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A new wireless underground network system for continuous monitoring of soil water contents

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[1] A new stand-alone wireless embedded network system has been developed recently for continuous monitoring of soil water contents at multiple depths. This paper presents information on the technical aspects of the system, including the applied sensor technology, the wireless communication protocols, the gateway station for data collection, and data transfer to an end user Web page for disseminating results to targeted audiences. Results from the first test of the network system are presented and discussed, including lessons learned so far and actions to be undertaken in the near future to improve and enhance the operability of this innovative measurement approach.

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1. Introduction

[2] Wireless embedded network systems generally consist of the following components: (1) a series of probe/sensor nodes, (2) a series of infrastructure nodes, (3) an end node for data gathering and transfer, and (4) a data logger or PC. Wireless sensor networks are an emerging technology, and research on the development of such systems is receiving increasing attention around the world [*Benini et al.*, 2006]. The main focus is on advancing the current technology in relation to network performance, reliability, security, efficient data propagation strategies, and network applicability [*Akyildiz et al.*, 2002; *Chatzigiannakis et al.*, 2008; *Powell et al.*, 2007].

[3] The potential uses of wireless network systems are countless, and application of wireless network technology can be used for instance for certain indoor domains like monitoring of industrial processes [*Howitt et al.*, 2006], buildings [*Jang et al.*, 2008], logistics [*Crowley et al.*, 2005; *Jedermann et al.*, 2006; *Ruiz-Garcia et al.*, 2008], mobile object tracking [*Tsai et al.*, 2007], healthcare [*Misic and Misic*, 2007], and the food industry [*Wang et al.*, 2006].

[4] Wireless embedded network systems are also been used in the outdoor world, for instance for monitoring and control of processes in the natural environment [*Hart and Martinez*, 2006]. *Mahfuz and Ahmed* [2005] review the prospects and challenges of wireless sensor networks for environmental protection, while *Bellis et al.* [2005] describe a first attempt to develop field programmable modular wireless sensor network nodes. *Cayirci et al.* [2006] describe a wireless sensor network for underwater surveillance using various types of microsensors. *Suri et al.* [2006] provide an overview of the potential use of wireless sensor networks for obtaining ecology related information, while *Nadimi et al.* [2008] apply this technology for tracking animal presence and behavior.

[5] Wireless sensor technology has also been tested recently for agricultural land use by *Camilli et al.* [2007] in relation to improving precision agriculture, by *Pierce and Elliott* [2008] to reveal regional and on-farm data on several meteorological parameters, and by *Cao et al.* [2008] to monitor the microclimatological conditions in a small tea garden. Recently, wireless sensor systems also entered the commercial markets in among other the United States, Australia and several European countries.

[6] However, one thing all systems and applications described above have in common, is that the transmitting and receiving network components are always installed and located aboveground, in direct contact with the air. *Akyildiz and Stuntebeck* [2006] speculate that wireless underground sensor networks (WUSNs) can be designed in theory as well, and outline associated research challenges, especially in relation to power conservation, underground communication, and antenna design. Several research groups around the world are currently working on developing and testing such underground systems, but none have yet presented results.

[7] This paper presents the first example and test results of a wireless underground sensor network (WUSN) capable of monitoring soil water contents at time intervals of minutes on multiple locations in an area of several km^2. Design and technical details of the WUSN will be high-

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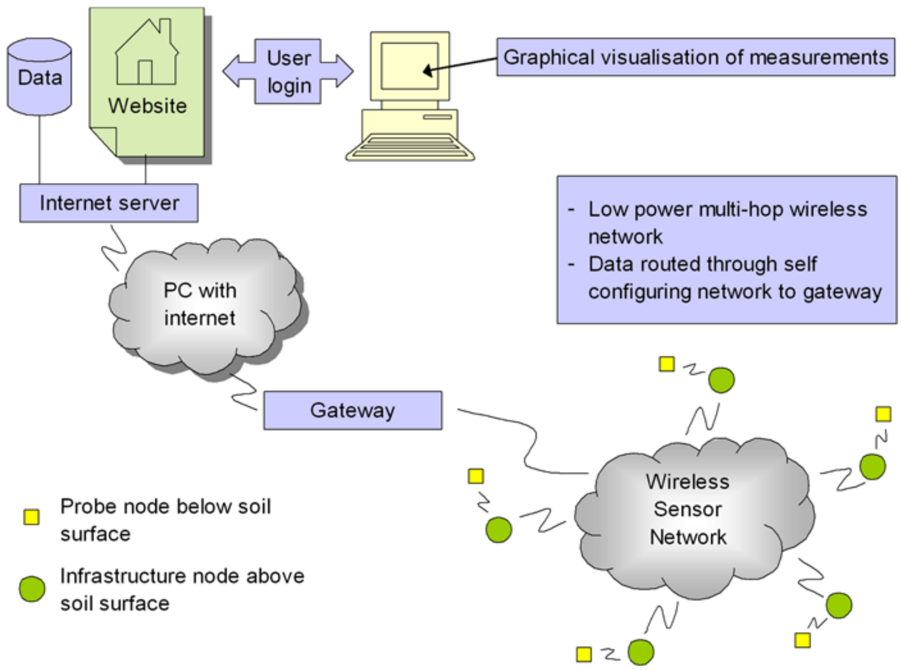

Figure 1. Network architecture comprising the following components: (1) probe nodes, (2) infrastructure nodes, (3) a gateway, (4) PC with Internet, and (5) an Internet server with a Web interface for end users.

lighted and discussed, and performance during an extensive field experiment outlined and evaluated.

