQTask(void *args);

static void _retransmitPkt(pseg_t *pkt);

static uint8_t _reference;
```

```
// ============================================================

void ARQInit(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(25);
#endif
    _reference = 0;
    VectorInit(VECTOR(_retryQueue), ARQ_QUEUE_SIZE);
}

void ARQReset(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(26);
#endif
    VectorClear(VECTOR(_retryQueue));
}

void ARQStart(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(27);
#endif
    OSTaskCreate(_ARQTask, NULL, (void *)&_arqStack[ARQ_TASK_STACK_SIZE-1],
                    ARQ_TASK_ID);
}

vector_t *ARQQueue(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(28);
#endif
    // return a reference to the underlying ARQ queue.  Use with care.
    return VECTOR(_retryQueue);
}

void ARQDidXmit(pseg_t *pkt) {
    // Note that MAC layer sent a packet.  If it has an ARQ segment
    // and the retry hasn't expired, queue a copy of the packet for
    // subsequent retransmission.  Called from the MAC task.
    pseg_t *as, *gs;
    arqPayload *ap;

#ifdef DEBUG_BUFFER
    debug_buffer(29);
#endif
    // quit if we're not the originator
    if (((gs = GRAdFindSegment(pkt)) == NULL) ||
          (((gradPayload *)PSegPayload(gs))->fOriginator != NodeGetID()))
    {
          return;
    }

    // quit if the packet lacks an ARQ segment
    if ((as = PSegFindType(pkt, PSEG_TYPE_ARQ)) == NULL) return;

    // quit if the retry count in the ARQ segment has expired
    ap = PSegPayload(as);
    if (ap->fRetries++ == ParamGet(PARAM_ARQ_RETRY))
    {
          StatsIncARQPktsDropped();
          return;
    }

    // Make a copy of the packet (with incremented retries) and
    // queue it for deferred transmission.  If enqueing the packet
    // causes the queue to fill up, remove and free the oldest.
    StatsIncARQPktsSent();
    PSegFree(VectorShove(VECTOR(_retryQueue), PSegCopy(pkt)));
    OSTaskResume(ARQ_TASK_ID);
}

// ============================================================
// Tack an ARQ segment on the front of this packet.  This has the
// effect that [1] a copy of the message will be queued for possible
// retransmission and [2] an ACK will be returned by the recipient.

pseg_t *ARQMakeARQ(pseg_t *pkt)
{
    pseg_t *arqSeg = PSegAlloc(PSEG_TYPE_ARQ, sizeof(arqPayload), pkt);
    arqPayload *ap = PSegPayload(arqSeg);

#ifdef DEbuG_BUFFER
    debug_buffer(30);
#endif
    ap->fReference = _reference++;
    ap->fRetries = 0;

    return arqSeg;
}


// ============================================================
// servicing ACKs.
// When an ACK message is received, the messages pending in the
// retry queue are searched for a matching ARQ.  If a match is
// found, it means the ARQ has been acknowleged, and can be
// deleted from the queue.

void ARQServiceACK(pseg_t *seg)
{
    // seg is known to be of type SEG_TYPE_ACK and part of a packet
    // targeted for this node.  Search the retry queue for a matching
    // ARQ packet, and if found, delete it.

    ackPayload *ackp = PSegPayload(seg);
    uint8_t i = VectorCount(VECTOR(_retryQueue));

#ifdef DEBUG_BUFFER
    debug_buffer(31);
#endif
    while (i--)
    {
          pseg_t *retryPkt, *arqSeg;
          retryPkt = VectorFastRef(VECTOR(_retryQueue), i);
          arqSeg = PSegFindType(retryPkt, PSEG_TYPE_ARQ);
          if (arqSeg != NULL)
          {
              arqPayload *arqp = PSegPayload(arqSeg);
              if (arqp->fReference == ackp->fReference)
              {
                    // Found the ARQ that is ACKed by this ACK.  Remove the ARQ
                    // packet from the retry queue so it won't be retransmitted.
                    if (SerialDoctorMode())
                    {
```

```
                    // Call back into the doctor so that we know the packet has
                    // been received.
                    SerialServiceAck(retryPkt);
                }

                PSegFree(VectorFastRemove(VECTOR(_retryQueue), i));
                StatsIncARCPktsRcvd();

#ifdef ARQ_PRINTFS
                Uart_Printf("  ARQ got ACK ref %d removing packet\n",
                            arqp->fReference);
#endif
                return;
            }
#ifdef ARQ_PRINTFS
            Uart_Printf("  ARQ got ACK ref %d\n",arqp->fReference);
#endif
        }
    }
}

// ============================================================
// servicing ARQ packets.
// Handle an incoming ARQ packet.  Respond by creating an ACK packet
// and returning it to the orginator of the ARQ.  seg argument is
// known to be of type SEG_TYPE_ARQ, grad argument (if non null) is
// known to be of type SEG_TYPE_GRAD.

void ARQServiceARQ(pseg_t *arqSeg, pseg_t *gradSeg)
{
    pseg_t *ackSeg;
    arqPayload *ap;
    gradPayload *gp;

#ifdef DEBUG_BUFFER
    debug_buffer(32);
#endif
    // can't handle a packet with no return address
    if (gradSeg == NULL)
    {
        return;
    }
    ap = PSegPayload(arqSeg);
    gp = PSegPayload(gradSeg);

    ackSeg = PSegAlloc(PSEG_TYPE_ACK, sizeof(ackPayload), NULL);
    ((ackPayload *)PSegPayload(ackSeg))->fReference = ap->fReference;
#ifdef ARQ_PRINTFS
    Uart_Printf("  ARQ sending ACK ref %d to %d\n",
                ap->fReference, gp->fOriginator);
#endif
    MACXmitPkt(GRAdMakePkt(ackSeg, gp->fOriginator));
}

pseg_t *ARQFindSegment(pseg_t *pkt) {
  // search the list of segments for a packet that contains an ARQ
  while (pkt != NULL) {
    pseg_type t = PSegType(pkt);
    if ((t == PSEG_TYPE_ARQ)) {
      return pkt;
    }
    pkt = PSegNext(pkt);
  }
  return NULL;
}

// ============================================================
// The ARQ thread.
// Wait for a packet to become available in the retry queue.  When
// a packet is queued, wait for a holdoff period before attempting
// transmission.  If, after the holdoff period, the packet hasn't
// been ACKd, send it to the MAC layer for retransmission.

static void _ARQTask(void *args)
{

    while (true)
    {
        pseg_t *pkt;

#ifdef DEBUG_BUFFER
        debug_buffer(33);
#endif
        //      Uart_Printf("ARQTask\n");

        // Wait for a packet to appear in the queue (but don't dequeue yet)
        while (VectorCount(VECTOR(_retryQueue)) == 0)
        {
            OSTaskSuspend(ARQ_TASK_ID);
        }

        // Defer for ARQ_DELAY tics
        OSTimeDly(ParamGet(PARAM_ARQ_DELAY));
#ifdef DEBUG_BUFFER
        debug_buffer(212);
#endif

        // Now see if the packet is still in the queue -- it might have been
        // removed by serviceAck() while we were waiting.  (Small bug here:
        // if the head packet was removed in the interim, the second packet
        // in line will be retransmitted before its full PARAM_ARQ_DELAY
        // has elapsed.  Typically not a problem.)

        if ((pkt = (pseg_t *)VectorDequeue(VECTOR(_retryQueue))) != NULL)
        {
            // Got a packet for retransmission.  Send it.
            _retransmitPkt(pkt);
        }
    } // while (1)...
}


static void _retransmitPkt(pseg_t *pkt)
{
    // Re-transmit pkt.  Before sending it, update the GRAd header in
    // the packet, boosting the fCostBudget by one for each time this
    // packet has been retransmitted.  This makes network try
    // progressively harder to get the packet to its destination.
    pseg_t *arqSeg = PSegFindType(pkt, PSEG_TYPE_ARQ);
#ifdef DEBUG_BUFFER
    debug_buffer(34);
#endif
    if (arqSeg != NULL)
    {
        arqPayload *arqp = PSegPayload(arqSeg);
        // boost fCostBudget by one for each retry
```

```
        GRAdUpdateSeg(pkt, arqp->fRetries);
#ifdef ARQ_PRINTFS
        Uart_Printf("  ARQ retransmitting ref %d w/ boost %d\n",
                    arqp->fReference, arqp->fRetries);
#endif
    }
    MACXmitPkt(pkt);
}
```

boottest.h

```
// File: boottest.h
// Description: node boot testing proceedure
// Author(s):   Andrew Wheeler <ajw@media.mit.edu>
//
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// warranty.

#ifndef BOOTTEST_H
#define BOOTTEST_H

#include "types.h"
#include "pseg.h"

typedef enum {
  BOOT_BOOTING,
  BOOT_GOT_SYNC,
  BOOT_STANDALONE,
  BOOT_FOUNDNEIGHBOR,
  BOOT_FINISHED
} bootcode_t;

typedef struct {
  node_id     node;
  bootcode_t  bootCode;
  uint8_t     bootData;
} bootPayload;

void BootInit(void);

void BootStart(void);

void BootSendPkt(bootcode_t code, uint8_t data);

#endif
```

boottest.c

```
// File: boottest.c
// Description: node boot proceedures
// Author(s):   Andrew Wheeler <ajw@media.mit.edu>
//
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// any purpose. It is provided "as is" without express or implied
// warranty.

#include "types.h"
#include "pseg.h"
#include "ping.h"
#include "mac.h"
#include "sysmanager.h"
#include "boottest.h"
#include "tephra.h"

static unsigned int _bootStack[BOOT_TASK_STACK_SIZE];

static void _bootTask(void *args);

void BootInit(void) {

}

void BootStart(void) {
  OSTaskCreate(_bootTask, NULL, (void *)&_bootStack[BOOT_TASK_STACK_SIZE-1],
               BOOT_TASK_ID);
}
```

```
static void _bootTask(void *args) {

  // put node into test
  SysSetTestMode(true);
  // send out boot anouncement
  BootSendPkt(BOOT_BOOTING, 0);
  // register the ping process to watch for sync messages

  while (SysGetTestMode() && (OSTimeGet() < 540*OS_TICKS_PER_SEC)) {
    PingStartAsyncLinkTest();
    OSTimeDly(60*OS_TICKS_PER_SEC);
    PingStopAsyncLinkTest();
  }
  SysSetTestMode(false);
  BootSendPkt(BOOT_FINISHED, 0);

  OSTaskDel(BOOT_TASK_ID);

  // watch for sync
  //   when sync'd send out a sync message
  // after sync, collect neighbor information and send
  // if all looks good, then go out of test
  // otherwise, stay in test, redoing the ping every once in a while
  //   and sending updates
}

// _bootSendPkt(bootcode_t code, uint8_t data)
//   sends a packet with code and data from this node as a broadcast
//   to anyone who cares
void BootSendPkt(bootcode_t code, uint8_t data) {
  pseg_t *bootPkt = PSegAlloc(PSEG_TYPE_BOOT_REPORT, sizeof(bootPayload), NULL);
  bootPayload *bp = PSegPayload(bootPkt);

  bp->node = NodeGetID();
  bp->bootCode = code;
  bp->bootData = data;

  MACXmitPkt(bootPkt);
}
```

cost.h

```
// File: cost.h
// Description: establish and maintain cost metrics to remote nodes
// Author(s):   Robert Poor <r@media.mit.edu>
//
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// warranty.

#ifndef COST_H
#define COST_H

#include "node_id.h"
#include "pseg.h"

typedef uint8_t cost_t;
// cost is measured in # of hops, assumed less than 256

#define COST_UNKNOWN 0xff
// Value for unknown cost

// Cost table support.

// Cost table packetizing:

// this is the data we actually send from costTableEntry
typedef struct {
  cost_t fCost;
  uint8_t fSequence;
} costTableXmitEntry;

#define MAX_USEFUL_COST_ENTRY 108
// divisible by COST_TRANSMIT_ENTRIES is better!
#define COST_TRANSMIT_ENTRIES 6
#define COST_MAX_CHUNKS MAX_USEFUL_COST_ENTRY/COST_TRANSMIT_ENTRIES

typedef struct {
  uint32_t fSampleTime;
  uint8_t fStartingEntry;
  uint8_t fNumEntries;
  costTableXmitEntry fTableChunk[COST_TRANSMIT_ENTRIES];
} costTablePayload;

// As a simplification, the cost table assumes 8 bit node IDs, so
// node IDs are used as direct indeces into the table.

typedef struct {
  cost_t fCost;                         // cost to node
  uint8_t fSequence;                    // last seen sequence #
  uint8_t fTTL;                         // agings before entry is pruned
} costTableEntry;

void CostInit(void);
// cold start initialization

void CostReset(void);
// warm start initialization

void CostStart(void);
// cost table aging thread start
```

```
costTableEntry *CostTable(void);
// return pointer to cost table

void CostAgeTable(void);
// count down cost table TTLs and prune expired entries.

cost_t CostTo(node_id target);
// return the cost to the given target, or COST_UNKNOWN if not known

bool CostUpdate(pseg_t *gradSeg);
// Update a single cost table entry according to the given gradSeg.
// Returns true if gradSeg refers to a fresh (non-duplicate) message,
// or if there is no grad segment at all.

bool CostShouldRelay(pseg_t *gradSeg);
// Return true if this packet should be relayed

pseg_t *CostMakeSegment(uint8_t chunkNo, pseg_t *next);
// Create a segment containing chunk number chunkNo
// [contains entries [COST_TRANSMIT_ENTRIES * chunkNo -
//                    (COST_TRANSMIT_ENTRIES * (chunkNo + 1)) - 1, inclusive.

#endif
```

grad.h

```
// File: grad.h
// Description: support for Gradient Routing
// Author(s):   Robert Poor <r@media.mit.edu>
//              Andrew Wheeler <ajw@media.mit.edu>
//
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// warranty.

#ifndef GRAD_H
#define GRAD_H

#include "node_id.h"
#include "pseg.h"
#include "cost.h"

// A gradPayload contains the information used by the gradient routing
// mechanism.  A gradPayload can be found in the payload of any packet
// segment whose type is PSEG_TYPE_GRAD or PSEG_TYPE_DISCO.

typedef struct {
  node_id fOriginator;
  uint8_t fSequence;
  uint8_t fCostAccrued;
  node_id fDestination;
  uint8_t fCostBudget;
} gradPayload;

void GRAdInit(void);
// intialize the gradient routing system

void GRAdReset(void);
// re-init the gradient routing system

pseg_t *GRAdFindSegment(pseg_t *pkt);
// Search pkt for a segment of type PSEG_TYPE_GRAD or PSEG_TYPE_DISCO.
// Return such segment if found, NULL if not found.

pseg_t *GRAdMakePkt(pseg_t *pkt, node_id destination);
// Create and push a GRAd header segment onto the front of pkt.  If
// the cost to destination is unknown, a DISCOvery segment is created,
// otherwise an appropriately initialized GRAD segment is created.

void GRAdUpdateSeg(pseg_t *pkt, cost_t boost);
// find the PSEG_TYPE_DISCO or PSEG_TYPE_GRAD segment in this packet.
// In place, fix up current sequence number and cost info.

bool GRAdIsForMe(pseg_t *gradSeg);
// seg must refer to a packet segment of type PSEG_TYPE_DISCO or
// PSEG_TYPE_GRAD.  Returns true if the packet is destined for this
// node (dest is either BROADCAST_ID or this node).

void GRAdRelayIfNeeded(pseg_t *pkt, pseg_t *gradSeg);
// seg must refer to a packet segment of type PSEG_TYPE_DISCO or
// PSEG_TYPE_GRAD.  Relay pkt if appropriate, else just free it.

#endif
```

grad.c

```
// File: grad.c
// Description: support for Gradient Routing
// Author(s):   Robert Poor <r@media.mit.edu>
//              Andrew Wheeler <ajw@media.mit.edu>
//
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// any purpose. It is provided "as is" without express or implied
// warranty.

#include "cost.h"
#include "grad.h"
#include "mac.h"
#include "node_id.h"
#include "param.h"
#include "types.h"
#include "stats.h"
#include "pseg.h"
#include "util.h"

// GRAd is responsible for the routing of packets.  Upon reception,
// GRAd decides whether to relay a packet, pass it to the application
// level, or to drop it.  For transmission, GRAd appends a routing
// header that will be used by the GRAd service in receiving nodes.

static unsigned char _sequence;
// Sequence number for next originated packet.

// ============================================================
// exported routines

void GRAdInit()
{
#ifdef DEBUG_BUFFER
    debug_buffer(53);
#endif
    _sequence = 0;
}

pseg_t *GRAdFindSegment(pseg_t *pkt) {
#ifdef DEBUG_BUFFER
    debug_buffer(54);
#endif
    // search the list of segments for a packet that contains a
    // gradPayload.
    while (pkt != NULL)
    {
          pseg_type t = PSegType(pkt);
          if ((t == PSEG_TYPE_GRAD) || (t == PSEG_TYPE_DISCO))
          {
              return pkt;
          }
          pkt = PSegNext(pkt);
    }
    return NULL;
}

static pseg_type _prepPayload(gradPayload *payload,
                              node_id dest,
                              cost_t boost)
{
    // fill in a gradPayload with dest, cost, sequence, etc.  Returns
    // PSEG_TYPE_DISCO if cost is known or PSEG_TYPE_GRAD if not.
    cost_t cost = CostTo(dest);

#ifdef DEBUG_BUFFER
    debug_buffer(55);
#endif
    payload->fOriginator = NodeGetID();
    payload->fSequence = ++_sequence;
    payload->fCostAccrued = 1;        // receivers are already one hop away
    payload->fDestination = dest;
    if (cost == COST_UNKNOWN)
    {
          payload->fCostBudget = ParamGet(PARAM_GRAD_DISCOVERY_COST) + boost;
          // ## stats_floodPkt();                // note a flood packet
          StatsIncGradFlooded();
          return PSEG_TYPE_DISCO;
    }
    else
    {
          payload->fCostBudget = cost + boost;
          // ## stats_origPkt();                  // note a routed packet
          StatsIncGradOriginated();
          return PSEG_TYPE_GRAD;
    }
}

void GRAdUpdateSeg(pseg_t *pkt, cost_t boost)
{
    // Find the PSEG_TYPE_DISCO or PSEG_TYPE_GRAD segment in this
    // packet.  In-place, fixup current sequence number and cost info,
    // adding boost to the initial fCostBudget.  Currently, this routine
    // is used to update ARQ packets when they are retransmitted.
    pseg_t *gradSeg;
    gradPayload *gp;

#ifdef DEBUG_BUFFER
    debug_buffer(56);
#endif
    if ((gradSeg = GRAdFindSegment(pkt)) == NULL)
    {
          return;
    }
    gp = PSegPayload(gradSeg);
    PSegType(gradSeg) = _prepPayload(gp, gp->fDestination, boost);
}


pseg_t *GRAdMakePkt(pseg_t *pkt, node_id dest)
{
    // Tack a GRAd routing header on the front of this packet.  If the
    // cost to dest is known, it creates a regular GRAd data packet.  If
    // the cost isn't known, it creates a discovery packet.
    pseg_t *gradSeg = PSegAlloc(0, sizeof(gradPayload), pkt);
    gradPayload *gp = PSegPayload(gradSeg);
    PSegType(gradSeg) = _prepPayload(gp, dest, 0);
#ifdef DEBUG_BUFFER
    debug_buffer(57);
```

```
#endif
    return gradSeg;
}

bool GRAdIsForMe(pseg_t *gradSeg)
{
    // Return true this packet is intended for this node:
    // [1] gradSeg is null, indicating no routing header
    // [2] fDestination == BROADCAST_ID, indicating any node
    // [3] fDestination == NodeGetID(), indicating this node
#ifdef DEBUG_BUFFER
    debug_buffer(58);
#endif
    if (gradSeg == NULL)
    {
          return true;
    }
    else
    {
          node_id id = ((gradPayload *)PSegPayload(gradSeg))->fDestination;
          return (id == NodeGetID()) || (id == BROADCAST_ID);
    }
}

void GRAdRelayIfNeeded(pseg_t *pkt, pseg_t *gradSeg)
{
#ifdef DEBUG_BUFFER
    debug_buffer(59);
#endif
    if ((gradSeg != NULL) &&
          (CostShouldRelay(gradSeg)) &&
          (ParamGet(PARAM_GRAD_ENABLE_RELAY) != 0) &&
          (((gradPayload *)PSegPayload(gradSeg))->fOriginator != NodeGetID()) &&
          (((gradPayload *)PSegPayload(gradSeg))->fDestination != NodeGetID()))
    {
          // pkt should be relayed.  Update the grad header and schedule the
          // packet for re-transmission.
          gradPayload *gp = PSegPayload(gradSeg);
          gp->fCostAccrued++;           // one hop further from originator
          gp->fCostBudget--;            // one hop closer to destination
          // ## stats_relayPkt();                // note a relayed packet
          StatsIncGradRelayed();
          MACXmitPkt(pkt);
    }
    else {
          PSegFree(pkt);                // Packet is not to be relayed.  Drop it.
    }
}
```

mac.h

```
// File: mac.h
// Description: Medium Access Control mechanism for sharing airwaves
// Author(s):   Robert Poor <r@media.mit.edu>
//              Andrew Wheeler <ajw@media.mit.edu>
//
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// warranty.

