Site-specific Fertilizer Application in Orchards, Nurseries, and Landscapes
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OBJECTIVES

Variations in plant nutrient demand and environmental regulations provide significant incentive for development of fertigation systems that allow control of water and chemicals at a resolution smaller than the entire field or nursery block. Ease of installation and simplicity of operation suggest elimination of wires from the system. Our objectives in this research project were:

1. Develop general operating strategies for site-specific fertigation to allow application of prescribed amounts of fertilizer at specific locations.
2. Design a wireless valve controller network to simplify the implementation of precision irrigation and fertigation.

ABSTRACT

Variations in plant water and nutrient demand and environmental regulations to protect water quality provide significant justification for development of site-specific irrigation and fertigation systems. But to be accepted by growers, a system must be easy to install and operate. Accurate fertilizer application to each zone in a spatially-variable system requires an intelligent approach to monitoring fertilizer concentration and flow through the system. We have developed wireless valve controllers that self-assemble into a mesh network. Mesh networking means that controllers pass messages to extend the effective communication range without using high power radios. Solar energy is collected with a miniature panel to operate each controller node without yearly battery replacement. Nodes open or close a latching valve to control water and fertilizer flow and send sensor data back to a central field controller. Valves are operated when commanded by the field controller or when initiated by a locally stored schedule. Transmission range using 900 MHz radios with dipole antennas varied from 32 m to 217 m depending on plant obstructions and antenna height. A node's average energy use was about 6.6 mA-h/day and the solar panel produced 52 to 81 mA-h in full sun and 6 to 10 mA-h in shade. Electrical conductivity (EC) probes were used to monitor fertilizer concentration and location within fertigation lines. We tested an EC probe in UAN-32 and 20-20-20 (NPK) fertilizer solutions with 0 to 2000 μS/cm conductivities. We applied different quantities of 20-20-20 fertilizer to two fertigation zones operating simultaneously. We also developed strategies that can be implemented for sites-specific fertigation in a variety of applications. Control of valves at each fertigation zone and at the fertilizer injector can be used to apply different amounts of fertilizer, but consideration must be given to the number of fertigation zones, duration and frequency of application, and application uniformity within each zone. A network of intelligent valve controllers will allow growers in orchards, vineyards, nurseries, greenhouses, and landscapes to develop management practices that improve water and fertilizer use efficiency.

INTRODUCTION

Site-specific irrigation and fertigation control has been shown to improve crop uniformity and reduce water, fertilizer, and chemical waste from over-application. Site-specific management means that hydrozones are smaller and contain plants with more uniform needs. Site-specific irrigation has been most thoroughly tested in center pivot and linear move systems for field crops. Much less development has occurred for fixed irrigation systems, which are used in high-value permanent crops and commercial horticulture. Site-specific technology for fixed irrigation and fertigation would be applicable in orchards, vineyards, landscapes, nurseries, and greenhouses, each of which has unique management challenges. The water and nutrient demand of trees, plants, and vines are impacted by variations in soil condition, elevation, or microclimate. To complicate matters, fertigation accuracy and uniformity may be adversely affected by factors such as flow time through the pipes, fertilizer mixing in the pipes, and emitter clogging.

Converting conventional fixed irrigation systems (sprinkler and microirrigation) to allow site-specific delivery of water and nutrients would create many small hydrozones, each with a valve that must be independently controlled. Additionally, each should have the capability to read in-field sensors such as temperature and soil moisture, which are commonly used to optimize irrigation control. Implementation of such systems has been limited because of the expense and complexity of installing wired irrigation valves and sensors for many zones. We addressed this problem by developing a wireless valve controller network. In orchards, a large block of trees in which water and nutrient needs vary could be made into multiple small blocks. In container nurseries, multiple beds of different plants that were previously irrigated together could be treated individually. In landscapes, valves could be placed at any location without worrying about a web of wires. Individual valve schedules would be different in order to match differing water and fertilizer requirements. Data from electrical conductivity, water pressure, soil moisture, and water flow sensors would allow intelligent water and fertilizer control, and automatic detection of line breaks and emitter clogging.

Literature Review

Conventional irrigation management delivers water and nutrients uniformly across an entire field and ignores the reality that demand varies due to differences in soil, topology, and plant water and nutrient status. For site-specific management, large plots are divided into several smaller management units based on variable site characteristics and each is provided individualized water and nutrient input to maximize profits, crop yield, and water-use efficiency, and lessen environmental impacts. The benefits of site-specific management have been reported for many years. Matching nitrogen delivery with plant needs has increased fertilizer-use efficiency and net returns in some field crops (Beckie et al., 1997) and reduced nitrate leaching in potato crop simulations (Verhagen, 1997). Variable-rate application of granular fertilizer based on individual tree size in citrus reduced overall nitrogen application by 38% to 40% compared to conventional treatment (Zaman et al., 2005). It seems logical that the benefits of variable-rate granular fertilization would be seen for variable-rate fertigation as well. Spatially variable management has also been shown to increase profits from corn (Wang et al., 2003; Koch et al., 2004) and improve yield in potatoes (King et al., 2002) and grain sorghum (Yang et al., 2001).

Site-specific irrigation has been most thoroughly tested in center pivot and linear move systems for field crops (Camp et al., 1998; King et al., 1999; King and Kincaid, 2004; King et al., 2005; Kim et al., 2006). Much less development has occurred for fixed irrigation systems, which are used in high-value permanent crops and commercial horticulture. Site-specific technology for fixed irrigation would be most applicable in orchards, vineyards, landscapes, nurseries, and greenhouses. The water and nutrient demand of trees, plants, and vines are impacted by variations in soil condition, elevation, or microclimate. When applied uniformly, water and fertilizer may leach in light textured soils and pool in heavy soils. Planting on steep slopes, as occurs with some vineyards and orchards, creates difficulty in preventing runoff and maintaining irrigation uniformity due to pressure variations. Commercial nurseries and greenhouses contain many different varieties of ornamental plants in close proximity to one another and must deal with continually changing inventory and strict environmental regulations. A single valve typically controls water flow to many emitters, and if there are plants of differing size or water requirements, some will receive too much water, while others will receive too little. Irrigation control for landscapes in arid parts of the United States is also important since a significant amount of water is used for public turf-grass and ornamentals.

Converting conventional fixed irrigation systems to allow site-specific delivery of water and nutrients would create many small management units, each with a valve that must be independently controlled. Additionally, each unit controller should have the capability to read in-field sensors such as temperature and soil moisture, which are commonly used for closed-loop irrigation control. Site-specific control for fixed irrigation systems has been limited. Torre-Neto et al. (2000) used latching solenoid valves to control two laterals per row in a citrus orchard. Each lateral uniformly irrigated half the trees in the row, which were grouped based on size (large and small trees). Miranda (2003) controlled water flow to individual laterals for potted plants based on soil moisture feedback. Coates et al. (2006a, 2006b) and Damas et al. (2001) designed systems to control latching valves and read sensors for irrigation control. In each of these systems, wiring between valves, sensors, and controllers is expensive to install and is subject to damage by animals and machinery. Miranda et al. (2005) recognized this by developing solar-powered, standalone irrigation controllers with soil moisture sensors. However, the system did not include any communication means for centralized aggregation of sensor data or remote monitoring and reprogramming. Wireless communication has been used to monitor in-field sensors, although many use large batteries and solar panels or still require hard-wired valves for irrigation control.

Recent low-cost, low-power wireless networking technology is well suited to replace wires as the communication medium in many agricultural applications (Gonda and Cugnasca, 2006; Hebel, 2006; Wang et al., 2006). In this report, we describe the development of a solar-powered, wireless network for site-specific application of water, fertilizer, and agricultural chemicals using completely autonomous units with mesh networking capability for both sensing and valve control. Large or small valves can be used to allow management of multiple sprinklers or drip emitters (e.g., laterals), or individual plants or trees (e.g., each microsprinkler). Each valve controller was programmed with a unique schedule to match differing water and nutrient requirements and could be changed to accommodate replants, disease, growth, or seasonal changes. Data from electrical conductivity sensors were used to monitor site-specific fertigation control. Pressure, soil moisture, or flow sensors could also be used to allow closed-loop irrigation and fertigation control. In our previous work, pressure sensors were used to improve water application accuracy compared to fixed-duration irrigation and provided automatic detection of line breaks and emitter clogging (Coates et al., 2006a).

WORK DESCRIPTION

Wireless development (Objective 2 tasks) was completed before testing of fertigation control strategies (Objective 1 tasks), so it is described first. Technical details on the wireless system design and testing were published by Coates et al., 2009 (Appendix A). A technical publication on the fertigation control strategies is also being prepared.

Wireless Network

Task 2.1. Design a valve controller capable of low-power, stand-alone operation, and wireless communication.

Task 2.2. Develop a communication network to link the valve controllers with a central field controller.

Since this system was intended for application in orchards, landscapes, and nurseries, the wireless network had to be versatile enough to operate in many environments. Mesh networking allows messages to pass from one node to any other node in the network by routing them through intermediate nodes (Figure 1). One advantage of this system is increased network range without using high-power radios. This allows greater flexibility in node placement since interference or poor range between two nodes is rendered moot by alternate communication paths. Another advantage is redundancy; a failed node does not disable the network since multiple routing paths exist. In the system presented here, an operator enters node addresses and irrigation schedules on the central field controller and they are distributed to individual nodes in the network. An optional personal computer can provide a graphical interface, but is not required to operate the system.

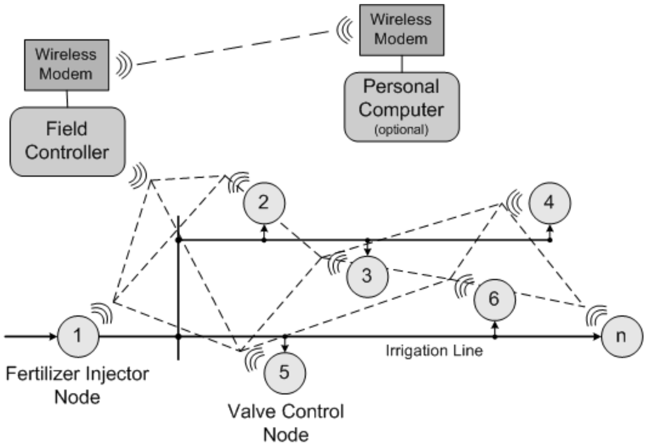

Figure 1. Layout of mesh network for wireless valve control.

Hardware

Bluetooth (IEEE 802.15.1) and ZigBee-based (IEEE 802.15.4) technologies were considered since they have been tested in agricultural environments (Kim et al., 2006; Hebel et al., 2007; Yiming et al., 2007). Bluetooth was deemed not suitable for this development due to its higher energy consumption, shorter range, and lack of support for mesh network routing (Baker, 2005; Hebel, 2006; Wang et al., 2006; Lee et al., 2007). A custom-built system that would require only a microcontroller and radio transceiver was not selected due to the complexity of implementing robust mesh networking software. Instead, commercially available low-power, mesh networking technologies were tested.

Our first-generation prototype for a wireless microsprinkler was designed using ZigBee demonstration boards (PICDEM Z, Microchip Technology, Chandler, Arizona). We found that the ZigBee implementation did not support battery-powered routers that can sleep between radio communications. While mesh networking is a key feature in ZigBee, routers are generally required to have main-line power, which was not desirable for our system. Our second-generation prototype used low-power wireless modules (Tmote Sky, Moteiv, San Francisco, California) designed specifically for battery powered mesh networking. However, testing of the mesh network showed that sending messages from the field controller to the valve controllers (downstream) was not as reliable or efficient as expected due to limitations of the manufacturer's software.

Another low-power wireless module, the MICA2 (MPR400CB, Crossbow Technology, San Jose, California), was adopted for our third-generation valve controller design (Figure 2). The MICA2 included improved downstream messaging, and the company was interested in developing products for agricultural monitoring and control, thus providing a good opportunity for collaboration and increased likelihood of future commercialization. The wireless modules used here operated at 916 MHz. The wireless module was connected to a circuit board with sensor inputs and valve control lines. A nickel-cadmium battery and a miniature solar panel were selected to provide continuous operation without yearly battery replacement. A latching solenoid valve (Netafim, Tel Aviv, Israel) was opened or closed with an 80 ms pulse from the battery. The wireless module was connected to a 1/2-wave dipole antenna (S467FL-5-RMM-915S, Nearson, Springfield, Virginia) for increased range.

A wireless module and RS-232 gateway (MIB510CA, Crossbow Technology) were connected by serial cable to an embedded controller (TD40, Tern, Davis, California), which served as the field controller for the network of remote nodes. The field controller contained a keypad to allow entry of schedules and manual operation of the remote valves, and a liquid crystal display (LCD) for viewing status information.

