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Regional and on-farm wireless sensor networks for agricultural systems in Eastern Washington

*F.J. Pierce**, *T.V. Elliott*

Center for Precision Agricultural Systems, Washington State University, Irrigated Agriculture Research & Extension Center, 24106 N. Bunn Road, Prosser, WA 99350-8694, United States

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ABSTRACT

Recent advances in sensor and wireless radio frequency (RF) technologies and their convergence with the Internet offer vast opportunities for development and application of sensor systems for agriculture. The objective was to create regional and on-farm sensor networks that provide remote, real-time monitoring and/or control of important farming operations that add value through improved efficiency and efficacy of targeted management practices. This paper describes hardware and software components of technologies we developed for regional and on-farm sensor networks and their implementation in two agricultural applications in Washington State, an agricultural weather network and an on-farm frost monitoring network. The regional sensor network consists of our AWN200 data logger equipped with a 900 MHz, frequency hopping, spread spectrum (FHSS) radio configured into master–repeater–slave network for broad geographic coverage. A single master is configured with multiple repeaters to provide a RF line-of-sight telemetry backbone network. Independent network backbones from disparate geographic regions are then aggregated in a central database via standard Internet protocols for further processing and dissemination. Software includes firmware to operate the data logger and radio telemetry aspects of the AWN200 in an agricultural weather network application called AgWeatherNet (http://www.weather.wsu.edu). The on-farm sensor network uses our SS100 radio/logger which includes a 900 MHz, FHSS radio, with software designed primarily for mobile, real-time farm operations and management applications. The network is deployed in a star topology in which a strategically placed base radio is responsible for network synchronization, data collection from remote stations within the network, and re-broadcasting collected data to roamer radio units attached to mobile computers and/or directly to the Internet. Client software, AgFrostNet, operating on a computer connected to a roamer, collects, manages, and display data in real-time. This software was designed specifically for air temperature monitoring during frost/freeze protection events. Both the regional AgWeatherNet WSN and the on-farm AgFrostNet networks were successfully implemented in Washington State. Problems encountered were mainly associated with power management under periods of low solar energy and with electrostatic discharge (ESD) damage to gallium-arsenide (GaAs) based transmit–receive switches in the radios during storms, a problem now corrected. Both systems have been made commercially available to growers via a novel arrangement between WSU and a local manufacturer.

* Corresponding author.
E-mail address: fjpierce@wsu.edu (F.J. Pierce).

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1. Introduction

Historically, Americans have met emerging requirements and overcome significant barriers to profitability through technological innovation (Cochrane, 1979; Schultz, 1964; Sunding and Zilberman, 2001). To avoid Blank's (1998) hypothesis that globalization will soon be the end of agriculture in the American portfolio, new technologies must provide a value stream for U.S. agriculture by increasing production/processing efficiency and producing food products preferred by consumers. Our underlying hypothesis is that the emerging technologies of wireless sensor networks (WSN) will provide new economic opportunities for U.S. agriculture through their application to remote, real-time monitoring and control of important aspects of high quality food production and processing systems. Our hypothesis is consistent with Wang et al.'s (2006) view that while WSN in agriculture are rare and just emerging on the farm, they will have a bright future.

The full vision for WSN is based on the growing convergence of computing and communication as Gelsinger (2006) foresees "every communication device will contain computing functionality and every computing device will communicate". Taken to its highest level, Butler (2006) suggests that WSN could measure everything, everywhere in an ecosystem at whatever scale might be appropriate. Moreover, WSN will be responsible not only for sensing but also for the first stages of processing hierarchy (Lewis, 2004), making it feasible for networks to learn. Weisman (2002) and Lewis (2004) provide thorough overviews of RF and wireless technologies. Although there are limited examples of WSN applications for agriculture (Beckwith et al., 2004; Burrell et al., 2004; Goense and Thelen, 2005; Ramanathan et al., 2005; Thelen et al., 2005; Zhang, 2004; Zhang et al., 2004), there are many potential applications of WSN in general (Akvildiz et al., 2002; Wang et al., 2006). The notable point here is that there are many tasks within agricultural production systems that lend themselves to WSN which could add value and improve US agricultural competitiveness in a global economy.

We first pursued WSN technologies in our efforts to upgrade the Public Agricultural Weather System (PAWS) network in Washington State (Ley and Muzzy, 1992). The PAWS network was developed in the mid-1980s initially to provide regional estimates of evapotranspiration, in support of irrigation scheduling for water conservation, and in frost monitoring, with more recent uses focusing on pest and disease modeling in support of integrated pest management (IPM). The PAWS network used commercially available data loggers and weather sensors to collect and store weather data, and licensed, fixed frequency, UHF radio systems to poll weather stations hourly. Since 1997, PAWS provided weather data and related information on an Internet web site. The primary problem with the PAWS network was the aging telemetry system. Direct replacements for the modems and radios were no longer commercially available. The need for a WSN derived from requirements to upgrade the aging PAWS network under a constraint of very limited funding. We found the needed telemetry solution in the license-free ISM 902–928 MHz spread spectrum frequency band radios. These systems were becoming increasingly available and affordable in 2001, when we began our search for replacement technologies for PAWS.

Our experience with regional weather networks brought us quickly to realize the value and need for an on-farm WSN where network topology, cost requirements, data frequency, energy use, and user connectivity to the WSN were distinctly different from the regional PAWS network. The application of interest was to assist fruit growers in frost protection by providing them with spatially distributed air temperature monitoring in near real-time anywhere on the farm.

A major problem in Eastern Washington State is a climate that poses a major threat of low-temperature plant injury, which requires most fruit growers to provide some form of active frost protection to prevent frost or freeze damage to their fruit (Perry, 1998). Growers use three primary methods of frost/freeze protection: heating, irrigation, and air mixing, all of which are intended to raise the temperature of the air surrounding the fruit and, in the case of irrigation, protect the fruit with a coating of ice (Jackson, 2000; Westwood, 1993). Many farmers use all three protection methods and vary their use depending on the characteristics of a given frost/freeze event. Most wine grapes are drip-irrigated so wine grape growers rely primarily on wind machines for frost protection, while progressive tree fruit growers use wind machines and irrigation in combination as needed to adequately modify temperature. In each case, the protection method is initiated just prior to the air temperature reaching the critical temperature for crop damage. All of the frost/freeze protection systems are costly in terms of capital, labor, and operating costs. In all cases, frost/freeze protection involves workers who must monitor air temperatures throughout the farm operation, initiate and operate the protection systems once protection threshold temperatures have been reached, and shut down the protection system once the threat of low-temperature damage has dissipated. On days when a frost or freeze event is forecasted, workers start monitoring air temperatures in early evening hours and begin to shut down soon after sunrise when temperatures rise above critical temperatures. During the following day, plants are checked for damage and equipment is made ready for the next event. For some weather systems, this cycle may last for several days. A typical frost protection event for a moderate size farm would involve multiple workers all monitoring the air temperature using a temperature sensor embedded in the grill of their pickup truck and connected to a display in the cab. Each worker drives from cold spot to cold spot to check temperatures and, when a critical temperature is reached in a given location, the worker would initiate the frost protection system often with the help of co-workers. The process would continue throughout the night, with all systems monitored manually to ensure they were operating correctly. Systems are shut down if conditions changed sufficiently to warrant it, and problems are addressed as they occur. All workers would be in radio contact throughout the night to coordinate their activities. On one local farm, for example, each worker would drive nearly 100 km each night but never leave the farm.