#ifndef MAC_H
#define MAC_H

#include "pseg.h"
#include "vector.h"

void MACInit(void);
// one-time cold start initialization

void MACReset(void);
// warm restart

void MACStart(void);
// start MAC thread

vector_t *MACQueue(void);
// returns the underlying MAC queue.

void MACXmitPkt(pseg_t *pkt);
// queue a packet for transmission

void MACStartTimer(void);
void MACStopTimer(void);
// Start and stop the holdoff timer.  The timer should be stopped
// when the radio is busy, restarted whenever it is idle.

void MACSystemTick(void);
// called by the OS whenever a system tick occurs

#endif
```

mac.c

```
// File: mac.c
// Description: Medium Access Control mechanism for sharing airwaves
// Author(s):   Robert Poor <r@media.mit.edu>
//              Andrew Wheeler <ajw@media.mit.edu>
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// warranty.

#include "arq.h"
//#include "clk.h"
#include "mac.h"
#include "param.h"
#include "pseg.h"
#include "rad.h"
#include "tephra.h"
#include "vector.h"
#include "includes.h"
#include <stdlib.h>

static unsigned int _macStack[MAC_TASK_STACK_SIZE];
static bool         _backoffTimerExpired;
static bool         _macCountDownFlag;
static bool         _macStopTimer;
static bool         _radStopTimer;
//static uint16_t     _macBackoffCounter;

// The MAC maintains a queue for outgoing packets and is the exclusive
// arbiter of the radio transmitter.

#define MAC_QUEUE_SIZE 10

// Define the raw storage for the transmit queue
static DEFINE_VECTOR(_macQueue, MAC_QUEUE_SIZE);

static void _MACTask(void *args);

static void _resetBackoff(void);
// reset backoff exponent to its minimum

static void _incrementBackoff(void);
// increment backoff exponent upto its maximum

static void _generateBackoff(void);
// set backoff timer according to current backoff exponent

static void _macTimerISR(void);
// handles MAC timer interrupt

//static bool _backoffHasExpired(void);
// returns true if the backoff timer has expired

// =============================================================

void MACInit(void)
{
#ifdef DEBUG_BUFFER
  debug_buffer(60);
#endif
  // initialize the transmit queue
  VectorInit(VECTOR(_macQueue), MAC_QUEUE_SIZE);
  _macCountDownFlag = false;
  //  _macBackoffCounter = 0;
  _backoffTimerExpired = false;

  // setup the MAC timer
  OS_ENTER_CRITICAL();
  ISR_TMC0 = (unsigned)_macTimerISR;
  TPRE0 = 0xFF;
  TDAT0 = 0x00FF;
  TCON0 = TCON_DISABLE | TCON_CLOCK_INTERNAL | TCON_CLEAR | TCON_INTERVAL_MODE;
  INTPND = ~INT_TMC0;
  INTMSK |= INT_TMC0;
  // each timer tick now equals 12.8uS

  _macStopTimer = true;
  _radStopTimer = false;
  OS_EXIT_CRITICAL();
}

void MACReset(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(61);
#endif
    // launch the mac task.  Called from INIT_TASK.
    VectorClear(VECTOR(_macQueue));
    _backoffTimerExpired = false;
}

void MACStart(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(62);
#endif
    // start the mac task
    OSTaskCreate(_MACTask, NULL, (void *)&_macStack[MAC_TASK_STACK_SIZE-1],
                 MAC_TASK_ID);
}

vector_t *MACQueue(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(63);
#endif
    // return a reference to the underlying MAC queue.  Use with care.
    return VECTOR(_macQueue);
}

// =============================================================
// =============================================================
```

```
// The MAC task runs essentially as follows:
//
// while (1) {
//        wait for a packet to appear in the MAC queue
//        set backoff counter according to exponential backoff
//        wait for backoff counter to expire
//        if packet is still in the MAC queue, transmit it
// }
//
// Note that the backoff counter only counts down when the radio
// is idle (not receiving).

void _MACTask(void *args)
{

    _resetBackoff();

    // zero the backoff counter
    //    _macBackoffCounter = 0;

    // Start MAC countdown timer.  The radio task will stop the timer
    // whenever the radio is busy.
    MACStartTimer();

    while (true)
    {
          pseg_t *pkt;

#ifdef DEBUG_BUFFER
          debug_buffer(64);
#endif

          //        Uart_Printf("MACTask\n");
          // Wait for a packet to become available in the MAC queue.  Don't
          // remove it until the backoff timer expires, since some other
          // task may prune it from the queue in the interim.
          while (VectorCount(VECTOR(_macQueue)) == 0)
          {
              _resetBackoff();          // Empty queue?  Reset backoff exponent...
              OSTaskSuspend(MAC_TASK_ID);
          }
#ifdef DEBUG_BUFFER
          debug_buffer(213);
#endif
          // Initialize the backoff counter according to the current backoff
          // exponent and then wait until it counts down to zero
          _generateBackoff();
          while (!_backoffTimerExpired)
          {
              OSTaskSuspend(MAC_TASK_ID);
          }
#ifdef DEBUG_BUFFER
          debug_buffer(214);
#endif
          // Backoff has expired.  If there's still a packet available,
          // format and transmit the packet.  Tell ARQ that the packet
          // was sent (in case ARQ wants to make a copy for retransmit),
          // then free it.
          if ((pkt = VectorDequeue(VECTOR(_macQueue))) != NULL)
          {
              RadXmitPkt(pkt);
              ARQDidXmit(pkt);
              PSegFree(pkt);
          }
    }
}

// ============================================================
// queue a packet for subsequent transmission by the MAC task
// Called by anybody that wishes to send a packet, but normally
// called from the application thread.  If the queue fills up,
// throw away the oldest.

void MACXmitPkt(pseg_t *pkt)
{
#ifdef DEBUG_BUFFER
  debug_buffer(65);
#endif
  if (RadIsBusy())
    {
      _incrementBackoff();
    }
  // Install a packet in the transmit queue and notify the MAC thread.
  // If the queue filled up as a result of enqueuing a new packet,
  // remove and free the oldest.
  PSegFree(VectorShove(VECTOR(_macQueue), pkt));
  OSTaskResume(MAC_TASK_ID);
}

// ============================================================
// ============================================================
// backoff timing

static unsigned char _backoffExponent;
#define MIN_BACKOFF 4
#define MAX_BACKOFF 10

static void _resetBackoff(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(66);
#endif
    _backoffExponent = MIN_BACKOFF;
}

static void _incrementBackoff(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(67);
#endif
    if (_backoffExponent < (MAX_BACKOFF-1)) {
          _backoffExponent++;
    }
}

// 1.228mS-2.5mS min
// 314.5mS-629.1mS max
static void _generateBackoff(void) {
  // generate a random backoff between 2^e and 2^(e+1)
    uint16_t minBackoff;
#ifdef DEBUG_BUFFER
    debug_buffer(68);
#endif
    minBackoff = 1<<_backoffExponent;
    OS_ENTER_CRITICAL();
    TCON0 |= TCON_CLEAR;
```

```
    TDAT0 = (rand() % minBackoff + minBackoff)*ParamGet(PARAM_MAC_TICS_PER_BACKOFF);
    _backoffTimerExpired = false;
    _macStopTimer = false;
    if (!_radStopTimer) {
      // start the timer
      TCON0 |= TCON_ENABLE;
    }
    OS_EXIT_CRITICAL();
    //MACStartTimer();
}

/*static bool _backoffHasExpired(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(69);
#endif
    return (_macBackoffCounter == 0);
}*/

void MACStartTimer(void)
{
#ifdef DEBUG_BUFFER
  debug_buffer(70);
#endif
  //  OS_ENTER_CRITICAL();
  _radStopTimer = false;
  if (!_macStopTimer) {
    TDAT0 += 100; // hack to account for post-packet data transfer
    TCON0 |= TCON_ENABLE;
  }
  //  OS_EXIT_CRITICAL();
}

void MACStopTimer(void)
{
#ifdef DEBUG_BUFFER
  debug_buffer(71);
#endif
  //  OS_ENTER_CRITICAL();
  _radStopTimer = true;
  TCON0 &= ~TCON_ENABLE; // stop the timer
  //  OS_EXIT_CRITICAL();
}

// handles the MAC timer (TIMER0) interrupt
void _macTimerISR(void) {
  INTPND = ~INT_TMC0;  // clear the interrupt

  // stop the timer
  TCON0 = TCON_DISABLE | TCON_CLOCK_INTERNAL | TCON_CLEAR | TCON_INTERVAL_MODE;

  _macStopTimer = true;
  // set countdown done flag
  _backoffTimerExpired = true;

  // wakeup the MAC task
  OSTaskResume(MAC_TASK_ID);
}
```

node_id.h

```
// File: node_id.h
// Description: support for per-node unique ID
// Author(s):   Robert Poor <r@media.mit.edu>
//              Paul Pham <ppham@mit.edu>
//
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// warranty.

#ifndef NODE_ID_H
#define NODE_ID_H

#include "types.h"

#define BROADCAST_ID 0xff

typedef uint8_t node_id;
// node ids are in the range of 0 to 0xff (256 max)

node_id NodeGetID(void);
// return the node ID of this node

#endif
```

param.h

```
// File: param.h
// Description: remotely set and query tunable system parameters
// Author(s):   Robert Poor <r@media.mit.edu>
//              Andrew Wheeler <ajw@media.mit.edu>
//
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// warranty.

#ifndef PARAM_H
#define PARAM_H
// param.h defines a set of tunable parameters.  Each parameter
// can be queried and set remotely.

#include "pseg.h"
#include "node_id.h"
#include "includes.h"

#define MAX_PARAMS 16

// A paramPayload struct is used to get or set the state of up
// to 16 tunable parameters in the tephra system.
typedef struct {
  uint16_t fMask;
  uint16_t fParams[MAX_PARAMS];
} paramPayload;


enum {
  PARAM_PING_SEARCH_COUNT,    // # pings to send searching for neighbors
  PARAM_PING_LINK_TEST_COUNT, // # pings to send per link test
  PARAM_PING_LINK_TEST_DELAY, // tics to wait between link pings
  PARAM_ARQ_DELAY,            // tics to wait before retransmit ARQ packets
  PARAM_ARQ_RETRY,            // # of times to retry retransmission
  PARAM_COST_TTL,             // cost entry time to live (cost quantum tics)
  PARAM_COST_AGE_QUANTUM,     // # of seconds between calling CostAgeTable()
  PARAM_GRAD_DISCOVERY_COST,  // default initial discovery cost budget
  PARAM_GRAD_ENABLE_RELAY,    // allow/inhibit relaying of packets
  PARAM_MAC_TICS_PER_BACKOFF,   // # of os tics per backoff
  PARAM_AWAKE_TIME,             // # of seconds the rock is awake
  PARAM_SLEEP_TIME,             // # of seconds the rock sleeps
  PARAM_BASESTATION_ADDR,       // # address of basestation
  PARAM_ARQ_REPORTS,            // do we put an arq request on the report packets
(sensor data/statistics?)
  MAX_PARAM_INDEX
};

#define PARAM_PING_SEARCH_COUNT_DEFAULT          20  // OK
#define PARAM_PING_LINK_TEST_COUNT_DEFAULT       100 // lower?
#define PARAM_PING_LINK_TEST_DELAY_DEFAULT       20  // lower?
#define PARAM_ARQ_DELAY_DEFAULT                          8*OS_TICKS_PER_SEC  //
in system ticks
#define PARAM_ARQ_RETRY_DEFAULT                          6
#define PARAM_COST_TTL_DEFAULT                           180
#define PARAM_COST_AGE_QUANTUM_DEFAULT           OS_TICKS_PER_SEC  // how often we
run through the cost table
#define PARAM_GRAD_DISCOVERY_COST_DEFAULT        60   // OK- check network diameter
#define PARAM_GRAD_ENABLE_RELAY_DEFAULT          1    // OK
#define PARAM_MAC_TICS_PER_BACKOFF_DEFAULT       12    // OK
#define PARAM_AWAKE_TIME_DEFAULT                90   // OK
#define PARAM_SLEEP_TIME_DEFAULT                510  // OK
#define PARAM_BASESTATION_ADDR_DEFAULT          16   //BROADCAST_ID  //OK
//#define PARAM_BASESTATION_ADDR_DEFAULT         11  //OK
#define PARAM_ARQ_REPORTS_DEFAULT               1

void ParamInit(void);
// reset all parameters to their defaults.  Normally used at
// cold start, but can also be used to beat the system back
// into a working state.

void ParamReset(void);
// warm restart.

uint16_t ParamGet(uint8_t index);
// fetch a value from the local param table

void ParamSet(uint8_t index, uint16_t value);
// set a param in the local param table

// ============================================================
// The following three functions are designed to be used in consort
// to set parameters on a remote node.
//
// First you call ParamPktAlloc() to allocate a parameter setting
// packet, then you call ParamPktSet() once per parameter you wish
// to set on a remote note.  Finally, you send the packet using
// ParamPktXmit().

pseg_t *ParamPktAlloc(void);
// allocate a SEG_TYPE_PARAM_SET packet, to be used in subsequent
// calls to ParamPktSet()

void ParamPktSet(pseg_t *pkt, uint8_t index, uint16_t value);
// Set a parameter in the given SEG_TYPE_PARAM_SET packet.

// void ParamPktXMit(pseg_t *pkt, node_id target);
// Send a SEG_TYPE_PARAM_SET packet to the given target.  The target
// can be BROADCAST_ID in which case it goes out to all nodes.

// ============================================================
// Handle incoming messages

void ParamServiceSet(pseg_t *pkt);
// handle a param setting packet.  For each 1 bit in the fMask field,
// set the corresponding system parameter from the body of the payload.

void ParamServiceGet(pseg_t *gradSeg);
// Handle a request for the current parameter.  Creates a param state
// packet and sends it to the requester.

void ParamServiceRequest(pseg_t *gradSeg);
// Handle a request for PSEG_TYPE_PARAM_REQUEST packet by
// replying with a PSEG_TYPE_PARAM_REPORT message.

#endif
```

ping.h

```
// File: ping.h
// Description: test link reliability with neighboring nodes
// Author(s):   Robert Poor <r@media.mit.edu>
//              Andrew Wheeler <ajw@media.mit.edu>
//              Paul Covell <pac@alum.mit.edu>
//
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// warranty.

#ifndef PING_H
#define PING_H

#include "node_id.h"
#include "types.h"
#include "pseg.h"

// Ping service:
//
// In response to a PSEG_TYPE_NEIGHBOR_REQUEST message, ping will
// find all neighboring nodes and send a PSEG_TYPE_NEIGHBOR_REPORT
// back to the requestor.
//
// In response to a PSEG_TYPE_LINK_REQUEST message, ping will enter
// into a link test loop with a specific neighbor and send the results
// back to the requestor in a PSEG_TYPE_LINK_REPORT message.
//
// Internally, ping will generate and receive PSEG_TYPE_PING and
// PSEG_TYPE_PONG messages as part of the discovery and link test
// procedures.

// Some things that the ping service does:
//
// find all (one hop) neighbors
// gather channel statistics to a specific (one hop) neighbor
// determine connectivity to a remote neighbor

#define PING_MAX_NEIGHBORS  10
// a NEIGHBORS_REPORT message will report up to PING_MAX_NEIGHBORS

// PSEG_TYPE_NEIGHBOR_REQEUST has an empty payload (but C doesn't
// like an empty struct).
typedef struct {
  uint8_t fUnused;
} neighborsRequestPayload;

// PSEG_TYPE_NEIGHBOR_REPORT has a payload with the node IDs of the
// first PING_MAX_NEIGHBORS with the most responses.
//
typedef struct {
  node_id fNeighbors[PING_MAX_NEIGHBORS];
} neighborsReportPayload;

// PSEG_TYPE_LINK_REQUEST messages name the node with which to enter
// a link test.
//
typedef struct {
  node_id fNeighbor;
} linkRequestPayload;

// PSEG_TYPE_LINK_REPORT messages give the results of a link test.
//
typedef struct {
  node_id fNeighbor;                    // neighbor in question
  uint8_t fPingsSent;                   // # pings this node sent
  uint8_t fPingsRcvd;                   // # pings rcvd (as reported by neighbor)
  uint8_t fPongsSent;                   // # pongs sent (as reported by neighbor)
  uint8_t fPongsRcvd;                   // # pongs rcvd at this node
} linkState;

// PSEG_TYPE_PING is what this node sends to elicit pongs from
// one or more neighbors

typedef struct {
  node_id fPinger;            // node sending the ping
  node_id fTarget;            // node recieving ping, can be BROADCAST_ID
  uint8_t fPingsSent;                   // # pings sent by this node
} pingPayload;

// PSEG_TYPE_PONG is what a node will send whenever it receives
// a ping message.

typedef struct {
  node_id fPonger;            // node sending the pong
  node_id fTarget;            // node that sent the ping
  uint8_t fPongsSent;                   // # pongs sent by this node
} pongPayload;

// ============================================================

void PingInit(void);
// cold start

void PingReset(void);
// warm restart

// ============================================================
// servicing and originating messages

void PingSendPing(node_id target);
// send a lone ping packet to a target- mainly for use in keeping a node awake
// should really use a special keepalive packet- but some nodes were deployed
```

```
// without it

void PingStartAsyncLinkTest( void );
// instructs the ping system to run a link tests on any new nodes it sees after this

void PingStopAsyncLinkTest( void );
// stops running link tests off of sync packets

void PingCheckSync(pseg_t *pkt);
// called by sync system to see if ping wants to do something with packet

void PingStartBeaconMode( void );
// enter a beacon testing mode where we try to discover devices
//  when a new device is discovered, a link test is run and the
//  results printed to the screen

void PingServiceNeighborsRequest(pseg_t *pkt, pseg_t *gradSeg);
// Handle a request to discover neighbors.  Respond by finding
// neighbors and sending a PSEG_TYPE_NEIGHBOR_REPORT to the
// originator.

void PingServiceLinkRequest(pseg_t *pkt, pseg_t *gradSeg);
// Handle a request for a link test with a specific neighbor.  Respond
// by performing link test and sending a PSEG_TYPE_LINK_REPORT to the
// originator.

void PingServicePing(pseg_t *pkt, pseg_t *gradSeg);
// Handle an incoming ping packet.  Respond by sending a pong packet.

void PingServicePong(pseg_t *pkt);
// Handle an incoming pong packet.

// Originating messages

void PingRequestNeighbors(node_id target);
// Originate a PSEG_TYPE_NEIGHBOR_REQUEST message, destined for the
// named target node.  Soon, a PSEG_TYPE_NEIGHBOR_REPORT message
// should arrive back at this node.

void PingRequestLinkTest(node_id target, node_id neighbor);
// Originate a PSEG_TYPE_LINK_REQUEST message, destined for the named
// target node.  Soon, a PSEG_TYPE_LINK_REPORT message should arrive
// back at this node.


#endif
```

ping.c

```
// File: ping.c
// Description: test link reliability with neighboring nodes
// Author(s):   Andrew Wheeler <ajw@media.mit.edu>
//              Paul Covell <pac@alum.mit.edu>
//              Robert Poor <r@media.mit.edu>
//
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// warranty.

#include "grad.h"
#include "mac.h"
#include "param.h"
#include "ping.h"
#include "pseg.h"
#include "tephra.h"
#include "includes.h"
#include "arq.h"
#include <stdlib.h>
#include "ucos_ii.h"
#include "serial.h"
#include "sysmanager.h"
#include "sync.h"
#include "boottest.h"

#undef PING_PRINTFS

// ============================================================
// local declarations

//#define LINK_TEST_COUNT     200
// # of ping messages to send to a specific neighbor in testing
// link reliability

#define TABLE_SIZE 256

#define PING_TABLE_SIZE 256

#define NEIGHBOR_DISC_SIZE 12
// The ping table keeps a history of ping messages sent by this node
// and the corresponding pong messages that have been received.  The
// Nth record corresponds to nodeID N.