Figure 2. Wireless valve controller with 1-inch latching valve.

Software

The mesh networking protocol (XMesh) was handled by software included with the wireless modules. Additional software was written for latching valve actuation, a software real-time clock, schedule storage and execution, and external sensor measurement. Commands received by a remote node could be executed immediately or stored in a schedule for later completion. Each remote node in the network was programmed with a unique address between 1 and 9999. External sensor signals and battery and solar panel voltages were measured every 10 minutes and transmitted to the field controller. Conductivity of the fertigation water was measured every 4 seconds during development and testing of fertigation strategies.

Wireless Range and Function

Maximum one-hop radio range was tested using a stationary node and remote node. The wireless nodes were tested with 1/4-wave whip antennas and 1/2-wave dipole antennas. Tests were conducted under visual line-of-sight conditions (open field) and obstructed conditions (young peach orchard with 4 m high canopy) with the nodes on the ground or elevated 1, 2, or 3 m on a wooden stake. The number of successful message transmissions between nodes was monitored. Maximum range was defined as the distance between the two nodes when six or seven of seven message transmissions were successful. For each antenna/field combination, three measurements were taken (moving the remote node away from the stationary node in different directions for each) and the mean range was calculated.

The general functionality of mesh-network messaging was tested by sending valve, time, and schedule commands to the remote nodes in a mesh network. Eight remote nodes were placed close to the field controller or in distant locations that forced them to create a multi-hop mesh network. Messages were transmitted to each remote node. The time for the field controller to receive an acknowledgement message was measured. Lack of acknowledgement or long acknowledgement times indicated poor network connectivity. Nodes were occasionally moved to a new location, forcing the network to find a new path along which to pass messages (re-routing test).

Proper schedule execution required the remote nodes to maintain the correct date and time during operation. However, the internal clock was subject to inaccuracy because of crystal frequency drift. A simple test was done to measure the amount of daily clock drift. To start, the clock of the embedded controller was set to the nearest second of a reference clock. The clocks of two remote nodes were set by radio transmission of the current time stored on the embedded controller. Over eight days, the clocks of the embedded controller and the two remote nodes were queried and compared to the reference time. The average clock drift per day was calculated.

Energy Management

Charge consumption of the remote nodes was measured during wake/sleep power cycling, radio operations, sensor measurement, and valve operation. To extend battery life, nodes were in sleep-mode most of the time and only used the radio when data transfer was required. This power-cycling feature was included with the wireless module software. Solar panel charge production was also tested in direct sunlight and shaded conditions to determine whether sufficient energy was produced to recharge a node battery.

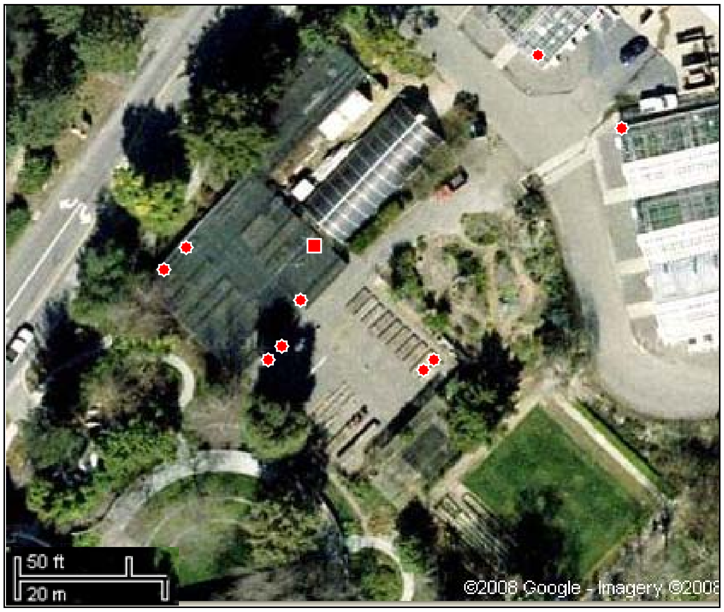

Figure 3. Nine wireless nodes (circles) and one field controller (square) installed in a small nursery and greenhouses.

Field Test

Nine nodes were installed at a campus nursery and greenhouse (Figure 3). The nodes had dipole antennas and were installed on nursery benches (1 m high). Network communication was checked and the system was monitored over 9 months to determine whether the batteries stayed charged or communication between nodes was lost. Irrigation schedules were sent to each node to confirm proper operation.

Fertigation Control

Task 1.1. Identify the factors involved in spatially variable control of fertigation.

As valves open and close in a spatially variable irrigation system, water pressure and flow rate will change. In large fertigation systems we will also need to consider the time it takes for dissolved fertilizer to reach each emitter. When attempting to deliver fertilizer to individually controlled blocks or emitters at different rates or times, standard operating procedures do not apply. One possibility for providing spatially variable control is to analyze the hydraulics of the irrigation system and develop an equation to predict flow through each branch of the fertigation lines based on the location of emitters and whether they are on or off. This would require information about the pump, irrigation piping, emitter sizes, etc. Under ideal conditions, equations would be able to determine the location of the fertilizer head and tail at any given time after initiation of fertilizer injection. Since field conditions are never ideal and frequently change, we chose not to use this approach. Instead, sensors were used to detect the fertilizer front.

In addition to the issue of long pipeline flow time, site-specific ferigation with different rates in each zone presents unique challenges. The concentration of injected fertilizer flowing to every zone in the system will be the same. This means that to apply a different amount of fertilizer to each zone requires each zone to fertigate for a different duration. Using a variable-rate injector eliminates the needs for variable application durations, but only if each zone were fertigated independently. With many small fertigation zones in a system, the grower may be required to fertigate multiple zones simultaneously. These problems and possible solutions are discussed further in the section on control strategies.

Task 1.2. Adapt our microsprinkler system to implement the application algorithm.

We decided that modification of the previous microsprinkler system would divert too much time from development of the wireless system. Instead, we implemented our fertigation strategies using the wireless system only.

Each node operated a latching solenoid valve to control the flow of water and dissolved fertilizer to a hydrozone. A positive-displacement fertilizer injector (DI16, Dosatron, Clearwater, Florida) was used to maintain the proper concentration of dissolved fertilizer as flow rate changed when valves were opened and closed. Electrical conductivity (EC) sensors in the fertigation lines allowed detection of the fertilizer head and tail by the change in conductivity as the fertilizer passed through. Using fertilizer-specific calibrations, the actual concentration of fertilizer was also determined and could be used to adjust fertigation duration at each control valve in real time.

A simple 2-pin EC probe (CDH-712, Omega Engineering, Stamford, Connecticut) with threaded body was selected for ease of installation into an irrigation system using a threaded tee (Figure 4). The meter has a conductivity range of 0 to 2,000 µS/cm. This would be suitable for many situations that require frequent fertigation using general fertilizer injected at about 100 to 450 parts per million (ppm) nitrogen (1 ppm equals 1 milligram nitrogen per liter of water). A sensor with greater range could be used for orchard and vineyard fertigations which may use higher concentrations of nutrient and operate less frequently. The conductivities of solutions containing Urea-Ammonium-

Nitrate-32% (UAN-32) or a general NPK fertilizer (20-20-20) were measured at known concentrations of nitrogen. Liquid UAN-32 alone has a nitrogen concentration of about 425,000 ppm. Solutions of known concentration were made by dilution in distilled water, which has a conductivity of 0 µS/cm. Quantities of 20-20-20 were weighed on a laboratory scale and dissolved in distilled water to create solutions of known nitrogen concentration based on the fact that the fertilizer is 20% nitrogen by weight. Calibration equations were calculated that allowed determination of nitrogen concentration based on conductivity measurements. Conductivities of fertilizer solutions using distilled and tap/irrigation water were also compared.

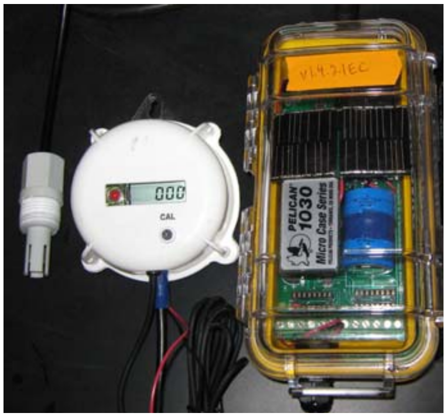

Figure 4. Electrical conductivity probe, display, and wireless node used for measurement of dissolved fertilizer in fertigation water.

Fertigation Control Tests

Task 1.3. Evaluate fertilizer application performance of the controllable system in field trials. (year 2)

Long Fertigation Lines

We first conducted tests to determine the behavior of injected fertilizer in relatively long irrigation lines. One EC sensor was installed in 5/8" drip tubing about 6 feet from the positive displacement fertilizer injector. A second EC sensor was installed after another 500 ft of drip tubing. At the end of the drip line were three microsprinklers with flow rates of 15 gallons per hour. The fertilizer injector was set to inject at a 1:100 ratio for a final nitrogen concentration of 200 ppm (20-20-20 NPK fertilizer). The EC at each sensor was recorded every 4 seconds and analyzed to depict detection of the head and tail of the fertilizer and to quantify applied fertilizer over time. The sensor can be used in routines that monitor fertilizer application (verify applied amount) or control fertilizer application by adjusting fertigation duration in real time.

Site-specific Delivery

We also conducted tests to develop site-specific fertigation strategies. Similar to the first test, we installed an EC sensor about 6 feet from the injector. Immediately downstream of the sensor, we installed a tee to provide flow to a zone controlled with a wireless node and valve. A single microsprinkler was installed and this was called fertigation zone 1. After another 12 ft along the main drip line, we installed the second EC sensor and a wireless node and valve with one microsprinkler for fertigation zone 2. Fertilizer was injected with a target rate of 200 ppm nitrogen. The goal of the tests was to apply the same quantity of water to each zone, but vary the amount of fertilizer. In the test results presented here, zone 2 was prescribed twice the amount of fertilizer as zone 1. EC was recorded over time to show how real-time monitoring and control will be implemented with the wireless nodes.

Control Strategies

Task 2.3. Develop improved control strategies for applying water and fertilizer. (years 1- 2)

Improved control strategies for fertigation were developed after testing of the fertigation control system. The control strategies are discussed in the Results and Discussion section.

Economic Feasibility

Task 2.4. Evaluate the economic feasibility of a wireless valve network for orchards, nurseries, and landscapes. (year 2)

The economic feasibility of the wireless control system is discussed in the Project Evaluation section.

RESULTS AND DISCUSSION

Wireless Network

Wireless Range and Function

Wireless range results (Table 1) showed that mean range varied greatly depending on the node configuration and the test environment. Range in the orchard was difficult to measure due to erratic connectivity near the maximum range. In some cases, the remote node could be moved a few centimeters between two locations with full and zero signal. This illustrates the value of a mesh network, which provides multiple paths of communication. To achieve a one-hop range of 100 m would, in the conditions tested here, require a dipole antenna mounted slightly higher than 1 m or a whip antenna mounted slightly higher than 2 m. In general, elevating a node with whip antenna by 1 m improved range as much as adding a dipole antenna. Dipoles antennas were used with all nodes for subsequent field testing. Ground level units would require about 20 to 30 m spacing to ensure adequate wireless connectivity. Extrapolation of these results for range estimation in other fields or orchards is difficult since the conditions would likely be different in each location.

Each node acknowledged commands, returned correct clock values, and properly opened or closed a valve. This indicated that the mesh network was operating correctly, although there were a few instances where nodes did not respond on the first attempt. This always occurred after moving the nodes to a new location or early in the re-routing test. In all cases, waiting several minutes allowed the network to stabilize and operate correctly. The average time between command and acknowledgment at the field controller was 2.2 s for a one-hop message, 5.6 s for a two-hop message, and 9.3 s for a three-hop message, giving a mean of 2.7 s per hop. Over the time frame of an irrigation cycle, such delays in communication are negligible. In a re-routing test, one node in the path to the furthest node was turned off. After several minutes of no response, subsequent messages were successfully routed along the new path, showing the self-healing properties of a mesh network.

A linear regression of the embedded controller data on clock drift gave an average lag of 0.4 s per day. A linear regression of the combined data of nodes 1 and 2 gave a lag of 6.3 s per day. If uncorrected for several weeks, scheduled irrigations or sensor measurements would occur minutes later than expected. To ensure the embedded controller and remote nodes maintained synchronized clocks, the remote nodes were updated with the correct time each day.

Table 1. Radio range under various conditions.