2. Materials and Methods

2.1. Network Architecture and Functionality

[8] The embedded network system that has been developed and installed is an ultra low power self-organizing multihop wireless mesh network that consists of five basic elements: (1) probe nodes, (2) infrastructure nodes, (3) a gateway node, (4) a PC, and (5) a Web interface (see Figure 1).

[9] The soil moisture sensors used are commercially available EC-5 sensors produced by Decagon, United States (http://www.decagon.com). This sensor has been selected from the many commercially available products (http://www.sowacs.com/sensors/) [*Robinson et al.*, 2008; *Topp and Ferre*, 2002] on the basis of its low cost and low-energy consumption. The network system related hard and software has been provided by Ambient Systems B.V., Netherlands (http://www.ambient-systems.net), and the Web interface protocols and data visualization tools have been designed specifically for this purpose by Pentanovation, Netherlands.

2.1.1. Probe Nodes

[10] The probe nodes which are installed below soil surface, are the endpoints of the sensor network and perform underground measuring tasks. The probe nodes are made up of a network node (controller, transceiver plus antenna, memory), two Decagon EC-5 soil moisture sensors, and a battery set.

[11] The network nodes are small, and each network node contains an interface bank that can connect to a number of different sensors. Sixteen pins are available for general purpose input/output (GPIO), and various digital protocols are implemented as well such as one wire, I2C, SPI, analog (ADC and DAC), and RS232/UART. In our case the Decagon EC-5 soil moisture sensors have been connected to the node interface bank. The network node contains a significant amount of memory (10KB RAM, 512KB ROM flash) for buffering sensor data in case network connectivity is unavailable. Network nodes contain a low-power transceiver (Nordic NRF905, frequency 868 MHz, see http://www.nordicsemi.com) for wireless connectivity with a wireless sensor network. The typical battery life of a network node is more than 7 years; see section 2.1.1.2 for more details.

[12] The Decagon EC-5 soil moisture sensors measure the dielectric permittivity of the soil to determine volumetric water content. Benefits of EC probes are among other things their (1) low cost compared to other soil moisture probes, (2) durable design and proven evidence of long-term performance in the field, (3) single calibration for all mineral soils (at normal salinity levels), (4) very low power requirement compared to other sensors, (5) low operating voltage (3V), and (6) ease of installation. Recently, the EC-5 probes have been extensively tested by *Bogena et al.* [2007] for potential use in wireless network applications and were found to be suitable for this purpose.

[13] The current version of the probe node has been designed to measure soil moisture content at two different points below the soil surface. For this purpose, a sensor housing has been designed containing two separate Decagon EC-5 sensors 6 cm apart vertically. The sensor device is designed to be installed below soil surface, with the Decagon sensors positioned in such way that measurements are obtained from two different soil depths. The minimum installation depth of the top of the sensor device is 2 cm below soil surface, making the measurement depths of the sensors 4 and 10 cm, respectively. The probe node system

Table 1. A 1-h Power Consumption Budget for the Probe Node Based on Four Recordings and Transmissions per Hour[a]

State	Time (s)	Current (mA)	Consumption (mA h)
Standby	3591.54	0.08	0.079812
Sample	1.5 × 4 = 6	15	0.025
Listen (worse case)	0.6 × 4 = 2.4	14	0.009333
Transmit	0.015 × 4 = 0.06	35	0.000583
Total	3600		0.114729

[a] Use of a lithium battery (C cell, 3.6 V, 8500 mA h, 90% efficiency) enables the probe node to function for more than 7.5 years.

used in this study is mounted in a specially designed waterproof housing that can be installed easily at the required soil depth. By using multiple sensor devices on one location, a soil moisture profile of multiple levels can be determined.

2.1.1.1. Probe Node Mechanical Design

[14] The probe node housing has been constructed using a front and a back shell that can be screwed together after the internal components have been mounted. After closing the housing, it is sealed using a waterproof resin, making it completely waterproof and suitable for long-term subsurface installation. The advantage of the two-shell construction is that the housing can be opened and the battery set replaced if necessary, or the separate components replaced or reused. The shape of the probe node housing is designed in order to make installation as simple as possible. Originally, the probe nodes were designed for use on golf courses. On golf courses, standardized 10.8 cm diameter cup cutters are used for (re)placing the holes and flags on a green. The probe node housings were designed to easily fit into a 10.8 cm diameter hole for installation.