Our main objective was to develop WSN hardware and software technologies for use in specific applications that would improve the management of the high-value, specialty crops grown in Washington State. Our specific objectives were to (1) develop a WSN to replace the PAWS network and (2) develop an affordable, real-time, mobile system for fruit growers to monitor air temperature and frost protection equipment, specifically wind machines. While the design of these technologies was driven by specific applications, the various hardware technologies are applicable to a range of agricultural and non-agricultural applications. New applications may require the addition of different devices or sensors and changes in firmware and application software.

2. Materials and methods

We developed two wireless network technologies, each designed for specific application categories: one for regional networks involving wireless backbone networks operating over large geographic areas and the other for on-farm networks. The hardware and software technologies developed for each WSN are described in the context of the initial application that drove the design.

2.1. *Regional WSN*

A typical PAWS weather station includes a data logger, sensors for measuring solar radiation, air temperature, relative humidity, leaf wetness, rainfall, wind speed, wind direction, soil temperature, and soil moisture; a solar power supply; and a radio with antenna. The core technology for the regional WSN is the AWN200 data logger, developed by us for this purpose. The AWN200 utilizes a Microhard Systems Corporation MHX910, frequency hopping, spread spectrum (FHSS) radio operating in the 902–928 MHz ISM band. The MHX910 has 127 channels, 64 hopping patterns, a −108 dBm receiver sensitivity, and 1 W of output power. The major feature of the MHX910 allows the AWN200 to be configured in a master-repeater-slave network topology (Fig. 1a), which is well suited to the creation of wireless, regional, weather networks. For long-range operation, the MHX910 requires near line-of-sight paths between the network components, which necessitates careful placement of nodes. Because of the synchronous nature of frequency hopping systems, placement is especially critical for the master and repeater nodes to achieve optimal performance. The network is synchronized by a single master. Repeaters may be used to extend the master sync-signal over multiple hops, with no set limit to the number of repeaters or hops in a single network. These features make it possible to arrange repeaters over large geographic areas utilizing combinations of topography and radio towers to form a contiguous wireless network backbone that can be populated with many slave stations. While the MHX910 network can be configured for up to 65,000 slaves, the practical limit is determined by a number of variables including the number of slave stations, data transfer protocol, packet error rates, and data collection interval. Our application requirements for a regional network with 15-min reporting cycles limit the number of slaves per network backbone to a conservative estimate of 300 nodes. Disparate geographic regions require separate networks to be formed. In our implementation, separate networks were aggregated in a central database utilizing standard Internet technologies for the remote data transfers (Fig. 1b).

The AWN200 logger uses standard Internet Protocol (IP) datagrams for communications. Although it can be a challenge to implement a TCP/IP (Transmission Control Protocol) stack on an 8-bit, low-power system, the ubiquitous nature of networking protocols such as TCP, HyperText Transfer Protocol (HTTP), and MySQL Connector Protocol drove the decision. One radical change from previous systems is the ability for each station to awake from sleep mode and insert data directly into the MySQL database (open source relational database management system), utilizing the master station as a network router. This feature eliminates many problems associated with a polled WSN system. Instead of trying to coordinate the wakeup time for each of the remote stations for centralized data retrieval, a station can simply wake up, transmit its data directly to the database, and go back to sleep. Many slave stations can wakeup and make database connections simultaneously, thus increasing the potential size of the network while minimizing the power consumption of remote stations. This also eliminates the need for any data retrieval software running on a PC. During power-up, the logger checks the flash memory for new firmware, which can be updated via a special file stored on the flash card. It then performs an auto-calibration of the analog circuitry utilizing high-precision voltage references. A linear function matches a/d and d/a converters to the accurate high and low voltage references to compensate for sources of variability in the

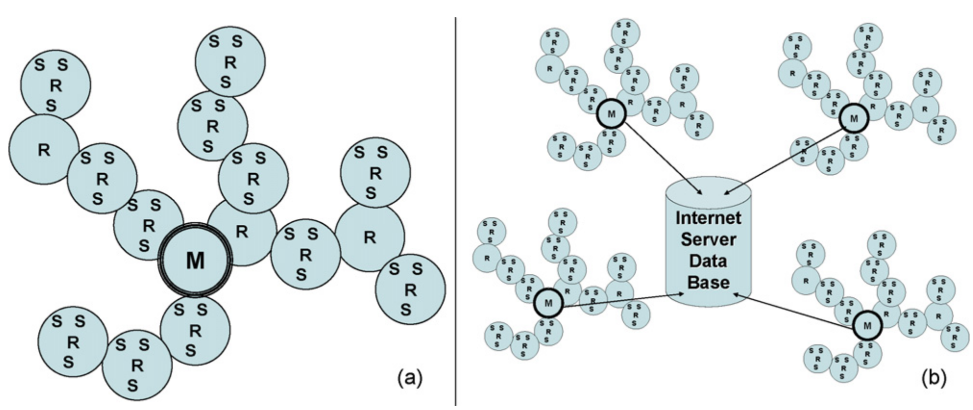

Fig. 1 – (a) Master–repeater–slave topology used for the regional wireless sensor network in which a single master (M) supports multiple repeaters (R) to form a network backbone populated with slaves (S); (b) the network-of-networks topology used for AgWeatherNet where each network operates independently and populates a remote database automatically.

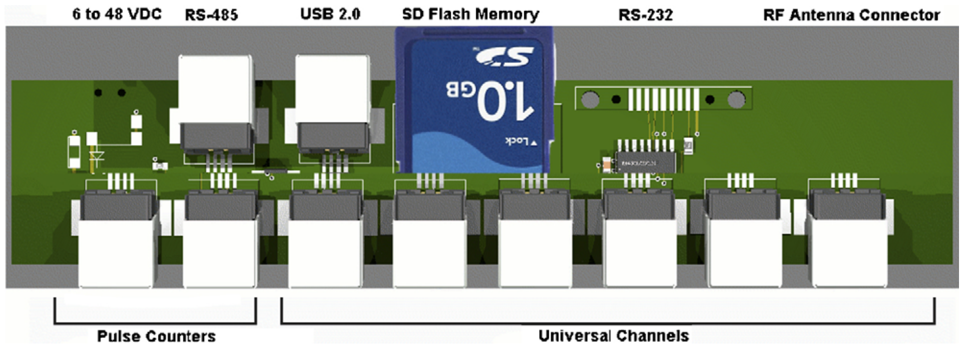

Fig. 2 – Schematic of the input and output ports available on the AWN200.

measurement circuitry. This feature allows the AWN200 to be highly interchangeable without manual calibration. All logger configuration and firmware is stored on the flash memory in a Microsoft FAT32 file system. The FAT32 file system was not appropriate for the data storage requirements of the data logger, due to inevitable FAT table corruption. Our solution was to store data in a MySQL log file format with a single record per 512 byte sector on the flash memory padded with spaces at the end of each record. By storing the data in this way, each record becomes self-contained and ready for direct database insertion, without the need for a typical file allocation system. This format also allows straightforward manual data retrieval from a flash card, without any chance of data loss due to file-system corruption. The AWN200 uses a multiplexed switching network to make the analog inputs generic and completely programmable. This feature allows almost any type of sensor to be connected to the AWN200. All measurements, except for the counter ports, are read as millivolts which can then be scaled with linear and/or non-linear functions to represent actual units of measurement before flash storage and database insertion. The input and output functionality of the AWN200 is illustrated in Fig. 2.