View	Antenna	Elevation (m)	Mean Range (m)
VLOS[1]	Whip	0	20.9
		1	67.6
		2	97.8
		3	205.2
	Dipole	0	32.7
		1	92.8
		2	192.6
		3	241.1
Orchard	Whip	0	21.7
		1	46.9
		2	94.0
		3	119.4
	Dipole	0	30.0
		1	83.2
		2	128.4
		3	145.9

[1] Visual line-of-sight

Energy Management

The total charge consumption of a node was estimated to be 6.76 mA·h per day. NiCd batteries self-discharge at 15-20% per month, which for the 170 mA·h battery used here was about 29.75 mA·h per month (1 mA·h per day). Node charge consumption and battery self-discharge had to be balanced by solar panel charge production in order to ensure continuous operation of the valve controller.

Tests of solar panel performance yielded a charge production of 26.0 - 81.3 mA·h in direct sunlight and 6.5 - 13.7 mA·h in shade. Full sunlight on a daily basis would overcharge the battery, whereas full shade on a daily basis might not provide adequate energy to recharge it. Theoretically, the 170 mA·h NiCd battery used here should be able to supply a 7.76 mA·h per day load (node and self-discharge) for 22 days. In testing, this duration was not achieved. A node without solar panel operated for just over 13 days before its battery voltage fell below 7.2 V, and finally to 3.5 V after a total of 17 days.

Field Test

The nodes installed in the campus nursery formed a mesh network and maintained adequate connectivity. Irrigation schedules resulted in the proper opening and closing of valves connected to each node. However, several nodes stopped working on several occasions due to drained batteries. This problem occurred during winter months when sunlight was poor for several consecutive days and primarily for nodes installed under shade canopies or large shade trees. Improvements to the energy management, battery size, or solar panel size will be needed to ensure perpetual operation during winter months. Though irrigation will not likely occur during this time, data from sensors (such as soil moisture and ambient temperature) would still be useful to growers.

Fertigation Control

The measured conductivity of fertigation-water was a linear function of nitrogen concentration (Figure 5). Fertilizer solutions using tap/irrigation water exhibited an offset in the measured EC compared to distilled water due to the background conductivity of the tap water itself (Figure 6). The background EC was slightly different depending on the source of water used for the fertilizer solution. In field tests, the background EC was first measured so that it could be subtracted from the EC measured during fertigation. In figure 6, tap water added about 520 µS/cm to the total conductivity of the fertilizer solution. The calibration equations used by the wireless nodes to determine fertilizer concentration were based on the digital value measured by the nodes instead of conductivity units (data not shown).

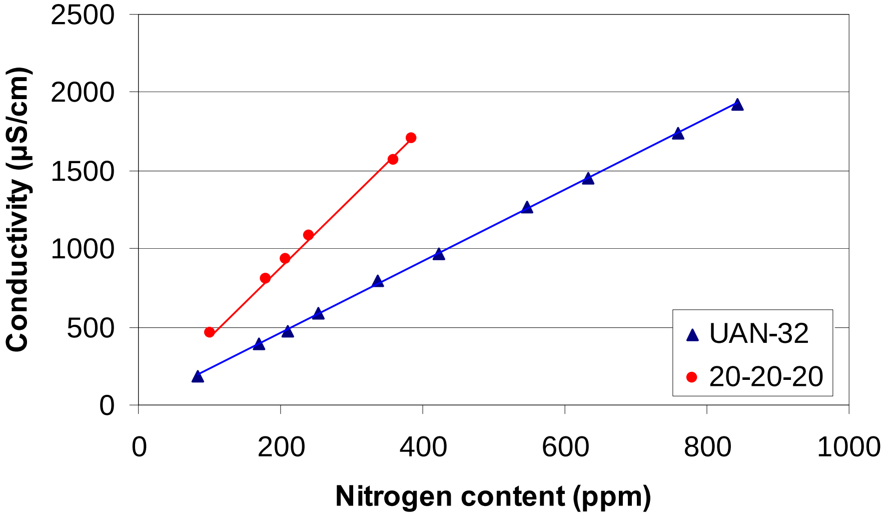

Figure 5. Electrical conductivity of fertilizer solutions with known nitrogen concentration in distilled water.

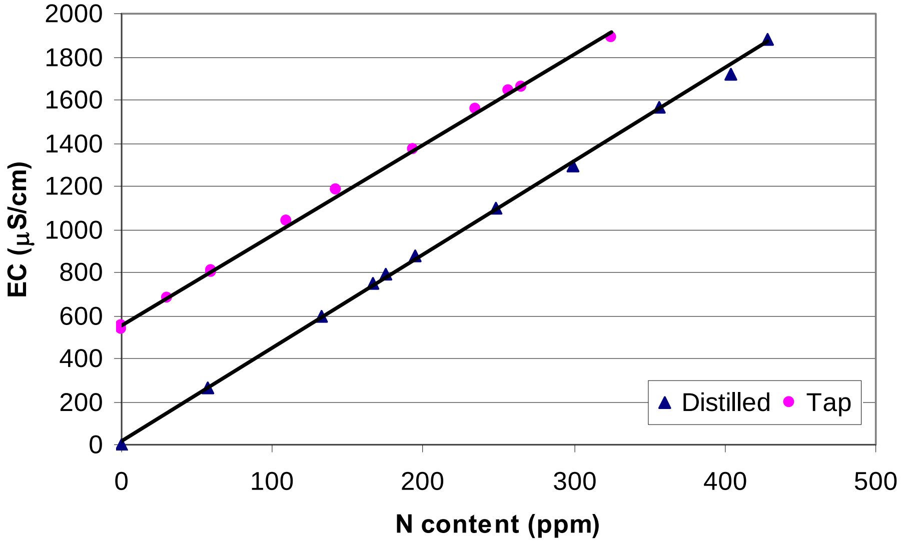

Figure 6. Electrical conductivity (EC) of 20-20-20 fertilizer solutions in distilled and tap water.

Long Fertigation Lines

Figure 7 shows the EC measurements taken near the injector and at the end of a 500 ft drip line. Irrigation was begun just after the 10-minute mark. Prior to this, water had partially drained from the line and gave an EC measurement of zero. For the first 4 minutes, only water flowed through the lines. This provided a background EC measurement of the irrigation water. The background EC was subtracted from subsequent EC measurements in order to calculate nitrogen concentration using our calibration equations. Fertilizer injection occurred between the 14 and 31-minute marks. The lines were then flushed with water for 16 minutes.

We made several observations about this simple test. EC measurements at node 1 varied over time due to the cyclical piston-action injection of fertilizer stock solution by the injector. EC measurements at node 2 were more stable, indicating the fertilizer was well mixed after traveling 500 ft. The fertilizer head and tail were clearly defined at both measurement nodes. In tests with a slower flow rate, the EC changed more gradually, indicating that the fertilizer head and tail had spread out. A dip in EC at node 2 occurred at 32 minutes and was due to air bubbles that became entrapped in the tip of the EC probe. The probe was inverted to release the bubbles and prevent entrapment of air in subsequent tests. EC at node 2 was also slightly higher than the EC at node 1 even though we would expect them to be the same. Integration of the EC (minus the background EC) over time at node 2 was 4% greater than for node 1. This would predict that more fertilizer has passed node 2, though this was not the case. Later comparison of the EC probes in the same solutions showed that the EC at node 2 was generally 40 µS/cm higher than the EC at node 1, which accounts for most of the difference seen in our measurements. Since the meters had been calibrated prior to these tests, this unexplained difference will require additional scrutiny to ensure accurate measurement of fertilizer concentration. Even with a difference in EC measurement, the sensors would be useful for monitoring fertilizer application duration in long-line systems.

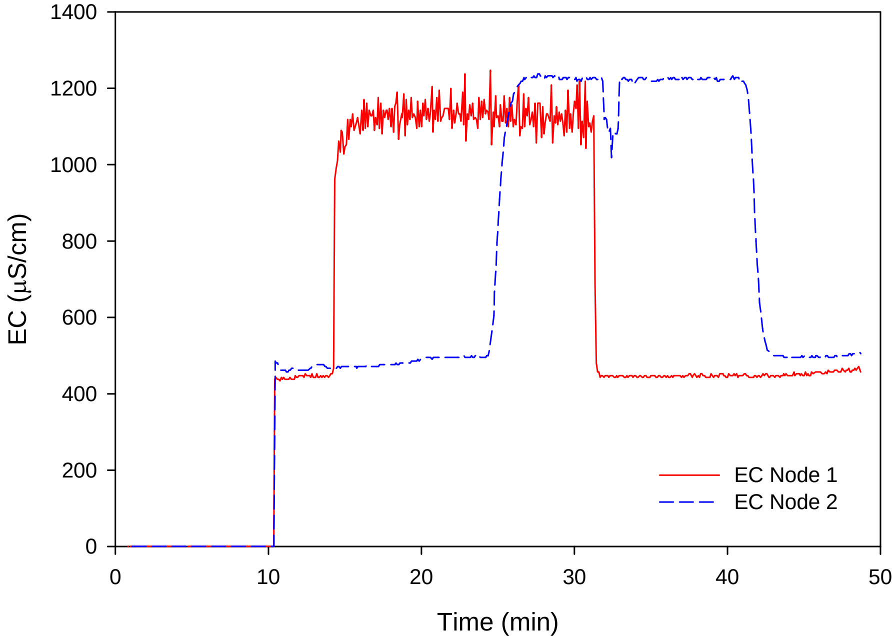

Figure 7. Electrical conductivity (EC) measurements near the fertilizer injector (node 1) and at the end of a 500 ft drip line (node 2).

Site-Specific Delivery

Application of different levels of water and fertilizer could be done through one of several methods. The simplest method would be to run each zone independently. However, in many systems, the flow rate of a single site-specific zone may result in too low a flow rate for the injector or pumps being used. Also, there might not be enough time in the day to fertigate each zone separately. This means that zones with different fertigation rates may have overlapping operating times. Figure 8 shows data for a test in which twice as much fertilizer was prescribed for zone 2 as for zone 1 by following these time points:

1. 1-minute: Irrigation in both zones began and continued for 6 minutes.
2. 7-minute: Zone 1 valve turned off, fertilizer injection began. Zone 2 fertigated for 4 minutes.
3. 11-minute: Zone 1 valve reopened, fertigation of both zones for 4 minutes.
4. 15-minute: Injector bypassed and both zones flushed for 3 minutes.
5. 18-minute: Zone 2 valve closed and zone 1 flushed for another 4 minutes.

This resulted in each zone receiving water for 17 minutes, zone 1 receiving fertilizer for 4 minutes, and zone 2 receiving fertilizer for 8 minutes. Since the flow rate to each zone was equal, the amount of fertilizer delivered to zone 2 was doubled by doubling the time. Fertigation time could be adjusted according to the expected or measured flow rate in each zone.

Figure 8 shows nitrogen concentration measured upstream of the inlet to each zone. Nitrogen concentration was calculated using our linear calibration equation applied to the measured EC minus the background EC of the irrigation water measured before injection began. Note that the EC sensor for zone 1 measured the EC of the fertigation water even when zone 1 was not fertigating. While it was possible to place the EC sensor downstream of the valve, we intentionally placed the sensor along the mainline to demonstrate that a single EC sensor could instead be used near the injector to provide feedback for site-specific fertilizer control of multiple zones. The shaded area under each curve represents the amount of fertilizer applied in each zone. The area of the shaded regions showed that zone 2 applied about twice as much fertilizer as zone 1. EC measurement of the collected water from each zone confirmed this.

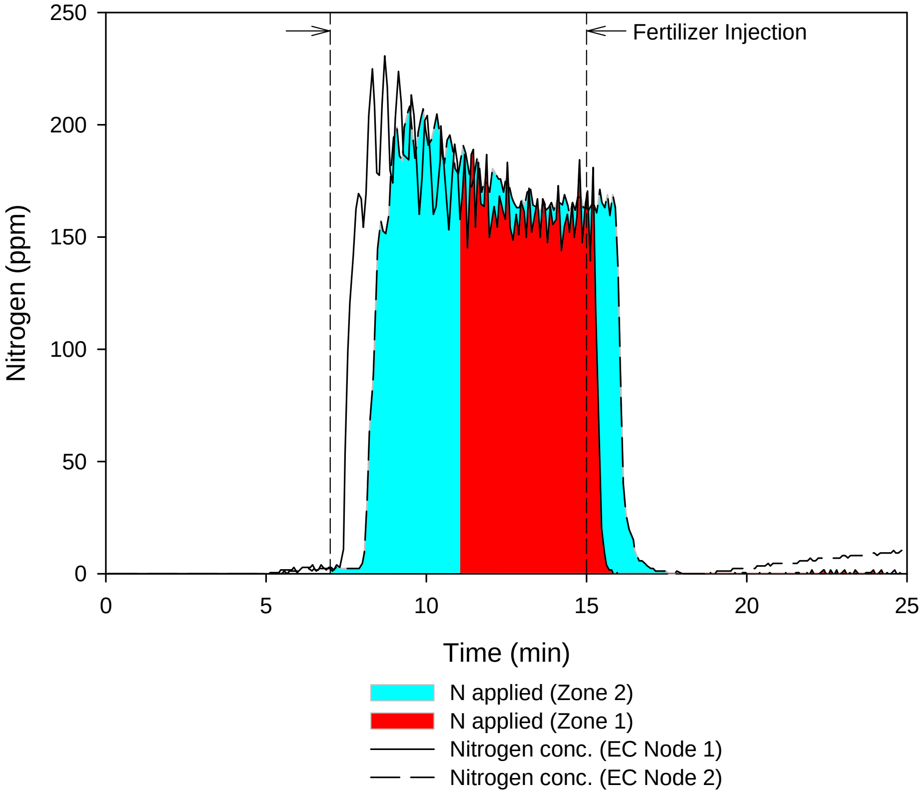

Figure 8. Nitrogen concentration (ppm) in fertigation water at inlet to two zones with area under each curve representing the applied fertilizer.

