WIRELESS SENSOR NETWORK FOR MONITORING SOIL MOISTURE AND WEATHER CONDITIONS

R. Sui, J. Baggard

ABSTRACT. *A wireless sensor network (WSN) was built and deployed in three fields to monitor soil moisture status and collect weather data for irrigation scheduling. The WSN consists of soil moisture sensors, weather sensors, wireless data loggers, and a wireless modem. Soil moisture sensors were installed at three depths below the ground surface in various locations across the fields. Weather sensors were mounted on a 3-m instrument tower. An antenna mount was designed and fabricated for use in the WSN. When field equipment such as a fertilizer or chemical applicator impacted the mount, the mount was capable of protecting the antenna from damage by the equipment. In the WSN, received radio signal strength of Em50R data logger decreased as the distance from the data logger to the receiver increased. It also decreased as the distance between the top of the plant canopy and the logger's antenna above the plant canopy decreased. The antenna of the Em50R logger required replacement above the plant canopy for effective data communication. The Em50G data logger was capable of transferring data as its antenna was inside the plant canopy. Using the WSN system, soil moisture and weather conditions including precipitation, solar radiation, wind speed, and humidity were measured every minute and the hourly averages were reported and stored at 1-h interval. The soil moisture data and weather data were automatically and wirelessly transmitted to the internet making the data available online. Data collected by the WSN have been used in irrigation scheduling research in cotton, corn and soybean crops.*

Keywords. *Irrigation, Soil moisture, Wireless sensor network, Weather station.*

To increase water use efficiency and productivity, novel sensing technologies are required to determine crop water status and conduct irrigation scheduling. Crop water status and the amount of supplementary water needed can be assessed by measuring soil moisture and plant physical response to water stress. Sensor technologies for measuring soil moisture include neutron probes, capacitance sensors, time domain reflectometry (TDR), electrical resistivity measurements, heat pulse sensors, and fiber optic sensors. Based on these technologies, various types of sensing devices have been developed and made commercially available for water management applications. Some of these devices are capable of wirelessly transferring the data collected from their sensors.

Various types of soil moisture sensors were evaluated by researchers in terms of accuracy, reliability, and cost (Chanzy et al., 1998; Seyfried and Murdock, 2004; Yao et al., 2004; Evett and Parkin, 2005; Kizito et al., 2008). The neutron probe was able to accurately measure the soil moisture content. However, the use of radioactive source in the probe limited its application. In recent years, electromagnetic (EM) sensors such as the capacitance sensors, resistance sensors, and TDR have been rapidly developed and adopted for soil moisture measurement (Fares and Alva, 2000; Dukes and Scholberg, 2004; Vellidis et al., 2008; Sui et al., 2012). The EM sensors were inexpensive, easy to install and maintain. A well-calibrated EM sensor was capable of monitoring soil moisture status for irrigation scheduling (Yoder et al., 1997; Leib et al., 2003; Kizito et al., 2008).

A weather station has been a very useful tool for irrigation in agriculture, including calculating grass reference evapotranspiration (ETo) and water budget for crops. A weather station uses various sensors to measure meteorological quantities such as precipitation, air temperature, wind speed and direction, solar radiation, and humidity. In general, the weather information is continuously collected at a given time interval, so a weather station can quickly generate a lot of data and the data such as air temperature, humidity, and precipitation need to be rapidly processed and reported for the users.

A wireless sensor network (WSN) is a sensing system consisting of a group of spatially-distributed sensors for automatically and wirelessly monitoring physical or environmental conditions. The most popular radio frequencies used in WSN are 2.4 GHz and 900 MHz depending on the application requirements. An advantage of a WSN is its ability to provide continuous, real-time, in-situ measurements under a variety of operating conditions. A WSN, in conjunction with cellular communication

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infrastructure and the internet technologies, offers great capacity for measurement, transmission, and access of information from remote locations. In recent years, a WSN has been used in agricultural research and production systems (Wang et al., 2006; Kitchen, 2008; Pierce and Elliott, 2008), including measurement of soil moisture, soil and air temperature, and plant growth status for irrigation scheduling and automation (Harms, 2005; King et al., 2005; Vellidis et al., 2008; Kim et al., 2009, Lea-Cox et al., 2009; Sui et al., 2012).

The objectives of this study were to build, deploy, and evaluate a wireless sensor network to collect soil moisture data and weather information for irrigation scheduling research.