// The linkTable keeps track of the link statistics for the local nodes
// and the remote nodes with which they are communicating.
// The local variables represent data relating to the local node, and the
// remote variables represent the `local-data-from-the-remote-node-relating-
// to-the-local-node.'
// This is desirable so that a single node can print bi-directional link
// statistics.

typedef struct
{
```

```
  node_id  fNeighbor;

  uint8_t fLocalPingsSent;
  uint8_t fLocalPingsRcvd;
  uint8_t fLocalPongsSent;
  uint8_t fLocalPongsRcvd;

  uint8_t fRemotePingsSent;
  // uint8_t fRemotePingsRcvd;  // We don't actually know this
  uint8_t fRemotePongsSent;
  // uint8_t fRemotePongsRcvd;  // We don't actually know this
} linkStatistics;

static linkStatistics _linkTable[TABLE_SIZE];
static node_id        beaconTable[TABLE_SIZE];
//linkState _linkTable[TABLE_SIZE];

// The pong table keeps a history of ping messages that have been
// received at this node.  The Nth entry corresponds to nodeID N.

typedef struct {
  uint8_t fPingsSent;                  // # of pings sent (as reported by pinger)
  uint8_t fPingsRcvd;                  // pings actually received (= pongs sent)
} pingState;

//pingState _pingTable[TABLE_SIZE];

unsigned int _linkRequestStack[LINK_REQUEST_STACK_SIZE];
unsigned int _pingNeighborsStack[PING_NEIGHBORS_STACK_SIZE];
unsigned int _beaconStack[BEACON_STACK_SIZE];
static node_id discNeighbors[NEIGHBOR_DISC_SIZE];
static node_id _neighborReqDest;
static node_id _linkTarget;
static node_id _linkReqDest;
static bool    _runLinkOnAsync;
static bool    _linkTestRunning;

static void _linkTableReset(void);
static void _linkTableResetEntry(node_id id);
static void _discoverNeighbors(void);
static void _linkTest(node_id id);
void _sendPing(node_id target, uint8_t pingsSent);
void _sendPong(node_id target, uint8_t pongsSent, bool useGrad);
static int _linkStatisticsCmp(const void *p1, const void *p2);
void _pingNeighborsTask(void *args);
void _linkRequestTask(void *args);
void _beaconTask(void *args);
static void _pingClearNeighbors( void );

// ============================================================
// exported routines

void PingInit(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(83);
#endif
    // cold start
    _runLinkOnAsync = false;
    _linkTestRunning = false;
}

void PingReset(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(84);
#endif
    // warm restart
    _runLinkOnAsync = false;
    _linkTestRunning = false;
}

// sets up a new link test session
void PingStartAsyncLinkTest( void ) {
  // clear out the neighbor table
  _pingClearNeighbors();
  // start the link tests running
  _runLinkOnAsync = true;
}

void PingStopAsyncLinkTest( void ) {
  _runLinkOnAsync = false;
}

// has the opportunity to check a sync packet that is recieved
//  to see if we want to do anything with it
void PingCheckSync(pseg_t *pkt) {
  int i;
  bool found;
  syncPayload *sp = PSegPayload(pkt);

  found = false;
  for (i=0; i<NEIGHBOR_DISC_SIZE; i++) {
    if (discNeighbors[i] == BROADCAST_ID) {
      discNeighbors[i] = sp->fSender;
      break;
    }
    if (discNeighbors[i] == sp->fSender) {
      found = true;
      discNeighbors[i+1] = sp->fSender;
      break;
    }
  }
  if ((i < (NEIGHBOR_DISC_SIZE - 1)) && !found) {
    if (_runLinkOnAsync && !_linkTestRunning) {
#ifdef PING_PRINTFS
      Uart_Printf("discovered node %d, running link test...\n", sp->fSender);
#endif
      _linkReqDest = BROADCAST_ID;
      _linkTarget = sp->fSender;
      OSTaskDel(LINK_REQUEST_TASK_ID);
      OSTaskCreate(_linkRequestTask,
                   NULL,
                   (void *)&_linkRequestStack[LINK_REQUEST_STACK_SIZE-1],
                   LINK_REQUEST_TASK_ID);
    }
  }
}


// activates a testing beacon task
void PingStartBeaconMode( void ) {
  OSTaskCreate(_beaconTask,
               NULL,
               (void *)&_beaconStack[BEACON_STACK_SIZE-1],
               BEACON_TASK_ID);
```

```
}

// searches for nodes every once in a while and then runs link tests on the
// new ones
void _beaconTask( void *args ) {
  int i;

  // TESTING
  _linkTest(96);
  Uart_Printf("   link test results:\n");
  Uart_Printf("   pings sent: %d, pings rcvd: %d, pongs sent: %d, pongs rcvd: %d\n",
                _linkTable[96].fLocalPingsSent,
                _linkTable[96].fRemotePongsSent,
                _linkTable[96].fRemotePongsSent,
                _linkTable[96].fLocalPongsRcvd);
  while (1);

  // END TESTING

  while (1) {
    _discoverNeighbors();

    qsort(_linkTable, TABLE_SIZE, sizeof(linkStatistics), _linkStatisticsCmp);
    // The neighbors who generated the most pong responses are now at
    // the top of _linkTable

    // copy the neighbors out of linkTable
    for (i = 0; i < TABLE_SIZE; i++) {
      linkStatistics *ls = &_linkTable[i];
      if (ls->fLocalPongsRcvd != 0) {
        beaconTable[i] = ls->fNeighbor;
      }
      else {
          beaconTable[i] = BROADCAST_ID;
      }
    }

    // run a link test on each of the discovered neighbors
    for (i = 0; i < TABLE_SIZE; i++) {
      if (beaconTable[i] == BROADCAST_ID) {
          break;
      }
#ifdef PING_PRINTFS
       Uart_Printf("discovered node %d, running link test...\n", beaconTable[i]);
#endif
       _linkTest(beaconTable[i]);
#ifdef PING_PRINTFS
       Uart_Printf("   link test results:\n");
       Uart_Printf("   pings sent: %d, pings rcvd: %d, pongs sent: %d, pongs rcvd:
%d\n",
                     _linkTable[beaconTable[i]].fLocalPingsSent,
                     _linkTable[beaconTable[i]].fRemotePongsSent,
                     _linkTable[beaconTable[i]].fRemotePongsSent,
                     _linkTable[beaconTable[i]].fLocalPongsRcvd);
      if (_linkTable[beaconTable[i]].fLocalPongsRcvd > 84) {
          Uart_Printf(" node %d passed\n", beaconTable[i]);
      } else {
          Uart_Printf(" NODE %d FAILED\n", beaconTable[i]);
      }
#endif
    }
    OSTimeDly(5*OS_TICKS_PER_SEC);
  }
}

void PingServiceNeighborsRequest(pseg_t *pkt, pseg_t *gradSeg)
{
#ifdef DEBUG_BUFFER
    debug_buffer(85);
#endif
    if (gradSeg != NULL)
    {
      _neighborReqDest = ((gradPayload *)PSegPayload(gradSeg))->fOriginator;
    }
    else
    {
          _neighborReqDest = BROADCAST_ID;
    }
    OSTaskDel(PING_NEIGHBORS_TASK_ID);
    OSTaskCreate(_pingNeighborsTask,
                    NULL,
                    (void *)&_pingNeighborsStack[PING_NEIGHBORS_STACK_SIZE-1],
                    PING_NEIGHBORS_TASK_ID);
}

void _pingNeighborsTask(void *args)
{
    // Handle a request to discover neighbors.  Send (broadcast) PING
    // messages to the neighbors, tally the incoming PONG messages to
    // figure out who the neighbors are, and send a
    // PSEG_TYPE_NEIGHBORS_REPORT to the originator.
    int i;
    pseg_t *report;
    neighborsReportPayload *reportPayload;

#ifdef DEBUG_BUFFER
    debug_buffer(86);
#endif
    // Emit a series of PING messages and tally the number of PONG
    // responses from each neighbor
    _discoverNeighbors();

    // At this point, _linkTable()[N]->fLocalPongsRcvd contains the number of
    // pong messages this node has received from neighbor N.  Sort the
    // table by decreasing number of pongs received.

    qsort(_linkTable, TABLE_SIZE, sizeof(linkStatistics), _linkStatisticsCmp);
    // The neighbors who generated the most pong responses are now at
    // the top of _linkTable

    // compose a PSEG_TYPE_NEIGHBOR_REPORT message
    report = PSegAlloc(PSEG_TYPE_NEIGHBOR_REPORT,
                          sizeof(neighborsReportPayload),
                          NULL);
    reportPayload = PSegPayload(report);

    // copy the node ids of the nodes with the most responses.
    for (i = 0; i < PING_MAX_NEIGHBORS; i++)
    {
          linkStatistics *ls = &_linkTable[i];
          if (ls->fLocalPongsRcvd != 0)
          {
              reportPayload->fNeighbors[i] = ls->fNeighbor;
          }
          else
          {
```

```
            // no more neighbors - write an out-of-band value
            reportPayload->fNeighbors[i] = BROADCAST_ID;
        }
    }

    // finally send the report back to the sender
    if (_neighborReqDest == NodeGetID())
    {
        SerialServiceNeighborReport(report);
        PSegFree(report);
    }
    else if (_neighborReqDest != BROADCAST_ID)
    {
        MACXmitPkt(ARQMakeARQ(GRAdMakePkt(report, _neighborReqDest)));
    }
    else
    {
        // no GRAd header received?  Reply with a headerless report...
        MACXmitPkt(report);
    }
    OSTaskDel(PING_NEIGHBORS_TASK_ID);
}

void PingServiceLinkRequest(pseg_t *linkPkt, pseg_t *gradSeg)
{
#ifdef DEBUG_BUFFER
    debug_buffer(87);
#endif
    if (gradSeg != NULL)
    {
        _linkReqDest = ((gradPayload *)PSegPayload(gradSeg))->fOriginator;
    }
    else
    {
        _linkReqDest = BROADCAST_ID;
    }
    _linkTarget = ((linkRequestPayload *)PSegPayload(linkPkt))->fNeighbor;

    OSTaskDel(LINK_REQUEST_TASK_ID);
    OSTaskCreate(_linkRequestTask,
                 NULL,
                 (void *)&_linkRequestStack[LINK_REQUEST_STACK_SIZE-1],
                 LINK_REQUEST_TASK_ID);
}

void _linkRequestTask(void *args)
{
    // Handle a request for a link test with a specific neighbor.  Respond
    // by performing link test and sending a PSEG_TYPE_LINK_REPORT to the
    // originator.
    pseg_t *reportPkt;
    linkState *reportP;

    _linkTestRunning = true;

    // HACK- bad place for this, but easiest to write at the moment
    if (_runLinkOnAsync) {
      BootSendPkt(BOOT_FOUNDNEIGHBOR, _linkTarget);
    }

#ifdef DEBUG_BUFFER
    debug_buffer(88);
#endif
      _linkTest(_linkTarget);

    // at tthis point, _linkTable[fNeighbor] has logged the number of
    // pings and pongs sent and pongs received.  Copy the info for that
    // neighbor into a link report message and send it back to the
    // requestor
    reportPkt = PSegAlloc(PSEG_TYPE_LINK_REPORT,
                          sizeof(linkState),
                          NULL);
    reportP = PSegPayload(reportPkt);
    reportP->fNeighbor = _linkTarget;
    reportP->fPingsSent = _linkTable[_linkTarget].fLocalPingsSent;
    reportP->fPingsRcvd = _linkTable[_linkTarget].fRemotePongsSent;
    reportP->fPongsSent = _linkTable[_linkTarget].fRemotePongsSent;
    reportP->fPongsRcvd = _linkTable[_linkTarget].fLocalPongsRcvd;

    // send the report to the requestor
    if(_linkReqDest == NodeGetID())
    {
        SerialServiceNeighborLinkReport(reportPkt);
        PSegFree(reportPkt);
    }
    else if (_linkReqDest != BROADCAST_ID)
    {
        MACXmitPkt(ARQMakeARQ(GRAdMakePkt(reportPkt, _linkReqDest)));
    }
    else
    {
        // no GRAd header received?  Reply with a headerless report...
        MACXmitPkt(reportPkt);
    }
#ifdef PING_PRINTFS
    Uart_Printf("   link test results:\n");
    Uart_Printf("   pings sent: %d, pings rcvd: %d, pongs sent: %d, pongs rcvd: %d\n",
                _linkTable[_linkTarget].fLocalPingsSent,
                _linkTable[_linkTarget].fRemotePongsSent,
                _linkTable[_linkTarget].fRemotePongsSent,
                _linkTable[_linkTarget].fLocalPongsRcvd);
#endif
    _linkTestRunning = false;
    OSTaskDel(LINK_REQUEST_TASK_ID);
}

void PingServicePing(pseg_t *pingPkt, pseg_t *gradSeg)
{
    // Handle an incoming ping packet.  Make a note of how many pings
    // have been receiced from that neighbor and send a pong packet in
    // reply.
    pingPayload *pip = PSegPayload(pingPkt);
#ifdef DEBUG_BUFFER
    debug_buffer(89);
#endif
    if ((pip->fTarget == BROADCAST_ID) || (pip->fTarget == NodeGetID()))
    {
        // message is for me...
        linkStatistics *ls = &_linkTable[pip->fPinger];

        // notify the system manager that we are currently participating in a ping
        SysSetPingParticipant();

        // note another ping message received, resetting if the pinger
        // has started a new sequence.
        if (pip->fPingsSent < ls->fRemotePingsSent)
```

```
        {
            ls->fLocalPingsRcvd = 0;
            ls->fLocalPongsSent = 0;
        }
        ls->fRemotePingsSent = pip->fPingsSent;
        ls->fLocalPingsRcvd++;

#ifdef PING_PRINTFS
        Uart_Printf("  Got a ping from %d, remote pings sent %d, local pings rcvd
%d, pkt %x\n",
                    pip->fPinger, ls->fRemotePingsSent, ls->fLocalPingsRcvd,
                    pingPkt);
#endif
        // compose and send a pong message in response.
        ls->fLocalPongsSent++;  // increment pongs sent
        _sendPong(pip->fPinger, ls->fLocalPongsSent, (gradSeg != NULL));
    }
}

void PingServicePong(pseg_t *pongPkt)
{
    // Handle an incoming pong packet.
    pongPayload *pop = PSegPayload(pongPkt);
    linkStatistics *pie = &_linkTable[pop->fPonger];
#ifdef DEBUG_BUFFER
    debug_buffer(90);
#endif
    if ((pop->fTarget == BROADCAST_ID) || (pop->fTarget == NodeGetID())) {
        // this pong is for me...
        pie->fRemotePongsSent = pop->fPongsSent;
        pie->fLocalPongsRcvd++;
    }
#ifdef PING_PRINTFS
    Uart_Printf("  Got a pong to %d, from %d, remote pongs sent %d, local pongs rcvd
%d\n",
                pop->fTarget,pop->fPonger, pie->fRemotePongsSent,
                pie->fLocalPongsRcvd);
#endif
}

// Originating messages

void PingRequestNeighbors(node_id target)
{
    // Originate a PSEG_TYPE_NEIGHBOR_REQUEST message, destined for the
    // named target node.  Soon, a PSEG_TYPE_NEIGHBOR_REPORT message
    // should arrive back at this node.
    pseg_t *nrPkt = PSegAlloc(PSEG_TYPE_NEIGHBOR_REQUEST,
                              sizeof(neighborsRequestPayload),
                              NULL);
#ifdef DEBUG_BUFFER
    debug_buffer(91);
#endif
    if (target != BROADCAST_ID)
    {
        MACXmitPkt(ARQMakeARQ(GRAdMakePkt(nrPkt, target)));
    }
    else
    {
        MACXmitPkt(nrPkt);
    }
}
```

```
void PingRequestLinkTest(node_id target, node_id neighbor)
{
    // Originate a PSEG_TYPE_LINK_REQUEST message, destined for the named
    // target node.  Soon, a PSEG_TYPE_LINK_REPORT message should arrive
    // back at this node.
    pseg_t *lrPkt = PSegAlloc(PSEG_TYPE_LINK_REQUEST,
                              sizeof(linkRequestPayload),
                              NULL);
    linkRequestPayload *lrp = PSegPayload(lrPkt);
    lrp->fNeighbor = neighbor;

#ifdef DEBUG_BUFFER
    debug_buffer(92);
#endif
    if (target != BROADCAST_ID)
    {
        MACXmitPkt(ARQMakeARQ(GRAdMakePkt(lrPkt, target)));
    }
    else
    {
        MACXmitPkt(lrPkt);
    }
}

// ============================================================
// internal routines

static void _pingClearNeighbors( void ) {
  int i;
  for (i=0; i<NEIGHBOR_DISC_SIZE; i++) {
    discNeighbors[i] = BROADCAST_ID;
  }
}

static void _linkTableReset(void)
{
    int i;
#ifdef DEBUG_BUFFER
    debug_buffer(93);
#endif
    for (i = 0; i<TABLE_SIZE; i++)
    {
        _linkTableResetEntry(i);
    }
}

static void _linkTableResetEntry(node_id id)
{
    linkStatistics *lr = &_linkTable[id];
#ifdef DEBUG_BUFFER
    debug_buffer(94);
#endif
    lr->fNeighbor = id;
    lr->fLocalPingsSent = 0;
    lr->fLocalPingsRcvd = 0;
    lr->fLocalPongsSent = 0;
    lr->fLocalPongsRcvd = 0;

    lr->fRemotePingsSent = 0;
    //lr->fRemotePingsRcvd = 0;
    lr->fRemotePongsSent = 0;
    //lr->fRemotePongsRcvd = 0;
}
```

```
static void _discoverNeighbors(void)
{
    // send a series of PING messages out, let PingServicePong() tally
    // how many replies arrive
    int i;

#ifdef DEBUG_BUFFER
    debug_buffer(95);
#endif
    _linkTableReset();
    for (i = 0; i < ParamGet(PARAM_PING_SEARCH_COUNT); i++)
    {
          _sendPing(BROADCAST_ID, i+1);
          OSTimeDly(ParamGet(PARAM_PING_LINK_TEST_DELAY));
    }
    // By now, a number of PSEG_TYPE_PONG messages should have arrived
    // and updated _pingTable[].
}

static void _linkTest(node_id id)
{
    int i;
#ifdef DEBUG_BUFFER
    debug_buffer(95);
#endif
    _linkTableResetEntry(id);
    for (i = 0; i < ParamGet(PARAM_PING_LINK_TEST_COUNT); i++)
    {
          _sendPing(id, i+1);
          OSTimeDly(ParamGet(PARAM_PING_LINK_TEST_DELAY));
    }
}

void _sendPing(node_id target, uint8_t pingsSent)
{
    // Send a PING message to the given target
    pseg_t *pingPkt = PSegAlloc(PSEG_TYPE_PING, sizeof(pingPayload), NULL);
    pingPayload *pip = PSegPayload(pingPkt);
#ifdef DEBUG_BUFFER
    debug_buffer(96);
#endif
    pip->fPinger = NodeGetID();
    pip->fTarget = target;
    pip->fPingsSent = pingsSent;

    // Set pings sent
    _linkTable[target].fLocalPingsSent = pingsSent;

    MACXmitPkt(pingPkt);
}

void PingSendPing(node_id target) {
  _sendPing(target, 0);
}

void _sendPong(node_id target, uint8_t pongsSent, bool useGrad)
{
    // Send a PONG message to the given target
    pseg_t *pongPkt = PSegAlloc(PSEG_TYPE_PONG, sizeof(pongPayload), NULL);
    pongPayload *pop = PSegPayload(pongPkt);
#ifdef DEBUG_BUFFER
    debug_buffer(97);
#endif
    pop->fPonger = NodeGetID();
    pop->fTarget = target;
    pop->fPongsSent = pongsSent;
    // Set pongs sent
    _linkTable[target].fLocalPongsSent = pongsSent;

    if (!useGrad)
    {
          MACXmitPkt(pongPkt);
    }
    else
    {
          // this was a remote ping.. relay
          MACXmitPkt(GRAdMakePkt(pongPkt, target));
    }
}

static int _linkStatisticsCmp(const void *p1, const void *p2)
{
  // Sorting predicate for qsort:
  // return neg / 0 / pos if the pongs received of p1 are
  // less than / eq / greater than the pongs received of p2
  // this is backwards to get descending order
#ifdef DEBUG_BUFFER
    debug_buffer(98);
#endif
    return ((linkStatistics *)p2)->fLocalPongsRcvd -
      ((linkStatistics *)p1)->fLocalPongsRcvd;
}
```

pseg.h

```
// File: pseg.h
// Description: support for Packets and Segments
// Author(s):   Robert Poor <r@media.mit.edu>
//              Andrew Wheeler <ajw@media.mit.edu>
//
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// warranty.

#ifndef PSEG_H
#define PSEG_H

#include "types.h"

// A packet carries data among nodes.  Each packet is a linked list of
// packet segments; each segment carries a segment type, a byte count,
// and a payload.
//
// Internally, a segment has a fixed size payload, and a type-specific
// structure is cast to the payload (typically using fewer bytes than
// the full payload).
//
// When a segment is transmitted, it is serialized and only the
// "active" bytes of its payload are sent over the airwaves.

