Wireless Sensor Network Deployment for Water Use Efficiency in Irrigation

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Abstract

Australia is facing a severe water shortage due to below-average rainfall received over the past decade. The agricultural industry is significantly affected by this shortage due to its high water demands. It is important to adopt changes in agricultural practices and employ innovative ideas for the agricultural industry to maintain its current rate of production. Sensor technology can be used to study soil dynamics based on information gathered at regular intervals, and the data collected can be used as feedback to improve irrigation efficiency. In this paper, we describe our experiences in the design, development and deployment of a wireless sensor network to improve water use efficiency for pasture production. Sensor nodes, called *sensor pods*, were developed using off the shelf components. The design of the sensor pod was a challenging task as the installation has to withstand seasonal weather changes, and be resistant to damages that may be inflicted by cattle in the field. Each sensor pod measures soil moisture, temperature and humidity. Granular matrix sensors are used to measure soil moisture at three different ground depths. Temperature and humidity are measured using the Tmote Sky's on-board sensors. 70 sensor pods were deployed at the TIAR (Tasmanian Institute for Agricultural Research) Elliott Research Farm near Burnie, in the North West of Tasmania, Australia, at the end of December 2007. Preliminary results are now available. The data gathered will be used to develop efficient data evaluation techniques so that irrigation regimes can be automated. This will lead to precision agricultural techniques involving the close monitoring of the field state, and the use of real time data to drive more efficient irrigation practices.

Categories and Subject Descriptors

B.4.1 [**INPUT/OUTPUT AND DATA COMMUNICATIONS**]: Data communications Devices; C.2.1 [**COMPUTER-COMMUNICATION NETWORKS**]: network Architecture and Design

General Terms

Design, Experimentation, Measurement, Management

Keywords

Sensor networks, water usage, Irrigation

1 Introduction

Fresh water is becoming an increasingly scarce commodity in many parts of the world due to combined effects of population growth and climate change. Long-term climate forecasts suggest that Australia will be confronted with severe water shortages over the next few decades [5]. Irrigation accounts for about 65% of the nation's annual fresh water usage [2]. The agricultural industry must become increasingly innovative in its efforts to use water more effectively.

The dairy industry, in particular, is a major consumer of water in the Australian state of Tasmania. It is estimated that 70% of the annual water allocation to the agricultural industry is used to irrigate dairy pastures. A significant amount of water can be saved through efficient irrigation strategies. One approach farmers can employ to increase water use efficiency is the technique of *deficit irrigation*. The idea behind deficit irrigation is to provide less than 100% of the potential evapotranspiration during the growing season [9]. This implies that some degree of plant stress is unavoidable; the key management challenge is to optimise the timing and degree of stress within the constraints of available water, climate and economics, so that plant yield is not compromised. This paper discusses the design, development and deployment of a wireless sensor network that enables the implementation of the deficit irrigation strategy. The aim of using sensor technology is to irrigate the field only when it is absolutely necessary.

Wireless sensor network technology development is driven by its use in different applications. There are many instances where it is used in the agricultural domain. Most of the work deals with gathering data from a field for offline analysis. The study was conducted to look at the use of wireless sensor networks in the wine industry [4]. The main aim of the study was to develop a computing technology for effective resource management and decision making in the wine industry. It was concluded that a flexible system architecture is required if the technology is to be useful to all stake holders (i.e., vineyard managers, labour, winemakers, vineyard owners). In another application, the wireless sensor networks was used to monitor micro-climates in an agricultural field [3]. The target application was fighting phytophtora disease in potato fields. Humidity, temperature and moisture on leaves were measured from each deployed sensor. The data collected from the sensors could potentially be used to predict the onset of the disease. The wireless sensor networks was also used for pasture assessment. The ECH2O sensors were used to measure soil moisture and cameras to determine greenness and grass height [10]. 16 nodes were used to profile six hectares of pasture. This is a low density deployment, making it difficult to estimate the moisture content accurately across the field.