MATERIALS AND METHODS

SYSTEM DESCRIPTION

A wireless sensor network (WSN) was built for irrigation scheduling research at the Research Farm of USDA-ARS Crop Production Systems Research Unit at Stoneville, Mississippi (latitude: 33°26’30.86”, longitude: -90°53’26.60”). The WSN consisted of soil moisture sensors, wireless data loggers, a data station, a weather station, a measurement and control data logger (MCDL), and a wireless modem (fig. 1). Detail information of main pars of the WSN was given in table 1. Multiple soil moisture sensors and wireless data loggers were installed across the fields while the data station coupled with the wireless modem was housed together with the MCDL in the weather station located in the center of the fields (fig. 2). The WSN was deployed across three fields under the coverage of a center pivot irrigation system. Cotton, corn, and soybean crops were grown in the fields in 2012 and 2013. The data logger location and the distance between soil moisture sensor data logger and the wireless modem were given in table 2.

Soil moisture sensors measured soil water content, soil water potential, and soil temperature. The data logger connected with the soil moisture sensors wirelessly transferred the measurements to the data station. Data received by the data station then were downloaded to the MCDL through a RS232 port. Weather information collected by the MCDL was combined with soil moisture and soil temperature data, and sent to the wireless modem. Then, the modem transmitted all data through a commercial wireless network to make the data accessible on the internet.

SOIL MOISTURE MEASUREMENT SYSTEM

Decagon soil moisture sensors and data loggers (Decagon Devices, Inc., Pullman, Wash.) were used in this WSN for soil moisture and soil temperature monitoring. Three models of the sensors were used, model EC-5, 5TM, and MPS-2. The EC-5 sensor measured soil volumetric water content only, while the 5TM sensor measured both soil water content and soil temperature. The MPS-2 sensor measured soil water potential. Two models of Decagon’s data loggers were involved in the network for collecting data from the sensors. One was the Model Em50R and the other was the Model Em50G. The Em50R used a 900-MHz frequency radio to transmit data to the data station. It was also able to store 1M data in its internal memory. The Em50G logger transmitted data through a cellular communication network to a service which made data available on the internet. Each data logger (Em50R and Em50G) had the capacity to collect data from up to five sensors. The data station received data sent by Em50R loggers. To combine the data from the soil moisture sensors

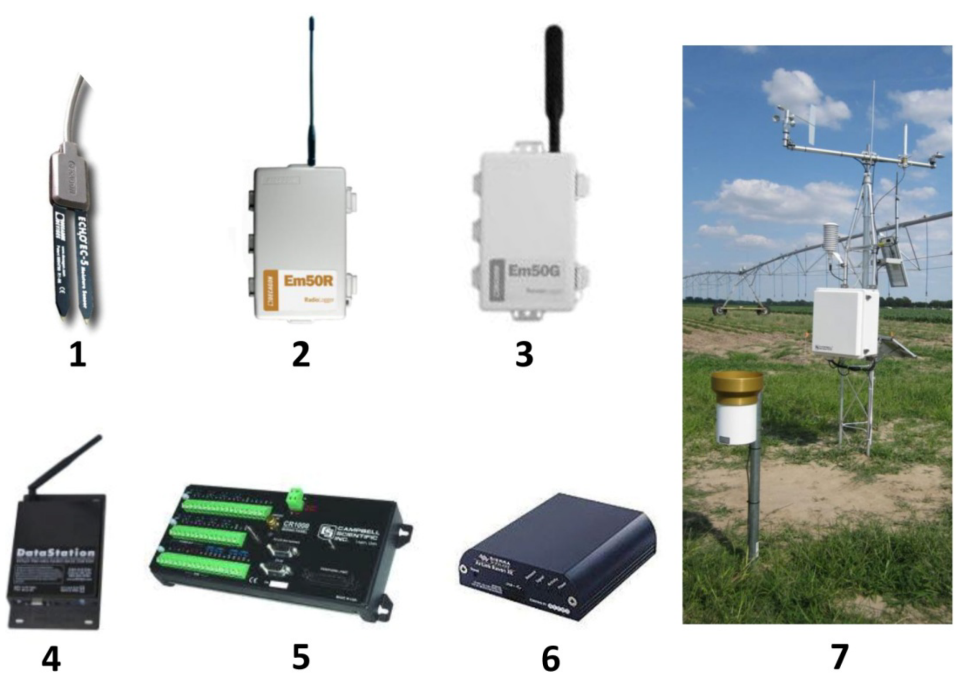

Figure 1. Major components of the wireless sensor network, including 1) soil moisture sensor, 2) Em50R data logger, 3) Em50G data logger, 4) data station, 5) CR1000 measurement and control data logger (MCDL), 6) wireless modem, and 7) weather station.

