IRT WIRELESS INTERFACE FOR AUTOMATIC IRRIGATION SCHEDULING OF A CENTER PIVOT SYSTEM

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ABSTRACT

Infrared thermometers (IRTs) have been widely used in agricultural research as a method to measure canopy temperatures, an indicator of crop water stress. Although IRTs have proven to be reliable within the critical range for plant stress, they would be cumbersome for the grower to set up, maintain, and dismantle each irrigation season in a commercial system. A wireless sensor network of IRTs integrated into a center pivot lateral can facilitate the implementation of a fully automated irrigation system with sensors that can easily be mounted and dismounted from the system lateral line. The objectives of this study were to build an economical wireless interface for IRTs using radio frequency (RF) mesh networking modules and to investigate the network characteristics in a field application comparing mesh networking and simpler point-to-point networking. Our main hypothesis was that the mesh networking system was best suited for installation on the pivot lateral and its self-healing capabilities would overcome the majority of interference issues associated with the pivot's metal trusses, pipeline, and towers. The mesh networking architecture was expected to outperform the non-mesh network.

Relatively inexpensive integrated silicon circuit components were utilized to construct the sensor interface module; the approximate cost was $150, which included the signal conditioning electronic circuit that interfaced the IRT with the microprocessor and the RF module, the battery, and the solar panel. As part of the network testing, the received signal strength index (RSSI) for two different antenna types was tested at two different heights above grade under the pivot and at thirteen different distances from the pivot point. The RSSI using a whip antenna was superior to that of a dipole antenna.

Wireless sensor networks were deployed in the field (Field-WSN) and along the pivot lateral (Pivot-WSN) in point-to-point topologies using both non-mesh and mesh firmware, respectively. The Field-WSN outperformed the Pivot-WSN. Data packet retrieval was more than 90% successful for 93% of the growing season using the non-mesh networking firmware for the WSN

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established in the field crop. The Pivot-WSN data packet retrieval was more than 90% successful for 70% of the time using mesh-networking firmware, but data packet retrieval dropped significantly to < 80% success for 100% of the time when the firmware was changed to a non-mesh networking protocol during a trial period after the growing season. These results indicate the potential role of mesh networking and wireless sensors in agricultural field settings.

KEYWORDS. Automated irrigation, crop water stress, infrared thermometry, wireless sensors

INTRODUCTION

Earlier research showed that the timing of drip irrigation applications could be triggered by a signal that is positive if the crop canopy temperature is greater than a threshold temperature for greater than a region-specific threshold time (Evett et al., 1996, 2000). Crop stress can be detected non-invasively by using infrared thermometers (IRTs) to measure canopy temperature (Wanjura et al., 2003). The Time Temperature Threshold (TTT) method has been successful in automatically scheduling irrigations based on the needs of well-watered corn and soybean crops (Evett et al., 2006; Peters and Evett, 2006a,b).

Commercialization of a fully automated center pivot system using the TTT method will require the elimination of sensor wiring to reduce costs and complexity, and to improve system robustness while avoiding conflicts with farming operations. Challenges inherent in any wireless system include adequate bandwidth, efficient routing protocols, power usage, electromagnetic interference, radio range, and battery life (Zhang et al., 2004). A wireless network for industrial applications based on the IEEE802.11 standard was investigated by Ferrari et al. (2006). The network architecture investigated was a master-slave configuration that demonstrated connectivity between a personal computer and three remote sensors. The network demonstrated a received signal strength indication (RSSI) of 80% and an indoor range of 60 m with no obstructions; however, the power consumption for their protocol sensor module was relatively high at 350 mW.

The XBee and XBee-Pro modules (MaxStream®, Orem, Utah)[2] are off-the-shelf, low cost, low power (~100 mW) modules that use the IEEE802.15.4 standard for wireless communication. These modules transmit in the 2.4 GHz range and take advantage of direct sequence spread spectrum channel selection where the bandwidth per channel is 2 MHz and the channel spacing is 5 MHz. Recently, two new versions of firmware for the XBee-Pro modules became available and enabled the use of the I/O ports and mesh networking capabilities. The objectives of this study were to build an economical wireless interface for IRTs and test the network behavior of the radio frequency (RF) modules in a field application for automated center pivot irrigation.