The master allows packets received and transmitted over the wireless network to be forwarded to a specific Ethernet Media Access Controller (MAC) address on its subnet. This feature allows powerful workstation-based network packet analyzers, such as Ethereal, to be utilized for network characterization, diagnostics, and overall performance assessment of the wireless portion of the network. These capabilities can be immensely useful for network troubleshooting.

Power consumption is a major concern for any solar-powered RF telemetry network. There are many things to consider including micro-controller architecture and clock speed, radio transmit and receive power requirements, solar panel regulation, solar panel wattage, battery capacity, data logger power requirements, and sensor power requirements. A number of power saving features were included in the design of the AWN200. For data logging applications to minimize power consumption, we used an 8 bit micro-controller with a low clock rate. The Atmel ATMega128 processor is an 8 Bit RISC processor with 128KB of code memory, of which a little over half was use for our weather station application. We used the low-voltage version of the processor clocked at 7.3728 Mhz for low power consumption, but enough power to keep track of data storage and TCP/IP communications efficiently. The ATMega128 has 4KB of internal SRAM, the minimal amount of RAM necessary for our application. The ATMega128 features various sleep modes to lower power consumption during idle periods in code execution. This feature of the microprocessor is accessed in the firmware and can potentially save several mW of power consumption. Additional power conservation is available through the radio. The MHX910 radio used in the AWN200 has good communication characteristics, but does require approximately 500 mW in receive mode and over 2 W in transmit mode. The receiver power requirement is far too much for continuous operation. The radio must therefore be switched off during times of non-use. These levels of power consumption make up the vast majority required by the weather station and also create some logistical problems for data collection. Initially, we used a central polling protocol for the master that would call each station in succession and then request that the station turn the radio off for the next 14.5 min. This approach was problematic because the radio was on for 30 s at high power consumption, a polling delay increases power consumption in the network, and if the poller system failed, the stations would remain awake waiting for a sleep command. Our current solution, whereby each station controls the radio on-time and population of the remote database, is much more efficient, increases network capacity, and increases overall network reliability.

Power consumption is a maximum with the master and repeater since they operate continuously. Where available, a 110 V power supply is recommended. For many repeaters in remote locations, a 40 W solar power supply was used in conjunction with a high capacity, 6 V battery. A 10 W solar panel, with a 6 V, 7 Ah battery, was used for slaves. For additional power conservation, a switching buck-type power supply was used to regulate the 6–48 V input voltage down to 5.5 V with >90% efficiency. To prevent switching power supply noise from affecting high resolution measurements, the switching regulator was followed with 3 separate linear regulators for digital, analog, and radio power supplies.

2.2. *On-farm WSN*

The data logger and radio requirements for the on-farm WSN were determined by the requirements for temperature monitoring in support of frost protection decision making at the farm level. Working with farmer cooperators, we determined that the WSN needed to report air temperature every minute to a computer operating anywhere on the farm during the frost-protection event, and that the temperature measurement had to be accurate to 0.1 °C. It was also important that multiple workers involved in the frost protection event be able to view current and trend data for each monitoring station in real time. The user needed to be able to set temperature thresholds that would trigger an alarm at their computer. Furthermore, the system had to be affordable, with the design cost of each radio unit less than US$ 400. The regional AWN200 based WSN described above did not meet these requirements.

We designed a new 900 MHz, ISM band, FHSS radio with data logging capabilities (SS100), a thermistor temperature sensor, and firmware to configure the radios in a star topology telemetry network. Client software (AgFrostNet) was created to collect, manage, and display data from the telemetry network.

The radio is the CPAS Technologies SS100 modular radio that received FCC Grant Certification (FCC identifier RHVC-PAS100) in January 2004. The SS100 is a point-to-multi-point wireless data acquisition system with the radio operating in the 902–928 MHz ISM frequency band for license-free operation in North America. Its frequency hopping mode of operation offers high reliability due to the inherent tolerance of interfering signals. The radio frequency (RF) output power is 501 mW. Features of the SS100 include two channel groups of 50 RF channels each, 16 user selectable hopping patterns consisting of 50 channels each, which facilitates co-existence of multiple networks, 32 bit encryption key for privacy and non-interference between networks, 32-bit CRC error detection for error-free data collection, and a low-drift, real-time clock. Collection systems shut down radio circuitry when not in use for battery conservation. The radio is designed for extended temperature range. Line-of-sight link range of 15 miles or more is possible depending on environment, antenna placement, and gain. The SS100 includes an RS232 serial port and the capability to connect up to two sensors. The SS100 accommodates a 1× and a 10× gain analog input, one digital input that can be used as a counter, one digital output which is buffered so that it can power sensors, and an I2C bus with two lines (clock and data) that can be used for digital input and/or output. Sensors currently supported include air temperature, leaf wetness, relative humidity, rain gauge, wind speed, wind direction, soil moisture, pressure sensor, and switch closure, with others forthcoming as needed. The serial port is used for a number of tasks including connectivity to computers, serial to Ethernet converters, and to monitor other devices such as control actuators. For the frost protection application, we were interested primarily in air temperature. However, other sensors useful in frost/freeze protection can be monitored, including wind speed and combined air temperature/relative humidity sensors used to calculate dew point, an important parameter in frost protection. The air temperature sensor uses a YSI Incorporated Model 44033 precision thermistor with a published range from −80 to 125 °C and an interchangeability of ±0.1 °C from 0 to 70 °C.

The firmware controls the radio operation, including the synchronization of the radios in a network (RF topology), and the data logger functions. The SS100 can be configured via the firmware in three ways: as a base, which provides synchronization for all radios in the network and is responsible

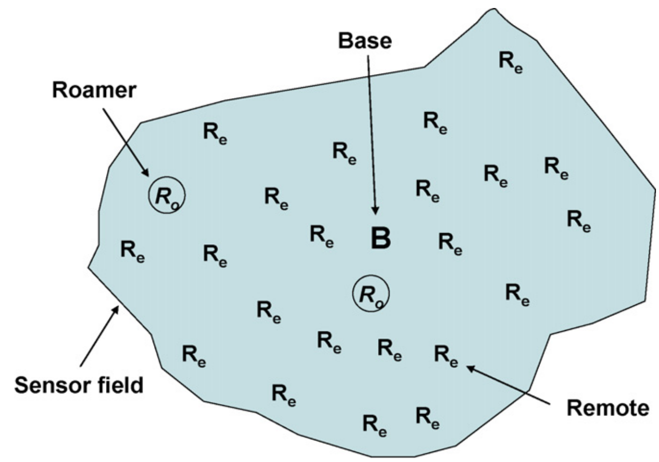

Fig. 3 – Star topology used for the on-farm wireless sensor network in which all remote (Re) stations transfer and receive data from the base (B) while roamers (Ro) directly connected to a PC receive data from the base and automatically population a database.