Table 1. List of main parts used in the wireless sensor network.

Part	Model	Vendor	Specification	Quantity (year)
Soil moisture sensor	EC-5	Decagon	Accuracy: soil volumetric water content: ± 3% for most mineral soils; ± 1-2% with soil specific calibration	40 (2012) 42 (2013)
	5TM	Decagon	Accuracy: soil volumetric water content: ± 3% for typical in mineral soils; Soil temperature: ± 1°C	4 (2012) 6 (2013)
	MPS-2	Decagon	Accuracy: soil water potential: ± 25% of reading from -10 kPa to -100 kPa; soil temperature: ± 1°C	6 (2013)
Data logger	Em50R	Decagon	Inputs: 5 channels, each supporting 12-bit analog, 32-bit digital, or pulse, compatible with any Decagon Devices sensor; Power: 5 AA batteries; Using a proprietary 900 MHz ISM band data radio; Max Transmit Power: 250 mWatt (24 dBm); Typical Receive Sensitivity: -110 dBm	12 (2012) 10 (2013)
	Em50G	Decagon	Inputs: 5 channels, each supporting 12-bit analog, 32-bit digital, or pulse, compatible with any Decagon Devices sensor; Power: 5 AA batteries; Using a quad-band class 10 cellular module; Max. Transmit Power: GSM 850 MHz power class 4, 2 watt (33 ± 2 dBm), PCS 1900 MHz power class 1, 1 watt (30 ± 2 dBm); Typical Receive Sensitivity: -106 dBm.	4 (2012) 6 (2013)
Data station	ECH_2O 900 MHz	Decagon	Collects data wirelessly from up to 80 data loggers within radio range (typically 1.6-4.8 km). Stores 36,000 packets of data; Using a proprietary 900 MHz ISM band data radio; Max Transmit Power: 100 mWatt (20 dBm); Typical Receive Sensitivity: -110 dBm	1
MCDL	CR1000	Campbell Scientific	Maximum Scan Rate: 100 Hz; Analog Inputs: 16 single-ended or 8 differential individually configured; Digital Ports: 8 I/Os or 4 RS-232 COM; Communications Ports: 1 CS I/O, 1 RS-232, 1 parallel peripheral; Power Requirements: 9.6 to 16 Vdc	1
GPRS modem	RavenXTG	Campbell Scientific	Quad Bands: 850/1900 MHz; 900/1800 MHz; Transmit Power: 1.0 W for 1900 MHz, 0.8 W for 850 MHz	1
Antenna	20679	Campbell Scientific	Frequency Bands Supported: 800 MHz and 1.9 GHz; Gain: 0 dBd for 800-MHz Band, 3 dBd for 1.9-GHz Band	1
Antenna cable	COAXSMA	Campbell Scientific	Type: LMR195 coaxial; Antenna Connector: Type N male; Transceiver Connector: SMA	1
Rain gage	TE525WS	Campbell Scientific	Resolution: 1 tip; 0.254 mm/tip; Funnel Collector Dia.: 20.3 cm	1
Temp. and RH probe	HMP155A	Campbell Scientific	Measurement Range: Relative humidity, 0.8–100%; Air temperature, -80 to +60°C; Operating Voltage: 7 to 28 Vdc	1
Radiation sensor	LI200X	Campbell Scientific	Light Spectrum Waveband: 400 to 1100 nm; Sensitivity: 0.2 kW m^{-2} mV^{-1}	1
Wind set	034B	Campbell Scientific	Wind Speed Range: 0 to 50 m/s; Wind Direction Range: Mechanical, 360°; Electrical, 356° (4° open); Accuracy: ±4°	1
Instrument tower	UT10	Campbell Scientific	Material: Hardened Aluminum; Weight: 17.2 kg; Height: 3 m	1
Solar panel	SP10	Campbell Scientific	Current at Peak: 0.59 A; Voltage at Peak: 16.8 V; Maximum Peak Power: 10 W	1
Power supply	PS100	Campbell Scientific	Power Out: Unregulated 12 V from battery; Nominal Rating: 7 Ah; Weight: 3.1 kg	1
Monitor and control software	RTMCPro	Campbell Scientific	Runs on Windows 7 (32 and 64 bit), Vista, or XP	1
Data logger support software	LoggerNet	Campbell Scientific	PC Operating System: Windows 7 (32 and 64 bit), Vista, or XP	1