MATERIALS AND METHODS

A prototype signal conditioner module (Fig. 1), using through-hole integrated silicon circuit chips (ICs) and electronic components, was designed to condition the small analog voltage (μV)

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[2] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

from an infrared thermometer (model IRt/c.5, Exergen, Inc., Watertown, Mass.) to a digital output of 10 mV ºC^{-1}. Other main components in the circuit included a cold conjunction compensation IC (Analog Devices, Mass.) specific to type 'T' thermocouples, operational amplifiers to provide isolation and buffering, a precision centigrade thermometer to measure sensor body temperature, and analog to digital converter (ADC) ICs. Use of an 8-bit microprocessor (Parallax, Inc., Rocklin, Calif.) enabled collection of several data outputs and control of the power mode ("sleeping") of the RF module for each wireless sensor.

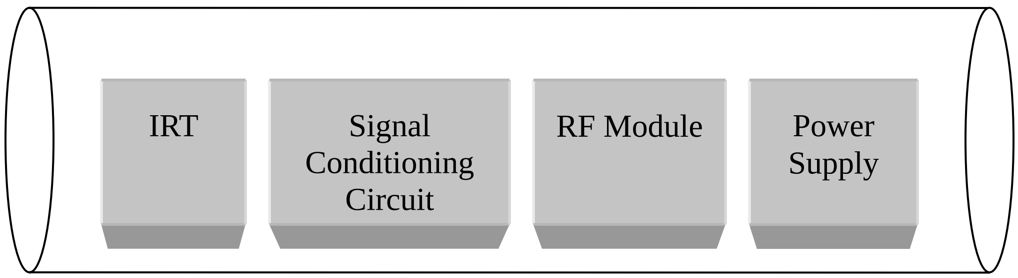


Figure 1. Prototype sensor module shown (within outline of plastic housing) was comprised of the infrared thermometer; signal conditioner module; RF module consisting of the XBee platform and a UART device; and power supply consisting of a battery, recharge circuit and external solar panel.

The digital output from the signal conditioning circuit was interfaced with the XBee RF modules, XBee/XBee-Pro Zigbee. Data from the microprocessor were fed to the RF module through an octal buffer that provided logic levels compatible with the XBee modules. The criteria for the RF module were low power consumption and possession of a practical transmission range, e.g., a minimum of 300 m, or 100 m with mesh networking capabilities. Meeting the criteria was critical to providing reliable transmission from the furthest remote module (at the end of the pivot lateral) to an embedded computer located near the control panel of the center pivot point.

The calibration of the wireless IRTs was completed using a black body calibrator (BB701, Omega Engineering, Stamford, Conn.) as the target temperature. The temperature of the IRT was held constant while the black body was varied from 0ºC to 45ºC. The temperature of the sensor body was incorporated into the calibration equation to adjust for drift. A datalogger (model 21-X, Campbell Scientific, Logan, Utah) was used to record the temperature of the blackbody and ambient room temperature. Sensor body temperature measurements were made using input from an LM35 digital temperature IC mounted to the body of the IRT. The circuit board and IRT were then placed into three controlled environments to obtain paired data sets. Calibrations were performed using wireless communications between the sensor module and a personal computer. Table 1 lists the outputs of the sensor module during the calibration process and to the base station (during field deployment) when polled by the base computer.

Similar to Kalma et al. (1988) and Bugbee et al. (1999), a calibration equation (Eq. 1) was developed for the IRTs using methods that included the IRT sensor body temperature, T_b (ºC). The difference between the IRT sensor temperature reading, T_s (ºC), and T_b was converted to thermoelectric voltage, E_d (mV) using

$$E_d = \sum_{i=0}^{3} c_i \left(T_s - T_b\right)^i \qquad \text{(Eq. 1)}$$

where the c_i are the coefficients for type-T thermocouples for the subrange, 0.000˚C to 400.00˚C (NIST, ITS-90 Thermocouple Database, 1995). A linear relationship was found between E_d and the energy radiated by the target, $\sigma(T_t + 273.16)^4$ (W m^{-2} K^{-4})

$$\sigma(T_t + 273.16)^4 = E_d m + b \qquad \text{(Eq. 2)}$$

where T_t is target temperature (˚C), the Stefan-Boltzmann constant σ = 5.67E-8 W m^{-2} K^{-4}, and m is the slope and b the intercept of the relation. IRT readings were taken at three sensor body temperatures (T_b = 44˚C, 23˚C, and 10˚C) and a range of target temperatures (0 to 45ºC).