For site-specific fertigation, long lines could pose a challenge due to uncertainties in the flow time to each zone. The flow time to individual zones may be known, but since multiple zones will likely be fertigated simultaneously, the flow time to each zone may depend on the flow rates of zones that share the same irrigation mainlines. To ensure accurate application, there must be adequate time for fertigation and flushing in each zone. If fertigation duration for zones must be relatively short, EC sensors could be used to detect the fertilizer head and tail at distant points in the system to ensure proper fertilizer application. Extensive spreading of the fertilizer head and tail could also be problematic if the application time was short and a zone valve was open during a dilute portion of the head or tail. However, our tests conducted with long fertigation drip lines indicate that fertilizer mixing did not cause a substantial spreading of the fertilizer head or tail, though pipes with more turbulent flow should be tested.

We demonstrated the capability for site-specific control by varying the durations of irrigation and fertigation in each zone. As with conventional fertigation, this method requires that the emitter rates in each zone are known in order to calculate the actual amount of fertilizer applied. EC meters could be used to improve the accuracy of fertilizer to each zone so long as proper calibration was maintained. A flow meter could be connected to a wireless node with an EC meter to provide system-side monitoring of applied water and fertilizer and detection of faults.

Control Strategies

There are several methods that could be used to deliver water and fertilizer on a site-specific basis with the wireless control system. The field would be divided into several fertigation zones, each with its own valve. Site-specific delivery of water is fairly simple to accomplish, since we only need to open or close valves at each zone to apply the desired amount, though issues of pump efficiency and pipe flow rates must be considered. A few growers already do this to some extent, but many require workers to open and close zone valves manually. Varying the amount of applied fertilizer is more complex and can be controlled by opening and closing valves at each fertigation zone, varying the fertilizer injection rate, or turning the injector on and off. Each method had advantages and disadvantages that will be discussed here.

The simplest method would be to fertigate each zone independently, one after the other. Depending on the number of zones, fertigation duration, and fertigation frequency, independent fertigation of each zone may not be feasible. To maximize the benefit of a site-specific system, it would be desirable to increase the number of fertigation zones such that each zone delivers a unique amount of fertilizer to properly match crop demand. However, there might not be enough time available to irrigate a large number of zones independently. There may also be resource limitations such as limited hours of water/pump availability and energy costs associated with running pumps longer, technical limitations such as minimum flow rate or peak efficiency for pumps, or biological criteria such as the best time of day to apply water and fertilizer. The result is that the operation of several fertigation zones would have to overlap.

The task of delivering different fertilizer rates to simultaneously-operating zones is not trivial. Zones could be fertigated at different rates by using different durations of fertilizer application within each zone. For example, to apply more fertilizer in a zone, the valve at that zone would be open for a longer duration during the fertigation phase of an irrigation cycle. The fertigation phase of multiple zones could be synchronized at the on-time or the off-time (Figure 9a,b). The scenarios pictured assume that fertilizer reaches each zone at about the same time. If this is not true, EC sensors would be used to determine when fertilizer reached each zone. The advantage to these methods is that fertigation in each zone is controlled by its own node, reducing the effort needed to coordinate with a control node at the fertilizer injector. The disadvantage is that air may be allowed to enter the fertigation line through emitters when a zone valve is turned off for a fertigation delay (zone 1 in Figure 9a, b). In conventional fertigation, water immediately precedes and follows injected fertilizer. This causes fertigation to start at the nearest emitter first and the farthest emitter last. The fertilizer is flushed from the line with clean water such that fertigation also stops at the nearest emitter first and the farthest emitter last. The result is a relatively uniform application of fertilizer within the zone. For on-synchronization, fertigation water could drip out of emitters along the line instead of being flushed down the line immediately. The result would be poor fertigation uniformity caused by over-application of fertilizer at the nearest emitters and under-application at the farthest emitters. For off-synchronization, lack of water in the line before fertigation allows fertilizer to flow to the last emitter at a higher rate than it is flushed, again causing poor uniformity. The problem may be relatively small for short irrigation lines or for sprinkler systems that do not allow water to drip out by gravity. Long lines with drip emitters may be the least suited for these control methods.

Controlling the injector in addition to the zone valves could also be used. The injector is operated on a bypass that can be controlled with a valve by the wireless network. Multiple injection phases would allow the zones to operate simultaneously for most of the irrigation cycle, and then run a little longer for zones that require more fertilizer and subsequent flushing (Figure 9c). Water pressure is maintained during the irrigation, so air entering the line is not a problem. The disadvantage is that the total irrigation cycle is longer to accommodate the added fertigation and flushing phase, which could be fairly long (up to an hour) if there is a long irrigation line between the injector and fertigation zone.

The best fertigation control strategy would likely depend on the intended application. Independent fertigation would be best strategy if it satisfied the grower’s fertigation needs. Small container nurseries or landscapes with sprinklers would also operate well with on or off-synchronization. Orchards with drip emitters and long lateral lines would be better suited with on/off control of the injector.

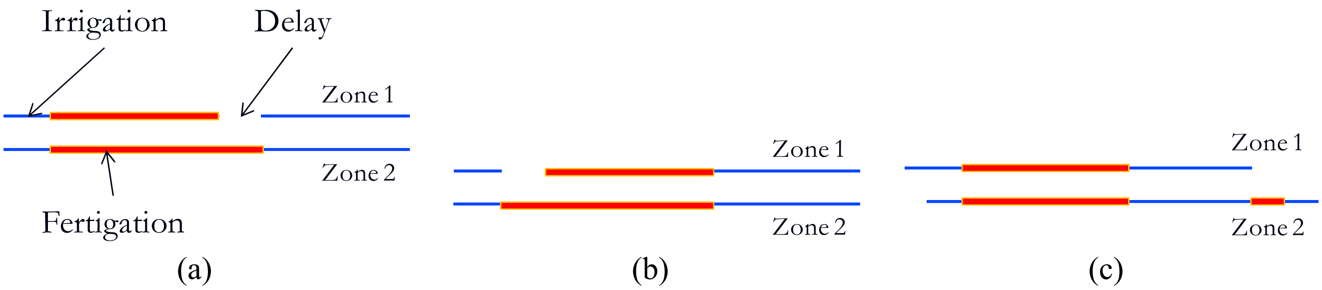

Figure 9. Timelines depicting fertigation control methods in which multiple zones apply fertilizer during an irrigation cycle: (a) on-time synchronization of fertigation phase, (b) off-time synchronization of fertigation phase, and (c) injector turned on and off.

PROJECT EVALUATION

Economic Feasibility

Two of the greatest challenges in promoting adoption of new technology among growers are demonstrating that the system is relatively simple to use and proving that the system will increase profit. For site-specific irrigation and fertigation control, a grower could conceivably install wires to operate a solenoid valve at each zone. The cost of control wire installation into open pipe trenches is about $1 per foot. Additional trenching, as would be required for a grower to add new zones, adds to the cost substantially. Adding soil moisture or other environmental sensors would increase cost further.

Usually, the task is too daunting for a grower to even consider. Wireless controllers could replace wires for both the valves and sensors, which would be especially useful to upgrade existing installations.

The wireless nodes developed here cost about $270 per unit in small quantity. This includes $110 for the wireless module, $60 for the electronic components, enclosure, antenna, battery, and solar module, and $100 for circuit board fabrication and assembly. A latching valve adds about $30 to the total cost. We estimate that high-volume production could drive the costs down about 50%. Integration of the wireless module with the main circuit board would likely be needed to minimize total production cost. The cost of installation of wireless nodes in nurseries, orchards, vineyards, or landscapes would be less than for the same number of wired valves since the labor associated with control wires is eliminated. Maintenance of the system should be similar to conventional wired irrigation systems. The only required operation would be replacement of the rechargeable battery every few years. Annual cleaning of the node enclosure would be recommended to improve light exposure of the solar panels. Both of these maintenance operations would not have significant cost since they are completed so infrequently.

Wireless nodes for agriculture are now commercially available, though most only offer sensing capability. Because the technology is still relatively young, nodes cost about $500 to $1000 each. Nodes can connect to multiple sensors or valves, but each device adds to the total node cost. Part of the cost associated with the node is that units are still manufactured in relatively small quantities. Another part of the cost for mesh-networking nodes comes from the communication software, which has taken years of development for robust operation. As growers begin to adopt this new technology, the price will fall due to economies of scale. Early adoption will likely be limited to growers of high-value crops, such as container nurseries and vineyards.

Economic benefit from improvements in crop quality and quantity due to reduced over-watering/fertilizing are still under investigation. We have started a multi-year project to quantify water and fertilizer savings, and crop and environmental impacts of wireless irrigation/fertigation control in container nurseries. This will allow us to estimate the payback period for the wireless system in nurseries. The payback period for other crops would likely be different. We have spoken with nursery and orchard growers that currently implement site-specific control using manually operated valves at each zone. The growers hire several laborers to simply drive around and open or close valves each day. Wireless control could provide substantial savings from reduced labor costs. One anecdotal report for a vineyard claimed that the cost of a wireless control system for irrigation valves was recovered from savings in labor costs alone (Holler, 2008).

Long-term savings in water, fertilizer, and energy when using a site-specific irrigation system are highly dependent on the crop and current irrigation management practices. In general, we estimate that water savings of 10-20% should be achievable. Agricultural customers in California could save a portion of the 8 trillion gallons of water used on farms (USDA-NASS 2002a), as well as water pumping costs, which amount to over $300M per year (USDA-NASS 2002b). While the amount of water use may decrease, on-site pumping costs may not decrease if pumps are operated longer in order to supply water to many smaller irrigation zones independently. Similar to the fertigation strategies described here, simultaneous operation of multiple zones to optimize pumping for irrigation would be an important consideration. Utility companies could also realize energy savings from reduced water treatment and pumping costs for growers using municipal water sources. We plan to investigate these energy saving benefits in another multi-year project using wireless irrigation control in commercial landscapes.

Continuing Work

We have two projects planned to continue the work that was described here. We will be working with technology companies to further develop and test wireless control systems in container nurseries and commercial landscapes. The goal is to estimate water and fertilizer savings, energy and labor savings, and environmental impact reductions.

CONCLUSION

We developed and tested a wireless valve controller network for site-specific irrigation and fertigation. Wireless nodes eliminate the need for wired valves and sensors. This allows simpler installation and management of small hydrozones. A field controller provided a simple interface for monitoring and control. Mesh network communication using 916 MHz radio modules was successful in allowing transmission and acknowledgement of commands for valve operation, scheduling, sensor measurement, and a remote node clock. A multi-hop mesh network allows greater network coverage, even when one-hop range is short. Energy management evaluation showed that there should be adequate solar energy collected to continuously power the node if direct sunlight is available part of the day. Based on results from testing during the winter season, we determined that energy demand must be further decreased or energy production or storage must be increased.

We developed fertigation control strategies for use with a site-specific system. The amount of fertilizer delivered to each zone can be controlled by varying the durations of irrigation and fertilizer injection. Electrical conductivity sensors were useful for detection of the fertilizer head and tail in long fertigation lines and for quantifying the amount of fertilizer being applied in each zone. The fertigation strategy selected for a particular application will depend heavily on the irrigation system layout and fertigation needs. We are working with technology companies to further develop and test wireless systems in container nurseries and commercial landscapes.

OUTREACH ACTIVITIES

We presented our work at several conferences during the project period (listed below). We met several growers and advisors that are interested in our work and we expect their input to aid in further development and commercialization of the technology.