with the weather information from the weather station, data received by the data station were transferred through a RS232 serial port to the CR1000 MCDL (Campbell Scientific, Logan, Utah). However, the original Em50R logger was not compatible with the CR1000 MCDL. We worked with both vendors (Campbell Scientific and Decagon) to get the Em50R logger reconfigured so that the MCDL could communicate with the data station via the serial port.

Figure 2 indicates the locations where the devices were installed. In 2012, four Em50R and two Em50G loggers were installed in the cotton field, four Em50R and one Em50G in the corn field, and four Em50R and one Em50G were installed in the soybean field. Three EC-5 soil moisture sensors were connected with each Em50R logger. Two EC-5 and one 5TM sensors were associated with each Em50G logger. In 2013, ten Em50R data loggers were deployed in two fields, five of them in the corn field and the other five in the soybean field. Six Em50G units were installed in the cotton field (fig. 2). In locations 1-6, four soil moisture sensors were installed with each logger, including two EC-5 sensors, one 5TM sensor, and one MPS-2 water potential sensor. The EC-5 sensors were installed at 15 and 61 cm depths below the ground surface while the 5TM and MPS-2 sensors were at the 30 cm depth. In locations 7-16, only EC-5 sensors were used with each logger and were installed at depths of 15 cm, 30 cm, and 61 cm, respectively. To install the sensors, a hole was drilled at the center of the crop row using a soil auger. The soil moisture sensors were inserted horizontally into the soil at the designated depths. All Em50R and Em50G data loggers continuously made one measurement of soil moisture and soil temperature in every minute and calculated the hourly average of the measurement. Then, the soil moisture and

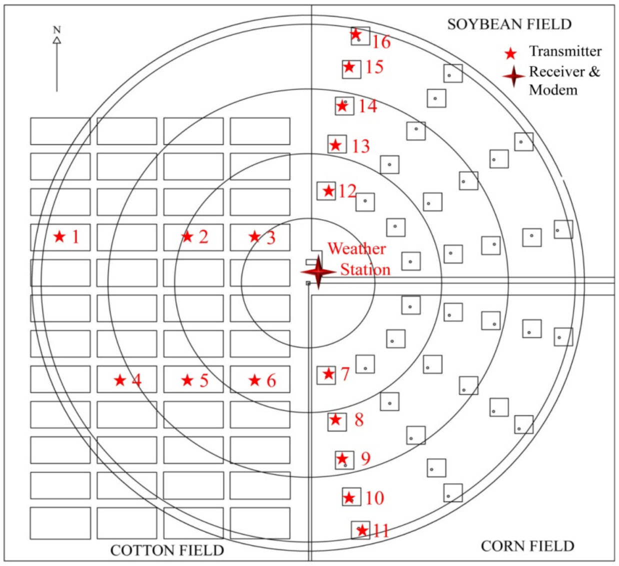

Figure 2. Showing field layout of the wireless sensor network. The rectangular areas in the cotton field were experimental plots for studies in cotton. The small squares in the corn and soybean fields indicated areas where the crop yield samples were collected.

soil temperature data were wirelessly transmitted to the data station at a time interval of 1 h.

WEATHER STATION

The weather station consisted of a CR1000 MCDL and multiple meteorological sensors including a TE525WS rain gauge, 034B wind speed and direction sensor, LI200X solar radiation sensor, HMP155A air-temperature and relative humidity probe, and real-time monitor and control software (Campbell Scientific, Logan, Utah). Except for the rain gauge, all the sensors were mounted on a 3 m tall instrument tower. The MCDL was housed inside a weather-proof enclosure with the data station and the wireless modem. The weather station was powered using an SP10 solar panel with a rechargeable battery. The MCDL collected data from the weather sensors and also through a serial port downloaded soil moisture data from the data station. A second RS232 serial port in MCDL was connected to a wireless modem for data output. The MCDL was programmable allowing the user to choose options for measurement and output intervals and data retrieval. We made one data collection from the weather sensors in every minute, then calculated and reported hourly average of the data for each weather sensor.