for all data collection and transmission; a remote, which collects data and transmits and receives data from the base; and a roamer, which receives data broadcast from the base, and is attached to a mobile laptop computer operating AgFrostNet software (described below). The network is configured in a star topology, with roamers free to roam throughout the sensor field, as illustrated in Fig. 3. The radio portion of the WSN functions is illustrated in Fig. 4. The base collects data from all remotes in a network, temporarily stores these data, and then broadcasts the data to all roamers in the network. Alternatively, either the base or a roamer can be connected via a computer or a serial-to-Ethernet converter to the Internet for purposes of storing data on a remote server. The base antenna must be within the RF line-of-sight communication ranges of the antennas of all remotes and roamers. Therefore, the base is usually configured with a 6 dBi, high gain, omnidirectional antenna and installed at a high point in the landscape, either within or external to the farm. As configured for this application, the base can communicate with 25 stations per second and collect data from up to 255 remote sites in a given network. Roamers are generally restricted to receive-only mode and if so, there is no limit to the number of roamers for a given base. All radios on the same network must be assigned the same encryption key, the same hopping pattern, and the same channel group as the base. The combination of encryption, channels, and hopping patterns limits the possibility of interference between co-existing networks. The base can be programmed to sleep between data collection cycles and to set the number of times a station is called during a data collection cycle without successfully establishing communications. In addition to sensor data, the base can request from each remote its battery voltage, the Received Signal Strength Indication (RSSI, an instantaneous measurement of the received signal power measured at the beginning of each received packet), and the internal temperature of the radio, all of which may be important in trouble shooting a remote. Any radio can communicate with a computer using any terminal emulation program.

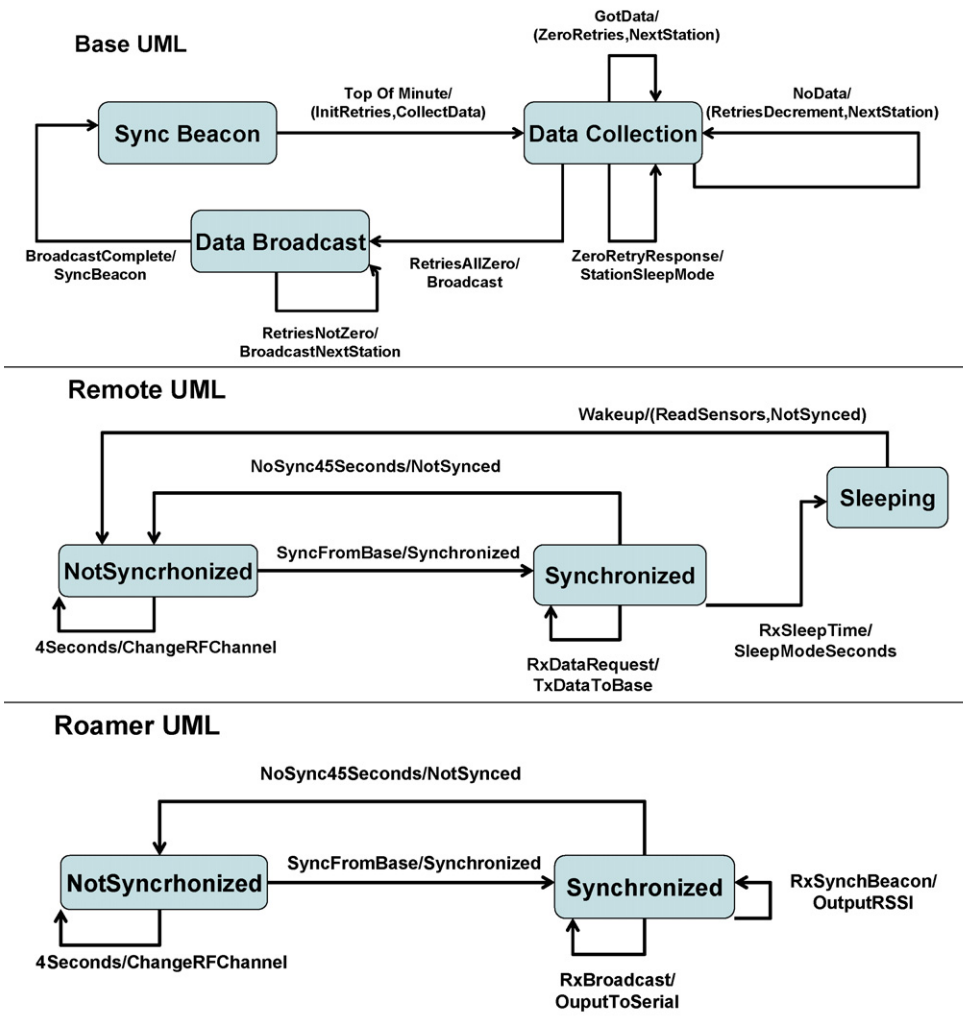

Fig. 4 – A Unified Modeling Language (UML) state diagram representing the SS100 base, remote, and roamer operation.

Power conservation was also considered in the design of the SS100. The major power savings is achieved through the firmware using the sleep mode functionality of the microprocessor. After the base successfully collects data from a remote, it requests that the remote enter sleep mode, which shuts down the microprocessor. The remote is set by the base to awaken at the next scheduled data collection interval. Power consumption is highest on the base because it operates in the transmission mode almost continuously. Therefore, a 110 V power supply is recommended, but a 40 W solar panel, with a high capacity 6 V battery has been used in some installations. All remotes are powered using 7 Ah, 6 V battery that lasts approximately 1 month at a data transmission frequency of 1 min. Batteries must be changed regularly unless a solar panel charger is installed. Many growers did not want to incur the additional cost of solar panels.

A client software program, called AgFrostNet, was created to communicate with the SS100 and provide a user interface between the data and the radios (Fig. 5). AgFrostNet is written in JAVA V1.4.x. Because Java is a cross-platform programming language, AgFrostNet can operate on all operating systems that support this version of JAVA. If a roamer or base radio is connected to a computer operating AgFrostNet, the computer receives data from that radio via the RS232 port and immediately stores all incoming data in a MySQL relational database. All data previously stored on the computer for a given network is available to AgFrostNet so that any remote station in the existing database for that network will be available for view.

The AgFrostNet software was designed to provide the user with the following functionality:

- View the radio link status for the base station.
- View the current time.
- View the current temperature of a pre-selected reference remote station.
- View a list of all remote stations in the network along with the time of the last data transmission, the current sensor reading, and the status of the threshold alarm set for each station.
- View a window display of (a) time series graphs of sensor output, battery strength, or radio signal strength, (b) a map