// MAX_PAYLOAD_SIZE defines the maximum number of payload bytes in a
// packet segment.
//
#define MAX_PAYLOAD_SIZE 64

// EOP_TRANSMIT_LENGTH defines the length of the EOP segment when it
// is transmitted -- one byte for the type, one byte for the length [0]
#define EOP_TRANSMIT_LENGTH 2

typedef enum {
  PSEG_TYPE_EOP = 0,
  PSEG_TYPE_SYNC = 1,                   // inter-node sync info
  PSEG_TYPE_GRAD = 2,                   // gradient routing info
  PSEG_TYPE_DISCO = 3,                  // discovery routing request
  PSEG_TYPE_PING = 4,                   // ping packet, request for pong
  PSEG_TYPE_PONG = 5,                   // reply to a ping
  PSEG_TYPE_ARQ = 6,                    // request and ack
  PSEG_TYPE_ACK = 7,                    // reply by sending an ack
  PSEG_TYPE_NEIGHBOR_REQUEST = 8,       // request list of neighboring nodes
  PSEG_TYPE_NEIGHBOR_REPORT = 9,        // here's my list of neighbors
  PSEG_TYPE_LINK_REQUEST = 10,          // request link test to specific neighbor
  PSEG_TYPE_LINK_REPORT = 11, // here's the result of the link test
  PSEG_TYPE_PARAM_SET = 12,             // set parameters from payload
  PSEG_TYPE_PARAM_REQUEST = 13,         // request current parameters
  PSEG_TYPE_PARAM_REPORT = 14,          // here are my current parameters
  PSEG_TYPE_STATS_RESET = 15, // clear current logging stats
  PSEG_TYPE_STATS_REQUEST = 16,         // request logging statistics
  PSEG_TYPE_STATS_REPORT_A = 17,// here are my logging statistics
  PSEG_TYPE_STATS_REPORT_B = 18,
  PSEG_TYPE_APPX_REPORT = 19, // here is the sensor data
  PSEG_TYPE_COST_TABLE = 20,    // contains a chunk of the cost table
  PSEG_TYPE_SET_IN_OPERATION = 21, // this node exits config mode and goes into
operational mode
  PSEG_TYPE_SDP_REQUEST = 22,
  PSEG_TYPE_SDP_REPLY = 23,
  PSEG_TYPE_BOOT_REPORT = 24,
  PSEG_TYPE_ENTER_TEST = 25,
  PSEG_TYPE_EXIT_TEST = 26,
  PSEG_TYPE_TESTING = 27,
  PSEG_TYPE_START_ASYNC = 28,
  PSEG_TYPE_STOP_ASYNC = 29,
  // add new seg types above this line and extend appr.c accordingly
  MAX_PSEG_TYPE
} pseg_type;

// generic segment structure
//
typedef struct _pseg_t {
  struct _pseg_t *fNext;      // link to the next segment in pkt
  uint32_t fPayload[MAX_PAYLOAD_SIZE];
  pseg_type fType;            // segment type
  uint8_t fSize;              // size of segment in bytes
} pseg_t;

void PSegInit(void);
// initialize the packet system

void PSegReset(void);
// reset pkt system after sleep

pseg_t *PSegAlloc(pseg_type type, uint8_t size, pseg_t *next);
// allocate a single packet segment

void PSegFree(pseg_t *head);
// free a chain of packet segments

pseg_t *PSegCopy(pseg_t *pkt);
// make a "deep copy" of pkt

#define PSegType(p) ((p)->fType)
// access the packet type for this segment

#define PSegSize(p) ((p)->fSize)
// access the number of bytes in the payload.

#define PSegNext(p) ((p)->fNext)
// access the link to the next packet in the list of packets

#define PSegPayload(p) ((void *)((p)->fPayload))
// access the first byte of the payload.

#define PSegTransmitSize(p) \
  ((p)->fSize + sizeof((p)->fSize) + sizeof((p)->fType))

pseg_t *PSegFindType(pseg_t *pkt, pseg_type type);
// find a segment of the given type in the packet chain, returning
// NULL if not found

uint8_t PSegCountBytes(pseg_t *pkt);
// Count the number of bytes in the packet chain

uint8_t PSegCountSegs(pseg_t *pkt);
// Count the number of segments in the packet chain

void PSegPrintSeg(pseg_t *seg);
// print one segment to stdout in hex

void PSegPrint(pseg_t *pkt);
// print a string of segments to stdout in hex

#endif
```

rad.h

```
// File: rad.h
// Description: send and receive packets over the radio hardware
// Author(s):   Andrew Wheeler <ajw@media.mit.edu>
```

```
//              Robert Poor <r@media.mit.edu>
//
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// warranty.

#ifndef RAD_H
#define RAD_H
// definitions for radio interface

#include "pseg.h"
#include "types.h"

// The radio normally runs a receive task at high priority, waiting
// for packets to appear from the radio processor (an Atmel device).
// When a packet is received, it is broken up into pseg_t segments and
// inserted in the application receive queue for processing by the
// application receive task.

void RadPrintStats(void);
void RadInit(void);
// cold start initialization, called once upon power up

void RadReset(void);
// Warm start re-initialization, called upon system wake up.

void RadStart(void);
// Start the radio receive thread.

void RadXmitPkt(pseg_t *packet);
// Transmit a packet immediately.  Called from the MAC_XMIT_TASK.
// Terminates the receive thread, configures the radio for xmit,
// transmits the packet, then restarts the receive thread.

bool RadIsBusy(void);
// Returns true if the radio is actively transmitting or receiving.

void RadSleep(void);
// puts the radio to sleep (unless it is already asleep, in which case the function
does nothing)

void RadWakeUp(void);
// wakes up the radio if it is asleep, otherwise it resets the recieve state of the
radio

uint32_t RadLastPktTime(void);

#define RAD_STAT_SIZE          4     // number of bytes of statistics sent with the
packet
#define RAD_MAX_PKT_SIZE       50    // number of bytes the longest packet can be
#define RAD_RCV_DMA_BYTE_COUNT ((RAD_MAX_PKT_SIZE*3) + RAD_STAT_SIZE + 1)  //
packet+stat+length byte + chk
#define RAD_TX_DMA_BYTE_COUNT ((RAD_MAX_PKT_SIZE) + 2) // packet + length + length2+
1 that is lost +chk

#define RX_GOOD_PKT_LOW  0
#define RX_GOOD_PKT_HIGH 1
#define RX_BAD_PKT_LOW   2
#define RX_BAD_PKT_HIGH  3
#define RX_LENGTH        4
#define RAD_TIMEOUT      (1 * MCLK / 96) // 1 second

#endif
```

rad.c

```
// File: rad.c
// Description: send and receive packets over the radio hardware
// Author(s):   Andrew Wheeler <ajw@media.mit.edu>
//              Robert Poor <r@media.mit.edu>
//
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// warranty.

#include "s3c3410x.h"
#include "tephra.h"
```

```
#include "pseg.h"
#include "rad.h"
#include "types.h"
#include "includes.h"
#include "sync.h"
#include "mac.h"
#include "appr.h"
#include "stats.h"
//#define THIS_IS_STUB_CODE

#undef RAD_PRINTFS

static void _RadSetupTxDma( void );
static void _RadSetupRxDma( void );
static void _RadBusyISR( void );
static void _RadDMADoneISR( void );
static void _RadExportPkt(pseg_t *pkt);
static void _RadTask(void *args);
static bool _RadPktValid( void );
static pseg_t * _RadImportPkt( void );

//volatile bool _radioBusyFlag;
volatile bool _radioTXModeFlag;
volatile bool _radioRXEnabledFlag;
volatile bool _radioAsleepFlag;
volatile bool _radioDmaTxDone;

static unsigned int _radStack[RAD_RCV_TASK_STACK_SIZE];

// receive and transmit buffers
static uint8_t _radTXBuffer[RAD_TX_DMA_BYTE_COUNT];
static uint8_t _radRCVBuffer[RAD_RCV_DMA_BYTE_COUNT];
//static uint8_t _radTXIntB[RAD_MAX_PKT_SIZE+1];
//static uint8_t _radRXIntB[RAD_MAX_PKT_SIZE+1];
static uint32_t _lastPktRcvTime;
int good, bad;

// signaling semaphore to indicate DMA done
static OS_EVENT *dmaDoneSem;

static unsigned char _toHex[16]={
  '0','1','2','3','4','5','6','7',
  '8','9','a','b','c','d','e','f'};

static void _putHex(unsigned char ch)
{
#ifdef DEBUG_BUFFER
    debug_buffer(109);
#endif
    Uart_SendByte(_toHex[ch >> 4]);
    Uart_SendByte(_toHex[ch & 0x0f]);
}

void RadInit()
{
  good = 0;
  bad = 0;
#ifdef DEBUG_BUFFER
    debug_buffer(112);
#endif

    // setup the dmaDone semaphore
    dmaDoneSem = OSSemCreate(0);

    // setting up variables
    //  _radioBusyFlag = false;
    _radioTXModeFlag = false;  // in receive by default
    _radioRXEnabledFlag = false; // not receiving yet

    // make sure radio is awake MOVED CALL TO LATER
    //  RadWakeUp();
    _radioAsleepFlag = false;  // radio starts out awake

    OS_ENTER_CRITICAL();
    // install the DMA interrupt handler
    ISR_DMA0 = (unsigned)_RadDMADoneISR;
    // install the radio busy interrupt handler
    ISR_EINT1 = (unsigned)_RadBusyISR;

    // setup the interrupt mask to enable EINT1 and SIO0
    EINTCON = EINTCON_EINT1_ENABLE;      // enable the EINT1 pin interrupt
                                         // generation
    EINTMOD = EINTMOD_EINT1_BOTH_EDGE;   // set the EINT1 interrupt mode to be
                                         // both edges
    INTPND  = ~EINT1;                    // clear any EINT1 pending interrupts
    INTMSK  |= EINT1;                    // activate the EINT1 interrupt

    OS_EXIT_CRITICAL();
}

void RadReset()
{
#ifdef DEBUG_BUFFER
    debug_buffer(113);
#endif
    RadWakeUp();
}

void RadXmitPkt(pseg_t *packet)
{
    uint32_t delay = RAD_TIMEOUT;
    int i;
#ifdef DEBUG_BUFFER
    debug_buffer(114);
#endif
    // make sure that the radio is not currently busy
    while (RadIsBusy() && delay)
    {
          delay--;
    }
    if (delay == 0)
    {
          return;
    }

    // delay?
    // deactivate receive DMA operation
    OS_ENTER_CRITICAL();
    SIOCON0 = SIOCON_MODE_DISABLE;
    DMACON0 = DMACON_RUN_DISABLE;
    OS_EXIT_CRITICAL();

    // setup flags for transmit
    _radioTXModeFlag = true;
    _radioDmaTxDone = false;
```

```
    // timestamp the packet
    SyncWillXmit(packet);

    // copies the packet to the transmit DMA buffer
    _RadExportPkt(packet);

    //    for (
    //    _radTXBuffer[1] = (PSegCountBytes(pkt)+1)
    // signal to the radio that we would like to transmit...
#ifdef RAD_PRINTFS
    Uart_Printf("pktlength = %x seglength = %x segtype = %x [%x %x %x %x %x]\n",
                    _radTXBuffer[1],
                    _radTXBuffer[2],
                    _radTXBuffer[3],
                    _radTXBuffer[4],
                    _radTXBuffer[5],
                    _radTXBuffer[6],
                    _radTXBuffer[7],
                    _radTXBuffer[8]);
#endif
    RAD_SIGNAL_TXPKT();
    RAD_SET_INTERRUPT();

    delay = RAD_TIMEOUT;
    while (!INTERRUPT_ACK() && delay)
    {
          delay--;
    }
    if (delay == 0)
    {
          return;
    }

    // setup transmit DMA operation
    _RadSetupTxDma();

    RAD_UNSET_INTERRUPT();    // tells the radio that we are ready to begin the
transmit operation

    // wait for DMA to complete
    delay = RAD_TIMEOUT;
    while (!_radioDmaTxDone);
    /*
    {
          delay--;
    }
    if (delay == 0)
    {
          return;
    }
    */
    // disable the DMA0 system
    OS_ENTER_CRITICAL();
    SIOCON0 = SIOCON_MODE_DISABLE;
    DMACON0 = DMACON_RUN_DISABLE;
    OS_EXIT_CRITICAL();

  // reset to receive mode
    _radioTXModeFlag = false;
    if (_radioRXEnabledFlag)
    { // if the RX dma was setup...
          _RadSetupRxDma();
          _radioRXEnabledFlag = true;
    }

  // go away
}

void RadStart()
{
#ifdef DEBUG_BUFFER
    debug_buffer(115);
#endif
    OSTaskCreate(_RadTask, NULL, (void *)&_radStack[RAD_RCV_TASK_STACK_SIZE-1],
                    RAD_RCV_TASK_ID);
}

bool RadIsBusy() {
#ifdef DEBUG_BUFFER
    debug_buffer(116);
#endif
    return ((bool)RAD_BUSY_PIN_SET());
}

uint32_t RadLastPktTime() {
#ifdef DEBUG_BUFFER
    debug_buffer(117);
#endif
    return _lastPktRcvTime;
}

// void _RadTask()
//  This thread sits in a loop waiting for a packet to arrive
//  It first sets up the DMA operation to recieve from the radio.
//  It then suspends itself until resumed by the DMA interrupt routine
static void _RadTask(void *args)
{
    pseg_t  *pkt;
    uint8_t errNo;

    while (true)
    {
#ifdef DEBUG_BUFFER
          debug_buffer(118);
#endif

          //        Uart_Printf("RadTask\n");
          // setup RX DMA
          _RadSetupRxDma();
          // suspend myself and wait for a packet to arrive via DMA
          //        OSTaskSuspend(RAD_RCV_TASK_ID);
          OSSemPend(dmaDoneSem, 0, &errNo);
#ifdef DEBUG_BUFFER
          debug_buffer(215);
#endif

          // disable SIO/DMA
          OS_ENTER_CRITICAL();
          _radioRXEnabledFlag = false;
          SIOCON0 = SIOCON_MODE_DISABLE;
          DMACON0 = DMACON_RUN_DISABLE;
          OS_EXIT_CRITICAL();

          _lastPktRcvTime = OSTimeGet();
          // call the timestamp function
          SyncWillReceive();
```

```
          // verify that a valid packet arrived?
          // CHECK PACKET HERE... make sure length field is between 3 bytes
          // and 50 bytes
          if ((_radRCVBuffer[RX_LENGTH] < 4) | (_radRCVBuffer[RX_LENGTH] >
(RAD_MAX_PKT_SIZE*3)))
          {
              // bad length somehow- just continue
            //        Uart_Printf("got bad pkt length: %d\n",
_radRCVBuffer[RX_LENGTH]);
            continue;
          }
#ifdef RAD_PRINTFS

          Uart_Printf("pktlength = %x seglength = %x segtype = %x [%x %x %x %x
%x]\n",
                        _radRCVBuffer[4],
                        _radRCVBuffer[5],
                        _radRCVBuffer[6],
                        _radRCVBuffer[7],
                        _radRCVBuffer[8],
                        _radRCVBuffer[9],
                        _radRCVBuffer[10],
                        _radRCVBuffer[11]);
#endif
          // check the packet to make sure it is OK DEBUGGING
          if (!_RadPktValid()) {
            continue;
          }
          //        continue;
          // parse out the packet
          pkt = _RadImportPkt();
          LED_4_ON();
          SyncDidReceive(pkt);
    // handle packet - hand it to appr
#ifdef RAD_PRINTFS
          Uart_Printf("     segtype = %x seglength = %x\n", pkt->fType,
                        pkt->fSize);
#endif

          AppRReceivePkt(pkt);
          LED_4_OFF();
    }
}


// void _RadExportPkt( pseg_t *pkt )
//   processes a packet for transmit an places it in the transmit DMA buffer
static void _RadExportPkt(pseg_t *pkt)
{
    uint8_t i,chksum;         // Points to current entry in buffer
#ifdef DEBUG_BUFFER
    debug_buffer(119);
#endif
    if (pkt == NULL)
    {
          return;
    }

    // 1. Reserved [byte 0]
    // 2. Write packet length [byte 1]
    // 3. While more segments & buffer space remain, stuff segments into buffer
    // _radTXBuffer[0] = 0;
    _radTXBuffer[1] = (PSegCountBytes(pkt)+2); // adding one for checksum and one
for length
    _radTXBuffer[2] = 3*(PSegCountBytes(pkt)+1); // adding one for checksum

    i = 3;
    chksum = 0;

    // 1.  Absolute bad condition: we've exceeded the array: stop
    //     Probably we've already crashed, though, so rely on 2 and 3.
    // 2.  Break when we've put the last segment into the array.
    // 3.  Break when the size of the next segment would cause us to
    //     exceed the array.
    while (i < RAD_TX_DMA_BYTE_COUNT)
    {
          uint8_t segmentSize;
          uint8_t *payload;

          if (pkt == NULL)
          {
              break;
          }

          if (i + PSegTransmitSize(pkt) > RAD_TX_DMA_BYTE_COUNT)
          {
              break;
          }

          segmentSize = PSegSize(pkt);

          _radTXBuffer[i++] = segmentSize + 1;
          //        _radTXBuffer[i++] = segmentSize + 1;
          //        _radTXBuffer[i++] = segmentSize + 1;
          chksum += (segmentSize + 1);
          _radTXBuffer[i++] = PSegType(pkt);
          //        _radTXBuffer[i++] = PSegType(pkt);
          //        _radTXBuffer[i++] = PSegType(pkt);
          chksum += PSegType(pkt);

          payload = PSegPayload(pkt);

          while (segmentSize-- > 0)
          {
            chksum += *payload;
            //        _radTXBuffer[i++] = *payload;
            //        _radTXBuffer[i++] = *payload;
            _radTXBuffer[i++] = *payload++;
          }
          pkt = PSegNext(pkt); // Advance packet
    }
    chksum = 0-chksum;
    //    _radTXBuffer[i++] = chksum;
    //    _radTXBuffer[i++] = chksum;
    _radTXBuffer[i++] = chksum;

    //    _putHex(_radTXBuffer[1]);
    //    for (i=0; i<=_radTXBuffer[1]; i++) {
    //      _putHex(_radTXBuffer[2+i]);
    //    }
    //    Uart_Printf("\n");

}
```

```
// pseg_t * _RadImportPkt( void )
//   processes the data contained in the recieve DMA buffer and creates a pseg chain
static pseg_t * _RadImportPkt( void )
{
  //    unsigned int goodPackets;  // These should go away with real storage
  //    unsigned int badPackets;   // : example only!

    uint8_t numBytes; // Number of bytes in packet
    uint8_t i;        // points to current entry in packet
    pseg_t *pkt;      // Return packet

#ifdef DEBUG_BUFFER
    debug_buffer(120);
#endif
  // 1.  Receive radio statistics and store them [byte 0-3]
  // 2.  Receive packet length [byte 4]
  // 3.  While more segments remain, create and link segments

    //  goodPackets = _radRCVBuffer[0];          // lo byte
    //  goodPackets |= (_radRCVBuffer[1] << 8);  // hi byte

    //  badPackets = _radRCVBuffer[2];          // lo byte
    //  badPackets |= (_radRCVBuffer[3] << 8);  // hi byte


  numBytes = _radRCVBuffer[4];

  pkt = (pseg_t *)NULL;

  i = 5;

  // So that countdown will work properly, increase numBytes -- then we
  // can stop when i == numBytes
  numBytes += i;

  // 1.  Absolute bad condition: we've exceeded the array: stop
  //     Probably we've already crashed, though, so rely on 2.
  // 2.  Break when we've read the appropriate number of bytes.
  while (i < RAD_RCV_DMA_BYTE_COUNT && i < numBytes)
  {
    // 1. Segment length
    // 2. Segment type
    uint8_t segmentLength = _radRCVBuffer[i++];
    uint8_t segmentType   = _radRCVBuffer[i++];
    uint8_t *pp           = NULL;  // payload -- generic 8 bit unsigned

    if(segmentType == PSEG_TYPE_EOP) // last segment
      break;

    if(i + segmentLength > RAD_RCV_DMA_BYTE_COUNT) // error; stop.
      break;

    // Create a new segment and copy the generic payload
    pkt = PSegAlloc(segmentType, segmentLength-1, pkt);
    pp  = PSegPayload(pkt);

    while (segmentLength-- > 1)
    {
      *pp++ = _radRCVBuffer[i++];
    }
  }

  return(pkt);
}


// checks to make sure all is well with the packet
/*static bool _RadPktValid( void ) {
  uint8_t checksum;
  int i;

  checksum = 0;
  for (i=0; i<_radRCVBuffer[4]; i++) {
    checksum += _radRCVBuffer[5+i];
  }
  checksum = 0-checksum;
  if (checksum != _radRCVBuffer[5+_radRCVBuffer[4]]) {
    bad++;
    Uart_Printf("good: %d, bad %d:\n    ", good, bad);
    _putHex(_radRCVBuffer[4]);
    for (i=0; i<=_radRCVBuffer[4]; i++) {
      _putHex(_radRCVBuffer[5+i]);
    }
    Uart_Printf("\n");
    return false;
  } else {
    good++;
    return true;
  }
  }*/

static bool _RadPktValid( void ) {
  uint8_t checksum, ab, bc, ac;
  int i;

  checksum = 0;

  _radRCVBuffer[4] = _radRCVBuffer[4]/3;

  for (i=0; i<(_radRCVBuffer[4]-1); i++) {
    ab = _radRCVBuffer[5+(i*3)] & _radRCVBuffer[5+(i*3)+1];
    bc = _radRCVBuffer[5+(i*3)+1] & _radRCVBuffer[5+(i*3)+2];
    ac = _radRCVBuffer[5+(i*3)] & _radRCVBuffer[5+(i*3)+2];
    _radRCVBuffer[5+i] = (ab | bc | ac);
    checksum += _radRCVBuffer[5+i];
  }

  checksum = 0-checksum;

  i = (_radRCVBuffer[4]-1);
  ab = _radRCVBuffer[5+(i*3)] & _radRCVBuffer[5+(i*3)+1];
  bc = _radRCVBuffer[5+(i*3)+1] & _radRCVBuffer[5+(i*3)+2];
  ac = _radRCVBuffer[5+(i*3)] & _radRCVBuffer[5+(i*3)+2];