WIRELESS MODEM

The wireless modem used in this system was a Raven-XTG digital cellular modem manufactured by Sierra Wireless (Carlsbad, Calif.) for use on the AT&T General Packet Radio Service (GPRS) network. An omni-directional antenna was selected to work with the modem. The antenna was mounted on the top of the 3 m tower (fig. 1). All data including weather data collected at the weather station and the soil moisture and soil temperature data measured by the sensors were wirelessly and automatically transmitted to the internet by the modem so that the data could be accessed online in real time.

ANTENNA MOUNT

One of the issues for wireless sensor applications in the field is potential damage to the wireless device, especially the antenna, by agricultural equipment during field management practices. Usually, before conducting practices such as fertilizer and chemical applications, the wireless device deployed in the field may need to be removed or lowered to the ground to avoid damage (Sui et al., 2012). However, this causes inconvenience for users and interruption of data collection. In order to solve this problem and make the wireless sensor network more practical for field use, an antenna mount was developed for each Em50R data logger. The antenna mount (fig. 3) includes a spring, a U-shaped metal base, and a PVC pipe. The spring was mounted between the center of the base and one end of the pipe. The U-shaped base was made of a steel strip of 6 mm thick and 51 mm wide. The base was 28 cm tall and 30 cm wide with two sharp ends for insertion into the ground. The PVC pipe was 1.8 m long and 25 mm in diameter. A hole was drilled in the pipe at about 30 cm from the spring-pipe joint for pulling antenna cable inside the pipe for cable protection. The antenna connected to the cable was installed inside the top end of the pipe. To use the antenna mount in field, the U-shaped base was inserted into the ground and the antenna cable was connected to the

Table 2. Location and distance between wireless sensor transmitter and the receiver with a wireless modem.

		2012			2013		
Location No.	Distance to Modem (m)	Logger ID	Logger Model	Plot No.	Logger ID	Logger Model	Plot No.
1	154.8	Logger 18	Em50G	cotton 409	Logger 20	Em50G	cotton 409
2	82.0	Logger 8	Em50R	cotton 209	Logger 19	Em50G	cotton 209
3	42.7	Logger 7	Em50R	cotton 109	Logger 18	Em50G	cotton 109
4	133.5	Logger 17	Em50G	cotton 305	Logger 17	Em50G	cotton 305
5	103.3	Logger 6	Em50R	cotton 205	Logger 16	Em50G	cotton 205
6	78.3	Logger 5	Em50R	cotton 105	Logger 15	Em50G	cotton 105
7	83.5	Logger 1	Em50R	corn 101	Logger 1	Em50R	corn 101
8	123.4	Logger 2	Em50R	corn 102	Logger 2	Em50R	corn 102
9	155.8	Logger 3	Em50R	corn 103	Logger 3	Em50R	corn 103
10	188.4	Logger 4	Em50R	corn 104	Logger 4	Em50R	corn 104
11	217.6	Logger 19	Em50G	corn 105	Logger 5	Em50R	corn 105
12	80.2	Logger 10	Em50R	soybean 101	Logger 6	Em50R	soybean 101
13	122.5	Logger 11	Em50R	soybean 102	Logger 7	Em50R	soybean 102
14	155.4	Logger 12	Em50R	soybean 103	Logger 8	Em50R	soybean 103
15	196.9	Logger 13	Em50R	soybean 104	Logger 9	Em50R	soybean 104
16	225.9	Logger 20	Em50G	soybean 105	logger 10	Em50R	soybean 105

Figure 3. Left: Antenna mount; Right: Em50R wireless soil moisture measurement device with the antenna mount installed in soybean field.

wireless device. As agricultural equipment passed over the wireless device and impacted the PVC pipe, the spring in the mount would be bent and the antenna inside the PVC pipe would be protected from damage. Performance of the antenna mount was field tested with a chemical sprayer and fertilizer applicator before it was used in the WSN.