[15] The installation of the probe node is as follows: a 15 cm deep circular hole is cut into the soil, using a standard cup cutter. After this, the probe node is lowered into the hole and pushed into the hole wall at the desired depth. The front of the probe node housing has a rounded shape that fits exactly to the curvature of the 10.8 cm diameter hole. This ensures optimal contact between the probe node housing and the hole wall. After installation, the hole is back filled with soil and the removed turf is replaced to cover the probe node so it is invisible to the eye. Optionally, in order to relocate the buried probe node easily, a small additional piece (circular in form, white colored, and with a size of a quarter dollar coin) can be connected to the top of the housing, and left exposed to the surface after installation. Installation requires only 10–15 min per node probe.

2.1.1.2. Probe Node Electrical Design

[16] The probe nodes have been designed for long-term maintenance-free operation while installed below the soil surface. To accomplish this, high-quality, high-durability lithium cells are used as a power supply. The total battery life depends on a number of factors. The most important are: standby energy consumption (the probe node is in the standby mode during more than 99.9% of its lifetime), measuring frequency, energy consumption during transmitting of the data (power needed to bridge the distance between sensor node and aboveground infrastructure node), installation depth (HF energy absorbing soil layer to be bridged), average moisture content of the soil that covers the probe node (moist soil absorbs more HF energy than dry soil), closest distance to the aboveground network (are broadcast repetitions necessary or not), and temperature. After the battery set is exhausted it can be replaced or the entire probe node can simply be replaced, whichever is most cost effective. In the current design, attempts have been made to achieve an optimum balance between the above mentioned factors and the functionality of the probe node, enabling the current version of the probe node to be used for many years on a single battery set. A 1-h power consumption budget for the probe node is shown in Table 1 on the basis of four samplings and transmissions per hour. On the basis of the use of a C lithium 3.6 V battery (Tadiran, SL-2770) with a total capacity of 8500 mA h, and an expected efficiency of 90%, the probe node battery can be used for around 2778 days, i.e., more than 7.5 years.

2.1.1.3. Probe Node Calibration

[17] The Decagon EC-5 sensors produce an analog signal that is proportional to the moisture content of the soil surrounding the sensor rods. Because this output voltage is also sensitive to the supply voltage, the sensors are powered with an internally stabilized voltage. The sensor's analog output voltages are converted to numbers using an internal 12-bit analog to digital converter. These voltage values are stored locally, transmitted over the wireless network, and finally stored in the central database.

[18] The EC-5 sensors are supplied with a standard calibration curve for the calculation of soil moisture values from the measured output voltages. Using the standard calibration curve, a limited accuracy of ±2% to 3% can be achieved. Output voltage values are determined during measurements, and transmitted by the network of infrastructure nodes to the gateway. Output voltage data are converted to actual soil water contents within the linked Web application to graphically present the obtained data to potential end users of the system. This procedure enables the use of both the standard calibration curve provided by Decagon, as well as a site-specific soil calibration curve if desired and/or required by the user. Also, recalibration is possible using this methodology. The parameters of the calibration curve for each separate sensor can be stored in the Web application database.

2.1.2. Infrastructure Nodes

[19] The battery-powered infrastructure nodes produced by Ambient Systems B.V. are installed above the ground and they are developed to form a wireless network for supporting all data transfer and routing. An infrastructure node consists of a transceiver, a microcontroller, memory, and a battery. The radio frequency used is 868 MHz, and a TDMA-based protocol is used for contention. Transmitted power is adjustable up to 10 mW. Infrastructure nodes receive data from probe nodes and other infrastructure nodes. The system is self-organizing so the data will be transported over the network using the most efficient and reliable route to the gathering point in the network, the gateway node. The most important features of the infrastructure nodes used in the study are that they (1) are meshing nodes, (2) typically cover 250 m or more outdoors, (3) are self-organizing, fault tolerant, and self-healing, (4) automatically find the best route to the gateway, (5) connect up to an almost unlimited amount (2^{32}) of probe nodes (limitation is two communications of a probe node per second

per infrastructure node), (6) store data from probe nodes in case a gateway is unavailable, (7) are energy efficient (battery powered with a lithium D cell 3.6 V 19000 mA h, ensuring at least 1.5 years of operation for the field test discussed later), and (8) are remotely controlled and serviceable via the device driver interface (DDI). Through the DDI it is possible to approach nodes in the network for retrieving simple operational information or to configure advanced business rules using a device like a GPRS/UMTS data logger or (embedded) PC. Ambient Studio (see point 6 in this section) provides a graphical user interface to perform such tasks easily.

2.1.3. Gateway Node

[20] The gateway node is a special network node that functions as a bridge between the mesh network and a logging device such as a PC or GPRS/UMTS logger. The gateway is the unit which ensures that information flows from the sensor network to the user and vice versa. Furthermore, the gateway node is the controller of the network, it keeps the network running. The features of the gateway used in this study are (1) an open, transparent gateway to/from the sensor network; (2) an RS232 interface; (3) industry standard compliance, (4) the ability to connect up to at least 31 infrastructure nodes; (5) remote control capability and serviceability via the DDI, and (6) auto discovery of an active logger. If no logger is available, the gateway is able to change its network mode in order to leave the data on the nodes. When the logger is switched on again the data is flushed to this device. The data gathered from the sensor network by the gateway is stored on the local storage device of the PC, and periodically transferred over the Internet to a database on an Internet server.