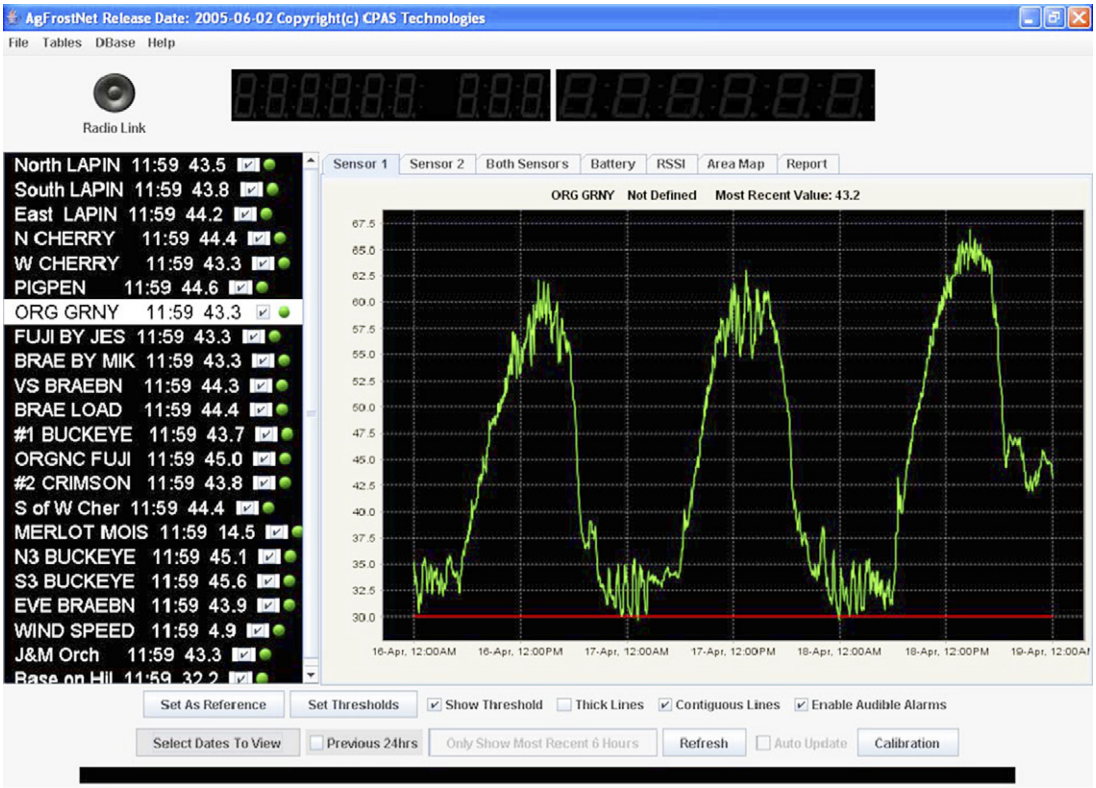

Fig. 5 – Screen shot of the AgFrostNet software when the computer is not connected to an active radio but various dates-to-view is selected.

of stations with their current sensor value, or (c) a comma delimited report of the data record for the current period.

- Set the time period for the window display to the last 6 h, the last 24 h, or any time period of historical data. An option is provided to save the data to a standard or comma delimited text file.
- Set sensor thresholds for each remote station and enable alarms that signal a sensor has reached the threshold. Threshold temperatures vary by crop type and phenology of the plant relative to susceptibility of various plant parts to low temperature injury. An electronic buzzer alarm can be connected to a roamer.
- Change the calibration coefficients for a sensor.
- Update firmware on any radio connected to serial port.

Another client software program, also written in JAVA V1.4.x, is provided for users to configure the SS100 radios to allow them to add new stations or switch unit operation modes (Fig. 6). This software is particularly important if the base or roamer fails, since the user can reconfigure a remote station, in the field, to replace either unit as needed. Options include setting the operations mode—(base, remote, or roamer); setting network identification, encryption codes, and hopping patterns; and setting operating parameters for the base and for each sensor. Functionality is also provided to read and write configurations files and update radio firmware as new versions become available.

3. Results

3.1. *Regional WSN deployment*

The regional WSN system was installed in Washington State to replace the PAWS telemetry system and upgrade each station to the AWN200 technology. Data and information products from the full AgWeatherNet system are accessible to the public at http://www.weather.wsu.edu. For purposes of discussion, we only describe the deployment of one portion of the AgWeatherNet network in the Lower Yakima Basin of Washington State. The Lower Yakima Valley extends from Benton City on the east to Union Gap on the west (approximately 83 km) and, as a basin, has excellent line-of-site needed for a wireless network backbone. The wireless backbone network consisted of a master located at the WSU Irrigated Agriculture Research & Extension Center located 6 km northeast of Prosser, Washington, a primary repeater located on Prosser Butte, with additional repeaters located on Snipes Mountain, Rado's Hill, and Ahtanum Ridge, 28, 14, and 69 km, respectively, from Prosser, Butte (Fig. 7). The range of the MHX910 radio provides adequate signal strength for the Prosser Butte for the full distances encountered in the Valley, but other repeaters are needed to complete line-of-sight coverage in selected areas of the Valley. There are 25 weather stations installed in the Lower Yakima Valley that have been operating successfully for the last few years. The master is connected to a local area network via an Ethernet connection and acts as a

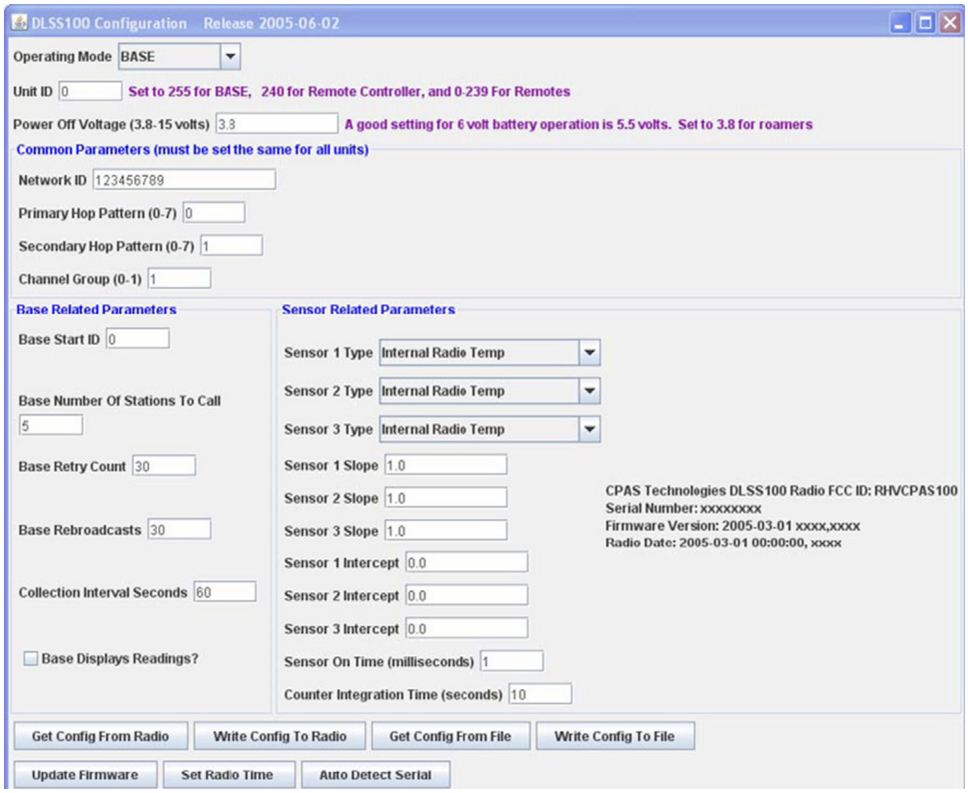

Fig. 6 – Screen shot of the configuration software for the SS100 radios.

router for the wireless network. This allows slaves to directly populate a MySQL database. The data for the Yakima Valley are integrated with the other networks in Washington State and made available to users via the AgWeatherNet Internet site. Currently, there are 18 networks comprising AgWeatherNet, providing a wireless network backbone with coverage of most of the approximately 1 million ha of irrigated cropland in Washington State.