SYSTEM EVALUATION

The system was tested for two crop seasons, 2012 and 2013. In these two years, cotton, corn, and soybean crops were grown in the three fields shown in figure 2. The Em50G data loggers were mounted on a wooden stake and installed beside the plants in the row. The antenna of these Em50G loggers was about 30 cm above the ground (fig. 4). The Em50R loggers were also installed using a similar method as the Em50G loggers in the cotton, corn, and soybean field. However, their antennas were placed about 1.8 m above the ground using the antenna mount. As the corn grew taller than the antenna mount, the antenna mount was replaced by a 3-m tall PVC pipe with the antenna on the top to position it higher than the corn plant canopy. Regular farming equipment and crop management practices were applied in the fields where the WSN was in action.

Figure 4. Em50G wireless soil moisture measurement device installed in cotton field.

The CR1000 data logger was programmed to collect weather data and report the weather information coupled with the soil moisture and soil temperature data in a time interval of 1 h. During plant growing seasons in 2012 and 2013, this WSN was continuously used to monitor soil moisture status and weather conditions. By using LoggerNet data logger support software (Campbell Scientific, Logan, Utah), the soil moisture and temperature data and the weather data from the WSN were frequently accessed via internet for irrigation scheduling research.

Received signal strength indication (RSSI) is an indicator of radio frequency signal strength at the point where it is received. The Em50R data logger and the data station reported their RSSI as a percentage between 0 (very poor) to 100 (excellent) while the Em50G data logger reported its RSSI as a unitless score between 0 (very poor) and 31 (excellent). The Em50G and Em50R loggers provided the RSSI as one of their output parameters. For evaluating field data transmission capability of the data loggers, the RSSIs of the Em50G and Em50R loggers were monitored in various growth stages of the crops.

RESULTS AND DISCUSSION

Two years of field tests showed that the WSN performed well in monitoring soil moisture status and weather information. Since being deployed in April 2012, no major operational issues occurred with the WSN except a couple of data transmission interruptions by the thunderstorms during the summer. The WSN was capable of making measurements, collecting data, and wirelessly transmitting the data onto the internet. The weather conditions, including precipitation, relative humidity, air temperature, wind speed and direction, solar radiation, and ETo were recorded by the WSN in every hour and the weather data could be accessed online using a computer in the lab. Raw data of soil moisture, which were collected by the WSN, were downloaded from the internet. Then, they were processed using the DataTrac software (Decagon Devices, Inc., Pullman, Wash.) to obtain the true soil moisture values (table 3). Data in table 3 were the soil moisture content measured by EC-5 soil moisture sensors coupled with an Em50R logger. Values under Port 1, Port 2, and Port 3 were the soil volumetric water content at soil depth of 15, 30, and 61 cm, respectively.

Soil water content can be used to determine how much water in the soil was available for plant to use. As the soil water content dropped to a certain point, irrigation should be scheduled to avoid crop damage from water stress. As an example, figure 5 showed the soil water content measured using the WSN in location 5 of the cotton field in 2012. The soil water content in this location was monitored from early May to late September. The change of the soil water content at three depths of the cotton root zone was illustrated across the growing season. The rapid increases of soil water content shown in figure 5 were resulted from heavy precipitation events. The pattern of plant water use was also clearly indicated in figure 5. As cotton plant canopy got developed in the middle of June, the plants

Table 3. Measurements of soil volumetric water content (VWC) obtained in 2012 season by converting the raw data using the DataTrac software.

Time	Port 1. (m^3/m^3 VWC)	Port 2. (m^3/m^3 VWC)	Port 3. (m^3/m^3 VWC)
7/7 11:00	0.291	0.313	0.225
7/7 12:00	0.290	0.311	0.225
7/7 13:00	0.290	0.310	0.225
7/7 14:00	0.291	0.31	0.224
7/7 15:00	0.292	0.309	0.224
7/7 16:00	0.292	0.309	0.223
7/7 17:00	0.293	0.309	0.222
7/7 18:00	0.293	0.311	0.222
7/7 19:00	0.293	0.315	0.222
7/7 20:00	0.294	0.315	0.222
7/7 21:00	0.294	0.315	0.222
7/7 22:00	0.294	0.316	0.222
7/7 23:00	0.295	0.317	0.222
7/8 0:00	0.294	0.317	0.222
7/8/ 1:00	0.293	0.317	0.222
7/8 2:00	0.293	0.317	0.222
7/8 3:00	0.293	0.317	0.222
7/8 4:00	0.293	0.317	0.222
7/8 5:00	0.293	0.317	0.222

Table 4. Received signal strength indication (RSSI) of Em50G loggers in 2012 season.