2.1.4. Web Interface

[21] A Web interface has been developed that enables users to log into the Internet server on which the measurement data are stored. Users can access various graphical visualizations of the data which are generated dynamically. The field data are displayed with a default delay of no more than 15 min, however this can be changed to any preferred time interval varying from every minute to for instance once a day.

2.1.5. Network Communication

[22] In the current network configuration, the probe nodes are programmed to measure soil moisture content from both sensors every 15 min. The measured data are stored in the internal memory of the probe node and sent from the probe node to an aboveground infrastructure node using a push method. A probe node will listen every 15 min if any infrastructure node can be reached. If communication has been established, the probe node will try to transmit its data from memory to the aboveground network, which will be followed by an acknowledgment of receipt by the infrastructure node. By keeping track of the received acknowledgments, the probe node can detect which measurements have successfully reached the aboveground infrastructure. Measurements that were sent but whose receipt was not acknowledged, will be resent later. The probe nodes and infrastructure nodes can store data for up to a week in a circular buffer. After more than a week the data will be overwritten, however the data storage buffer can be increased depending on user wishes.

[23] The wireless network uses a lightweight medium access protocol (based on LMAC) to reduce the number of transceiver state switches and hence the energy wasted in preamble transmissions. Although the protocol uses TDMA to give nodes in the wireless network the opportunity to communicate collision free, the network is self-organizing in terms of time slot assignment and synchronization. The protocol has been compared to SMAC and EMACs by simulation. The LMAC protocol is able to extend the network lifetime by a factor 2.4 and 3.8, compared to EMACs and SMAC, respectively.

2.1.6. Ambient Studio

[24] Ambient Studio is the generic software used for deployment and configuration of the network system, data collection and data dissemination. It builds strongly on the generic DDI and addresses all resources in the network using DDI. Extensive tools are available for configuration, remotely upgrading nodes, network debugging, etc. Ambient Studio has been used in this study to install the network, and to verify its functionality. The wireless sensor network can be connected through Ambient Studio with multiple databases (ODBC) in order to store measurement data. Database queries can be edited in XML which is used by Ambient Studio to parse the raw measurement data. The same XML file is used for visualization and configuration of the sensor network in Ambient Studio.

2.2. Field Installation and Testing

[25] An extensive field test of the wireless sensor network was started in October 2007 at golf course Almkreek (www.golfpark-almkreek.nl) located near Almkerk in the central part of Netherlands, close to the town of Gorinchem. The golf course covers approximately 100 ha and has, among other things, an 18-hole course consisting of a mixture of push-up and sand greens, constructed using on-site clayey soil and sand brought in from elsewhere, respectively. The field test is still ongoing and being used for further fine tuning and improvement of the overall methodology.

[26] On 4 October 2007, the following items were installed: (1) one probe node on each of the 18 greens of the golf course, (2) 24 infrastructure nodes, (3) one gateway, with a high-gain antenna, and (4) a network PC for data transmission to a server. The average distance between the below ground probe nodes and first aboveground infrastructure node was 28 m, with a minimum of 6 m for green 18 and a maximum distance of 62 m for green 16. The probe nodes have been installed at fixed positions in the green, basically at a certain distance between two sprinklers surrounding each of the greens.

[27] After installation of all network components, including the gateway, use was made of the customer installation software package in order to (1) check the reachability of the different probe nodes and infrastructure nodes in the network, (2) determine the strength of the transmission between the separate network components, and (3) view the data routing paths across the network to the gateway.

3. Results

3.1. Network Installation and Aerial Coverage

[28] Before installing the network components on golf course Almkreek, all probe nodes and infrastructure nodes