The AWN200, and its predecessor the AWN100, have been deployed in a variety of other agricultural applications. By changing the sensor configuration and the firmware, it was relatively easy to add new applications to this regional network technology.

For soil moisture/irrigation monitoring, the firmware on the AWN100 was changed so that the sensor configuration included a rain gage and three Decagon Echo soil moisture probes and three soil temperature sensors installed at three depths. A number of these soil moisture/irrigation monitoring stations were added to the AgWeatherNet backbone with subsequent changes to the AgWeatherNet Web site to allow farmers to monitor irrigation system performance. For example, Fig. 8 shows the irrigation and soil moisture pattern in an onion (*Allium cepa*) crop for a 2-week period in July 2004 that the grower could view at the AgWeatherNet web site. The four irrigation events, for the most part, affected only the surface soil moisture content and the water application amounts were not adequate to maintain soil moisture levels over the 2-week period.

In another application, the AWN100 was modified to accommodate crop-load monitoring in grapes using a new sys-

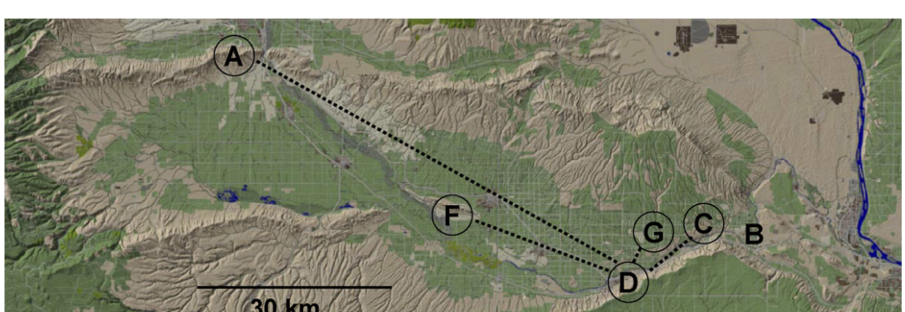

Fig. 7 – Map of lower Yakima Valley showing wireless backbone network for AgWeatherNet WSN application. A is a repeater at Ahtanum Ridge, B Benton City, C a repeater at Rado's Hill, D a repeater at Prosser Butte, F a repeater at Snipes Mountain, and G is a Master at the WSU Irrigated Agriculture Research and Extension Center.

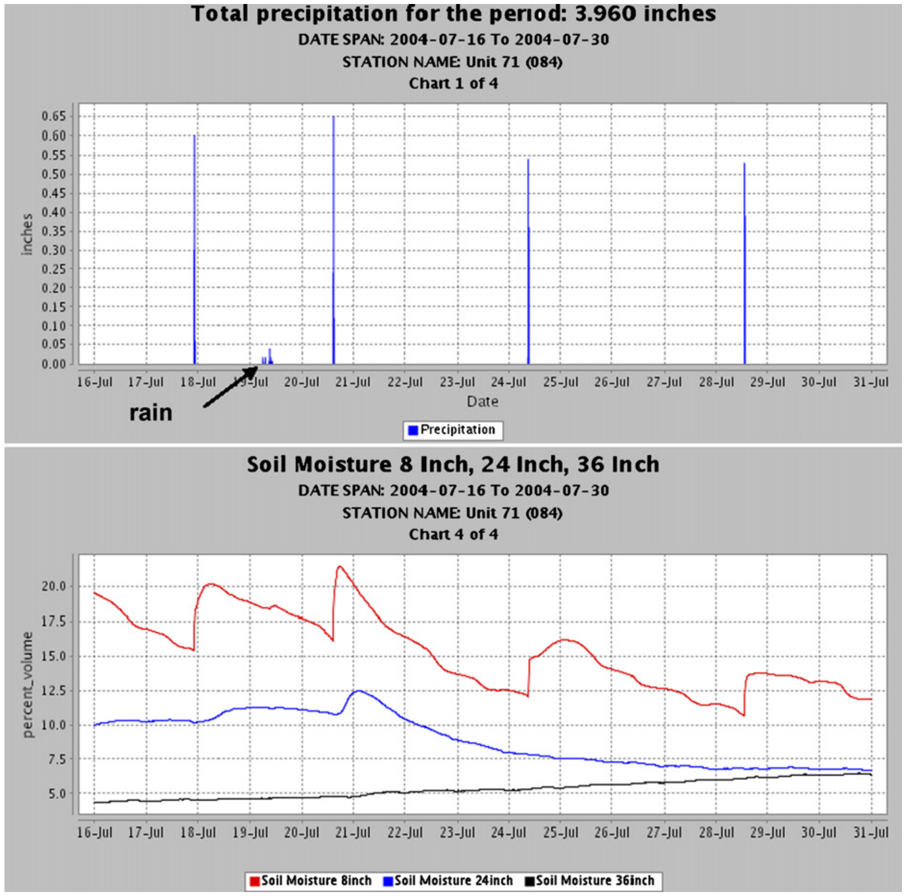

Fig. 8 – Screen shots of AgWeatherNet showing (a) irrigation and (b) soil moisture for the 2-week period in late July, 2004 for a center pivot monitoring system. A small amount of rain was recorded on July 19.

tem developed by Tarara et al. (2004) in which the tension on the trellis wire, as measured by a load cell, is directly proportional to crop load in grapes. The AWN100 monitors a load cell that measures trellis wire tension and a temperature sensor that monitors wire temperature. These data are integrated with wind speed obtained from an AgWeatherNet weather station and algorithms derived by Tarara et al. (2004) are used to calculate grape mass on a 15-min interval.

In another application, a load cell was used in a system to remotely monitor manure applications in Wisconsin in near-real time as described by Cabot et al. (2006). A wireless backbone consisting of a master located at the University of Wisconsin and a remote repeater located on a hill overlooking the target farm. To measure manure application rates, a physical torque-sensing system developed by McFarlane (2000, 2001) was installed on the Kuhn–Knight Model 8032 Pro Twin Slinger side-discharge spreader used for manure application on the farm. The force inside the assembly resisting the expeller shaft chain was measured from the voltage obtained with an in-line load cell. A GPS was also connected to the AWN100 and the force and position data transmitted in near real-time through network backbone to the Master where the data are automatically stored in a MySQL database. Using a GIS, the manure application spreading pattern map can be updated at any time.

Power consumption was the major problem in the operation of the regional network. In Washington State, there is a very large range in solar radiation throughout the year, depending on location. While a 10 W solar panel would be sufficient most of the year, there are usually 2 or 3 months of very overcast skies that coincide with months with very little solar radiation. During these periods, the power from a 20 W solar panel was not sufficient in some locations for stations outfitted with lower capacity batteries. For those situations, we used a 10 W solar panel with a 6 V, 36 Ah battery, which provided enough reserve capacity to make it through the low-solar, overcast days in most systems. However, where extended periods (>a month) of cloud cover occurred (in the winter months in western Washington State), a solar power solution, in any form, was not viable. The only solution in these cases is to swap batteries when they are sufficiently discharged.