	Cotton Field (logger 18)		Corn Field (Logger 19)		Soybean Field (Logger 20)	
Date	RSSI	Attempts	RSSI	Attempts	RSSI	Attempts
5/14	19	1	14	1	NA[a]	NA
5/21	19	1	10	1	NA	NA
5/28	19	1	11	1	NA	NA
6/4	20	1	9	1	NA	NA
6/11	19	2	9	1	NA	NA
6/18	18	1	9	1	10	1
6/25	17	1	9	2	13	1
7/2	14	1	10	1	12	1
7/9	10	1	10	1	10	1
7/16	11	1	8	1	11	1
7/23	13	1	8	1	10	1
7/30	10	1	9	1	13	1
8/6	10	1	11	1	13	1
8/13	15	1	9	1	12	1
8/20	16	1	NA	NA	12	1
8/27	16	1	NA	NA	16	1
9/3	17	1	NA	NA	20	1
9/10	17	1	NA	NA	NA	NA

[a] The logger was not available in that time period.

begun to use more water, which made the soil water content drop quickly. After being defoliated in the early September, the plants used less water which resulted in a higher level of the soil water content. Combining the soil moisture data with the weather data from the WSN, five irrigation events were scheduled, resulting in a water depth of 16 cm in total applied in the cotton field in 2012 season. In a similar way to the cotton, the weather data and soil moisture data in the corn and soybean fields have also been used for irrigation scheduling research in corn and soybean.

Tables 4, 5, and 6 provided the RSSI readings of the Em50G and Em50R loggers in 2012 and 2013 seasons and showed the effect of plant canopy on radio signal transmission. In the 2012 season, the Em50G logger in the corn field had the lowest RSSI compared with the loggers in the cotton and soybean fields (table 4). The RSSI of the loggers in the cotton and soybean fields was about the same as the plants grew taller and the canopies were fully developed in early July. After defoliation of cotton and soybean in late August and early September, the RSSI in both cotton and soybean fields increased (table 5 and 6). In 2013, for all Em50G loggers in the cotton field, a tendency

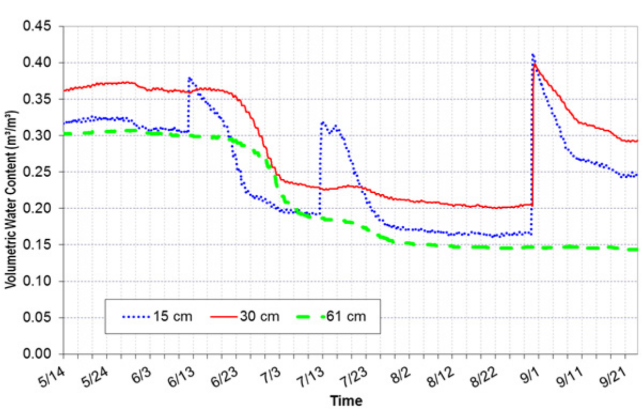

Figure 5. Soil volumetric water content during the 2012 growing season at depths of 15 cm, 30 cm, and 61 cm in a plot of the cotton field.

for RSSI values to decrease was clearly shown as the plant canopy developed. Low RSSI values from May to June in location 20 were caused by the broken antenna associated with that logger (table 5). After replacement of the antenna the RSSI returned to normal. Table 6 indicates that development of the corn plant canopy had a great influence on radio frequency signal transmission. From May to July, as corn grew taller, the RSSI value gradually decreased. For example, in location 9, the RSSI reduced from 70.1 in early May to 10.3 in early August. The RSSI was also affected by the distance between the logger and the modem. For example, in early July of 2013, the RSSI in the soybean field decreased from 76.4 in location 12 to 49.8 in location 16 (table 6). Though the RSSI varied during the growth seasons, the loggers and the data station in the WSN communicated well with the RSSI values given in tables 4-6. In almost all data transfer events, the communication could get through with only one connection attempt. However, while the Em50G logger could be installed under the plant canopy without raising up its antenna, the antenna of the Em50R logger required placement above the plant canopy; otherwise, the data station would not be able to receive the data. In table 6, the RSSIs of loggers 1-5 in corn field showed a jump from the 1st half to the 2nd half of August. That was due to the increase of antenna height from 1.8 m to 3.0 m. In general, RSSI of the loggers in soybean field was strong across the season (table 6). However, it was observed that there was an obvious decrease at location 16 in late July, which was caused by the tall pigweed growing around that location.