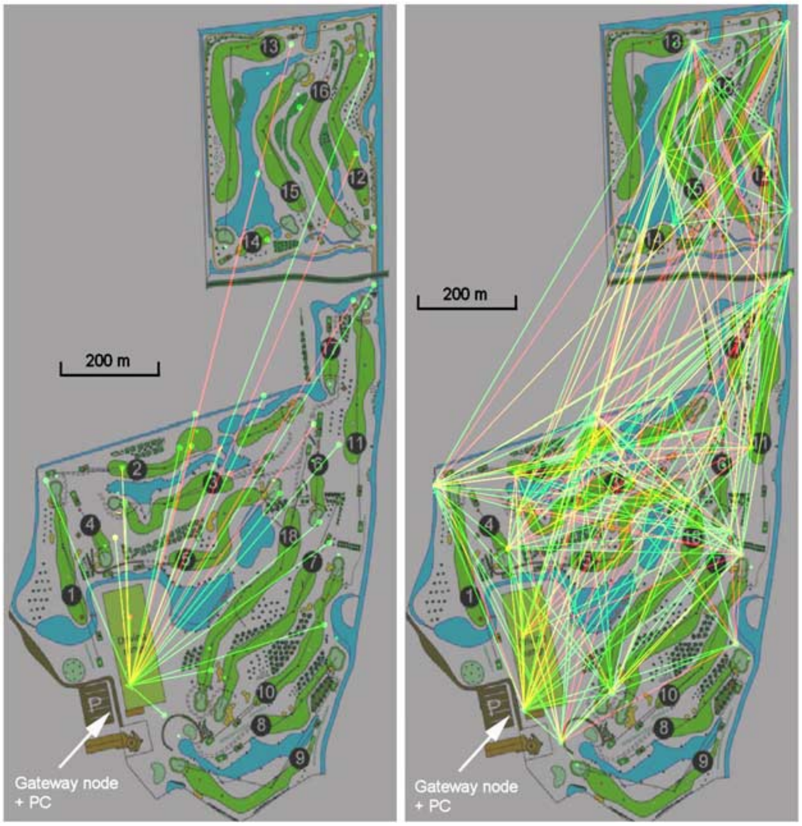

Figure 2. Layout of implemented wireless network on golf course Almkreek, Netherlands, with (left) a screen dump of Ambient Studio showing that after field installation most of the infrastructure nodes can reach the gateway station directly without using neighboring infrastructure nodes and (right) a screen dump of network communication performance on an arbitrary day during the experimental period (green, yellow, and red lines represent good, moderate, and insufficient/sporadic connections, respectively).

were quality checked using the Ambient Studio software. After checking the performance of the network components, including transmission strength, two activities were undertaken simultaneously: (1) installation of the gateway in the golf course office and (2) installation of one probe node in each of the greens and one infrastructure node in the direct surroundings of each green. The gateway installation procedure is easy and can be performed by a single experienced person in approximately 30 min. Installing the probe nodes and infrastructure nodes on the greens was done by a team of two other people, and took around 3 to 4 h in total. In general, the infrastructure nodes were installed at an approximate height of 1.5 m above the soil surface and attached to tree trunks or branches in the surroundings of the greens.

[29] Thereafter, connection quality and data pathways between the probe nodes, infrastructure nodes, and the gateway were evaluated using the Ambient Studio software. If certain probe nodes were not able to transfer their data to the gateway node easily, extra infrastructure nodes were placed at strategic positions on the golf course in order to ensure smooth connecting pathways between all individual network components. This procedure was repeated until the network obtained full functionality. Within 1 day, the total installation was successfully completed.

[30] The left-hand side of Figure 2 shows the direct connection performance between the individual infrastructure nodes and the gateway after installation on the golf course. It is clearly visible that most infrastructure nodes are able to send data to the gateway without even using neighboring nodes. This suggests that the average transmission range of the infrastructure nodes is far above the indicated 250 m, and is more likely to be in the range of 1000–1500 m instead. The actual transmission range in the network varies per infrastructure node depending on interfering landscape elements like wooded areas, buildings and/or other obstacles.

[31] The right-hand side of Figure 2 shows an example of the overall network performance at a certain moment during the field trial. It shows that there are a large number of transmission paths within the network. This is desired so the nodes are able to choose a good path, under all conditions. For example, during rainy periods radio range might decrease so a path with more hops will be chosen. If, for whatever reason, an infrastructure node stops functioning, other nodes are able to choose alternative paths to the gateway.

3.2. Soil Moisture Content Behavior

[32] Measurements of soil moisture content at the 18 greens started on 4 October 2007. As indicated earlier, measurement frequency was set on a 15 min time interval. Per day, 96 soil moisture content measurements were performed by each of the sensors. By March 2008, roughly