3.2. *On-farm wireless sensor networks*

We deployed an on-farm network of SS100 radios equipped with air temperature sensors and a SS100 connected to a wind anemometer (Met One, Model 014A) on a 160-ha fruit farm located in the lower Yakima Valley near Prosser, Washington (Fig. 9). The farm is on the north side of the valley sloping south towards the Yakima River but has complex slopes cre-

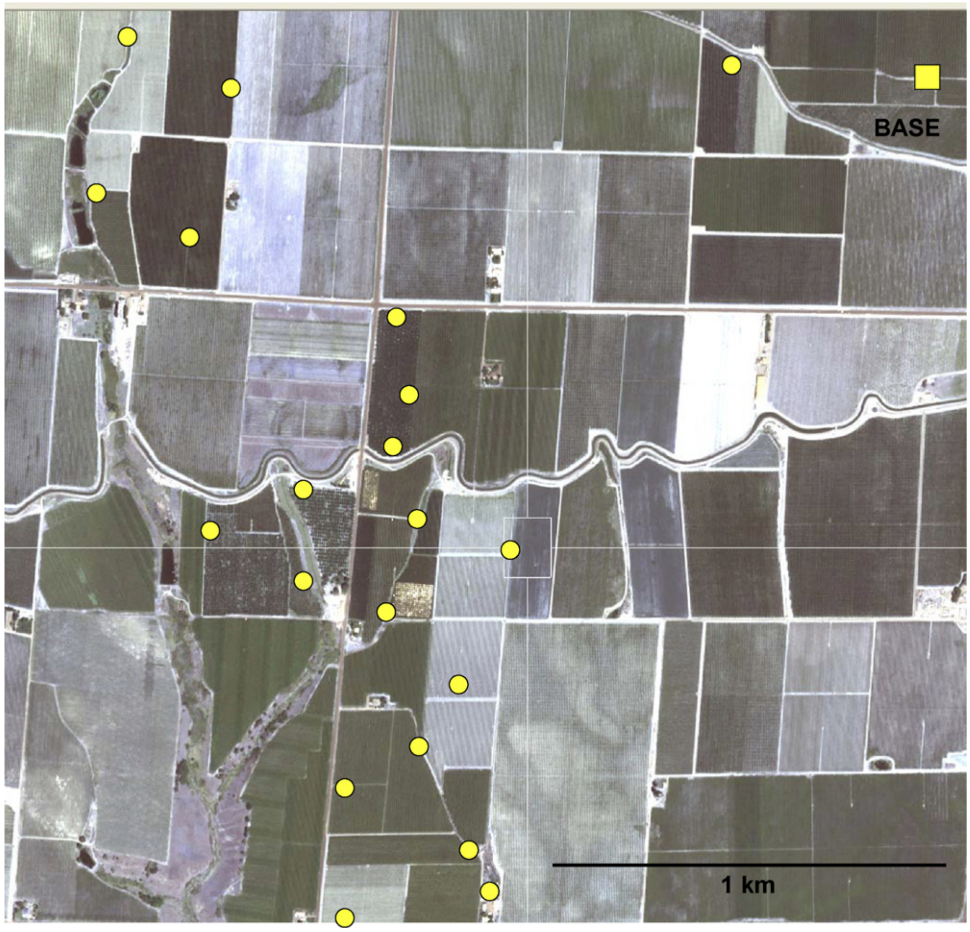

Fig. 9 – Location of BASE and remote stations at the test farm in Prosser, WA.

ating variation in temperatures across the farm. The farm has 16 wind machines installed at strategic places, which are used in conjunction with irrigation for frost/freeze protection. A base was installed at a high elevation point on the northeastern portion of the farm and 21 remote units with temperature sensors were installed in locations considered by the growers as cold spots distributed around the farm. Two roamers were connected to laptop computers operating AgFrostNet software and were used continuously to record and monitor air temperatures. The two roamer systems were kept in the vicinity of the network and stayed with the growers most of the time whether they were at home, in the office, or in their trucks. The base was powered by a switching power supply connected to a 110 V outlet available at the site. The remote units were powered by a 6 V batteries recharged using solar panels (Silicon Solar thin film 65, 4.8 W, 8 V@600 mA). For this non-regulated solar panel, a diode was required in series to prevent battery discharge through the panel. The base was set to poll the remote units and broadcast the data to the roamers on a 1-min interval.

A typical temperature curve is given in Fig. 10 for an 18 h period (6 pm April 19 through noon April 20, 2006). Wind machines operated each night to raise temperatures that were at or below the temperature threshold, set by the farmer at 0 °C. The temperature trend line showed the farmer how a given wind machine was performing. As illustrated in Fig. 10, the wind machine cycled on and off for 6 cycles beginning late on April 17 and then remained on for 3 h until temperatures rose at sunrise. The decision rules that prompted farmers to start wind machines have changed using AgFrostNet as growers now wait until temperatures trend towards the set

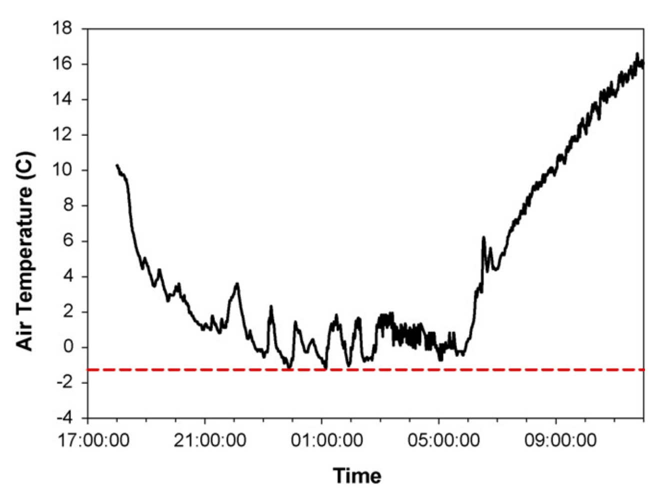

Fig. 10 – Illustration of the effect of wind machine on temperature variation during a frost event on April 19–20, 2006.

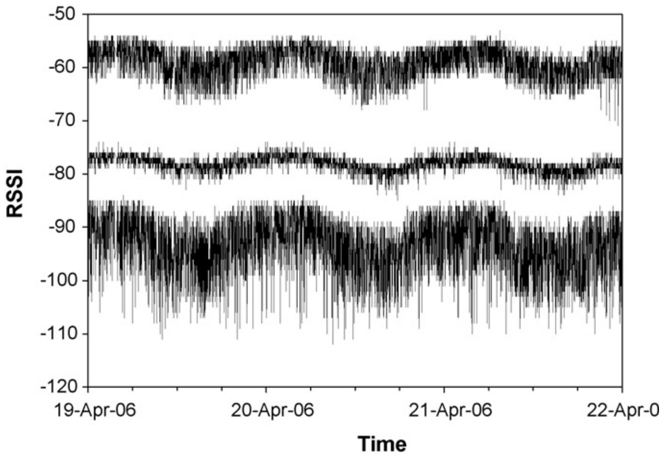

Fig. 11 – Temporal pattern of RSSI for three remote stations for a 3-day period showing the range of radio performance.

threshold before they decide to activate frost protection measures.