Dahlia Greidinger Symposium
    Haifa, Israel, March 12-14, 2007
    Paper & Presentation: Wireless Network for Irrigation Valve Control
UC Precision Ag Workgroup Meeting & Miniconference
    UC Davis, June 12-13, 2007
    Presentation: Wireless Valve Controller Network for Site-specific Irrigation
ASABE Annual Meeting
    Minneapolis, MN, June 17-20, 2007
    Paper & Presentation: Site-Specific Water and Nutrient Application by Wireless Valve Controller Network (paper #072247)
FREP/WPHA Conference
    Tulare, CA, November 27-28, 2007
    Paper & Presentation: Wireless Valve Control Network for Fertigation Control and Monitoring
CITRIS Research Exchange
    Berkeley, CA, March 19, 2008
    Presentation: Site-Specific Water and Fertilizer Application by Wireless Valve Controller Network

AgEng Conference
  Crete, Greece, June 23 – 25, 2008
  Paper and Presentation: Site-specific Water and Chemical Application by Wireless Valve Controller Network
ASABE Annual Meeting
  Providence, RI, June 29 - July 2, 2008
  Paper & Presentation: Site-Specific Water and Chemical Application by Wireless Valve Controller Network (paper #084483)
FREP/WPHA Conference
  Modesto, CA, November 12–13, 2008
  Paper & Presentation: Using Site-Specific Fertilization in Orchards, Nurseries, and Landscapes
UC ANR Floriculture & Nursery Workgroup
  Davis, CA, January 27, 2009
  Presentation: Nursery Irrigation by Wireless Valve Controller Network
ASABE Annual Meeting
  Reno, NV, June 21 – June 24, 2009
  Presentation: Site Evaluation of Wireless Mesh Network for Site-Specific Irrigation and Fertigation Control
FREP/WPHA Conference
  Visalia, CA, November 17-18, 2009
  Paper & Presentation: Precision Delivery of Fertilizer to Satisfy Crop Demand

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Appendix A

Wireless System Design and Testing Publication

WIRELESS MESH NETWORK FOR IRRIGATION CONTROL AND SENSING

R. W. Coates, M. J. Delwiche

ABSTRACT. *Variations in plant water and nutrient demand and environmental regulations to protect water quality provide significant justification for site-specific irrigation and fertigation systems. We have developed wireless valve controllers that self-assemble into a mesh network. Mesh networking means that controllers pass messages to extend the effective communication range without using high-power radios. Solar energy is collected with a 200 mW panel to operate each controller node without yearly battery replacement. Nine nodes were tested in a mesh network, and each properly responded to commands. Measurements of battery voltage, solar panel voltage, enclosure temperature, and external sensors were transmitted every 10 min. Irrigation schedules were stored locally on each node and executed automatically. Schedules for each node were unique, based on the needs of the particular area being irrigated. Internal clock drift was an average 6.3 s per day. Clock offset was removed using daily time stamps. One-hop transmission range using 916 MHz radios varied from 20.9 m with a whip antenna at ground level to 241.1 m with a dipole antenna at 3 m. Node commands were acknowledged after an average of 2.7 s per hop. Charge consumption was approximately 7.03 mA·h per day for the node circuit and 1 mA·h per day for battery self-discharge. The solar panel produced 26.0 to 81.3 mA·h in direct sunlight and 6.5 to 13.7 mA·h in shade. Node operation is expected to be continuous with occasional sunlight exposure. Soil moisture, pressure, temperature, and other environmental sensors will be used for feedback control and detection of problems. Such a network of intelligent valve controllers will allow growers in orchards, vineyards, nurseries, greenhouses, and landscapes to develop management practices that improve water- and fertilizer-use efficiency.*

Keywords. *Control, Irrigation, Fertigation, Latching valve, Mesh network, Precision agriculture, Radio, Sensing, Site specific, Solar energy, Spatially variable, Variable-rate application, Water-use efficiency, Wireless.*

Conventional irrigation management provides water and nutrients uniformly across an entire field and ignores the reality that demand varies due to differences in soil, topology, and plant water and nutrient status. For site-specific management, large plots are divided into several smaller management units based on variable site characteristics and each is provided individualized water and nutrient input to maximize profits, crop yield, and water-use efficiency, and lessen environmental impacts. The benefits of site-specific management have been reported for many years. Matching nitrogen delivery with plant needs has increased fertilizer-use efficiency and net returns in some field crops (Beckie et al., 1997) and reduced nitrate leaching in potato crop simulations (Verhagen, 1997). Variable-rate application of granular fertilizer based on individual tree size in citrus reduced overall nitrogen application by 38% to 40% compared to conventional treatment (Zaman et al., 2005). It seems logical that the benefits of variable-rate granular fertilization would be seen for variable-rate fertigation as well. Spatially variable management has also been shown to increase profits from corn (Wang et al., 2003; Koch et al., 2004) and improve yield in potatoes (King et al., 2002) and grain sorghum (Yang et al., 2001).

Site-specific irrigation has been most thoroughly tested in center pivot and linear move systems for field crops (Camp et al., 1998; King et al., 1999; King and Kincaid, 2004; King et al., 2005; Kim et al., 2006). Much less development has occurred for fixed irrigation systems, which are used in high-value permanent crops and commercial horticulture. Site-specific technology for fixed irrigation would be applicable in orchards, vineyards, landscapes, nurseries, and greenhouses, each of which has unique management challenges. The water and nutrient demand of trees, plants, and vines are impacted by variations in soil condition, elevation, or microclimate. When applied uniformly, water and fertilizer may leach in light textured soils and pool in heavy soils. Planting on steep slopes, as occurs with some vineyards and orchards, creates difficulty in preventing runoff and maintaining irrigation uniformity due to pressure variations. Commercial nurseries and greenhouses contain many different varieties of ornamental plants in close proximity to one another and must deal with continually changing inventory and strict environmental regulations. A single valve typically controls water flow to many emitters, and if there are plants of differing size or water requirements, some will receive too much water, while others will receive too little.

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Mention of trade names or commercial products is for descriptive purposes only and does not imply endorsement by the University of California.

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Irrigation control for landscapes in arid parts of the U.S. is also important since a significant amount of water is used for public turf-grass and ornamentals.

Converting conventional fixed irrigation systems to allow site-specific delivery of water and nutrients would create many small management units, each with a valve that must be independently controlled. Additionally, each should have the capability to read in-field sensors such as temperature and soil moisture, which are commonly used for closed-loop irrigation control. Site-specific control for fixed irrigation systems has been limited. Torre-Neto et al. (2000) used latching solenoid valves to control two laterals per row in a citrus orchard. Each lateral uniformly irrigated half the trees in the row, which were grouped based on size (large and small trees). Miranda (2003) controlled water flow to individual laterals for potted plants based on soil moisture feedback. Coates et al. (2006a, 2006b) and Damas et al. (2001) designed systems to control latching valves and read sensors for irrigation control. In each of these systems, wiring between valves, sensors, and controllers is expensive to install and is subject to damage by animals and machinery. Miranda et al. (2005) recognized this by developing solar-powered, standalone irrigation controllers with soil moisture sensors. However, the system did not include any communication means for centralized aggregation of sensor data or remote monitoring and reprogramming. Wireless communication has been used to monitor in-field sensors, although many use large batteries and solar panels or still require hard-wired valves for irrigation control.

Recent low-cost, low-power wireless networking technology is well suited to replace wires as the communication medium in many agricultural applications (Gonda and Cugnasca, 2006; Hebel, 2006; Wang et al., 2006). In this article, we describe the development of a solar-powered, wireless network for site-specific application of water, fertilizer, and agricultural chemicals using completely autonomous units with mesh networking capability for both sensing and valve control. Large or small valves can be used to allow management of multiple sprinklers or drip emitters (e.g., laterals), or individual plants or trees (e.g., each microsprinkler). Each valve was programmable with a unique schedule to match differing water and nutrient requirements and could be changed to accommodate replants, disease, growth, or seasonal changes. Data from electrical conductivity, pressure, soil moisture, or flow sensors could allow closed-loop irrigation and fertigation control. In previous work, pressure sensors were used to improve water application accuracy compared to fixed-duration irrigation and provided automatic detection of line breaks and emitter clogging (Coates et al., 2006a).

The objectives of this research were to: (1) design an intelligent valve controller with low-power, wireless communication, (2) design an energy management system to allow stand-alone operation of each valve controller, and (3) develop a communication protocol to link the valve controllers with a central field controller.

Materials and Methods

System Design

Overview

Since this system was intended for application in orchards, greenhouses, landscapes, and nurseries, the wireless network had to be versatile enough to operate in many environments. Mesh networking allows messages to pass from one node to any other node in the network by routing them through intermediate nodes (fig. 1). One advantage of this system is increased network range without using high-power radios. This allows greater flexibility in node placement since interference or poor range between two nodes may be rendered moot by an alternate communication path. Another advantage is redundancy; a failed node does not disable the network since multiple routing paths exist. In the system presented here, an operator enters node addresses and irrigation schedules on the central field controller, and they are distributed to individual nodes in the network. An optional personal computer can provide a graphical interface, but is not required to operate the system.

Hardware

Bluetooth (IEEE 802.15.1) and ZigBee-based (IEEE 802.15.4) technologies were considered since they have been tested in agricultural environments (Kim et al., 2006; Hebel et al., 2007; Yiming et al., 2007). Bluetooth was deemed not suitable for this development due to its higher energy consumption, shorter range, and lack of support for mesh network routing (Baker, 2005; Hebel, 2006; Wang et al., 2006; Lee et al., 2007). A custom-built system that would require only a microcontroller and radio transceiver was not selected due to the complexity of implementing robust mesh networking software. Instead, commercially available low-power, mesh networking technologies were tested.

Our first-generation prototype for a wireless microsprinkler was designed using ZigBee demonstration boards (PICDEM Z, Microchip Technology, Chandler, Ariz.). The mesh network communication protocol was handled by the company's implementation of the ZigBee wireless networking standard (www.zigbee.org). At that time, we found that the ZigBee implementation did not support battery-powered routers that can sleep between radio communications. While mesh networking is a key feature in ZigBee, routers are generally required to have main-line power. There is a provision allowing for battery-powered "beaconed" networks (time-synchronized networks that allow routers to sleep), but no ZigBee vendors could be found that had implemented it in their software. It was decided to use different technology instead of attempting to implement time-synchronization in this system.

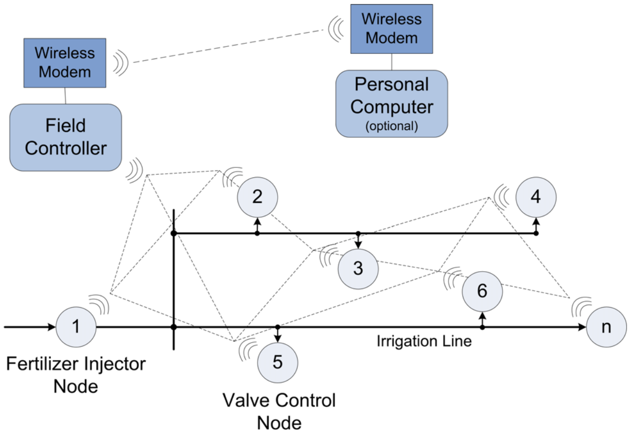

Figure 1. Layout of mesh network for wireless valve control.

Our second-generation prototype used low-power wireless modules (Tmote Sky, Moteiv, San Francisco, Cal.) designed specifically for battery-powered mesh networking. A low-power wireless module like this is commonly called a "mote," which is defined as a small particle or speck, because it is the result of research aimed at sensors only a cubic millimeter in size (Warneke et al., 2001). The modules were programmed with TinyOS (www.tinyos.net), an open-source operating system written for wireless sensors. TinyOS includes its own communication protocol, but ZigBee-compliant modules running TinyOS are being developed (Suh and Horton, 2004). ZigBee compliance would provide the benefits of industry standardization, such as vendor product interoperability, security, and marketability. The second-generation prototype was tested using two communication protocols: a broadcast messaging component (Drip) was used when sending downstream messages from the field controller to the valve controllers, and a mesh routing routine (Multihop) was used for sending upstream messages from the valve controllers to the field controller. Testing of the mesh network showed that sending messages from the field controller to the valve controllers was not as reliable or efficient as expected.

Another TinyOS-based wireless module, the MICA2 (MPR400CB, Crossbow Technology, San Jose, Cal.), was adopted for our third-generation valve controller design, to be discussed here (fig. 2). The reasons for moving to these modules were that the mesh networking software, XMesh, still used TinyOS but included improved downstream messaging, and the company was interested in developing products for agricultural monitoring and control, thus providing a good opportunity for collaboration and increased likelihood of future commercialization. The wireless modules used here operated at 916 MHz.

A prototype circuit board was provided by Crossbow Technology for development of the valve controller (remote node). It included a 51-pin connector to interface with the wireless module, a 3.0 V voltage regulator, thermistor, signal multiplexer, and input/output (I/O) screw terminals. Figure 3 shows a simplified block diagram of the circuit components and connection to valve and sensors. Valve actuation and sensor excitation were controlled by microcontroller outputs on the wireless module. The input channel multiplexer allowed a single analog-to-digital converter (ADC) input on the microcontroller to measure each of eight signals in succession, including board-level temperature, solar panel voltage, and six external sensors. A second ADC input measured battery voltage. A valve switching circuit was connected to the prototype board for valve control.