Table 1. Wireless Sensor Module Output

Source	Purpose	Units
Infrared thermocouple	Measure crop canopy temperature	mV
Precision IC thermometer	Measure sensor body temperature	mV
Voltage divider	Monitor power supply	mV
RF address	Identify data source	ASCII

The XBee modules were evaluated for their range and consistency in transmission using a prototype white, rigid polyvinyl chloride (PVC) plastic enclosure for the signal conditioner circuitry and RF module. Testing included the use of the two types of modules (the X-Bee and the X-Bee Pro), four different power levels (programmable) and three different types of antenna designs [chip, wire and dipole] (Table 2). The sensor modules were positioned at two different heights under the pivot lateral, 0.6 m and 1.8 m, to simulate the range of required height above crop canopy over the growing season; the base modem (containing the XBee-Pro module) and the remote sensor modules were kept in line-of-sight of one another during the testing.

Table 2. Variables Used in the Antenna Evaluation

Antenna Type	Chip, XBee-Pro Wire, XBee Wire, XBee Dipole
RF power level (DB†)	0 (10 dbm), 1 (12 dbm), 2 (14 dbm), 3 (16 dbm), 4 (18 dbm)
Sensor height (m)	0.61, 1.83
Horizontal distance from base modem (m)	15, 30, 45, 61, 77, 91, 106, 122, 213, 243, 260

† Power dissipation ratio, $X_{DB} = 10\log_{10}\left(\frac{X}{X_0}\right)$, where X was the distance of the XBee and XBee-Pro transceiver from the modem and X_0 was the reference distance (1m).

A total of 14 bytes of data were transmitted from each wireless sensor node, including the sensor node address, the temperature reading of the IRT, the body temperature of the IRT sensor and the battery voltage supplying power to the sensor module. Using notation similar to Andrade-

Sanchez, et al., (2007), we defined this total package of 14 bytes as a data packet and the packet reception rate as:

$$PRR_x = \left[\frac{RR_x}{TR_x}\right]100$$

where PRR is the packet reception rate, RR is the number of records received during the time interval *x*, and TR_x is the total number of records transmitted during the interval time *x*.

To test the reliability of data transmission and compare mesh-networking protocol to non-mesh networking protocol, eight wireless sensors for each wireless sensor network (WSN) were deployed in the field and along the pivot lateral in a point-to-point topology (Fig. 2). Each WSN transmitted data on its own specific channel to a specific coordinator (base modem); data were collected using an embedded computer located at the pivot point. The programming of the microcontrollers was accomplished with PBASIC (Basic Stamp Editor, 2005; Parallax, Inc., Rocklin, Calif.); and communication between the XBee base RF module and the embedded computer was accomplished with Visual Studio 2005.

Network Topology

Pivot-WSN

Initially, all RF modules associated with this network were configured using the Zigbee firmware and the broadcast mode of communication. This mode entailed the coordinator sending its outgoing messages to all of the sensor nodes in the network at the same time; each message contained a node identifier code identifying the target sensor. However, only the targeted sensor returned data back to the coordinator while utilizing the other nodes as routers.

In the alternative unicast mesh-networking mode, the coordinator sent a message to a specific sensor node and the other nodes performed as routers to transmit the data back and forth to the targeted node; the network established the pathways. Again, only the sensor node, whose address was encrypted in the message, acted on the message and returned data to the coordinator through the network pathway (Fig. 2a).

Field-WSN

Firmware (802.15.4) was downloaded to each of the RF modules that comprised the Field-WSN. In this experiment, the Field-WSN coordinator individually polled each of the remote sensor devices using unicast addressing; the coordinator sent a message directed to a specific sensor node; the outgoing message and returning data packet traveled from the coordinator to the sensor node and back; the other nodes did not play an active role in the data routing (Fig. 2b).