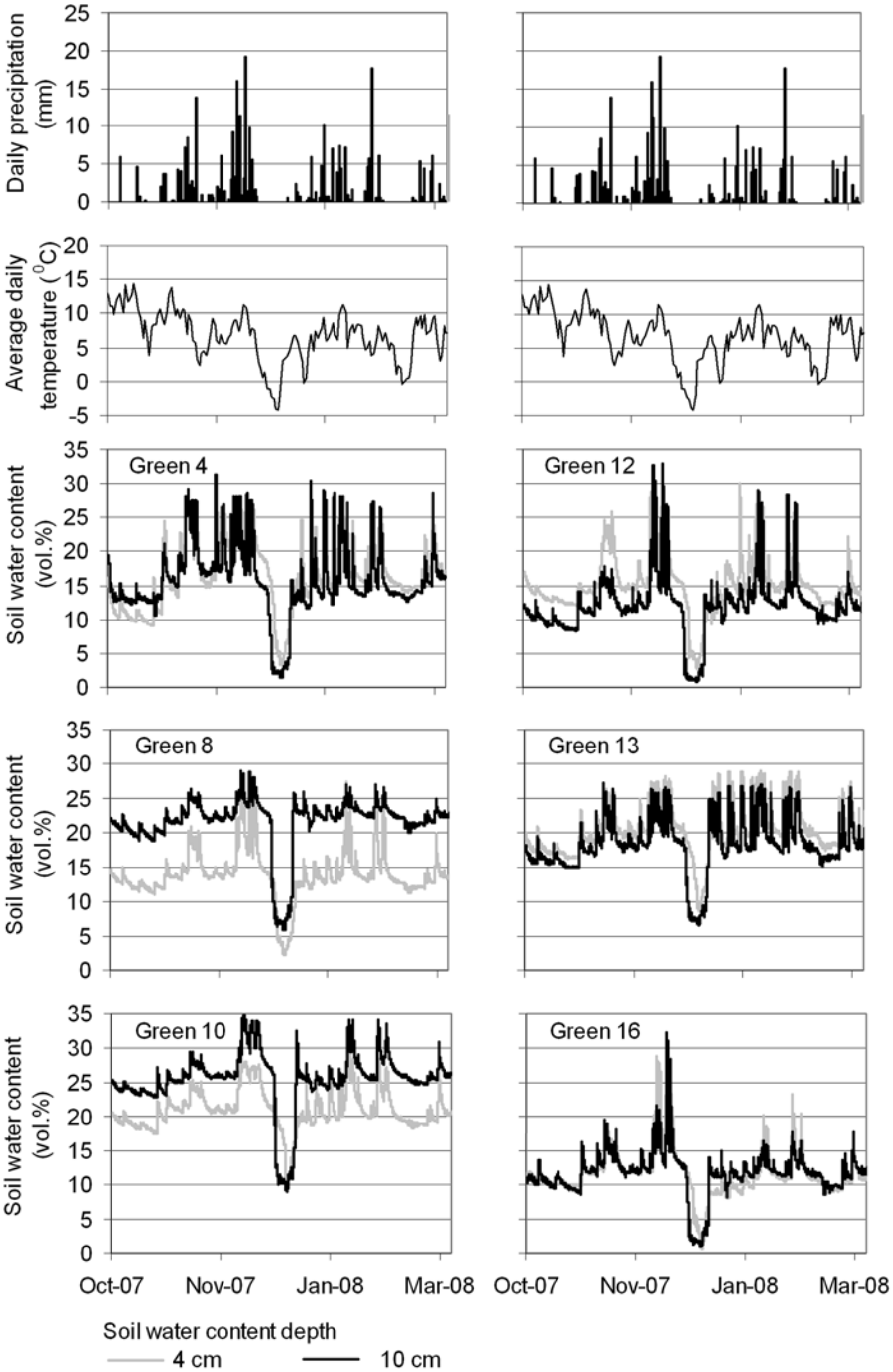

Figure 3. Soil moisture content measurements for six greens retrieved by the wireless underground network system, including recorded daily rainfall amounts and average air temperatures (data from a nearby meteorological station). Note that for each green per soil depth, around 17,000 soil moisture recordings were obtained between October 2007 and March 2008.

17,000 soil moisture recordings were obtained for each sensor.

[33] As an example of the data collected, Figure 3 shows the measured soil moisture contents at two depths for six of the eighteen greens during the period October 2007 to March 2008. Soil moisture contents were calculated with the standard calibration curve provided by Decagon. Also depicted in Figure 3 are the results obtained on hole 16, which is the hole where the distance between the buried probe node and nearest aboveground infrastructure node is the largest (62 m).

[34] It is obvious from the measurements that at all sites and depths, soil moisture contents are very responsive to the recorded rainfall, which is depicted at the top of the diagrams in Figure 3 as well. In general, sensors at 4 cm depth respond slightly quicker and more distinctly than the ones at 10 cm depth. Furthermore, differences can be observed between the different greens. In particular, green