  _radRCVBuffer[4] = _radRCVBuffer[4]-1;
  if (checksum != (ab | bc | ac)) {
    bad++;
    //    Uart_Printf("good: %d, bad %d:\n    ", good, bad);
    //    _putHex(_radRCVBuffer[4]);
    //    for (i=0; i<=_radRCVBuffer[4]; i++) {
    //      _putHex(_radRCVBuffer[5+i]);
    //    }
    //    Uart_Printf("\n");
    StatsSetBadPackets(bad);
    StatsSetGoodPackets(good);
    return false;
```

```
  } else {
    StatsSetBadPackets(bad);
    StatsSetGoodPackets(good);
    good++;
    //    Uart_Printf("good: %d, bad %d:\n    ", good, bad);
    //    _putHex(_radRCVBuffer[4]);
    //    for (i=0; i<=_radRCVBuffer[4]; i++) {
    //      _putHex(_radRCVBuffer[5+i]);
    //    }
    //    Uart_Printf("\n");
    return true;
  }
}

void RadPrintStats(void) {
  Uart_Printf("STATS good: %d, bad: %d\n", good, bad);
}

// void _RadSetupRxDma( void )
// does all the register twiddling to setup and enable Radio->ARM DMA transfer
static void _RadSetupRxDma( void )
{
#ifdef DEBUG_BUFFER
    debug_buffer(121);
#endif
  // --------------- ENTERING NON-INTERRUPTABLE CODE -----------------
  OS_ENTER_CRITICAL();

  // ensure that the DMA interrupt is clear and enabled
  INTPND  = ~INT_DMA0;                  // clear any DMA0 pending interrupt
  INTMSK  |= INT_DMA0;                  // activate the DMA0 interrupt

  // reset DMA/SIO for receive operation
  DMASRC0 = (SFR_BASE + 0x6002);
  DMADST0 = (uint32_t)_radRCVBuffer;
  DMACNT0 = RAD_RCV_DMA_BYTE_COUNT;
  DMACON0 = DMACON_SOURCE_SIO_TIMER     |
    DMACON_SRC_ADDRESS_FIX      |
    DMACON_DST_ADDRESS_INCREASE |
    DMACON_STOP_INT_ENABLE      |
    DMACON_SINGLE_MODE          |
    DMACON_8_BITS               |
    DMACON_RUN_ENABLE;

  // setup SIO operation
  // SIO0 Configuration : Mode=DMA1, Auto run, Rising edge, Rx/Tx mode, MSB,
Internal clk
  SIOCON0 = SIOCON_MODE_DMA0_REQUEST  |
    SIOCON_FALLING_EDGE_CLOCK |
    SIOCON_RCV_MODE           |
    SIOCON_MSB_MODE           |
    SIOCON_CLOCK_EXTERNAL;
  // enable SIO again
  SIOCON0 |= SIOCON_CLEAR_AND_START;

  _radioRXEnabledFlag = true;

  //  OS_EXIT_CRITICAL();
  // ------------ EXITING NON-INTERRUPTABLE CODE --------------------

}

// void _RadSetupTxDma( void )
// does all the register twiddling to setup and enable ARM->Radio DMA transfer
static void _RadSetupTxDma( void ) {
#ifdef DEBUG_BUFFER
    debug_buffer(122);
#endif
  // --------------- ENTERING NON-INTERRUPTABLE CODE -----------------
  OS_ENTER_CRITICAL();

  // sets up DMA/SIO for transmit
  DMASRC0 = (uint32_t)_radTXBuffer;
  DMADST0 = (SFR_BASE + 0x6002);  // SIODAT0
  DMACNT0 = RAD_TX_DMA_BYTE_COUNT;
  DMACON0 = DMACON_SOURCE_SIO_TIMER     |
    DMACON_SRC_ADDRESS_INCREASE |
    DMACON_DST_ADDRESS_FIX      |
    DMACON_STOP_INT_ENABLE      |
    DMACON_SINGLE_MODE          |
    DMACON_8_BITS               |
    DMACON_RUN_ENABLE;

  // SIO0 Configuration : Mode=DMA0, Auto run, Rising edge, Rx/Tx mode, MSB,
External clk
  SIOCON0 = SIOCON_MODE_DMA0_REQUEST  |
    SIOCON_FALLING_EDGE_CLOCK |
    SIOCON_RCV_XMT_MODE       |
    SIOCON_MSB_MODE           |
    SIOCON_CLOCK_EXTERNAL;

  // activate SIO
  SIOCON0 |= SIOCON_CLEAR_AND_START;

  // alert radio via interrupt that we are ready to send data
  RAD_SIGNAL_TXPKT();
  RAD_SET_INTERRUPT();

  OS_EXIT_CRITICAL();

  // ------------ EXITING NON-INTERRUPTABLE CODE --------------------
}


// void _RadBusyISR( void )
//  This function should be installed as the interrupt handler for external
interrupt 1 (EINT1)
//  On a rising edge, this function sets the _radioBusyFlag to true, and on a
falling
//  edge, it sets it to false
void _RadBusyISR( void )
{
#ifdef DEBUG_BUFFER
    debug_buffer(123);
#endif
    INTPND = ~EINT1;
    if (RAD_BUSY_PIN_SET())
    {
          //    _radioBusyFlag = true;
          MACStopTimer();
    }
    else
    {
          //    _radioBusyFlag = false;
          MACStartTimer();
    }
```

```
}

// void _RadDMADoneISR( void )
//  This function should be installed as the DMA
void _RadDMADoneISR( void )
{
#ifdef DEBUG_BUFFER
    debug_buffer(124);
#endif
    INTPND = ~INT_DMA0;
    if (!_radioTXModeFlag)
    {
          // we are recieving... unblock the radio task
      //  OSTaskResume(RAD_RCV_TASK_ID);
      OSSemPost(dmaDoneSem);
    }
    else
    {
          // we are transmitting... set the finished flag
          _radioDmaTxDone = true;
    }
}

// void RadSleep( void )
//  This function puts the radio to sleep if it is not already asleep, otherwise it
does
//  nothing
void RadSleep( void )
{
    uint32_t delay = RAD_TIMEOUT;
#ifdef DEBUG_BUFFER
    debug_buffer(125);
#endif
    if (!_radioAsleepFlag)
    {
          RAD_SIGNAL_SLEEP();
          // signal an interrupt
          RAD_SET_INTERRUPT();
          while (!INTERRUPT_ACK() && delay)
          {
              delay--;
          }
          // release the interrupt line
          RAD_UNSET_INTERRUPT();
          _radioAsleepFlag = true;
    }
}

// void RadWakeUp( void )
//  This function asserts the wakeup interrupt to the radio.  If the radio is
already awake,
//  this will do nothing
void RadWakeUp( void )
{
  //    uint32_t delay = RAD_TIMEOUT;
#ifdef DEBUG_BUFFER
    debug_buffer(126);
#endif
    RAD_SIGNAL_WAKEUP();
    // signal an interrupt
    RAD_SET_INTERRUPT();
    while (!INTERRUPT_ACK());
    RAD_UNSET_INTERRUPT();
    _radioAsleepFlag = false;
    OSTimeDly(4);
}
```

rtc.h

```
// File: rtc.h
// Description: support for the hardware Real Time Clock
// Author(s):   Paul Pham <ppham@mit.edu>, Robert Poor <r@mit.edu>
//
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// warranty.

#ifndef RTC_H
#define RTC_H
// file: rtc.h
//
// Access to the system's real time clock.  We don't need to keep time
// beyond one hour, so we ignore the higher order fields.

#include "types.h"

typedef uint32_t rtc_t;
// rtc_t encodes time as s + (60 * (m + (60 * h)))

#define MAKE_TIME(h, m, s) ((h * 3600) + (m + 60) + s)

#define RTC_EPOCH MAKE_TIME(24, 0, 0)
// maximum time (exclusive) recorded by the system

#define RTC_HALF_EPOCH MAKE_TIME(12, 0, 0)
// half of the maximum time recorded by the system

void RTCInit(void);
// called once when the system boots up

void RTCReset(void);
// called on system restarts/wakeups
```

```
void RTCStart(void);
// called to start the LED blinking thread for sync stuff

rtc_t RTCGetTime(void);
// fetch the current time

void RTCSetTime(rtc_t t);
// set the RTC from the given time value

void RTCSetAlarmTime(rtc_t t);
// set the RTC Alarm for the given time value

void RTCAdvanceTime(rtc_t delta);
void RTCRetardTime(rtc_t delta);
// advance or retard the real time clock by delta

#endif
```

serial.h

```
#ifndef SERIAL_H
#define SERIAL_H

#include "pseg.h"

// Exported functions
void SerialInit( void );
void SerialReset( void );
void SerialStart( void );

// Sets the neighbor list
void SerialServiceNeighborReport(pseg_t *seg);

// Reports on the strength of a neighbor
void SerialServiceNeighborLinkReport(pseg_t *seg);

void SerialServiceBootReport(pseg_t *seg);

// When we receive an ack
void SerialServiceAck(pseg_t *seg);

// Used to determine if we're in doctor mode or gateway mode
bool SerialGatewayMode( void );
bool SerialDoctorMode( void );
void SerialCheckSync(pseg_t *pkt);
void SerialStartInGateway( void );
#endif
```

serial.c

```
// File: serial.c
// Description: Drops into special modes for serial interfacing
// Author(s):   Paul Covell <pac@alum.mit.edu>
//              Andrew Wheeler <ajw@media.mit.edu>
//
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// warranty.

#include <ctype.h>
#include <stdlib.h>

// #define PC_DEBUG // define this when running on a PC and want to debug menuing

#include "serial.h"

#ifndef PC_DEBUG
#include <stdio.h>

#include <util.h>      // Provides serial handling headers
#include <ping.h>      // Provides segment types

#include "mac.h"
#include "node_id.h"
#include "param.h"
#include "pseg.h"
#include "tephra.h"
#include "types.h"
#include "vector.h"

#include "includes.h"
#include "os_cfg.h"    // Keep ucos_ii.h happy
#include "ucos_ii.h"   // Provides OSTimeGet(), OSTimeDly()
#include "arq.h"
#include "grad.h"
#include "sync.h"
#include "ping.h"
#include "appr.h"
#include "sysmanager.h"
#include "boottest.h"

#endif

#ifdef PC_DEBUG
#include <sys/types.h>
#include <poll.h>
#include <unistd.h>
#include <stdio.h>
#include <stdlib.h>

typedef int uint8_t;
```

```
typedef int node_id;

#define BROADCAST_ID 0xFF

#endif

#ifdef PC_DEBUG
#define SENDSTRING(s) fprintf(stdout, s); fflush(stdout)
#else
#define SENDSTRING(s) Uart_SendString(s)
#endif

// stack for the serial task
static unsigned int _serialStack[SER_RCV_TASK_STACK_SIZE];
static pseg_t *queuedPkt;
static bool   waitOnPkt;
static bool  printSync;
static bool  syncFlood;
static node_id _targetNode;
static uint8_t _serialState;  // Used to store the current state machine state

static void _SerialTask(void *args);
uint8_t _fromHex(char c);
uint8_t _receiveLinkRequestInfo(pseg_t *pkt, char inCh, int reset);
uint8_t _receiveParamSetInfo(pseg_t *pkt, char inCh, int reset);
uint8_t _receiveSyncInfo(pseg_t *pkt, char inCh, int reset);
uint8_t _theRightATOI(const char *);
void _wakeupSerial(void);
void _sendOperationOnPacket(node_id targetNode);
void _sendEnterTestPkt(node_id targetNode);
void _sendExitTestPkt(node_id targetNode);

// ============================================================
#define BAUD_RATE 19200

#define WAIT_KEYPRESS 0
#define ENTER_GATEWAY 1
#define ENTER_DOCTOR  2
#define ENTER_BEACON  3
#define DOCTOR_MAIN   16
#define EXIT_DOCTOR   17
#define BEACON_MAIN   20
#define GATEWAY_MAIN  128

//--
// Description:  Initializes the serial thread for the first time.
//--
void SerialInit()
{
#ifdef DEBUG_BUFFER
    debug_buffer(139);
#endif
    ISR_URX = (uint32_t)_wakeupSerial;
    INTPND = ~INT_URX;
    INTMSK |= INT_URX;    // activate serial interrupt

    queuedPkt = NULL;
    waitOnPkt = false;
    _targetNode = BROADCAST_ID;
    printSync = false;
    syncFlood = false;
  _serialState = WAIT_KEYPRESS;
}


//--
// Description:  Resets the serial thread, called before serialStart()
//--
void SerialReset()
{
#ifdef DEBUG_BUFFER
    debug_buffer(140);
#endif
    //#ifndef PC_DEBUG
    Uart_Init(TEPHRA_BAUD_RATE);
    //#endif
    printSync = false;
    queuedPkt = NULL;
    waitOnPkt = false;
    syncFlood = false;
    _targetNode = BROADCAST_ID;
  _serialState = WAIT_KEYPRESS;
}

void SerialStartInGateway() {
  _serialState = GATEWAY_MAIN;
  AppRSetIsPrinting(TRUE);
  SysSetGatewayMode(true);
}

//--
// Description:  Runs a thread that blocks until serial input is received,
//   at which time it may change the operating mode of the processor.  This
//   thread should not be killed unless <Doctor Mode> is off AND
//   <Gateway Mode> is off.
//--
void SerialStart()
{
#ifdef DEBUG_BUFFER
    debug_buffer(141);
#endif
  // Initialize state
    OSTaskCreate(_SerialTask, NULL,
                     (void *)&_serialStack[SER_RCV_TASK_STACK_SIZE-1],
                     SER_RCV_TASK_ID);

}

/*-- Begin definitions for functionality --*/

#define DOCTOR_KEY  'D'
#define GATEWAY_KEY 'G'
#define BEACON_KEY  'B'


static node_id _neighborList[PING_MAX_NEIGHBORS]; // List of neighbors of target
static uint8_t _updateInProgress;  // Receiving input from the packet handler?
volatile static uint8_t _serialChar;   // last character

#define REDRAW_SCREEN     0
#define NO_REDRAW_SCREEN  1

#define PROMPT_SET_TARGET "\n\rSet target node to: "
#define PROMPT_SET_GATEWAY_NODE "\n\rSet gateway node to: "
#define PROMPT_SET_NEIGHBOR_NODE "\n\rRequest strength on node: "
```

```
#define INFO_CHECK_ALL_NEIGHBOR_STRENGTH "\n\rCollecting link strength from all
neighbors to target node..\n\r"
//   Format:  [nnn | s-ping | r-ping | s-pong | r-pong]
#define INFO_CHECK_ALL_NEIGHBOR_FORMAT "\n\r[nid | spi | rpi | spo | rpo ]\n\r"

#define INFO_SET_TARGET_NODE "\n\rTarget node set.\n\r"
#define INFO_SET_GATEWAY_NODE "\n\rGateway node set.\n\r"
#define INFO_SET_NEIGHBOR_NODE "\n\rNeighbor node set.\n\r"
#define INFO_OPERATIONAL_MODE "\n\rTarget node set operational.\n\rNOTE:  It will
now sleep.  Play accordingly.\n\r"
#define INFO_COLLECT_NEIGHBORS "\n\rCollecting neighbors from target node..\n\r"
#define INFO_COLLECT_NEIGHBORS_DONE "\n\rNeighbor collection completed.\n\r"

#define ERROR_TARGET_NODE_NOT_SET "\n\r**Target node not set.  Set target node
first.\n\r"
#define ERROR_NEIGHBOR_STRENGTH_TIMEOUT "**Timeout receiving node strength**\n\r"
#define ERROR_COLLECT_NEIGHBORS_TIMEOUT "**Timeout receiving node neighbors**\n\r"
#define ERROR_DOCTOR_NO_OPERATIONAL "**Can't set the doctor to operational
mode**\n\r"
#define ERROR_NODE_SELF "**Can't execute this operation ON the same node you're
using!**\n\r"

void _process_gateway_input(void);
void _print_doctor_screen(void);
uint8_t _process_doctor_keypress(void);
void _updateStarted(void);
void _updateFinished(void);


void _SerialTask(void *args)
{
  char inCh;

#ifdef PC_DEBUG
  Uart_Printf("Starting main serial loop.\n\r");
#endif

  while (true)
  {
#ifdef DEBUG_BUFFER
      debug_buffer(142);
#endif
      // Delay every time through the loop for 20ms -- good?  bad?
      switch(_serialState)
      {
      case WAIT_KEYPRESS:
          // block until receive key
          OSTaskSuspend(OS_PRIO_SELF);
#ifdef DEBUG_BUFFER
          debug_buffer(219);
#endif
          inCh = _serialChar;

          if (inCh == DOCTOR_KEY)
          {
              _serialState = ENTER_DOCTOR;
          }
          else if(inCh == GATEWAY_KEY)
          {
              _serialState = ENTER_GATEWAY;
          }
          else if (inCh == BEACON_KEY)
          {
              _serialState = ENTER_BEACON;
          }
      // else do nothing
          break;

      case ENTER_DOCTOR:
          // set doctor flags XXX
#ifdef PC_DEBUG
          Uart_Printf("Entering doctor main\n\r");
#endif
          _print_doctor_screen();
          _updateInProgress = 0;
          SysSetDoctorMode(true);
          _serialState = DOCTOR_MAIN;
          break;

      case ENTER_GATEWAY:
          Uart_Printf("Entering Gateway Mode\n");
          AppRSetIsPrinting(TRUE);
          SysSetGatewayMode(true);
          _serialState = GATEWAY_MAIN;
          break;

      case ENTER_BEACON:
          Uart_Printf("Beacon Mode activated, searching for devices...\n");
          SysSetTestMode(true);
          PingStartBeaconMode();
          _serialState = BEACON_MAIN;
          break;

      case DOCTOR_MAIN:
          // 1.  display the interface screen
          // 2.  wait for menu command / watch for incoming data
          // 3.  act on menu command / act on incoming data
          if(_process_doctor_keypress() == REDRAW_SCREEN)
          {
              _print_doctor_screen();
          }
          break;

      case EXIT_DOCTOR:
          SysSetDoctorMode(false);
          _serialState = WAIT_KEYPRESS;
          break;

      case BEACON_MAIN:
          // spin here indefinitely
          OSTaskSuspend(OS_PRIO_SELF);
          break;

      case GATEWAY_MAIN:
          // 1.  wait for data from base station to retransmit
          // 2.  incoming network data is handled by Rob's code in the
          //     lower network layer.
          _process_gateway_input();
          break;

      default:
          _serialState = WAIT_KEYPRESS;
          break;
      }
  }
}
```

```
void _wakeupSerial(void)
{
    INTPND = ~INT_URX;
    _serialChar = URXH;
    OSTaskResume(SER_RCV_TASK_ID);
}

#define KEY_SET_TARGET_NODE             'T'
#define KEY_COLLECT_NEIGHBORS           'C'
#define KEY_OPERATIONAL_MODE            'O'
#define KEY_CHECK_NEIGHBOR_STRENGTH     'S'
#define KEY_SET_GATEWAY                 'G'
#define KEY_CHECK_ALL_NEIGHBOR_STRENGTH 'A'
#define KEY_EXIT_DOCTOR_MODE            'E'
#define KEY_ENTER_TEST                  'X'
#define KEY_EXIT_TEST                   'Y'
#define KEY_START_ASYNC                 'D'
#define KEY_STOP_ASYNC                  'F'
#define KEY_CHECK_NODE                  'H'
#define KEY_UPDATE_PARAMS               'P'
#define KEY_SYNC_FLOOD                  'Z'
#define KEY_TOOGLE_SYNC_INFO            'I'
#define KEY_REDRAW_SCREEN               13  // Hit enter to redraw

//--
// Description: draws the interface screen using VT100 commands
// Preconditions: None.
// Postconditions: the screen contents have been sent via the uart
// Returns: None.
//--
void _print_doctor_screen()
{
#ifdef DEBUG_BUFFER
    debug_buffer(143);
#endif
    SENDSTRING("Doctor Main Menu\n\r");
    SENDSTRING("\n\r");
    SENDSTRING("[T]arget Node\n\r");
    SENDSTRING("[C]ollect Neighbors\n\r");
    SENDSTRING("[A]ll Neighbor Strength\n\r");
    //    SENDSTRING("[G]ateway Node Set\n\r");
    SENDSTRING("[X] Enter Test Mode\n\r");
    SENDSTRING("[Y] Exit Test Mode\n\r");
    SENDSTRING("[D] Start Async Ping\n\r");
    SENDSTRING("[F] Stop Async Ping\n\r");
    SENDSTRING("[H] Check Node Existance\n\r");
    SENDSTRING("[P] Update Params\n\r");
    SENDSTRING("[Z] Sync Flood\n\r");
    SENDSTRING("[I] Toggle Sync Info\n\r");
    //    SENDSTRING("[O]perational Mode\n\r");
    SENDSTRING("[S]pecific Neighbor Strength\n\r");
    SENDSTRING("\n\r");
    SENDSTRING("[E]xit Doctor Mode\n\r");
    SENDSTRING("\n\r>");
}

//--
// Descriptin: If a key is pressed, handle the key
// Preconditions: None.
// Postconditions: Keypress [if any] is handled properly
// Returns: 0 if screen should be redrawn; 1 if it should not be
//--
```