An important performance consideration for WSN is RSSI. The general guideline for the SS100 radio is that an RSSI of −110 dBm (decibel relative to a milliwatt) is nearly inadequate and a RSSI of −50 dBm is excellent. The RSSI for the 22 stations observed at 11:58 pm on April 29, 2004 ranged from −52 to −107 dBm. The variance of RSSI also varied by station and may be an important performance indicator (Fig. 11). While stations showed a slight diurnal fluctuation, the trends were consistent for a given station. In general, more negative RSSI values indicate higher packet loss (data not received at the roamer). The low RSSI station did result in a loss of data intermittently over the 3-day period but not enough to make the grower feel he needed to alter the position of the radio or antenna. For all stations, the grower installed the radios with the antenna pointing down and often within tree canopies. There was no effort to optimize the antenna placement that would have improved RSSI. For the three stations depicted in Fig. 11, the data loss was 3.0, 3.5, and 7.0% for the best to the worst RSSI, respectively.

The use of solar panels in this deployment kept the batteries charged for most of a year. On occasion, during the winter months, some batteries required replacement, which was easily done by the farmer. Without a solar charger, the batteries for the remotes lasted approximately one month. If a battery alone was used for the base, it lasted only a few days.

The major problem encountered with the SS100 was electrostatic discharge (ESD). The transmit-receive switch used in the SS100 is made of GaAs. While this is a common switch used in radios, it is susceptible to ESD because it has a low-voltage damage threshold. During selected storms, the GaAs switch failed due to ESD. This problem was resolved by placing a 120 nH inductor at the antenna port to provide a direct current path to ground before the transmit-receive switch. This modification was also made to the MHX910 radios used in the AWN200 since we discovered they also have the same ESD vulnerability associated with the GaAs transmit–receive switch. Since the fix was installed, no further problems of this nature have been reported. A desired feature for future development would be the ability to wirelessly update firmware on remote stations. Manually updating firmware on in-field remotes for the 21 station network took approximately 6 h if all went well.

Currently, the AgFrostNet WSN is being used for many other uses including monitoring soil moisture, conditions for pests and diseases, crop load in grapes (Tarara et al., 2004), and irrigation performance in orchard systems. Pierce et al. (2006) used this WSN to monitor pressure and flow on continuous move irrigation systems and to integrate a WSN for soil moisture monitoring within an irrigated field, as part of a remote, real-time irrigation monitoring and control system.

4. Conclusions

Two WSN for agriculture were developed in Washington State, one designed for regional-scale applications, such as weather networks, and the other designed for on-farm applications, such as temperature monitoring for frost protection. Both WSN applications were successfully implemented in the intended applications of AgWeatherNet and AgFrostNet, respectively. Power supply using solar panels is a major problem in areas experiencing extended periods of clouds during winter months. In addition, both WSN systems were implemented in other applications demonstrating the range of uses of WSN for agriculture. Both systems have been made commercially available to growers via a novel arrangement between WSU and a local manufacturer. Growers have purchased these systems and are eager to expand their capabilities in their farming operation.

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REFERENCES

Akvildiz, I.F., Su, W., Sankarasubramaniam, Y., Cayirci, E., 2002. Wireless sensor networks: a survey. Comput. Networks 38, 393–422.

Beckwith, R., Teibel, D., Bowen, P., 2004. Report from the field: results from an agricultural wireless sensor network. In: Proceedings of the 29th Annual IEEE International Conference on Local Computer Networks.

Blank, S.C., 1998. The end of agriculture in the American portfolio. Quorum Books, Westport, CT.

Burrell, J., Brooke, T., Beckwith, R., 2004. Vineyard Computing: sensor networks in agricultural production. IEEE Pervasive Comput. 3 (1), 38–45.

Butler, D., 2006. Everything, everywhere. Nature 440, 402–405.

Cabot, P.E., Pierce, F.J., Nowak, P., Karthikeyan, K.G., 2006. Monitoring and predicting manure application rates using

precision conservation technology. J. Soil Water Conserv. 61 (5), 282–292.
Cochrane, W.W., 1979. The Development of American Agriculture: A Historical Analysis. University of Minnesota Press, Minneapolis.
Gelsinger, P., 2006. Expanding Moore's law with convergence. http://www.intel.com/technology/silicon/mooreslaw/eml01031.htm.
Goense, D., Thelen, J., 2005. Wireless sensor networks for precise phytopthora decision support. ASABE Paper No. 053099, St. Joseph, MI.
Jackson, R.S., 2000. Wine Science Principles, Practice, Perception, second ed. Academic Press, New York.
Lewis, F.L., 2004. Wireless sensor networks. In: Cook, D.J., Das, S.K. (Eds.), Smart Environments: Technology, Protocols and Applications. John Wiley, New York.
Ley, T.W., Muzzy, A.S., 1992. Experiences with an RF telemetry based automated weather station network in Washington State. Am. Soc. Agric. Eng. Pap. 922144, St. Joseph, MI.
McFarlane, C.L. 2000. Discharge apparatus for discharging materials. U.S. Patent No. 6024305.
McFarlane, C.L. 2001. Discharge apparatus for discharging materials. U.S. Patent No. 6206306.
Perry, K.B., 1998. Basics of frost and freeze protection for horticultural crops. Hort. Technol. 8 (1), 10–15.
Pierce, F.J., Chavez, J.L., Elliott, T.V., Matthews, G., Evans, R.G., Kim, Y., 2006. A remote-real-time continuous move irrigation control and monitoring system. ASABE Paper No. 062162. St. Joseph, MI.
Ramanathan, N., Balzano, L., Estrin, D., Hansen, M., Harmon, T., Jay, J., Kaiser, W., Sukhatme, G., 2005. Designing Wireless Sensor Networks as a Shared Resource for Sustainable Development. UCLA Center for Embedded Network Sensing.
Schultz, T.W., 1964. Transforming Traditional Agriculture. Yale University Press, New Haven.
Sunding, D., Zilberman, D., 2001. The agricultural innovation process: research and technology adoption in a changing agricultural sector. In: Agricultural Production, In: Gardner, B.L., Rausser, G.C. (Eds.), Handbook of Agricultural Economics, vol. 1. Elsevier, New York.
Tarara, J.M., Ferguson, J.C., Blom, P.E., Pitts, M.J., Pierce, F.J., 2004. Automated estimation of grapevine yields via trellis tension. Trans. ASAE 47 (2), 647–657.
Thelen, J., Goense, D., Langendoen, K., 2005. Radio wave propagation in potato fields. In: First Workshop on Wireless Network Measurements, Riva del Garda, Italy, April 2005.
Wang, N., Zhang, N., Wang, M., 2006. Wireless sensors in agriculture and food industry—recent development and future perspective. Comput. Electron. Agric. 50, 1–14.
Weisman, C.J., 2002. The Essential Guide to RF and Wireless, second ed. Prentice Hall, PTR, New Jersey.
Westwood, M.N., 1993. Temperate-zone Pomology: Physiology and Culture, third ed. Timber Press, Portland.
Zhang, Z., 2004. Investigation of wireless sensor networks for precision agriculture. ASAE/CSAE Meeting Paper No. 041154. St. Joseph, MI.
Zhang, W., Kanton, G., Singh, S., 2004. Integrated wireless sensor/actuator networks in an agricultural application. In: Second ACM International Conference on Embedded Networked Sensor Systems (SenSys), Baltimore, MD, USA, November 2004, p. 317.