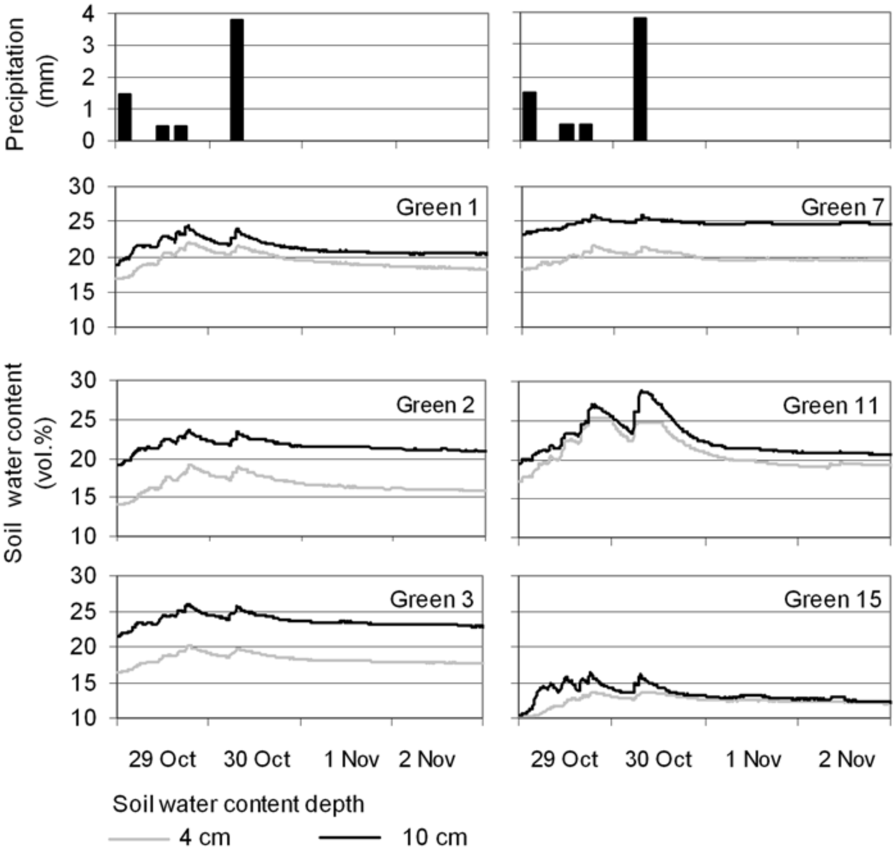

Figure 4. Soil moisture content behavior in six other greens during a 4-day period with a few small rain events. Note that infiltration behavior differs per green, as well as the degree of wetness/dryness of the greens.

16 appears to be much drier than the others. This is in accordance with observations and experiences of the head greenkeeper who indicated that certain greens on the golf course, including green 16, are susceptible to drought and sometimes very difficult to (re)wet. By contrast, green 10 is one of the wettest in the examples shown, which matches observations that this green exhibits regular problems related to waterlogging, compaction and thatch formation.

[35] As a further example, Figure 4 shows detailed information on soil moisture content behavior for a 4-day period at the end of October beginning of November 2007 for six other greens on the golf course. In this period, a few rain showers were recorded, each several mm in total. Response to rainfall differs per green and depth. Green 15 is a dry one, similar to green 16 discussed earlier, and green 7 is relatively wet compared to the others shown in Figure 4.

[36] In addition to precipitation and measured soil water contents versus time, Figure 3 shows the average daily air temperature for this entire period as well. It can be seen clearly that the drop in soil moisture content values in the second half of December is directly related to temperatures dropping below 0°C. A detailed view of this process is provided in Figure 5. After air temperatures rise above 0°C, it takes another 3–4 days before the EC-5 recordings show normal values again. Generally, it can be stated that within this first field experiment external influences like rain,

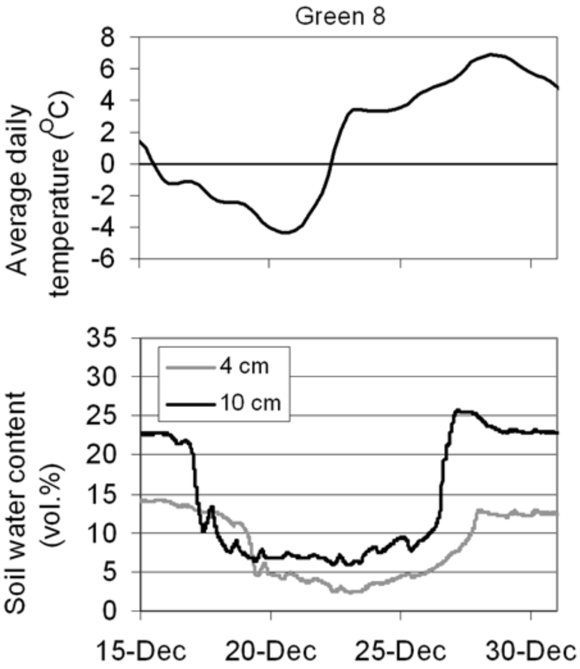

Figure 5. Effect of cold weather on soil moisture content recordings. Note that after the air temperature rises back above 0°C it takes another 3–4 days before recorded soil moisture contents are back to their original values as observed before the start of the period with frost.