```
#define INPUT_STATE                 0
#define COLLECT_NEIGHBORS           2
#define CHECK_NEIGHBOR_STRENGTH     3
#define CHECK_ALL_NEIGHBOR_STRENGTH 4

#define SET_TARGET_NODE             5
#define SET_NEIGHBOR_NODE           6
#define SET_GATEWAY_NODE            7

// Timeouts
#define TIMEOUT_CHECK_DELAY .5*OS_TICKS_PER_SEC   // Wait for 1/2 sec before
checking; in 5ms ticks
#define RECEIVE_TIMEOUT     60*OS_TICKS_PER_SEC  // Timeout in 60 seconds; in 5ms
ticks

uint8_t _process_doctor_keypress()
{
    static uint8_t  _keypressState = INPUT_STATE;
    static char _tempString[4];
    static uint8_t _stringPos = 0;
    static uint32_t _timerStart;   // used for timeouts for receiving packets

    uint8_t neighborNode = BROADCAST_ID;  // Used by check neighbor
    uint8_t retVal = NO_REDRAW_SCREEN;
    uint8_t i;

    char inCh;

#ifdef PC_DEBUG
    // Setup polling
    struct pollfd pfd;

    pfd.fd = STDIN_FILENO;
    pfd.events = POLLIN;
#endif

#ifdef DEBUG_BUFFER
    debug_buffer(144);
#endif
#ifdef PC_DEBUG
    if(poll(&pfd, 1, 1) > 0)  // poll for 1ms
#else
      OSTaskSuspend(OS_PRIO_SELF);
    if((inCh = _serialChar) > 0)
#endif
    {

#ifdef PC_DEBUG
          read(STDIN_FILENO, &inCh, 1);
          //printf("Read '%c'\n\r", inCh);
#endif

          switch(_keypressState)
          {
          case INPUT_STATE:
            switch(inCh)
            {
            case KEY_SET_TARGET_NODE:
              SENDSTRING(PROMPT_SET_TARGET);
              retVal = NO_REDRAW_SCREEN;
              _stringPos = 0;
              _keypressState = SET_TARGET_NODE;
```

```
  break;

case KEY_COLLECT_NEIGHBORS:
  SENDSTRING(INFO_COLLECT_NEIGHBORS);
  if(_targetNode == BROADCAST_ID)
  {
        SENDSTRING(ERROR_TARGET_NODE_NOT_SET);
  }
  else
  {
        // 1.  Request neighbor nodes from target
        // 2.  Wait for neighbor nodes to be returned [with timeout]
        // 3.  Print out neighbor nodes

        if(_targetNode == NodeGetID())
        {
            // Fake a packet to self if we're the target node
            pseg_t *gradSeg = GRAdMakePkt(NULL, NodeGetID());
            PingServiceNeighborsRequest(NULL, gradSeg);
            PSegFree(gradSeg);
        }
        else
        {
            PingRequestNeighbors(_targetNode);
        }

        //OSTaskSuspend(OS_PRIO_SELF);
        // Wait for status update to finish [with timeout]
        _updateStarted();
        _timerStart = OSTimeGet();
        while(_updateInProgress == 1)
        {
            OSTimeDly(TIMEOUT_CHECK_DELAY);
            if(OSTimeGet() - _timerStart > RECEIVE_TIMEOUT)
            {
                  SENDSTRING(ERROR_COLLECT_NEIGHBORS_TIMEOUT);
                  break;
            }
        }

        // Done
        SENDSTRING(INFO_COLLECT_NEIGHBORS_DONE);
  }
  retVal = REDRAW_SCREEN;
  break;

case KEY_SET_GATEWAY:
  SENDSTRING(PROMPT_SET_GATEWAY_NODE);
  retVal = NO_REDRAW_SCREEN;
  _stringPos = 0;
  _keypressState = SET_GATEWAY_NODE;
  break;

case KEY_OPERATIONAL_MODE:
  if(_targetNode == BROADCAST_ID)
  {
        SENDSTRING(ERROR_TARGET_NODE_NOT_SET);
        retVal = REDRAW_SCREEN;
  }
  else
  {
        if(_targetNode == NodeGetID())
        {
                  // can't put the doctor in operational mode
                  SENDSTRING(ERROR_DOCTOR_NO_OPERATIONAL);
            }
            else
            {
                _sendOperationOnPacket(_targetNode);
                SENDSTRING(INFO_OPERATIONAL_MODE);
            }
            retVal = REDRAW_SCREEN;
        }
        break;

      case KEY_ENTER_TEST:
        if(_targetNode == BROADCAST_ID)
          {
              SENDSTRING(ERROR_TARGET_NODE_NOT_SET);
              retVal = REDRAW_SCREEN;
          }
        else
          {
              if(_targetNode == NodeGetID())
                {
                  // can't put the doctor in operational mode
                  SENDSTRING(ERROR_DOCTOR_NO_OPERATIONAL);
                }
              else
                {
                  _sendEnterTestPkt(_targetNode);
                  //SENDSTRING(INFO_OPERATIONAL_MODE);
              }
              retVal = REDRAW_SCREEN;
        }
        break;

      case KEY_EXIT_TEST:
        if(_targetNode == BROADCAST_ID) {
          SENDSTRING(ERROR_TARGET_NODE_NOT_SET);
          retVal = REDRAW_SCREEN;
        } else {
          if(_targetNode == NodeGetID()) {
              // can't put the doctor in operational mode
              SENDSTRING(ERROR_DOCTOR_NO_OPERATIONAL);
          } else {
              _sendExitTestPkt(_targetNode);
              //SENDSTRING(INFO_OPERATIONAL_MODE);
          }
          retVal = REDRAW_SCREEN;
        }
        break;

      case KEY_START_ASYNC:
        if(_targetNode == BROADCAST_ID) {
          SENDSTRING(ERROR_TARGET_NODE_NOT_SET);
          retVal = REDRAW_SCREEN;
        } else {
          if(_targetNode == NodeGetID()) {
              // can't put the doctor in operational mode
              SENDSTRING(ERROR_DOCTOR_NO_OPERATIONAL);
          } else {
              queuedPkt = PSegAlloc(PSEG_TYPE_START_ASYNC,
sizeof(dummyPayload), NULL);
              queuedPkt = ARQMakeARQ(GRAdMakePkt(queuedPkt, _targetNode));
              waitOnPkt = true;
```

```
                }
                retVal = REDRAW_SCREEN;
              }
              break;

            case KEY_STOP_ASYNC:
              if(_targetNode == BROADCAST_ID) {
                SENDSTRING(ERROR_TARGET_NODE_NOT_SET);
                retVal = REDRAW_SCREEN;
              } else {
                if(_targetNode == NodeGetID()) {
                    // can't put the doctor in operational mode
                    SENDSTRING(ERROR_DOCTOR_NO_OPERATIONAL);
                } else {
                    queuedPkt = PSegAlloc(PSEG_TYPE_STOP_ASYNC,
sizeof(dummyPayload), NULL);
                    queuedPkt = ARQMakeARQ(GRAdMakePkt(queuedPkt, _targetNode));
                    waitOnPkt = true;
                }
                retVal = REDRAW_SCREEN;
              }
              break;


            case KEY_UPDATE_PARAMS:
              if(_targetNode == BROADCAST_ID) {
                SENDSTRING(ERROR_TARGET_NODE_NOT_SET);
                retVal = REDRAW_SCREEN;
              } else {
                if(_targetNode == NodeGetID()) {
                    // can't put the doctor in operational mode
                    SENDSTRING(ERROR_DOCTOR_NO_OPERATIONAL);
                } else {
                    paramPayload *pp;
                    queuedPkt = PSegAlloc(PSEG_TYPE_PARAM_SET, sizeof(paramPayload),
NULL);
                    // hacking- just putting in hardcode now
                    pp = PSegPayload(queuedPkt);
                    pp->fParams[PARAM_ARQ_DELAY] = 8;
                    pp->fParams[PARAM_ARQ_RETRY] = 6;
                    pp->fParams[PARAM_COST_TTL] = 180;
                    pp->fParams[PARAM_AWAKE_TIME] = 90;
                    pp->fParams[PARAM_SLEEP_TIME] = 510;
                    pp->fMask = (1<<PARAM_ARQ_DELAY) | (1<<PARAM_ARQ_RETRY) |
(1<<PARAM_COST_TTL) |
                      (1<<PARAM_AWAKE_TIME) | (1<<PARAM_SLEEP_TIME);
                    queuedPkt = ARQMakeARQ(GRAdMakePkt(queuedPkt, _targetNode));
                    waitOnPkt = true;
                    Uart_Printf("sending update params\n");
                }
                retVal = REDRAW_SCREEN;
              }
              break;

            case KEY_SYNC_FLOOD:
              // sync flood- wait for ping packet from the node and then send lots
of syncs
              syncFlood = true;
              waitOnPkt = true;
              Uart_Printf("preparing for sync flood\n");
              retVal = REDRAW_SCREEN;
              break;
```

```
case KEY_TOOGLE_SYNC_INFO:
  // sets a flag that causes current node sync info to be printed
  if (printSync) {
    Uart_Printf("turning off sync printing\n");
  } else {
    Uart_Printf("turning on sync printing\n");
  }
  printSync = !printSync;
  waitOnPkt = true;
  retVal = REDRAW_SCREEN;
  break;

case KEY_CHECK_NODE:
  if(_targetNode == BROADCAST_ID) {
    SENDSTRING(ERROR_TARGET_NODE_NOT_SET);
    retVal = REDRAW_SCREEN;
  } else {
    if(_targetNode == NodeGetID()) {
        // can't put the doctor in operational mode
        SENDSTRING(ERROR_DOCTOR_NO_OPERATIONAL);
    } else {
        waitOnPkt = true;
    }
    retVal = REDRAW_SCREEN;
  }
  break;

case KEY_CHECK_NEIGHBOR_STRENGTH:
  if(_targetNode == BROADCAST_ID)
  {
        SENDSTRING(ERROR_TARGET_NODE_NOT_SET);
        retVal = REDRAW_SCREEN;
  }
  else
  {
        SENDSTRING(PROMPT_SET_NEIGHBOR_NODE);
        retVal = NO_REDRAW_SCREEN;
        _stringPos = 0;
        _keypressState = SET_NEIGHBOR_NODE;
  }
  break;

case KEY_CHECK_ALL_NEIGHBOR_STRENGTH:
  if(_targetNode == BROADCAST_ID)
  {
        SENDSTRING(ERROR_TARGET_NODE_NOT_SET);
  }
  else
  {
        SENDSTRING(INFO_CHECK_ALL_NEIGHBOR_STRENGTH);

        // For each entry in the neighbors list, ask for the strength
        // and report it.

        //   Format:  [nnn | s-ping | r-ping | s-pong | r-pong]
        SENDSTRING(INFO_CHECK_ALL_NEIGHBOR_FORMAT);

        for(i = 0;
            _neighborList[i] != BROADCAST_ID && i < PING_MAX_NEIGHBORS;
            i++)
        {
            //--
            // 1. Request link strength
```

```
                        // 2. Wait for link data to come back [with timeout]
                        // 3. Print out link data

                        if(_targetNode == NodeGetID())
                        {
                              // fake a link request packet
                              pseg_t *linkPkt = PSegAlloc(PSEG_TYPE_LINK_REQUEST,
sizeof(linkRequestPayload),
                                                          NULL);
                              pseg_t *gradSeg = GRAdMakePkt(NULL, NodeGetID());

                              ((linkRequestPayload *)PSegPayload(linkPkt))-
>fNeighbor = _neighborList[i];
                              PingServiceLinkRequest(gradSeg, linkPkt);
                              PSegFree(linkPkt);
                              PSegFree(gradSeg);
                        }
                        else
                        {
                              PingRequestLinkTest(_targetNode, _neighborList[i]);
                        }

                        // Wait for status update to finish [with timeout]

                        _updateStarted();
                        _timerStart = OSTimeGet();
                        while(_updateInProgress == 1)
                        {
                              OSTimeDly(TIMEOUT_CHECK_DELAY);
                              if(OSTimeGet() - _timerStart > RECEIVE_TIMEOUT)
                              {
                                  SENDSTRING(ERROR_NEIGHBOR_STRENGTH_TIMEOUT);
                                  break;
                              }
                        }

                        // Done
                        //--
                    }
                }
                retVal = REDRAW_SCREEN;
                break;

              case KEY_REDRAW_SCREEN:
                retVal = REDRAW_SCREEN;
                break;

              case KEY_EXIT_DOCTOR_MODE:
                _serialState = EXIT_DOCTOR;
                retVal = NO_REDRAW_SCREEN;
                break;

              default:
                break;
              }
              break;

            case SET_TARGET_NODE:
              if(inCh == 13 || _stringPos == 4)
              {
                  _targetNode = _theRightATOI(_tempString);
                  SENDSTRING(INFO_SET_TARGET_NODE);

#ifdef PC_DEBUG
                        Uart_Printf("Set node to: %d\n\r", _targetNode);
#endif

                        _keypressState = INPUT_STATE;
                        retVal = REDRAW_SCREEN;
                    }
                    else
                    {
                        _tempString[_stringPos++] = inCh;
                        _tempString[_stringPos] = 0;      // auto-terminate

#ifdef PC_DEBUG
                        Uart_Printf("%c", inCh);
#else
                        Uart_SendByte(inCh);
#endif
                        retVal = NO_REDRAW_SCREEN;
                    }
                    break;

                  case SET_GATEWAY_NODE:
                    if(inCh == 13 || _stringPos == 4)
                    {
                        if(_targetNode == NodeGetID())
                        {
                              ParamSet(PARAM_BASESTATION_ADDR, _theRightATOI(_tempString));
                        }
                        else
                        {
                              char buffer[100];
                              pseg_t *pkt = ParamPktAlloc();
                              ParamPktSet(pkt, PARAM_BASESTATION_ADDR,
_theRightATOI(_tempString));
                              pkt = ARQMakeARQ(GRAdMakePkt(pkt, _targetNode));

                              // ARQ is the current seg type
                              sprintf(buffer, "Sending packet with ARQ reference %2d\n\r",
                                        ((arqPayload *)PSegPayload(pkt))->fReference);

                              SENDSTRING(buffer);

                              MACXmitPkt(pkt);
                        }

                        SENDSTRING(INFO_SET_GATEWAY_NODE);

#ifdef PC_DEBUG
                        Uart_Printf("Set node to: %d\n\r", _targetNode);
#endif

                        _keypressState = INPUT_STATE;
                        retVal = REDRAW_SCREEN;
                    }
                    else
                    {
                        _tempString[_stringPos++] = inCh;
                        _tempString[_stringPos] = 0;      // auto-terminate

#ifdef PC_DEBUG
                        Uart_Printf("%c", inCh);
#else
```

```
                Uart_SendByte(inCh);
#endif
                retVal = NO_REDRAW_SCREEN;
            }
            break;

          case SET_NEIGHBOR_NODE:
            if(inCh == 13 || _stringPos == 4)
            {
                neighborNode = _theRightATOI(_tempString);
                SENDSTRING(INFO_SET_NEIGHBOR_NODE);

#ifdef PC_DEBUG
                Uart_Printf("Set node to: %d\n\r", neighborNode);
#endif

                //--
                // 1. Request link strength
                // 2. Wait for link data to come back [with timeout]
                // 3. Print out link data
                if(_targetNode == NodeGetID())
                {
                      // fake a link request packet
                      pseg_t *linkPkt = PSegAlloc(PSEG_TYPE_LINK_REQUEST,
                                                  sizeof(linkRequestPayload),
                                                  NULL);
                      pseg_t *gradSeg = GRAdMakePkt(NULL, NodeGetID());

                      ((linkRequestPayload *)PSegPayload(linkPkt))->fNeighbor =
_neighborList[i];
                      PingServiceLinkRequest(gradSeg, linkPkt);
                      PSegFree(linkPkt);
                      PSegFree(gradSeg);
                }
                else
                {
                      PingRequestLinkTest(_targetNode, neighborNode);
                }
                // Wait for status update to finish [with timeout]

                _updateStarted();
                _timerStart = OSTimeGet();
                while(_updateInProgress == 1)
                {
                      OSTimeDly(TIMEOUT_CHECK_DELAY);
                      if(OSTimeGet() - _timerStart > RECEIVE_TIMEOUT)
                      {
                          SENDSTRING(ERROR_NEIGHBOR_STRENGTH_TIMEOUT);
                          break;
                      }
                }
                // Done
                //--

                _keypressState = INPUT_STATE;
                retVal = REDRAW_SCREEN;
            }
            else
            {
                _tempString[_stringPos++] = inCh;
                _tempString[_stringPos] = 0;

#ifdef PC_DEBUG
                Uart_Printf("%c", inCh);
#else
                Uart_SendByte(inCh);
#endif

                retVal = NO_REDRAW_SCREEN;
              }

              break;

            default:
              break;
            }
    }

    return(retVal);
}

#define WAIT_PACKET 0
#define RECV_PACKET_TYPE 1
#define RECV_TARGET_HI 2
#define RECV_TARGET_LO 3
#define RECV_SYNC_INFO 4
#define RECV_LINK_REQUEST_INFO 5
#define RECV_PARAM_SET_INFO 6

//--
// Description: handles input from the base station
// Preconditions: none
// Postconditions: data is handled as received
// Returns: none
//--
void _process_gateway_input()
{
    static uint8_t _gatewayState;
    static pseg_t *curPkt = NULL;
    static pseg_type packetType;
    static node_id destination;
    int error;

    char inCh;

#ifdef PC_DEBUG
    // Setup polling
    struct pollfd pfd;

    pfd.fd = STDIN_FILENO;
    pfd.events = POLLIN;
#endif
#ifdef DEBUG_BUFFER
    debug_buffer(145);
#endif
#ifdef PC_DEBUG
    if(poll(&pfd, 1, 1) > 0)  // poll for 1ms
#else
      OSTaskSuspend(OS_PRIO_SELF);
    if((inCh = _serialChar) > 0)
#endif
    {

#ifdef PC_DEBUG
          read(STDIN_FILENO, &inCh, 1);
#endif
```

```
error = 0;
switch(_gatewayState)
{
case WAIT_PACKET:
  curPkt = NULL;
  if(inCh == '0')
  {
      _gatewayState = RECV_PACKET_TYPE;
  }
  else if(inCh == '1')
  {
      curPkt = ARQMakeARQ(curPkt);
      _gatewayState = RECV_PACKET_TYPE;
  }
  else
  {
      _gatewayState = WAIT_PACKET;
  }
  break;

case RECV_PACKET_TYPE:
  switch(inCh)
  {
  case 'y':
    packetType = PSEG_TYPE_SYNC;
    break;
  case 'n':
    packetType = PSEG_TYPE_NEIGHBOR_REQUEST;
    break;
  case 'l':
    packetType = PSEG_TYPE_LINK_REQUEST;
    break;
  case 'm':
    packetType = PSEG_TYPE_PARAM_SET;
    break;
  case 'q':
    packetType = PSEG_TYPE_PARAM_REQUEST;
    break;
  case 's':
    packetType = PSEG_TYPE_STATS_REQUEST;
    break;
  case 't':
    packetType = PSEG_TYPE_STATS_RESET;
    break;
default:
    error = 1;
    break;
  }
  if (error) {
    _gatewayState = WAIT_PACKET;
  } else {
    _gatewayState = RECV_TARGET_HI;
  }
  break;

case RECV_TARGET_HI:
  destination = (_fromHex(inCh) << 4);
  _gatewayState = RECV_TARGET_LO;
  break;

case RECV_TARGET_LO:
  destination |= _fromHex(inCh);
  curPkt = GRAdMakePkt(curPkt, destination);

  switch(packetType)
  {
  case PSEG_TYPE_SYNC:
    curPkt = PSegAlloc(packetType, sizeof(syncPayload), curPkt);
    _gatewayState = _receiveSyncInfo(curPkt, inCh, 1);
    break;
  case PSEG_TYPE_NEIGHBOR_REQUEST:
    curPkt = PSegAlloc(packetType, sizeof(neighborsRequestPayload),
curPkt);
    _gatewayState = WAIT_PACKET;
    break;
  case PSEG_TYPE_LINK_REQUEST:
    curPkt = PSegAlloc(packetType, sizeof(linkRequestPayload), curPkt);
    _gatewayState = _receiveLinkRequestInfo(curPkt, inCh, 1);
    break;
  case PSEG_TYPE_PARAM_SET:
    curPkt = PSegAlloc(packetType, sizeof(paramPayload), curPkt);
    _gatewayState = _receiveParamSetInfo(curPkt, inCh, 1);
    break;
  case PSEG_TYPE_PARAM_REQUEST:
    curPkt = PSegAlloc(packetType, 1, curPkt);
    _gatewayState = WAIT_PACKET;
    break;
  case PSEG_TYPE_STATS_REQUEST:
    curPkt = PSegAlloc(packetType, 0, curPkt);
    _gatewayState = WAIT_PACKET;
    break;
  case PSEG_TYPE_STATS_RESET:
    curPkt = PSegAlloc(packetType, 0, curPkt);
    _gatewayState = WAIT_PACKET;
    break;
  default:
    _gatewayState = WAIT_PACKET;
    break;
  }

  if(_gatewayState == WAIT_PACKET)
  {
      MACXmitPkt(curPkt);
      curPkt = NULL;
  }

  break;

case RECV_SYNC_INFO:
  _gatewayState = _receiveSyncInfo(curPkt, inCh, 0);
  break;

case RECV_LINK_REQUEST_INFO:
  _gatewayState = _receiveLinkRequestInfo(curPkt, inCh, 0);
  break;

case RECV_PARAM_SET_INFO:
  _gatewayState = _receiveParamSetInfo(curPkt, inCh, 0);
  break;

default:
  _gatewayState = WAIT_PACKET;
  break;
}
```

```
    }
}

// Description: Called to notify the serial routine that its information
//   is being updated.
void _updateStarted()
{
#ifdef DEBUG_BUFFER
    debug_buffer(146);
#endif
    _updateInProgress = 1;
}