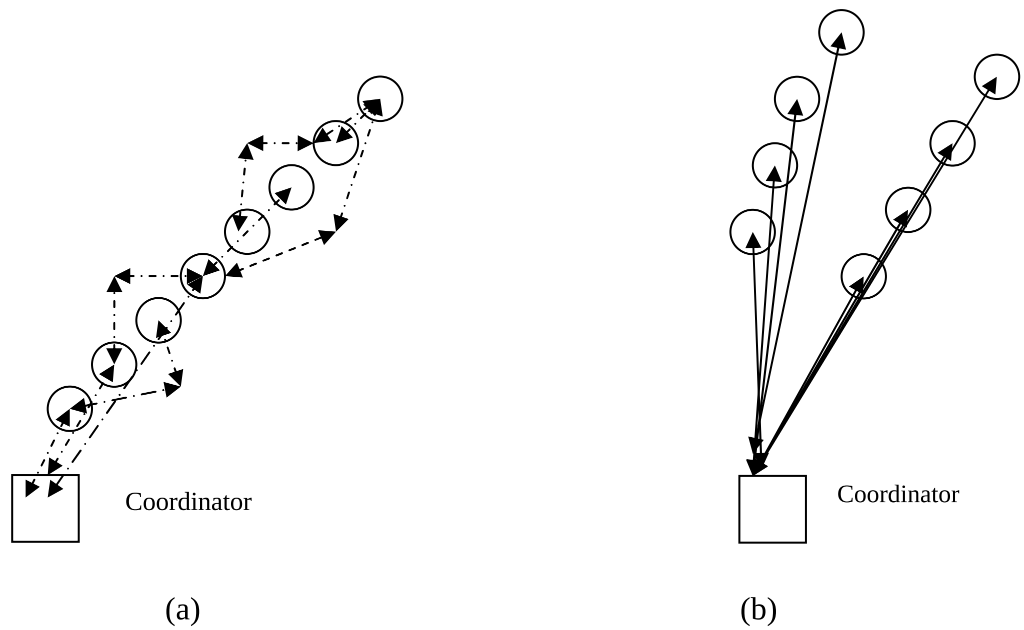


Figure 2. Network topologies showing: (a) Pivot WSN: unicast, mesh-networking where each sensor node acts as a router; (b) Field-WSN: unicast, non-mesh networking protocol where data is sent from the coordinator to each sensor node and back, the sensor nodes do not act as routers.

RESULTS

Sensor Module Calibration

An example of the calibration results is shown for a single wireless sensor module in Fig. 3, where residual error is the difference between the predicted temperature and the measured temperature. The largest error occurs when the sensor body is near 10ºC and the least amount of error occurs when the sensor body is near 24ºC. In both cases, the sensor reading and sensor body temperature are nearly the same.

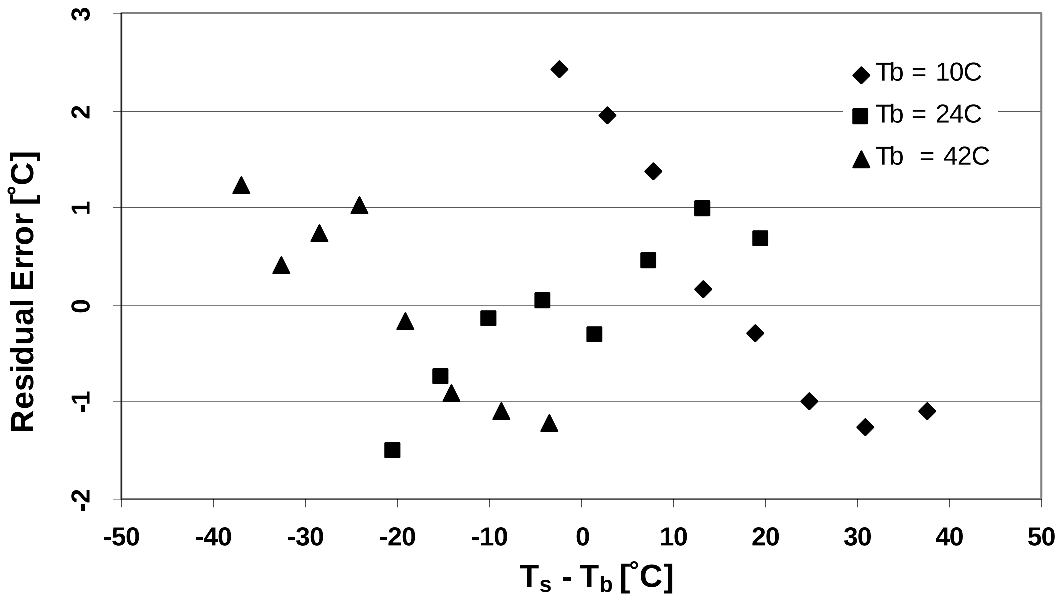
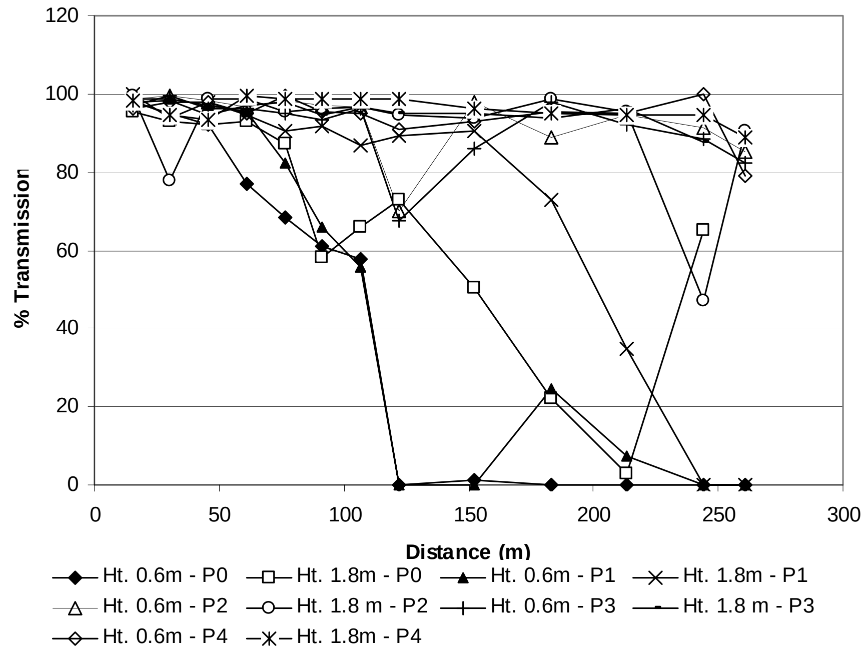