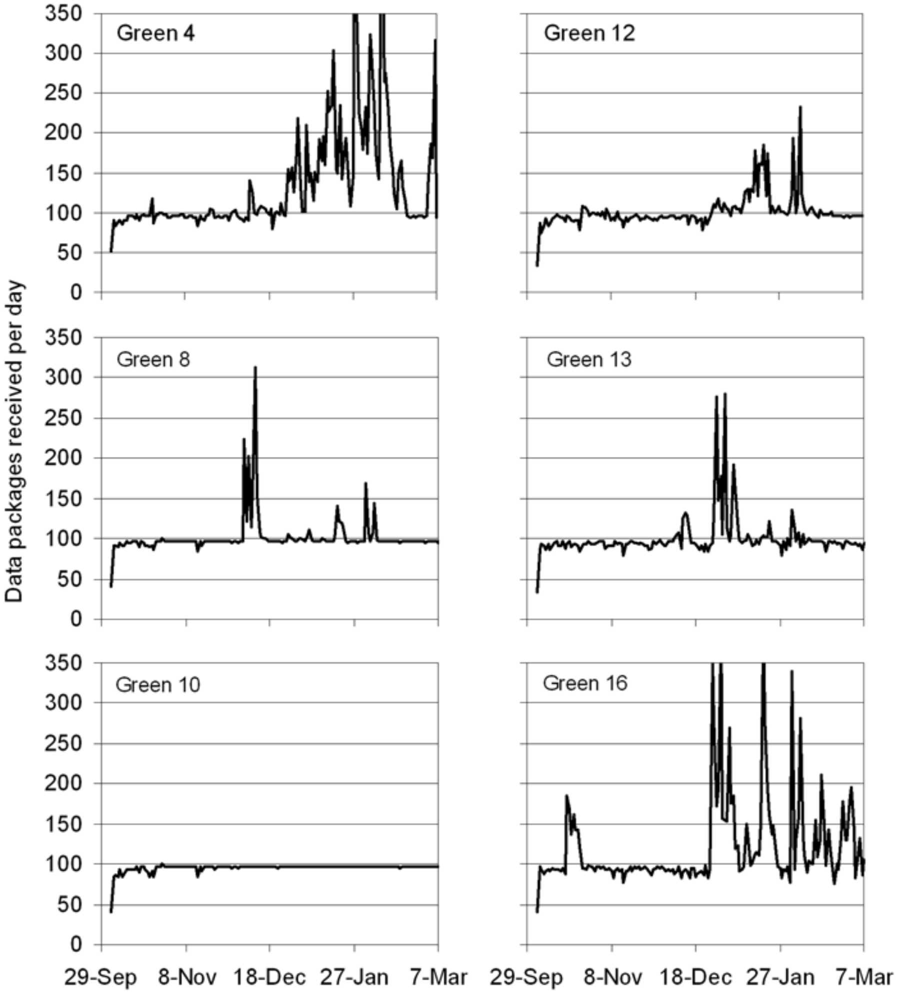

Figure 6. Number of data packages received per day for six different greens. Under ideal conditions, 96 data packages should be transferred over the wireless network to the gateway per day per green. Note that sometimes more data packages are received by the gateway. This is because of suboptimal communication between the aboveground infrastructure node and buried probe node (acknowledgment of receipt messages from infrastructure nodes are not always received by buried probe nodes, leading to repeated sending of the same data packages by probe nodes).

temperature and humidity are not interfering with data retrieval and network performance to any notable degree.

3.3. Communication Performance

[37] Overall communication between network components functioned well during the entire experimental period, and data were retrieved securely and accurately. However, in analyzing the data streams across the entire network in detail, one important observation was made. Figure 6 shows the amount of data received per day by the gateway and PC for a series of greens. When communication over the network is perfectly streamlined and working to expectations, 96 data packages per green should be delivered to the gateway and transferred to the PC and Web server. Figure 6 shows that generally this is the case, however starting from around the middle of December several of the probe nodes start to send data packages to the aboveground infrastructure node network sometimes more than once. In exceptional cases, 3 to almost 4 times the required number of data packages were delivered to the gateway. As previously noted, the network communication protocol is programmed in such a way that an infrastructure node receiving a data package from a buried probe node, should send an acknowledgment of receipt to the respective probe node. Apparently, receipt of these acknowledgments by the respective probe nodes did not always occur, causing the probe node to send the same data package again until it finally received a confirmation from the infrastructure node. Further analysis revealed that the distance between buried probe nodes and the nearest aboveground infrastructure node plays a role in this process: the larger the distance, the more repeated messages were found. It is clear that from a technological point of view, the network communication from aboveground infrastructure nodes back to the buried probe nodes needs further improvement, perhaps by optimizing the antenna position spatially or by using a different type of antenna or transmitting frequency. This point will receive the required attention during the further develop-

ment and testing of this new wireless underground network system.

4. Conclusions

[38] To conclude, initial results indicate that the wireless underground network system to continuously monitor soil water contents at different locations and soil depths across an 18 hole golf course area is performing well, and that measurement data are being retrieved as expected. This innovative measurement system opens a new range of possible applications from agriculture to research to environmental monitoring and beyond. Main advantages of the system as described and presented in this paper are that (1) it is based on combining state-of-the-art knowledge on soil physics, electronics and computer sciences; (2) use has been made of commercially available products and technologies to assemble the new wireless underground network system; (3) installation of the wireless network system is fast and use is easy; (4) data retrieval potentials are enormous; (5) monitoring information over large spatial scales can be obtained in (near) real-time mode and made accessible to end user groups instantaneously using the Web interface; (6) related costs are reasonable; and (7) other type of sensors can be connected to the system also, offering wide potentials for application.

[39] Apart from certain minor technological aspects requiring some improvement, it is expected that this system can be made available to other external users soon. Additionally, a second field trial with the wireless underground network system will be initiated during 2008, using the digital Decagon ECH$_2$O-TE sensors to continuously monitor soil moisture, temperature and electrical conductivity simultaneously. Recently, these new generation Decagon sensors have been extensively tested by *Kizito et al.* [2008]. It is expected that results of this second field trial will be released sometime in 2009.

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