Figure 2. Third-generation valve controller with 1-inch latching valve.

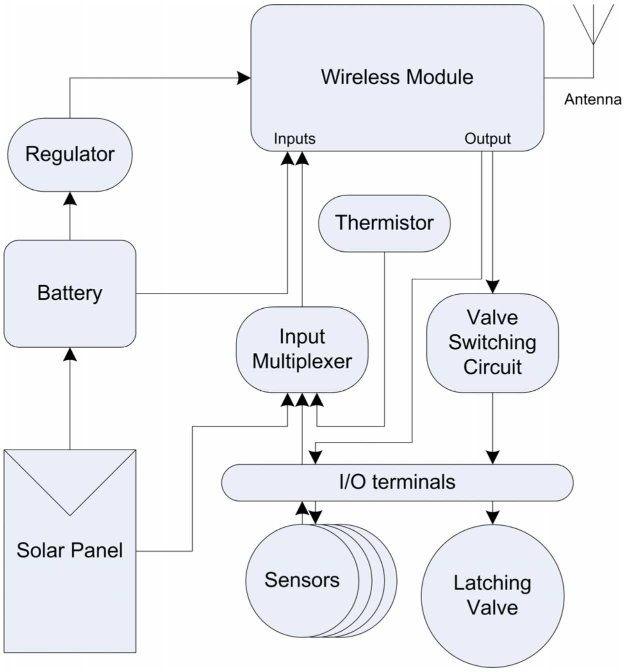

Figure 3. Block diagram of valve controller (node) primary components.

A 7.2 V, 170 mA·h nickel cadmium battery constructed from two 3.6 V batteries in series (BattR5, Solarbotics, Alberta, Canada) and a 200 mW (13.4 V, 15 mA) solar panel constructed from two 6.7 V panels in series (SCC3733, Solarbotics, Alberta, Canada) were selected to provide continuous node operation without yearly battery replacement. The solar panel was selected to provide a higher peak voltage than the expected 9 V maximum battery voltage during charging, and current that would supply enough charge to replenish all energy used by the node. A nickel cadmium (NiCd) battery was chosen because it is more resilient to overcharging, is generally less expensive than nickel metal hydride (NiMH) and lithium ion (Li-ion) battery chemistries, and has a lower internal resistance for providing pulses of high current with less voltage drop (Linden and Reddy, 2001). The disadvantages of NiCd are self-discharge of about 15% to 20% per month, larger size than NiMH and Li-ion, and disposal restrictions. Shallow discharge from the low-power circuitry may also cause voltage depression (commonly referred to as memory effect), which would reduce the effective capacity of the battery. However, shallow discharge/charge cycles may increase the life of the NiCd battery to allow several thousand daily cycles, more than expected from deep discharge cycles (Linden and Reddy, 2001).

Many wireless sensors are designed to operate on only 3 V, but a higher level was used here in order to provide adequate voltage for operating a 1-inch or 1/8-inch latching solenoid valve (Netafim, Tel Aviv, Israel). The valves were rated for 12 VDC or more, but operated effectively at 7.2 V. Valve control voltage could easily be boosted by using a slightly larger battery or charge pump with storage capacitors. Bidirectional current to the valves was controlled using an H-bridge switching circuit composed of two N-channel metal-oxide-semiconductor field-effect transistors (MOSFETs) and two P-channel MOSFETs. Two more N-channel MOSFETs inverted the microcontroller signals to drive the P-channel MOSFETs. Four diodes were used to suppress inductive voltage spikes produced by the valve when turning off the MOSFETs. Valves were opened or closed with an 80 ms pulse from the battery.

The wireless modules had an MMCX jack used with a 1/4-wave whip (purchased with the module) or 1/2-wave dipole antenna (S467FL-5-RMM-915S, Nearson, Springfield, Va.). The circuit components were housed in a clamshell-style polycarbonate enclosure (1030 Micro Case, Pelican Products, Torrance, Cal.) to provide dirt and moisture protection during outdoor testing (fig. 2). Holes were drilled in the box for the antenna, valve, and sensor wires. The antenna was mounted directly to the box, and cable ports were used to provide a seal for valve and sensor wires.

A base node consisting of a wireless module and RS-232 gateway (MIB510CA, Crossbow Technology) was connected by serial cable to an embedded controller (TD40, Tern, Davis, Cal.), which served as the field controller for the network of remote nodes. The field controller was mains powered with a 12 V power supply, but could also use a 12 V lead-acid battery with a solar panel recharger. A high-efficiency switching regulator supplied 5 V to the embedded controller, and a 3 V linear regulator provided power to the base node. The field controller contained a keypad to allow entry of schedules and manual operation of the remote valves, and a liquid crystal display (LCD) for viewing status information (fig. 4). Several keys were labeled with functions: Time, Schedule, Manual Control, Node Status, Enter, and Delete. The remaining keys were numbered 0 to 9 for input of addresses, time, commands, etc. A wireless modem was available for wireless access to the embedded controller (Coates et al., 2006b), but was not used here.

Software

The mesh networking protocol (XMesh) was handled by software included with the wireless modules. Formation and operation of a mesh network was as follows. When powered, the nodes automatically began forming a network by transmitting “route update” messages. Route update messages were broadcast by each node so that neighboring nodes could determine the “cost” of routing messages between each other (Teo et al., 2006; Crossbow, 2007). This information was used to determine the best path for message routing from a remote node (valve controller) to the base node (field controller). Every remote node created a routing table that included an entry for each neighboring node. Associated with each neighbor was a routing cost metric, based on the shortest path-to-base and link quality indicators (transmit/receive success rates) from the route update messages. A remote node transmitted data messages to the neighbor with the lowest cost (called its parent). If a transmission failed, the message was re-routed to the neighbor with the next lowest cost. Route update messages were transmitted every 5 min to ensure that the routing tables in each node were updated as network conditions changed, reducing the likelihood that impromptu re-routing would be necessary. Once these routing paths were established, messages could be sent upstream from remote to base or downstream from base to remote. Upstream messages were passed (hopped) from one node to the next along the best route until the base node was reached. Downstream messages simply hopped between nodes along the reverse route of the upstream messages until the destination node was reached. The base node of the field controller was programmed to run the manufacturer’s software (XMesh-Base).

The remote nodes were programmed with code written in nesC, an extension of the C language used for programming with TinyOS. The primary features used for irrigation control and sensing were valve actuation routines, a software real-time clock, schedule storage and execution, and individual sensor measurement routines (table 1). One-time valve commands (i.e., open, close, toggle valve) were sent using the XCommand messaging component provided by the manufacturer. A CustomCommand message type was created for commands requiring additional data (e.g., irrigation duration). Recurrent valve operations and other commands were triggered by a CustomCommand

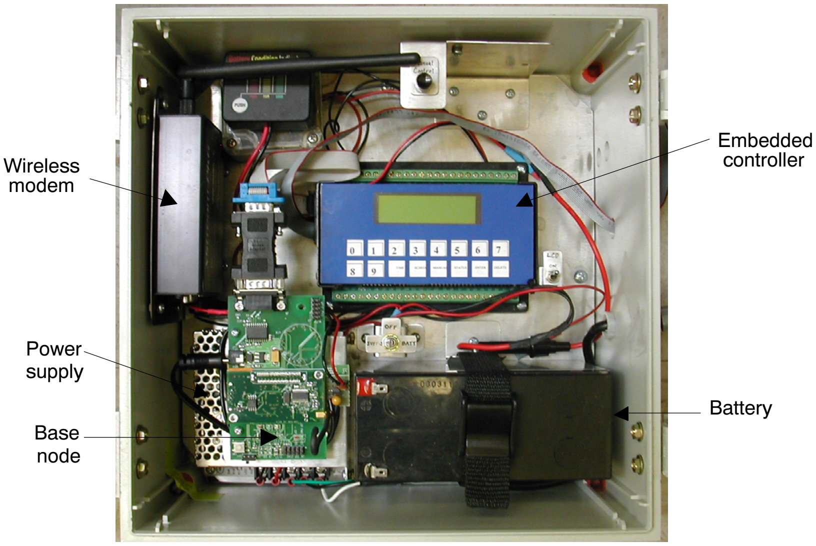

Figure 4. Field controller with embedded controller and wireless module (base node).

Table 1. Remote node command descriptions.

Group	Command	Trigger(s)	Function
Valve operation	OpenValve	XCommand Msg, Schedule	Latch valve open
	CloseValve	XCommand Msg, Schedule	Latch valve closed
	ToggleValve	XCommand Msg, Schedule	Latch valve to opposite state
	IrrigationCycleTime	CustomCommand Msg, Schedule	Open valve, wait for *t* min, close valve
Clock	SetClock	CustomCommand Msg	Set remote node clock to match field controller (FC)
	GetClock	CustomCommand Msg	Get remote node clock time, transmit to FC
Command scheduling	ScheduleOneTime	CustomCommand Msg	Schedule a command for a specific date/time
	ScheduleInterval	CustomCommand Msg	Schedule a command for a specific time and every *t* min thereafter
	ScheduleDayOfWeek	CustomCommand Msg	Schedule a command for specific weekdays/times
	ScheduleDeleteOne	CustomCommand Msg	Delete one previously scheduled command
	ScheduleDeleteAll	CustomCommand Msg	Delete all previously scheduled commands
Sensor measurement	ReadAllSensors	CustomCommand Msg, Schedule	Measure all sensors, transmit values to FC
	ReadSoilMoisture	CustomCommand Msg, Schedule	Measure soil moisture sensor, transmit value to FC
	ReadPressure	CustomCommand Msg, Schedule	Measure pressure sensor, transmit value to FC
	ReadOnboard	CustomCommand Msg, Schedule	Measure temp. and battery/solar voltages, transmit values to FC

message or entry in the stored schedule. OpenValve, CloseValve, and ToggleValve simply actuated the valve accordingly. IrrigationCycleTime opened the valve, waited for the specified duration to elapse, and then closed the valve. The SetClock command was used to send time stamps to synchronize the remote node clock with the field controller (FC). Time stamps were automatically transmitted to nodes when joining the mesh network and once each day. GetClock caused the remote node to send the current time of its software clock. ReadSoilMoisture, ReadPressure, ReadOnboard, and ReadAllSensors caused the appropriate sensors or onboard voltages (i.e., solar panel, battery, thermistor) to be measured with the analog-to-digital converter and returned in a message to the field controller. These four commands were not used in the tests presented here. Instead, all sensor inputs and internal voltages were transmitted by the remote node every 10 min. ScheduleInterval caused a command to be executed at a recurring interval. For example, a sensor reading could be scheduled to occur every 30 min or an irrigation cycle every 4 days. ScheduleDayOfWeek executed a command at a specific time on one or more days of the week. For example, an irrigation cycle could be scheduled to run every Tuesday and Saturday at 7:00 a.m. ScheduleOneTime scheduled a single execution of a command to occur at a later time and date. Since the objective is for the remote nodes to run continuously for years without loss of power, schedules were stored in RAM. Schedules could be stored in the non-volatile EEPROM, but at the expense of slower access time and higher energy consumption. Scheduled commands were deleted individually or all at once using the ScheduleDeleteOne or ScheduleDeleteAll commands.

Each remote node in the network was programmed with a unique address between 1 and 9999 (XMesh allows addresses between 1 and 65534, excluding 126). Upon power-up, the node initialized variables and started timers that controlled how often internal events were triggered (fig. 5). The node then operated in an event-driven fashion; functions were called when triggered by an interrupt event (e.g., received a radio message, a timer expired). When a SetClock command was received, the time stamp included with the message was assigned to the clock variables of the node. Each second, an internal timer caused the clock variables to be incremented by 1 s. When a valve or sensor command was received by the node, it was parsed and entered into a pending-command queue for execution. Schedule messages caused the command and related data parameters to be stored in memory. Immediately after processing any radio message, an acknowledgement (Ack) was transmitted back to the base node. This only acknowledged that the command was received, but did not confirm its proper execution (e.g., that the valve actually opened properly). Once per minute, the internal schedule was checked for entries requiring execution (i.e., the scheduled time matched the clock time), and the associated commands were added to the pending-commands queue. Every 10 min, a sensor timer triggered the measurement of sensor inputs and internal voltages. These values were transmitted to the field controller. Closed-loop irrigation control based on soil moisture measurements and fault detection based on pressure measurements were tested in previous work (Coates et al., 2006a) and will be added in future software revisions. Closed-loop fertigation control using conductivity sensors and flow meters is also being investigated.