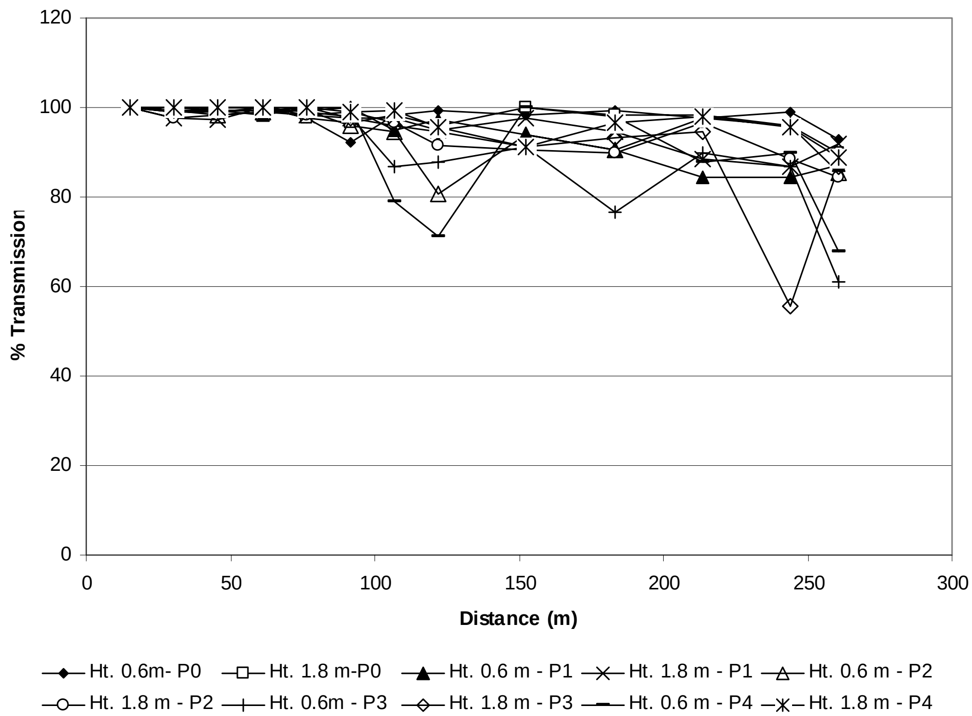
Figure 3. Graph showing residual error between the predicted and measured infrared sensor reading vs. the difference between the target temperature (T_t) and the sensor body temperature (T_b).