A couple of issues affecting the normal performance of the WSN were observed during field testing. One issue was that thunderstorms caused interruption of the data transmission in the loggers, data station, and modem. In the case when an interruption occurred, a reset of these devices would be required for recovering WSN performance. The other issue was that sensor cables (above or underground) were occasionally damaged by animals in the field.

Table 5. Received signal strength indication (RSSI) of Em50G loggers at cotton field in 2013.

Logger ID	5/16-5/31	6/1-6/15	6/16-6/30	7/1-7/15	7/16-7/31	8/1-8/15	8/16-8/31	9/1-9/13	9/16-9/30	10/1-10/15	10/16-10/24
Logger 15	18.5	17.7	17.2	13.9	8.5	8.2	10.7	8.3	8.8	6.4	8.1
Logger 16	19.6	19.1	18.5	16.6	10.7	10	6.3	10	8.5	7.7	6.5
Logger 17	19.2	18.2	20.0	19.7	14.2	10.9	9.9	9.1	8.7	6.1	NA[a]
Logger 18	18.8	19.6	19.7	19.3	16	9.8	10.6	12.7	10.6	10.6	9.1
Logger 19	17.2	19.1	19.0	18.2	9.6	9.5	10.3	8.0	7.4	7.9	10.2
Logger 20	7.9	12.4	10.5	20.2	20.0	19.3	17.8	18.1	17.2	15.9	15.2

[a] The logger was not available in that time period.

Table 6. RSSI of Em50R loggers in 2013 season.

Logger ID	Location No.	5/1-5/15	5/16-5/31	6/1-6/15	6/16-6/30	7/1-7/15	7/16-7/31	8/1-8/15	8/16-8/31	9/1-9/13
Logger 1	7	76.9	72.4	56.6	54.9	51.8	35.9	30.9	42.6	NA[a]
Logger 2	8	70.8	64.1	40.4	53.5	54.6	53.0	54.2	60.0	NA
Logger 3	9	70.1	61.6	33.3	24.6	18.1	12.4	10.3	16.6	NA
Logger 4	10	65.9	58.9	25.3	29.4	29.5	30.5	30.6	43.8	NA
Logger 5	11	62.0	43.1	28.6	11.9	11.8	19.0	15.2	23.8	NA
Logger 6	12	NA	70.5	76.8	77.0	76.4	68.4	68.1	68.6	72.9
Logger 7	13	NA	61.6	63.1	60.9	70.1	65.8	60.3	61.1	66.1
Logger 8	14	NA	66.7	67.4	64.4	59.7	51.0	43.5	47.1	56.4
Logger 9	15	NA	62.6	64.4	62.4	58.8	42.0	31.5	43.5	54.2
Logger 10	16	NA	59.9	60.1	56.5	49.8	23.0	14.3	22.5	36.2

[a] The logger was not available in that time period.

Chemical or physical measures to protect the cables might be needed.

SUMMARY

A WSN was built to monitor soil moisture status and weather conditions for irrigation scheduling. The WSN consists of soil moisture sensors and wireless data loggers for soil moisture measurement, sensors and electronic devices for collecting weather information, and a wireless modem to transmit the soil moisture data and weather data to the internet.

An antenna mount was designed and fabricated for use in the WSN. The mount, which was installed with a data logger for soil moisture measurement, was a spring-loaded device including a U-shaped base, a PVC pipe, and a spring between the base and the PVC pipe. As field equipment such as a fertilizer or chemical applicator impacted the mount, the mount was capable of protecting the antenna from damage by the equipment. After the equipment passed through, the antenna is able to return to the vertical position desired for signal transmission.

Received radio signal strength of Em50R data logger decreased as the increase of distance from the data logger to the receiver. It also decreased with the decrease of the distance between the top of plant canopy and the logger's antenna above the canopy. For effective data communication, the antenna of Em50R logger required to be placed above the plant canopy. Em50G data logger was capable of transferring data as its antenna was inside the plant canopy of cotton, soybean, and corn.

The WSN was deployed and operated in fields with cotton, corn, and soybean crops for two years. The WSN performed well in data collection and transmission. No major operational issues occurred with the WSN except data transmission interruptions by the thunderstorms during the summer. During the crop growing seasons, data including soil moisture and weather information measured by the WSN were successfully accessed online and used for irrigation scheduling and relevant researches.

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