// Description: Called to notify the serial routine that its information
//   is done being updated.
void _updateFinished()
{
#ifdef DEBUG_BUFFER
    debug_buffer(147);
#endif
    _updateInProgress = 0;
}

// Description: add neighbors to the list and print out to uart
void SerialServiceNeighborReport(pseg_t *seg)
{
    uint8_t i;
    neighborsReportPayload *report = PSegPayload(seg);
    char buffer[20]; // careful!  string can only be 11 chars long in our use

#ifdef DEBUG_BUFFER
    debug_buffer(148);
#endif
    if(!SerialDoctorMode())
      return;

    _updateStarted();

    // Fortunately, BROADCAST_ID is also used in this code to denote an
    // unused entry.
    for(i = 0; i < PING_MAX_NEIGHBORS; i++)
    {
          _neighborList[i] = report->fNeighbors[i];
          // don't change this without checking the buffer length!
          sprintf(buffer, "%d: %d  ", i & 0xFF, report->fNeighbors[i] & 0xFF);
          SENDSTRING(buffer);
    }
    SENDSTRING("\n\r");

    _updateFinished();

}

void SerialServiceBootReport(pseg_t *seg) {
  bootPayload *bp = PSegPayload(seg);

  if(!SerialDoctorMode())
    return;

  switch (bp->bootCode) {
  case BOOT_BOOTING:
    Uart_Printf("\n Node %d booting\n", bp->node);
    break;
  case BOOT_GOT_SYNC:
    Uart_Printf("\n Node %d got sync\n", bp->node);
    break;
  case BOOT_STANDALONE:
    Uart_Printf("\n Node %d forced standalone\n", bp->node);
    break;
  case BOOT_FOUNDNEIGHBOR:
    Uart_Printf("\n Node %d found neighbor %d, running test\n", bp->node, bp-
>bootData);
    break;
  case BOOT_FINISHED:
    Uart_Printf("\n Node %d exiting test mode\n", bp->node);
    break;
  default:
    Uart_Printf("bad boot report\n");
    break;
  }
}

// Preconditions: seg is the acked packet
// Postconditions: the ack has been relayed, if doctor mode is on.
void SerialServiceAck(pseg_t *seg)
{
    char buffer[100];
    pseg_t *gradSeg = GRAdFindSegment(seg);
    pseg_t *arqSeg = PSegFindType(seg, PSEG_TYPE_ARQ);
#ifdef DEBUG_BUFFER
    debug_buffer(149);
#endif
    if(!SerialDoctorMode())
      return;

    if(arqSeg == NULL)
      return;

    if(gradSeg != NULL)
    {
          sprintf(buffer, "Received ack for packet %2d to node %2d\n\r",
                    ((arqPayload *)PSegPayload(arqSeg))->fReference,
                    ((gradPayload *)PSegPayload(gradSeg))->fOriginator);

    }
    else
    {
          sprintf(buffer, "Received ack for packet %2d\n\r",
                    ((arqPayload *)PSegPayload(arqSeg))->fReference);
    }

    SENDSTRING(buffer);

}

// Preconditions: none
// Postconditions: the link statistics for neighbor are printed to the uart and
//   the received packet flag is set to true so that anyone watching can move on.
//
//   Format:  [nnn | s-ping | r-ping | s-pong | r-pong]
//   Where nnn is the neighbor
//         s-ping is the number of pings the target sent to the neighbor
//         r-ping is the number of pings the neighbor received from the target
//         s-pong is the number of pongs the neighbor sent to the target
//         r-pong is the number of pongs the target received from the neighbor
//
```

```
void SerialServiceNeighborLinkReport(pseg_t *seg)
{
    char buffer[40]; // 32 character long
    linkState *sr = PSegPayload(seg);
#ifdef DEBUG_BUFFER
    debug_buffer(150);
#endif
    if(!SerialDoctorMode())
      return;

    _updateStarted();

    // don't change this without checking the buffer length!
    sprintf(buffer, "[%3d | %3d | %3d | %3d | %3d ]\n\r", sr->fNeighbor,
              sr->fPingsSent, sr->fPingsRcvd,
              sr->fPongsSent, sr->fPongsRcvd);

    SENDSTRING(buffer);

    _updateFinished();
}

uint8_t _receiveSyncInfo(pseg_t *pkt, char inCh, int reset)
{
    static uint8_t _i;
    uint8_t retVal = RECV_SYNC_INFO;
    syncPayload *sp = PSegPayload(pkt);
#ifdef DEBUG_BUFFER
    debug_buffer(151);
#endif
    if(reset == 1)
    {
          _i = 7;
          sp->fXmitTime = 0;
    }
    else
    {
          sp->fXmitTime |= (_fromHex(inCh) << (_i*4));

          if(_i == 0)
          {
              MACXmitPkt(pkt);
              retVal = WAIT_PACKET;
          }
          else
          {
              _i--;
          }
    }

    return(retVal);
}

uint8_t _receiveLinkRequestInfo(pseg_t *pkt, char inCh, int reset)
{
    static uint8_t _i;
    uint8_t retVal = RECV_LINK_REQUEST_INFO;
    linkRequestPayload *lrp = PSegPayload(pkt);
#ifdef DEBUG_BUFFER
    debug_buffer(152);
#endif
    if(reset == 1)
    {
          lrp->fNeighbor = 0;
          _i = 1;
    }
    else
    {
          lrp->fNeighbor |= (_fromHex(inCh) << (_i*4));

          if(_i == 0)
          {
              MACXmitPkt(pkt);
              retVal = WAIT_PACKET;
          }
          else
          {
              _i--;
          }
    }

    return(retVal);
}

uint8_t _receiveParamSetInfo(pseg_t *pkt, char inCh, int reset)
{
    static uint8_t _shift;
    static uint8_t _index;
    uint8_t retVal = RECV_PARAM_SET_INFO;
    uint8_t *payload = PSegPayload(pkt);
#ifdef DEBUG_BUFFER
    debug_buffer(153);
#endif
    if(reset == 1)
    {
          _index = 0;
          _shift = 1;
    }
    else
    {
          payload[_index] = (_fromHex(inCh) << (_shift * 4));

          if(_shift == 0)
          {
              _index++;
              _shift = 1;
          }
          else
          {
              _shift--;
          }

          if(_index == PSegSize(pkt))
          {
              MACXmitPkt(pkt);
              retVal = WAIT_PACKET;
          }
    }
    return(retVal);
}

uint8_t _fromHex(char c)
{
#ifdef DEBUG_BUFFER
    debug_buffer(154);
#endif
```

```
    if(c >= '0' && c <= '9')
      return(c - '0');
    else if(c >= 'a' && c <= 'f')
      return(c - 'a');
    else if(c >= 'A' && c <= 'F')
      return(c - 'A');
    else
      return(0);
}

uint8_t _theRightATOI(const char *s) {
    uint8_t value;
    value = 0;
#ifdef DEBUG_BUFFER
    debug_buffer(155);
#endif
    while (*s != 0) {
          value = (value * 10) + (*s++ - '0');
    }
    return value;
}

void _sendOperationOnPacket(node_id targetNode)
{
    char buffer[50];
    pseg_t *pkt = PSegAlloc(PSEG_TYPE_SET_IN_OPERATION,
sizeof(setOperationalPayload), NULL);
    pkt = ARQMakeARQ(GRAdMakePkt(pkt, targetNode));
#ifdef DEBUG_BUFFER
    debug_buffer(156);
#endif
    // ARQ is the current seg type
    sprintf(buffer, "Sending packet with ARQ reference %2d\n\r",
              ((arqPayload *)PSegPayload(pkt))->fReference);

    SENDSTRING(buffer);

    MACXmitPkt(pkt);
}

void _sendEnterTestPkt(node_id targetNode)
{
  pseg_t *pkt = PSegAlloc(PSEG_TYPE_ENTER_TEST, sizeof(dummyPayload), NULL);
  pkt = ARQMakeARQ(GRAdMakePkt(pkt, targetNode));

  MACXmitPkt(pkt);
}

void _sendExitTestPkt(node_id targetNode)
{
  pseg_t *pkt = PSegAlloc(PSEG_TYPE_EXIT_TEST, sizeof(dummyPayload), NULL);
  pkt = ARQMakeARQ(GRAdMakePkt(pkt, targetNode));

  /*  Uart_Printf("  sending dst %d, src %d, seq %d\n",
                ((gradPayload *)PSegPayload(GRAdFindSegment(pkt)))->fDestination,
                ((gradPayload *)PSegPayload(GRAdFindSegment(pkt)))->fOriginator,
                ((gradPayload *)PSegPayload(GRAdFindSegment(pkt)))->fSequence);
  */
  MACXmitPkt(pkt);
}

void SerialCheckSync(pseg_t *pkt) {
  syncPayload *sp = PSegPayload(pkt);

  node_id id = sp->fSender;

  if (waitOnPkt) {
    if (id == _targetNode) {
      Uart_Printf("saw target node %d", id);
      if (printSync) {
          rtc_t diff;
          diff = sp->fXmitTime - sp->fRecvTime;
          Uart_Printf("\n  time diff = %d, cycle time = %d\n  ", diff, (sp-
>fXmitTime%600));
      }
      if (queuedPkt != NULL) {
          Uart_Printf("... sending queued pkt\n");
          MACXmitPkt(queuedPkt);
      } else if (syncFlood) {
          Uart_Printf("... performing sync flood\n");
          PingSendPing(_targetNode);
          OSTimeDly(15);
          PingSendPing(_targetNode);
          SyncDoFlood();
      } else {
          Uart_Printf("\n");
      }
      queuedPkt = NULL;
      waitOnPkt = false;
      syncFlood = false;
    }
  }
}

bool SerialGatewayMode( void )
{
#ifdef DEBUG_BUFFER
    debug_buffer(157);
#endif
    return SysGetGatewayMode();
}

bool SerialDoctorMode( void )
{
#ifdef DEBUG_BUFFER
    debug_buffer(158);
#endif
    return SysGetDoctorMode();
}

#ifdef PC_DEBUG
int main(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(159);
#endif
    SerialInit();
    SerialReset();
    SerialStart();
}
#endif
```

stats.h

```
// File: stats.h
// Description:
// Author(s):   Andy Wheeler <ajwheele@mit.edu>
```

```
//
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// warranty.

#ifndef STATS_H
#define STATS_H

#include "types.h"
#include "pseg.h"

typedef struct {
  uint32_t   maxTimeDiffThisPeriod;
  uint32_t   uptime;
  uint16_t   badPackets;
  uint16_t   goodPackets;
  uint16_t   duplicatePackets;
} statsReportPayloadA;

typedef struct {
  uint16_t   gradOriginated;
  uint16_t   gradFlooded;
  uint16_t   gradRelayed;
  uint16_t   arqPktsSent;
  uint16_t   ackPktsRcvd;
  uint16_t   arqPktsDropped;
} statsReportPayloadB;


void StatsInit( void );
// called on startup- zeros the stats

void StatsReset( void );
// clears the "period" stats

void StatsStart( void );
// starts the statistics reporting task

pseg_t * StatsMakePktA( pseg_t *next );
// returns a PSEG_TYPE_STATS_REPORT

pseg_t * StatsMakePktB( pseg_t *next );
// returns a PSEG_TYPE_STATS_REPORT

void SendStatsPkt( pseg_t *gradSeg );
// Sends both segment types in two different packets

void StatsClearData( void );
// clears the currently held data

// statistics functions
void StatsSetBadPackets(uint16_t bad);

void StatsSetGoodPackets(uint16_t good);

void StatsTimeDiff(uint32_t timeDiff);

void StatsIncDupPkts( void );

void StatsIncGradOriginated( void );

void StatsIncGradFlooded( void );

void StatsIncGradRelayed( void );

void StatsIncARQPktsSent( void );

void StatsIncARCPktsRcvd( void );

void StatsIncARQPktsDropped( void );

#endif
```

sync.h

```
// File: sync.h
// Description: establish and maintain network-wide synchronization
// Author(s):   Robert Poor <r@media.mit.edu>
//              Andrew Wheeler <ajw@media.mit.edu>
//
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// warranty.

#ifndef SYNC_H
#define SYNC_H

#include "node_id.h"
#include "pseg.h"
#include "types.h"
#include "rtc.h"

// rtc_t is "synchronization time", or
// seconds + 60 * (minutes + (60 * hours))
// as measured from the real time clock

// A sync message carries the ID of the sending node, the
// value of the sender's real time clock, and the value of
// the receiver's real time clock, captured at the onset
// time of the reception.

typedef struct {
   rtc_t fXmitTime;
   rtc_t fRecvTime;
   node_id fSender;
} syncPayload;

void SyncInit(void);
// cold start

void SyncReset(void);
// warm start

void SyncStart(void);
// start up the sync transmission task

pseg_t *SyncMakePkt(void);
// create a sync packet for transmission

void SyncDoFlood( void );
// runs a sync flood

void SyncServicePkt(pseg_t *pkt);
// handle an incoming sync packet.  Tweaks the real time clock
// to average between sender and receiver.

void SyncWillXmit(pseg_t *pkt);
// to be called by radio code just prior to passing the packet
// to the radio.  If the packet contains a sync segment, it will
// be time stamped with the current time and node id.

void SyncWillReceive(void);
// to be called by the radio code when a packet first arrives
// at the host.  It simply caches a copy of the current time.

void SyncDidReceive(pseg_t *pkt);
// to be called by the radio code at the completion of receiving
// a packet.  If the packet contains a sync segment, the receive
// time (cached in SyncWillReceive) is copied into the segment.

#endif
```

sync.c

```
// File: sync.c
// Description: establish and maintain network-wide synchronization
// Author(s):   Andrew Wheeler <ajw@media.mit.edu>
//              Robert Poor <r@media.mit.edu>
//
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// warranty.

#include "node_id.h"
#include "sync.h"
#include "types.h"
#include "rtc.h"
#include "mac.h"
#include "includes.h"
#include "tephra.h"
#include "stats.h"
#include "sysmanager.h"
#include "ping.h"
#include <stdlib.h>

#define IS_ODD(x) (((x) & 1) == 1)

// snapshot of time at which receive starts
static rtc_t _recvTime;
static rtc_t _lastTimeDiff;
static int   _rcvdPktNum;
static unsigned int _syncStack[SYNC_TASK_STACK_SIZE];

static void _SyncTask(void *args);

void SyncInit()
{
#ifdef DEBUG_BUFFER
  debug_buffer(178);
```

```
#endif
  // cold start
  srand((uint32_t)NodeGetID());
  RTCSetTime(10500);
  // record that we are starting up for the first time ever
  _lastTimeDiff = 20000;
  _rcvdPktNum = 0;
}


void SyncReset()
{
#ifdef DEBUG_BUFFER
    debug_buffer(179);
#endif
  // warm start
}

void SyncStart()
{
#ifdef DEBUG_BUFFER
    debug_buffer(180);
#endif
    // start the sync task
    OSTaskCreate(_SyncTask, NULL, (void *)&_syncStack[SYNC_TASK_STACK_SIZE-1],
                     SYNC_TASK_ID);
}

static void _SyncTask(void *args)
{
  uint32_t delay;

  while (true)
    {
#ifdef DEBUG_BUFFER
      debug_buffer(181);
#endif
      delay = (10*OS_TICKS_PER_SEC) + (rand() % (6*OS_TICKS_PER_SEC));    // delay
10-16 seconds
      //  Uart_Printf("SyncTask: system time: %d \n", RTCGetTime());
      OSTimeDly(delay);
      if (SysGetSyncState() && !SysGetDoctorMode()) {
          LED_3_ON();
          MACXmitPkt(SyncMakePkt());
          LED_3_OFF();
      }
    }
}

pseg_t *SyncMakePkt()
{
   // create a sync packet for transmission.  The payload will
   // be filled in by the SyncWillXmit() and SyncDidReceive()
   // methods below.
#ifdef DEBUG_BUFFER
    debug_buffer(182);
#endif
    return PSegAlloc(PSEG_TYPE_SYNC, sizeof(syncPayload), NULL);
}

void SyncDoFlood() {
  // perform a sync flood- basically 5 seconds of just sending syncs
  int i;
  for (i=0; i<30; i++) {
    OSTimeDly(15);
    MACXmitPkt(SyncMakePkt());
  }
}

void SyncServicePkt(pseg_t *pkt)
{
  // Handle an incoming sync packet, adjusting the real time clock to
  // average between sender's time and receiver's time.

  syncPayload *sp = PSegPayload(pkt);
  rtc_t diff;
  bool advance;

#ifdef DEBUG_BUFFER
  debug_buffer(183);
#endif
  // Pretend EPOCH is 60 seconds (one minute):
  // case A: x=15 r=05, e=10 => advance by e/2
  // case B: x=55 r=05, e=50 => retard by (60-e)/2
  // case C: x=05 r=15, e=10 => retard by e/2
  // case D: x=05 r=55, e=50 => advance by (60-e)/2


  if (SysGetSyncState() && SysGetDoctorMode()) {
    return;
  }

  if (SysGetSyncState() && SysGetGatewayMode() && (sp->fSender != 93)) {
    return;
  }

  if (sp->fXmitTime == sp->fRecvTime) {
    //     Uart_Printf("SyncServicePkt: got packet, diff = 0\n");
    if ((++_rcvdPktNum > 2) && (_lastTimeDiff < 3)) {
      // if we have received some packets and the time difference is low
      // then we can exit starting up mode
      SysSetSyncState(true);
    }
    _lastTimeDiff = 0;
    return;
  } else if (sp->fXmitTime > sp->fRecvTime) {
    diff = sp->fXmitTime - sp->fRecvTime;
    advance = 1;              // assume case A
  } else /* if (sp->fXmitTime < sp->fRecvTime) */ {
    diff = sp->fRecvTime - sp->fXmitTime;
    advance = 0;              // assume case C
  }

  if (diff > RTC_HALF_EPOCH) {
    // difference exceeds half the epoch.  Convert to case B or D.
    diff -= RTC_HALF_EPOCH;
    advance = !advance;
  }

   StatsTimeDiff(diff);

   if (!SysGetSyncState()) {
     // we are starting up- don't average time- just set it
     //     Uart_Printf("SyncServicePkt: setting RTC time, diff = %d\n", diff);
     if (advance) {
       RTCAdvanceTime(diff);
```

```
    } else {
      RTCRetardTime(diff);
    }
    if ((++_rcvdPktNum > 2) && (_lastTimeDiff < 3) && (diff < 3)) {
      // if we have received some packets and the time difference is low
      // then we can exit starting up mode
      SysSetSyncState(true);
    }
  } else {
    // we are not starting up, average times
    //     Uart_Printf("SyncServicePkt: averaging RTC time\n");
    // halve difference and adjust RTC clock
    if (IS_ODD(diff)) {
      diff += rand() & 1;              // dither before divide by 2
    }
    diff = diff / 2;                   // divide by 2
    if (advance) {
      RTCAdvanceTime(diff);
    } else {
      RTCRetardTime(diff);
    }
  }
  _lastTimeDiff = diff;
}

void SyncWillXmit(pseg_t *pkt)
{
   // to be called by radio code just prior to passing the packet
   // to the radio.  If the packet contains a sync segment, it will
   // be time stamped with the current time and node id.
  //  uint32_t a;
   pseg_t *syncSeg = PSegFindType(pkt, PSEG_TYPE_SYNC);
#ifdef DEBUG_BUFFER
   debug_buffer(184);
#endif
   if (syncSeg != NULL)
   {
       syncPayload *sp = PSegPayload(syncSeg);
       sp->fSender = NodeGetID();
       //     sp->fRecvTime = 69000;
       //     a = RTCGetTime();
       //     sp->fXmitTime = a;
       sp->fXmitTime = RTCGetTime();
   }
}

void SyncWillReceive()
{
#ifdef DEBUG_BUFFER
    debug_buffer(185);
#endif
    // to be called by the radio code when a packet first arrives
    // at the host.  It simply caches a copy of the current time.
    _recvTime = RTCGetTime();
}

//Note:  You should not call SyncWillReceive twice before calling SyncDidReceive;
//if you did, you would have the same _recvTime value for both, which would not
//be happy.

void SyncDidReceive(pseg_t *pkt)
{
   // to be called by the radio code at the completion of receiving
   // a packet.  If the packet contains a sync segment, the receive
   // time (cached in SyncWillReceive) is copied into the segment.
   pseg_t *syncSeg = PSegFindType(pkt, PSEG_TYPE_SYNC);
#ifdef DEBUG_BUFFER
   debug_buffer(186);
#endif
   if (syncSeg != NULL) {
     syncPayload *sp = PSegPayload(syncSeg);
     sp->fRecvTime = _recvTime;
   }
}
```

sysmanager.h

```
// File: sysmanager.c
// Description: manages system power and runtime state
// Author(s):   Andrew Wheeler <ajw@media.mit.edu>
//
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// warranty.
#ifndef SYSMANAGER_H
#define SYSMANAGER_H

#include "includes.h"


// tunable parameters

// number of seconds before the node gives up on syncing and decides to go
standalone
#define SYNC_TIMEOUT 160
// base number of seconds to sleep for at a time
#define SLEEP_BASE_TIME 20
// randomization factor in seconds (average sleep time is base + rand/2)
#define SLEEP_RAND_TIME 20
// number of OSTicks a PING keeps the system awake for
#define PING_AWAKE_TIME 5*OS_TICKS_PER_SEC
```

```
typedef struct
{
  uint8_t unused; // c doesn't like empty structures
} dummyPayload;

void SysInit(void);
// intializes the system manager

void SysStart(void);
// starts the system manager

bool SysAwakeNow(void);
// returns true if the system is sync'd and in the "awake" cycle of the network

bool SysGetSyncState(void);
// returns true if the system is determined to either be synched to its
// surrounding nodes, or if sync has timed out and we are now running standalone

void SysSetSyncState(bool state);
// sets the sync state

void SysSetPingParticipant(void);
// tells the power manager that we are now participating in some sort
// of link test, which means that we should interrupt the normal sleep schedule

void SysUnsetPingParticipant(void);
// tells the power manager we are no longer participating in a link test

void SysSetTestMode(bool state);
// tells the power manager to enter test mode.  This causes the node to stay
//  awake until the test mode is turned off.  This is not intended to be used
//  in running code- and is primarily for things like packet beacons

bool SysGetTestMode( void );

bool SysRequestNoSleep(uint32_t time);
// requests that the system not sleep for a time equal to time as expressed
//  in system ticks- the system manager replies with a true if the request
//  is granted, and false otherwise

bool SysGetGatewayMode(void);
// returns true if this node is currently a gateway, false otherwise

void SysSetGatewayMode(bool state);
// if state is true, indicates we are now a gateway, otherwise we are not one
//  in this code revision, gateways are assumed to be powered devices, and thus
//  never sleep.  They also broadcast "authoritative" synchronization packets

bool SysGetDoctorMode(void);
// returns true if this node is currently in "doctor" mode, false otherwise

void SysSetDoctorMode(bool state);
// sets if this node is in doctor mode- if state is true then we are a doctor

#endif
```

sysmanager.c

```
// File: sysmanager.c
// Description: manages system power and runtime state
// Author(s):   Andrew Wheeler <ajw@media.mit.edu>
//
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// makes no representations about the suitability of this software for
// any purpose. It is provided "as is" without express or implied
// warranty.