RF Antenna Testing

Received signal strength indication (RSSI) was compared for wire type and dipole antennas (Fig. 4). Transmission of data with the XBEE-Pro RF modules using a loop-back range test and X-CTU software (MaxStream2®, Orem, Utah) provided an RSSI of 95% at outdoor ranges > 500 m. Wire type antennas at a power level of 2 (on a scale of 0-4) were determined to be better suited than the dipole antenna for mounting on the center pivot lateral due to the superior performance of the XBee/XBee-Pro modules incorporated in evaluation boards supplied by MaxStream. The transmission of the dipole antenna may have been adversely affected by interference from the metal hardware of the center pivot trusses and towers compared with the wire antenna (Fig. 4).



(a)



(b)

Figure 4. Received signal strength indication (RSSI) for data received during the loop-back range test using: (a) the dipole antenna; and (b) the wire antenna. The RF module was placed at 0.6 m and 1.8 m above grade to simulate the range of the sensor height during a growing season.

Network performance:

Overall, the Field-WSN (unicast, non-mesh network) performed superior to the mesh networking system on the pivot lateral, probably due to interference from the pivot lateral on the mesh network. The Field-WSN required 8 seconds to collect data reliably from all eight sensors. However, it is important to note that using a non-mesh networking protocol on the Pivot-WSN resulted in a less than ideal level of reliability for data transmission, <80% reliability, 100% of the trial period (Table 3). The information below breaks down the results for the different network configurations.

The time required to collect data from a set of 8 sensors, using the broadcast communication mode and mesh networking, increased the latency of transmission of the entire network by 400% as compared to the Field-WSN. After reconfiguring the communication mode to a unicast method, while maintaining mesh networking capabilities, the latency was reduced to only 37% of the transmission rate of the Field-WSN.

The firmware installed on the RF modules for the Field-WSN was the 802.15.4, which enabled “sleeping” and therefore reduced energy consumption (Table 3). However, this firmware did not allow for mesh networking. On the other hand, the Zigbee protocol was installed on the RF modules comprising the Pivot-WSN and did allow for mesh networking but did not enable us to “sleep” the RF modules. Energy consumption for the sensor devices located on the Pivot-WSN was 300% greater than that for the Field-WSN.

Power issues

The wireless sensor module is currently powered by a nominal 6 V sealed lead acid battery that is trickled charged by a 5 watt, 6 V solar panel through a voltage regulating and isolation recharge circuit. The power consumption of the prototype sensor module is 360 mW when transmitting and less than 180 mW during its idle state. Power savings of 66% were realized by the ability to configure the “sleep mode” for the RF modules (Table 3).

Table 3. Results of deployed wireless networks.

Network System (# of devices)	Communication	Average % Packet Reception Rate	Energy Consumption
Field-WSN (8)	Unicast, non-mesh networking	>90% for 93% of the time (42 day trial period)	0.72 AH (sleep mode enabled)
Pivot-WSN (9)	Unicast, mesh networking	> 90% for 71% of the time (42 day trial period)	2.10 AH (sleep mode not available)
Pivot-WSN (9)	Unicast, non-mesh networking	< 80% for 100% of the time (6 day trial period)	Not assessed

CONCLUSION

The production of a wireless interface with an infrared thermometer for integrating the sensor into a commercialized center pivot system is critical to realizing a fully automated sprinkler system. It is possible to design an economical signal conditioner to interface with an "off-the-shelf" infrared thermometer and RF modules. The comparison of data packet reception rates in the mesh and non-mesh networking protocols demonstrated the beneficial application of wireless sensor networks in agricultural applications. The Field-WSN, installed as a non-mesh networking system in a point-to-point topology, out-performed the Pivot-WSN (configured with mesh networking firmware) in terms of reliability of data transmission; however, this was probably due to the interference that the pivot lateral caused in the Pivot-WSN. Supplementary benefits of the non-mesh networking system were speed (relative) of data transmission and the ability to "sleep" the RF modules and thereby significantly reduce total daily power consumption. However, it is significant to note that the mesh capabilities enable the wireless sensor network mounted on the pivot lateral to operate in a reliable manner. The manufacturer of the RF module is expanding the memory and "sleep" capabilities of its on-chip microprocessor. With these enhancements, the scalability and reliability of WSNs are expected to improve. In addition, further refinement of the signal conditioner components and the power supply module for the wireless sensor devices will be addressed to reduce maintenance of the electronic hardware, decrease total daily power consumption, and improve the accuracy of the sensor readings. An in depth investigation must occur with the wireless modules in a field setting during a growing season with the combination of new firmware and power conservation methods to determine the extent of the improvements and the feasibility for integrating the WSN into the center pivot system.

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