Software was written in C++ for operation of the embedded controller. Commands were entered on the field controller (embedded controller keypad) and sent by RS-232 serial port to the base node and then by radio to the remote nodes. While idle, the field controller displayed the number of active nodes, indicated when a new node had joined the network, or displayed an error message when a node had not responded for more than 1 h. Four function keys were used to enter specific modes of operation (table 2). When a function key was pressed, the controller simply prompted the user to select from a menu of commands, enter a remote node address, and enter any specific data associated with the selected command. Commands properly received by the remote node triggered an application-level acknowledgement, which was sent back to the embedded controller. Success or failure to receive this acknowledgment was displayed on the embedded controller display.

Packets sent to the base node from the embedded controller used a specific message format and framing protocol according to the manufacturer (table 3). Packets were framed at the beginning and end with a *sync* byte (0x7E). Any instance of 0x7E or 0x7D within the framed portion of the packet was preceded with an *escape* byte (0x7D) and exclusive-ORed with 0x20 (e.g., 0x7E becomes 0x5E). The *packet type* was always 0x42. *Destination*

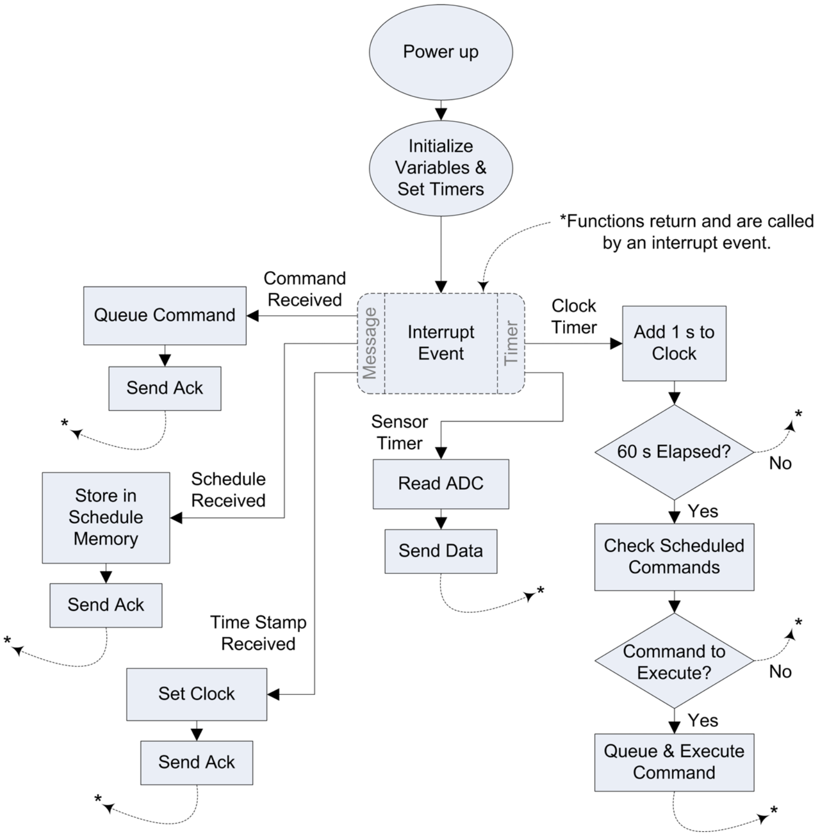

Figure 5. Remote node software flow diagram.

address for downstream messages was that of the remote node. For upstream messages, the base node forwarded them to its serial port (to reach the embedded controller), which had an address of 0x007E. *AM Type* indicated the type of XMesh message (e.g., downstream message to node, upstream message to base). *Group number* was set to the default 0x6F. *Data length* was the number of bytes for the *source address*, *origin address*, *sequence number*, *application ID*, and *payload*. For downstream messages sent by the embedded controller, the *source address*, *origin address*, and *sequence number* were set to zero since they were automatically set by the base node before radio transmission. In upstream messages received by the embedded controller, the *source address* was that of the most recent sender (base, address 0x0000), the *origin address* was the original remote node that sent the message, and *sequence number* was a message counter incremented by the origin node. The *application ID* (*app ID*) was set to a value indicating the type of message content. XCommand (0x30) or CustomCommand (0x1E) were *app ID*s used for downstream messages from base to remote. SensorData (0xF0), ClockData (0xF1), or CmdAck (0xF7) were used for upstream messages from remote to base. The message *payload* was filled with data, which differed depending on the *app ID* and command. All two-byte values in the message were stored in little-endian order (least significant byte first). In table 3, serial port address 0x007E is stored in little-endian order (0x7E00) and then converted for transmission (since 0x7E is reserved, it is exclusive-ORed with 0x20 and preceded with an *escape* byte as described above). A cyclic redundancy check (CRC) checksum was calculated on all bytes before framing with *sync* and *escape* bytes. The complete packet was sent to the base node through the RS-232 serial connection. The base node then transmitted the message to the proper remote node. Conversely, upstream messages received by the embedded controller were unframed and parsed into individual variables. An upstream

Table 2. Field controller function key descriptions.

Function Key	Description
Time	Change FC clock or view/update remote node clock
Manual control	Send command to remote node for execution
Schedule	Schedule one-time or recurrent commands
Status	View remote node data or time of last message

Table 3. Components and examples of framed packets between the embedded controller and base node.

	Sync	Packet Type	Destination Address	AM Type	Group No.	Data Length	Source Address	Origin Address	Seq. No.	App ID	Payload	CRC	Sync
Bytes[a]	1	1	2	1	1	1	2	2	2	1	Data Len - 7	2	1
US Msg[b]	0x7E	0x42	0x7D5E00	0x0B	0x6F	28	0x0000	0x0200	37	0xF0	0x01010A...	0xE1A9	0x7E
DS Msg[c]	0x7E	0x42	0x0100	0x0C	0x6F	22	0x0000	0x0000	0	0x1E	0x090307...	0x23D4	0x7E

[a] Number of bytes without escape bytes.

[b] Example for upstream (US) sensor data message from node 2, received at serial port of embedded controller.

[c] Example for downstream (DS) command (ScheduleOneTime, IrrigationCycleTime) to node 1, sent from embedded controller.

sensor-data message contained a total of 40 bytes (27 bytes for payload) without framing or CRC.

SYSTEM EVALUATION

Wireless Range and Function

Maximum one-hop radio range was tested using the base node and one remote node. A simple program was written in which the remote node transmitted seven messages to the base node and summed the number of acknowledgements received in return. The sum was displayed in binary on three LEDs of the remote node and audibly signaled on a piezoelectric buzzer by varying duty cycle. The acknowledgement status at the remote node was monitored while moving farther from or closer to the base node. At each location, the remote node was rotated around the axis of its antenna. Maximum range was defined as the distance between the two nodes when six or more acknowledgements were consistently received. In most cases, all seven messages were consistently acknowledged at the recorded maximum range, and moving farther away resulted in frequent fluctuations below six acknowledgements. The wireless nodes were tested with 1/4-wave whip antennas and 1/2-wave dipole antennas. Tests were conducted under visual line-of-sight conditions (open field) and obstructed conditions (young peach orchard) with the nodes on the ground or elevated 1, 2, or 3 m on a wooden stake. For each antenna/field combination, three measurements were taken (moving away from the base in different directions for each) and the mean range was calculated. Tests were conducted on a dry, sunny day in mid-spring. The open field contained bare soil and the peach trees had 4 m tall, leafed out canopies.

The general functionality of network messaging was tested by sending valve, time, and schedule commands to the remote nodes in a mesh network. Eight remote nodes were placed close to the base or in distant locations that forced them to create a multi-hop mesh network. Confirmation of mesh connectivity was obtained by monitoring radio traffic near the base node. The GetClock command was transmitted to remote nodes at one (nearest base), two, and three hops away. Acknowledgement and upstream transmission of the clock time after each command indicated correct functionality of the nodes and network. OpenValve and CloseValve commands were also transmitted to remote nodes with valves. Message acknowledgement and correct valve actuation were noted. The delay between issuance of the command and receipt of acknowledgment at the base was used to estimate the per-hop time required for completion of messages. Automatic re-routing of messages was tested by turning off one node along the preferred routing path, thus forcing a new path to be selected. Re-routing was successful if messages still reached their destination and resulted in an acknowledgement.

Proper schedule execution required the remote nodes to maintain the correct date and time during operation. However, the internal clock was subject to inaccuracy because of crystal frequency drift. For a ±30 ppm rated crystal, this would amount to about ±2.6 s per day. A simple test was done to measure the amount of daily clock drift. To start, the clock of the embedded controller was set to the nearest second using a reference time provided by a U.S. government website (NIST and USNO, 2008). While not an official NIST standard when accessed through the website, it claims to be accurate to within 0.1 s. The clocks of two remote nodes were set by radio transmission of the current time stored on the embedded controller. Over the following eight days, the clocks of the embedded controller and the two remote nodes were queried and compared to the reference time. The average clock drift per day was calculated. Any offset introduced by radio delay when setting the remote clock was theoretically canceled out by the same delay when the clock was queried. For example, say the embedded controller transmitted the current time, t_1, to a node. If there was a 2 s radio delay, the remote node had local time t_1-2 relative to the embedded controller. At time t_2, the embedded controller transmitted a clock query to the remote node. After the 2 s radio delay, the embedded controller time was t_2+2, and the remote node was just receiving the message and returned its local time of t_2, i.e., the same time (on the embedded controller) at which it was queried.

Energy Management

To extend battery life, nodes were in sleep mode most of the time and only used the radio when data transfer was required. This power-cycling feature was included with the wireless module software. The nodes spent most time in sleep mode and synchronously woke every 125 ms to listen for radio activity. If no activity was detected, the node returned to sleep. Current consumption of the remote nodes was measured by reading the voltage drop across a 10 Ω resistor placed in series with the battery. The resistor had a relatively large value compared to typical current-sensing resistors of less than 1 Ω, but allowed greater resolution when monitoring small currents. The greater voltage drop it produced did not induce low-voltage problems with the circuit since the battery voltage (7.2 V) was far above the circuit operational voltage of 3.0 V. Voltage drop was viewed on an oscilloscope during wake/sleep power cycling, radio operations, sensor measurement, and valve operation. The resulting waveforms were used to estimate current and duration for each operation. A Riemann sum with 20 μs interval was used to calculate charge consumed for power cycling. Each wake-up was brief (about 7 ms) and capacitors supplied most of the momentary current, not the battery, so measured voltage drop did not reach the expected peak current for a radio operation. After cessation of the wake cycle, the battery recharged the capacitors over 23 ms. For other operations, abrupt current changes resulted in nearly square waveforms, so charged consumed per day was estimated by:

$$q = \frac{itn}{10^6} \quad (1)$$

where q is the charge consumed per day (C), i is the current (mA), t is the duration of a single operation (ms), and n is the number of times the operation occurred each day. NiCd batteries self-discharge at 15% to 20% per month (Linden and Reddy, 2001), which for the 170 mA·h battery used here, was about 29.75 mA·h per month (1 mA·h per day or an average current of 42 μA). The total estimated node charge consumption plus self-discharge was compared to solar panel charge production.

Solar panel performance was tested in full sunlight and shade conditions during clear weather in late fall. A data logger recorded open-circuit voltage from one panel and output current as the voltage drop across 10 Ω load resistors for two panels every 3 min over 17 days. The open-circuit panel and one load-connected panel were mounted horizontally in direct sunlight. The second load-connected panel was mounted horizontally in the shadow of an opaque board to produce complete shading from direct sunlight. Indirect sunlight could still illuminate the panel, but all sources were relatively non-reflective surfaces such as buildings. The total charge produced each day was estimated using a Riemann sum with a 3 min interval.

Solar charging of the NiCd battery was checked using two valve-controller nodes, one with a solar panel and one without. The node enclosures, which had a clear lid, were covered with paper to reduce direct solar heating of the internal components. They were placed outside for nine sunny days and set to transmit data messages every 15 s (to increase energy use). The messages contained measurements for microcontroller voltage, battery voltage, solar panel voltage, thermistor resistance, and sensor inputs. One message was logged at the field controller every 2 min. Battery and thermistor measurements were converted from ADC integers to voltage and temperature. Battery voltage and temperature inside the enclosure were plotted over time. Theoretical battery life without recharging was calculated by dividing the battery capacity by the node charge consumption. This assumed that the battery fully discharged its rated capacity. A more realistic battery life estimate was made by operating a node without solar panel until its voltage fell below the nominal 7.2 V level.