#include "tephra.h"
#include "types.h"
#include "includes.h"
#include "rad.h"
#include "mac.h"
#include "pseg.h"
#include "param.h"
#include "appr.h"
#include "appx.h"
#include "ping.h"
#include "sync.h"
#include "grad.h"
#include "rtc.h"
#include "cost.h"
#include "arq.h"
#include "util.h"
#include "serial.h"
#include "stats.h"
#include "sysmanager.h"
#include "boottest.h"
#include <stdlib.h>

#ifndef BIT
#define BIT(x)      (1 << (x))
#endif

#ifndef min
#define min(x1,x2) ((x1<x2)?x1:x2)
#endif


// internal functions

static void _sleepSystem( rtc_t delay );
// sets the registers and alarms to put the system to sleep for delay seconds
//  - also sleeps the radio hardware
```

```
//  assumes that all tasks and non-essential hardware regsiters
//  are prepared to sleep
//  returns when the system is awake again with alarms disabled

static void _startTasks(void);
// starts all the system tasks in the correct order

static void _killTasks( void );
// kills all the system tasks

static void _restartTasks( void );
// calls reset on all the tasks and restarts them

static void _SysTask(void *args);
// performs power and task management

static void _wakeupISR( void );
// ISR that is called when the system wakes up

static void _sendSleepingSyncPkt( void );
// sends a sync packet while the system is not running
// starts and stops essential services

// private variables
static bool syncState;
static uint32_t pingExpires;
static uint32_t endofNoSleep;
static bool gatewayMode;
static bool doctorMode;
static bool testMode;
static unsigned int _sysStack[SYS_TASK_STACK_SIZE];
static bool _systemAsleep;
static bool systemRunning;

void SysInit() {

  // install the wakeup ISR
  ISR_RTCA = (unsigned)_wakeupISR;

  // initialize the state variables
  syncState = false;
  pingExpires = 0;
  endofNoSleep = 0;
  gatewayMode = false;
  doctorMode = false;
  testMode = false;
  _systemAsleep = false;
  systemRunning = false;
}

// void SysStart()
// starts the system manager main thread that is responsible for
// controlling other tasks and power managing the system
void SysStart() {
  OSTaskCreate(_SysTask, NULL, (void *)&_sysStack[SYS_TASK_STACK_SIZE-1],
               SYS_TASK_ID);
}

// void _SysTask(void *args)
// system manager main thread- starts all the other tasks and does power
// management
void _SysTask(void *args) {
  rtc_t curCycleTime;
```

```
/*  int i;
pseg_t  *pkt;
char    *payload;*/
// run tests
//AppRStart();
////MACStart();
////RadStart();   // start the radio task
//  ARQStart();
//  SerialStart();
////CostStart();
//  AppXStart();
//    RTCStart();  // TESTING ONLY
//  SyncStart();
//  StatsStart();

//  PingStartBeaconMode();

/*while (1) {
  OSTimeDly(15*OS_TICKS_PER_SEC);
  RadPrintStats();
}
for (i=0; i<100; i++) {
  pkt = PSegAlloc(PSEG_TYPE_TESTING,
                  10,
                  NULL);
  payload = PSegPayload(pkt);
  payload[0] = 0x01;
  payload[1] = 0x23;
  payload[2] = 0x45;
  payload[3] = 0x67;
  payload[4] = 0x89;
  payload[5] = 0x0A;
  payload[6] = 0xBC;
  payload[7] = 0xDE;
  payload[8] = 0xFE;
  payload[9] = 0xDC;

  OSTimeDly(25);
  MACXmitPkt(pkt);
}

while(1);*/

// startup everything
Uart_Printf("SysTask: starting tasks\n");
_startTasks();
OSTimeDly(OS_TICKS_PER_SEC);
BootInit();
BootStart();
Uart_Printf("SysTask: tasks started\n");

SysSetTestMode(true);
//  PingStartAsyncLinkTest();

// wait for us to be sync'd or for sync to time out before continuing
while (!syncState && (OSTimeGet() < (SYNC_TIMEOUT * OS_TICKS_PER_SEC))) {
  OSTimeDly(OS_TICKS_PER_SEC);
}

if (!syncState) {
  if (doctorMode) Uart_Printf("SysTask: forcing standalone mode\n");
  BootSendPkt(BOOT_STANDALONE, 0);
```

```
  } else {
    if (doctorMode) Uart_Printf("SysTask: sync attained\n");
    BootSendPkt(BOOT_GOT_SYNC, 0);
  }
  // force us to go into standalone mode if we haven't sync'd
  syncState = true;

  while (true) {
    OSTimeDly(OS_TICKS_PER_SEC/4);
    // calculate current cycle time
    curCycleTime = RTCGetTime() % (ParamGet(PARAM_AWAKE_TIME) +
                                   ParamGet(PARAM_SLEEP_TIME));

    // the asleep period is the first SLEEP_TIME seconds of a cycle
    while (curCycleTime < ParamGet(PARAM_SLEEP_TIME)) {
      // looks like we should be asleep
      // check if there is a reason we shouldn't be asleep
      if ((pingExpires > OSTimeGet())|| gatewayMode || testMode || doctorMode ||
            (OSTimeGet() < endofNoSleep)) {
          // try again later
          if (gatewayMode && (curCycleTime < 305) && (curCycleTime > 299)) {
            // restart gateway
            _killTasks();
            _sleepSystem(5);
            _restartTasks();
          }
          OSTimeDly(OS_TICKS_PER_SEC/4);
          curCycleTime = RTCGetTime() % (ParamGet(PARAM_AWAKE_TIME) +
                                         ParamGet(PARAM_SLEEP_TIME));
          if (!systemRunning) {
            _killTasks();  // kill tasks just in case
          _restartTasks();
        }
          continue;
      }
      // OK- we should go to sleep now
      _killTasks();
      _sleepSystem(min((SLEEP_BASE_TIME + (rand() % SLEEP_RAND_TIME)),
                       (ParamGet(PARAM_SLEEP_TIME)-curCycleTime)));
      // send the sleeping sync packet
      _sendSleepingSyncPkt();
      // delay to see if we rcv a packet forcing a test mode or ping exchange
      OSTimeDly(OS_TICKS_PER_SEC);

      // update the current cycle time
      curCycleTime = RTCGetTime() % (ParamGet(PARAM_AWAKE_TIME) +
                                     ParamGet(PARAM_SLEEP_TIME));
      //      Uart_Printf("cycle time = %d\n, systemRunning = %d", curCycleTime,
systemRunning);
    }
    // turn back on the system if we are asleep
    if (!systemRunning) {
      _killTasks();  // kill tasks just in case
      _restartTasks();
    }
  }
}

// bool SysAwakeNow();
// returns true if the node is currently sync'd and in the "awake" phase
bool SysAwakeNow() {
  rtc_t curCycleTime;
  curCycleTime = RTCGetTime() % (ParamGet(PARAM_AWAKE_TIME) +
                                 ParamGet(PARAM_SLEEP_TIME));
  return (syncState && (curCycleTime > ParamGet(PARAM_SLEEP_TIME)));
}

// bool SysGetSyncState();
// returns true if the system is determined to either be synched to its
// surrounding nodes, or if sync has timed out and we are now running standalone
bool SysGetSyncState() {
  return syncState;
}

// sets the sync state
void SysSetSyncState(bool state) {
  //  Uart_Printf("SysSetSyncState: set to %d\n", state);
  syncState = state;
}

// tells the power manager that we are now participating in some sort
// of link test, which means that we should interrupt the normal sleep schedule
void SysSetPingParticipant() {
  pingExpires = OSTimeGet() + PING_AWAKE_TIME;
}

// indicates that we are in a test mode
// currently doesn't sleep until test mode is unset
// also kills off "reporting" tasks like appx and stat
void SysSetTestMode(bool state) {
  testMode = state;

  if (testMode) {
    //    if (!systemRunning) {
    //      _killTasks();  // kill tasks just in case
    //      _restartTasks();
    //    }
    OSTaskDel(APPX_TASK_ID);
    OSTaskDel(STAT_TASK_ID);
  }
}

bool SysGetTestMode( void ) {
  return testMode;
}

// requests that the system not sleep for a time equal to time as expressed
//  in system ticks- the system manager replies with a true if the request
//  is granted, and false otherwise
bool SysRequestNoSleep(uint32_t time) {
  if (time < 1000) {
    endofNoSleep = OSTimeGet() + time;
    return true;
  } else {
    return false;
  }
}

// returns true if this node is currently a gateway, false otherwise
bool SysGetGatewayMode() {
  return gatewayMode;
}

// if state is true, indicates we are now a gateway, otherwise we are not one
//  - in this code revision, gateways are assumed to be powered devices, and thus
```

```
//  never sleep.  They also broadcast "authoritative" synchronization packets
void SysSetGatewayMode(bool state) {
  gatewayMode = state;

  if (gatewayMode) {
    //syncState = true; // force sync'd state
    testMode = false; // turns off test mode
    PingStopAsyncLinkTest();
  }
}

// returns true if this node is currently in "doctor" mode, false otherwise
bool SysGetDoctorMode() {
  return doctorMode;
}

// sets if this node is in doctor mode- if state is true then we are a doctor
void SysSetDoctorMode(bool state) {
  doctorMode = state;
  if (doctorMode) {
    testMode = false;
    PingStopAsyncLinkTest();
  }
}

static void _sendSleepingSyncPkt( void ) {
  // wakes up the proper services to send a ping packet, and then

  // rad, mac, appr, ping, arq
  ParamReset();
  RTCReset();
  RadReset();   // reset the radio task
  PSegReset();
  MACReset();
  AppRReset();
  PingReset();
  ARQReset();

  AppRStart();
  MACStart();
  RadStart();   // start the radio task
  ARQStart();

  // send a sync packet
  MACXmitPkt(SyncMakePkt());
}

static void _startTasks()
{
    AppRStart();
    MACStart();
    RadStart();   // start the radio task
    ARQStart();
    SerialStart();
    CostStart();
    AppXStart();
    //    RTCStart();  // TESTING ONLY
    SyncStart();
    StatsStart();
    systemRunning = true;
}

static void _killTasks() {
#ifdef DEBUG_BUFFER
    debug_buffer(4);
#endif
    OSSchedLock();            // lock the scheduler
    OSTaskDel(SER_RCV_TASK_ID);
    OSTaskDel(RTC_TASK_ID);
    OSTaskDel(RAD_RCV_TASK_ID);
    OSTaskDel(MAC_TASK_ID);
    OSTaskDel(APPR_TASK_ID);
    OSTaskDel(APPX_TASK_ID);
    OSTaskDel(ARQ_TASK_ID);
    OSTaskDel(PING_NEIGHBORS_TASK_ID);
    OSTaskDel(LINK_REQUEST_TASK_ID);
    OSTaskDel(SYNC_TASK_ID);
    OSTaskDel(STAT_TASK_ID);
    OSSchedUnlock();
    systemRunning = false;
}

static void _restartTasks() {
#ifdef DEBUG_BUFFER
    debug_buffer(5);
#endif
    ParamReset();
    StatsReset();
    RTCReset();
    RadReset();   // reset the radio task
    PSegReset();
    MACReset();
    AppRReset();
    AppXReset();
    PingReset();
    SyncReset();
    CostReset();
    ARQReset();
    SerialReset();

    if (gatewayMode) {
      SerialStartInGateway();
      AppRStart();
      MACStart();
      RadStart();   // start the radio task
      ARQStart();
      SerialStart();
      CostStart();
      //     AppXStart();
      //    RTCStart();  // TESTING ONLY
      SyncStart();
      //     StatsStart();
    } else {
      AppRStart();
      MACStart();
      RadStart();   // start the radio task
      ARQStart();
      SerialStart();
      CostStart();
      AppXStart();
      //    RTCStart();  // TESTING ONLY
      SyncStart();
      StatsStart();
    }

    systemRunning = true;
```

```
}

static void _wakeupISR(void)
{
#ifdef DEBUG_BUFFER
    debug_buffer(6);
#endif
    INTPND = ~INT_RTCA;
    _systemAsleep = false;
}

static void _sleepSystem( rtc_t delay )
{
    char savedSYSCON;

#ifdef DEBUG_BUFFER
    debug_buffer(7);
#endif
    RadSleep();

    OS_ENTER_CRITICAL();

    OSSchedLock();            // Lock the OS Scheduler

    PDAT0 |= BIT(2);        // turns SENSORPWR off (inverse logic)
    PDAT0 &= ~BIT(3);        // turns TEMP sensor off
    LED_1_OFF();
    LED_2_OFF();
    LED_3_OFF();
    LED_4_OFF();
    RTCSetAlarmTime(RTCGetTime() + delay);    // setup the RTC alarm for now + delay

    RTCALM = RTCALM_SECOND_ENABLE |
             RTCALM_MINUTE_ENABLE |
             RTCALM_HOUR_ENABLE   |
             RTCALM_GLOBAL_ENABLE;
    // enable the RTC alarm on hours/minutes/seconds (days+ not used by RTC)

    savedSYSCON = SYSCON;     // save the system configuration register

    INTPND = ~INT_RTCA;       // make sure that an RTC alarm interrupt is not
pending


    INTMSK &= ~INT_TMC2;      // turn off the system timer interrupt
    INTMSK |= INT_RTCA;       // enable the RTC alarm interrupt to wake us back up

    _systemAsleep = true;
    LED_4_ON();

    EnterPWDN(0x59);          // sleep the chip

    while (_systemAsleep);    // wait for sleep and rewakeup

    // after sleep period when we reach here
    SYSCON = savedSYSCON;     // restore the syscon register

    LED_4_OFF();
    RTCALM = 0x00;            // disable the RTC alarm
    INTMSK &= ~INT_RTCA;      // disable the RTC alarm interrupt
    INTPND = ~INT_TMC2;      // clear the system timer interrupt
    INTMSK |= INT_TMC2;       // re-enable the system timer

    OSSchedUnlock();          // unlock the OS Scheduler
    Uart_Init(TEPHRA_BAUD_RATE);

    OS_EXIT_CRITICAL();
}
```

vector.h

```
// File: vector.h
// Description: support for arrays of pointer sized objects
// Author(s):   Robert Poor <r@media.mit.edu>
//
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// warranty.

#ifndef VECTOR_H
#define VECTOR_H

#include "types.h"

typedef void *obj_t;
// Vectors hold "pointer sized" objects

// A vector is a sequence of pointer-sized elements, densely packed
// starting at index 0 and ending at VectorCount()-1.

typedef struct _vector_t {
  uint32_t fCount;             // number of elements in the array
  uint32_t fCapacity;                   // size of the array
  obj_t fElements[1];                   // a dense array of objects
} vector_t;

#define VECTOR_INDEX_NOT_FOUND          0xff
// value to return when VectorIndexOf() can't find the object

// create static storage for a vector, masquerading as an array of char
#define DEFINE_VECTOR(name, cap) char name[sizeof(vector_t) + ((cap - 1) *
sizeof(obj_t))]
```

```
// turn a static char reference into a vector pointer.
#define VECTOR(v) ((vector_t *)&v)

// ============================================================

// initialize a vector.  Must call this before first use
// void VectorInit(vector_t *v, uint8_t cap)
#define VectorInit(v, cap)    (v)->fCount = 0; (v)->fCapacity = (cap)

void VectorPrint(vector_t *v);

vector_t *VectorInsert(vector_t *v, obj_t elem, uint8_t index);
// insert element into the vector.  return v if inserted, or null if
// the vector was full prior to the call or if index is out of range.

obj_t VectorRemove(vector_t  *v, uint8_t index);
// remove and return the element at the given index, or return
// null if index is out of range.

vector_t *VectorSwap(vector_t *v, uint8_t i1, uint8_t i2);
// swap two elements in the vector.  return null if i1 or i2 are out
// of range.

obj_t VectorShove(vector_t *v, obj_t element);
// Like VectorPush(), inserts element at the high end of the
// array.  Unlike VectorPush(), removes the first element and
// returns it to make room for the new element as needed.

uint8_t VectorIndexOf(vector_t *v, obj_t element);
// return the index of the element in the vector, or -1 if not found

obj_t VectorRef(vector_t *v, uint8_t index);
// return the indexth entry of the table, or null if index out of range

vector_t *VectorSet(vector_t *v, obj_t element, uint8_t index);
// set the indexth entry of the table to element.  Returns v on
// success, null if index is out of range.

// ============================================================
// Everything else are macro definitions...

// vector_t *VectorClear(vector_t *v);
#define VectorClear(v) ((v)->fCount) = 0

// uint8_t VectorCount(vector_t *v);
#define VectorCount(v) ((v)->fCount)

// uint8_t VectorCapacity(vector_t *v);
#define VectorCapacity(v) ((v)->fCapacity)

// obj_t *VectorElements(vector_t *v);
#define VectorElements(v) ((v)->fElements)

// vector_t *VectorPush(vector_t *v, obj_t element);
#define VectorPush(v, e) VectorInsert((v), (e), (v)->fCount)

// obj_t VectorPop(vector_t *v);
#define VectorPop(v) VectorRemove((v), ((v)->fCount)-1)

// vector_t VectorEnqueue(vector_t *v, obj_t element);
#define VectorEnqueue(v, e) VectorInsert((v), (e), (v)->fCount)

// obj_t VectorDequeue(vector_t *v);
#define VectorDequeue(v) VectorRemove((v), 0)

// bool VectorIsEmpty(vector_t *v);
#define VectorIsEmpty(v) ((v)->fCount == 0)

// bool VectorIsFull(vector_t *v);
#define VectorIsFull(v) ((v)->fCount == (v)->fCapacity)

// ============================================================
// fast versions - call only when you know arguments to be safe!

void VectorFastInsert(vector_t *v, obj_t element, uint8_t index);

obj_t VectorFastRemove(vector_t *v, uint8_t index);

void VectorFastSwap(vector_t *v, uint8_t index1, uint8_t index2);

// obj_t VectorFastRef(vector_t *v, uint8_t index);
#define VectorFastRef(v, i) ((v)->fElements[(i)])

// void VectorFastSet(vector_t *v, obj_t element, uint8_t index);
#define VectorFastSet(v, e, i) ((v)->fElements[(i)]) = e

#define VectorFastPush(v, e) VectorFastInsert((v), (e), (v)->fCount)

#define VectorFastPop(v) VectorRemove((v), ((v)->fCount)-1)

#define VectorFastEnqueue(v, e) VectorFastInsert((v), (e), (v)->fCount)

#define VectorFastDequeue(v) VectorFastRemove((v), 0)

#endif
```

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