RESULTS AND DISCUSSION

WIRELESS RANGE AND FUNCTION

The radio range results (table 4) showed that mean range varied greatly depending on the node configuration and the test environment. Orchard range was difficult to measure due to erratic changes in acknowledgement status near the maximum range. In some cases, the remote node could be moved a few inches between two locations, causing the number of acknowledgements to change from zero to seven. This illustrates the value of a mesh network, which provides multiple paths of communication. To achieve a one-hop range of 100 m would, in the conditions tested here, require a dipole antenna mounted slightly higher than 1 m or a whip antenna mounted slightly higher than 2 m. In general, elevating a node with whip antenna by 1 m improved range as much as adding a dipole antenna. Ground level units would require about 20 to 30 m spacing to ensure adequate wireless connectivity. Extrapolation of these results for range estimation in other fields or orchards would be difficult since the conditions would likely be different in each location.

Careful node placement during network deployment, even if not ideal, can help ensure good connectivity. Using a start-up sequence similar to our seven-acknowledgement test would allow radio communication quality to be assessed during installation. In addition, IEEE 802.15.4 compliant wireless modules operating at 2.4 GHz have become more popular among manufacturers. These modules have improved range due to increased sensitivity, and could be adopted as replacements for the current 916 MHz models.

In the mesh network test, each node acknowledged commands, returned correct clock values, and properly opened or closed a valve. This indicated that the mesh network was operating correctly, although there were a few instances in which nodes did not respond on the first attempt. This always occurred after moving the nodes to a new location or early in the re-routing test. In all cases, waiting several minutes allowed the network to stabilize and operate correctly. The average time between command and acknowledgment at the base was 2.2 s for a one-hop message, 5.6 s for a two-hop message, and 9.3 s for a three-hop message, giving a mean of 2.7 s per hop. In the re-routing test, one node in the path to the farthest node was turned off. Initially, the downstream path was broken and commands resulted in no acknowledgement from the remote node. Since downstream messages must follow the path formed by upstream messages, a new path was not established until upstream data and health messages initiated the re-routing process (i.e., selection of a new parent to replace the removed node). After several minutes of no response, subsequent downstream messages were successfully routed along the new path. An acknowledgement and correct time data were received from the destination node.

Figure 6 shows the clock drift for the embedded controller and two nodes over 8 days. The clock of each remote node lagged the reference time after only half a day. A linear regression of the embedded controller data gave an average lag of 0.4 s per day. A linear regression of the combined data of nodes 1 and 2 gave a lag of 6.3 s per day of operation. This was longer than expected, possibly due to greater than rated

Table 4. Radio range under various conditions.

View	Antenna	Elevation (m)	Mean Range (m)
Visual line-of-sight	Whip	0	20.9
		1	67.6
		2	97.8
		3	205.2
	Dipole	0	32.7
		1	92.8
		2	192.6
		3	241.1
Orchard	Whip	0	21.7
		1	46.9
		2	94.0
		3	119.4
	Dipole	0	30.0
		1	83.2
		2	128.4
		3	145.9

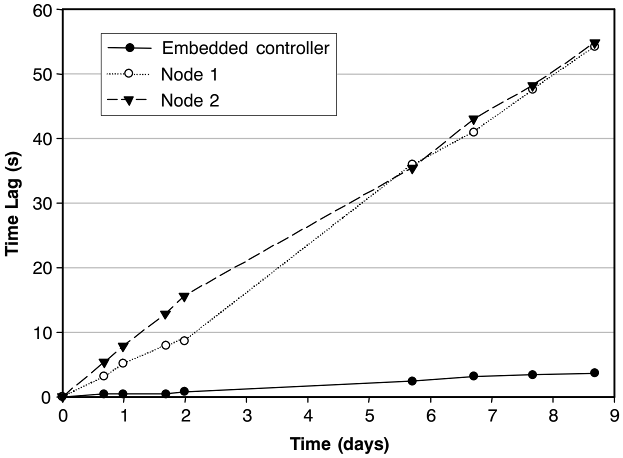

Figure 6. Time lag of remote node clocks and embedded controller clock compared to reference time.

crystal skew. To ensure that the embedded controller and remote nodes maintained synchronized clocks, the remote node clocks were updated with a new time stamp each day. Based on the per-node message delay in one direction (half the measured command-to-acknowledgement delay), the clock of a node five hops from the base would lag 6.8 s upon initialization. For synchronized power-cycling of the network, the remote nodes calculate clock skew and offset to maintain an accurate internal clock (not based on real-world time). While this method may be implemented for the real-time clock, an accuracy of several seconds is adequate for irrigation control.

ENERGY MANAGEMENT

Current and consumed charge for each valve controller operation are shown in table 5. The average sleep current of 66 μA was higher than the wireless module's rated current of 15 μA due to several resistor bridges on the circuit boards used to measure solar panel and battery voltages, and to set regulator output voltage. Other sensors, such as the thermistor and external sensor inputs, were connected to digital outputs and were disabled when not in use. Additional circuit modifications could reduce sleep current further. The current consumption for sensor measurements was based on the specifications of an integrated pressure sensor. The total charge consumption of a node was estimated to be 25.30 C per day, which is equivalent to 7.03 mA·h per day and a mean current of 0.29 mA. Several radio communication parameters could be modified to decrease the frequency of radio use and save additional energy. Node charge consumption and battery self-discharge have to be balanced by solar panel charge production in order to ensure continuous operation of the valve controller.

Figure 7 shows the open-circuit voltage in full sunlight and calculated output currents from solar panels in sunlight and shade for four typical days. Peak open-circuit voltage was 12.7 V, and peak current was about 15 mA in direct sunlight and 1.5 mA in shade. Integration of current over a single day yielded a minimum and maximum charge production of 93.6 and 292.7 C (26.0 and 81.3 mA·h) in direct sunlight and 23.4 and 49.3 C (6.5 and 13.7 mA·h) in shade. Full sunlight on a daily basis would overcharge the battery, whereas full shade on a daily basis might not provide adequate energy to recharge it. Daily charge production may be worse in the winter and better in the spring and summer due to differences in daylight duration and solar altitude (USNO, 2009). For comparison, the duration of daylight around the time of this test (late fall, Davis, Cal.) was approximately 10 h. Compared to the winter solstice of 9.5 h and summer solstice of nearly 15 h, this test was conducted on a relatively short day. Solar altitude is the angle of the sun with respect to the horizon. During this test, peak solar altitude (occuring around noon each day) was 32°, which was relatively low compared to ~75° on the summer solstice and similar to ~28° on the winter solstice. Extended periods of overcast or cloudy weather (acting as shade) would be of greater concern than daylight duration or solar altitude. Based on our data, at least two 10 h direct-sunlight days would be needed to completely recharge a depleted battery. Energy management will be critical to ensure continuous node operation without battery degradation from overcharging or node shutdown from low battery voltage. A refined design could include a transistor switch to disconnect the solar panel when battery overcharging occurs. Minimizing radio use during periods of poor energy production could be enabled through software. Jiang et al. (2005) described an energy management scheme using supercapacitors and a Li-ion battery that could also be adopted.

Figure 8 shows the battery voltages and enclosure temperatures for the solar recharged and non-recharged nodes. It is evident by the voltage peaks that the solar panel charged the battery each day. However, the daily voltage low-point started to decrease after day 5. We think this was due to overcharging of the battery and excessive heating of the enclosure. A daytime enclosure temperature over 40°C resulted in a reduced battery voltage the following morning, likely due to a combination of poor charging and increased self-discharge at high temperatures (Linden and Reddy, 2001). Voltage depression is a long-term effect not likely responsible for the voltage changes seen here. Solar radiation shielding of the enclosures will be necessary to protect the circuit and battery. Continued operation of this node following the test indicated that the battery did not suffer from a permanent depression in voltage. However, the long-term capacity of the battery may be reduced. The battery voltage of the non-recharged node slowly decreased through the duration of the test, with fluctuations due to changes in battery voltage and resistance during daily temperature variation.

Table 5. Current, duration, frequency, and calculated charge consumption during remote node operations.

Operation	Peak Current (mA)	Duration (ms)	Frequency	Charge Consumed (C/day)
Sleep	0.066	If not awake	If not awake	4.78
Power cycling (RX)	4.1[a]	7[a]	Every 125 ms	16.31
Route Msg (TX)	31	150	Every 5 min	1.339
Route Msg Neighbors (RX)	14	100	Every 1 min[b]	2.016
Data Msg (TX)	31	40	Every 10 min	0.179
Command Msg (RX)	14	120	Every 6 h	0.007
Command Ack Msg (TX)	31	40	Every 6 h	0.005
Health Msg (TX)	31	50	Every 7 min	0.319
Health Ack Msg (RX)	14	80	Every 7 min	0.231
Valve Actuation	615	80	Twice per day	0.098
Sensor Measurement	7	20	Every 10 min	0.020
Total				25.30

[a] Because of short duration, capacitors supplied most momentary current, clipping the measured voltage drop at 41 mV; battery then recharged capacitors over 23 ms.

[b] Route messages were assumed to come from five neighbors at 5 min intervals resulting in an average of one per minute.

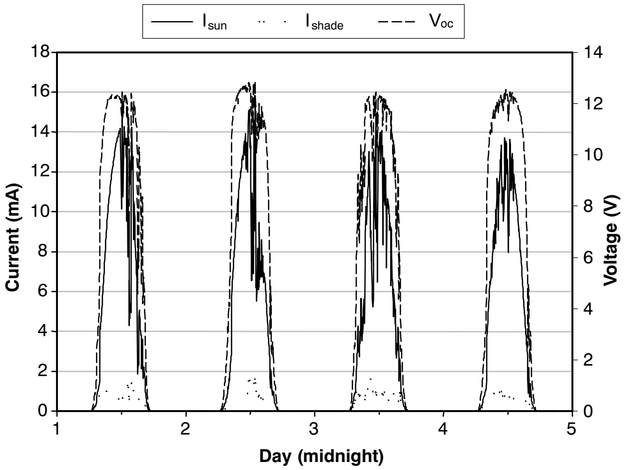

Figure 7. Solar panel open-circuit voltage (V_{oc}) and current for a sunlit panel (I_{sun}) and shaded panel (I_{shade}) through 10 Ω load over 4 days.

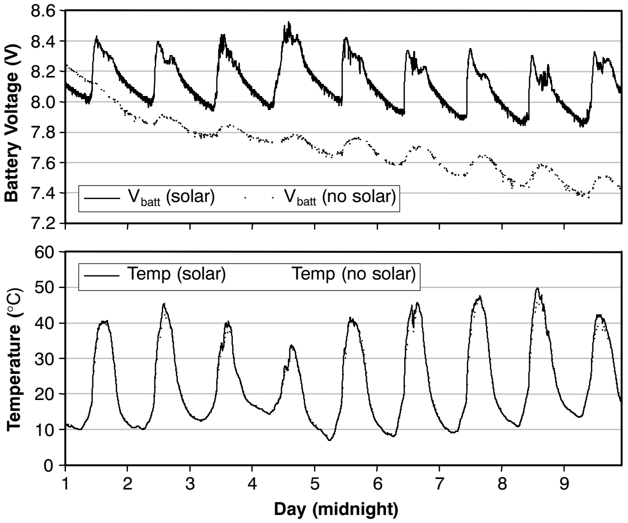

Figure 8. Battery voltage (V_{batt}) and enclosure temperature (Temp) over 9 days for valve controllers with and without a solar panel.

Theoretically, the 170 mA·h NiCd battery used here should be able to supply a load of 8.03 mA·h per day (node and self-discharge) for 21 days. In testing, this duration was not achieved. A node without solar panel operated for about 13 days before its battery voltage fell below 7.2 V, and finally to 3.5 V (battery considered exhausted) after a total of 17 days. One reason for the less than theoretical operating duration is a difference in the load used here compared to that used for battery capacity determination.

CONCLUSION

A wireless, solar-powered valve controller network was designed and tested. A field controller provided a simple interface for monitoring and control. Mesh network communication using 916 MHz radio modules was successful in allowing transmission and acknowledgement of commands for valve operation, scheduling, sensor measurement, and a remote node clock. Messages were sent to nodes up to three hops away with a mean command-to-acknowledgment time of 2.7 s per hop. Clock drift of 6.3 s per day was removed with daily time updates. Mean one-hop radio range was between 20.9 m and 241.1 m, depending on antenna type, elevation above ground, and surrounding environment. We recommend using a dipole antenna and node mounted greater than 1 m high. A multi-hop mesh network allows greater network coverage even when one-hop range is short. Energy management evaluation showed that a 200 mW solar panel produced at least 6.5 mA·h per day in shade and 26.0 mA·h per day in direct sunlight. With a total charge consumption of 8.03 mA·h per day, there should be adequate solar energy produced to continuously power the node if direct sunlight is available part of the day. Solar radiation shielding is needed to reduce enclosure over–heating. Continuing developments will include improved energy management techniques such as energy-use monitoring and solar panel switching to prevent battery overcharge.

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