Interactions between soil and water are highly dynamic. The movement of water through an unsaturated zone (portion of the subsurface above the ground water table) has been widely accepted as a complex phenomenon. The precipitation, soil texture, profile, presence of plants, land use and various meteorological variables influence the spatial distribution and temporal evolution of soil moisture [7]. A typical method is to apply soil physical models that are called "empirical domains" to specific cases. Since a physical model is a simplified abstraction of reality, the accuracy of such a model depends on how well one can address uncertainties in initial conditions, time-varying inputs and parameters. The recent advancements in wireless sensor network technology and its application to hydrologic observation could change the way we approach soil physical modelling. Ground-based in-situ hydrologic observation networks provide a means for us to directly measure and monitor real time hydrologic events of interests. The purpose of the wireless sensor network depicted in this paper is to enable us to understand a spatial-time soil water behaviour in the root zone of a plant.

In this paper, we outline the system architecture we have developed to collect soil moisture, temperature and humidity data from a pasture field, for use in deficit irrigation. Each sensor pod consists of three Granular Matrix Sensors (GMS), the Sentilla (formerly Moteiv) Tmote Sky [8] with on-board temperature and humidity sensors, a high-gain antenna, battery pack and solar panel. The granular matrix sensors are deployed underground at different depths to gather soil moisture data. These sensors were used because they are low cost, last at least twice as long as ECH2O sensors, and measure soil water tension, which is a good measure of *when* to irrigate rather than how much. The sensors specifically monitor the root zone soil water behaviour. In future, the system could provide information to farmers on when to irrigate their fields. This decision making will be influenced by sensor readings, a physical soil model, and data from a weather station we have installed in the vicinity of the field. We are also working with agricultural scientists to develop an accurate physical soil model. In this paper we focus only on the sensor development and deployment at the Elliott research farm. The key features of our development and deployment are:

- Field deployable sensors have been developed. Ease of deployment is a key feature. It takes approximately 9 minutes to deploy a sensor pod and the associated granular matrix sensors. Overall, 70 sensor pods, two pairs of relay nodes and a gateway node have been installed in the field.
- The sensors are resistant to damage from the environment and from cattle in the field.
- TinyOS is used as the sensor operating system. The sensors are reprogrammable over the air using Deluge.
- Each node transmits data every 5 minutes. Multi-hop routing is used to carry data to a gateway PC (located in an office near the field) via two pairs of relay nodes.
- A unique method of retrieving readings from the GMS sensors has been developed, using only passive electronic components and software based stimulation.

The rest of the paper is organised as follows: Section 2 describes the sensor pod design and development. The network software is described in Section 3. In Section 4, the sensor pod deployment strategy is discussed. We provide some initial results in Section 5, and Section 6 concludes the paper with a description of future work.

2 Sensor Pod Design and Development

The main components of a sensor pod are three granular matrix sensors and the Tmote Sky. The sensors are deployed vertically at three different depths, 15 cm, 30 cm and at 45 cm. This allows the detection of soil moisture in the root zone as well as detection of any wasted water that falls below the root zone. The soil moisture sensors are inexpensive Watermark 200SS GMS, also known as "gypsum block" sensors. These sensors detect soil moisture potential in the range 0 to 200 kPa, which is calculated from a measurement of the sensor's electrical resistance. The relationship between resistance and moisture potential is a non-linear function which is determined through laboratory calibration.

There were several requirements we wanted to satisfy with the physical design of the sensor pod. These include issues relating to cost, ease and speed of installation, ability to withstand the environment. Due to the high density of sensor pods in the network, we needed to design cheap and rapidly deployable sensor pods. The uniqueness of the design is the ease of servicing and replacement of any parts with minimum effort. The final critical aspect to the design was the ability of individual sensor pods to survive in the field whilst cattle are grazing. Cattle will rub and scratch on any rigid structures; this leads to rapid failure on all but the most solid structures. The two common strategies for protecting equipment in the field whilst cattle are grazing are to either protect the equipment with an electric fence or to enclose all the equipment in metal enclosures and on solid mounting poles. Neither of these solutions fitted with our needs. The high density of sensor pods made it difficult to use electric fences, as they would either restrict cattle movement, or would take too long to install if sections were run underground. The second solution of building a metal enclosure on solid mounting poles was not feasible from a cost and deployment time perspective. A dismantled sensor pod design is shown in Figure 1.

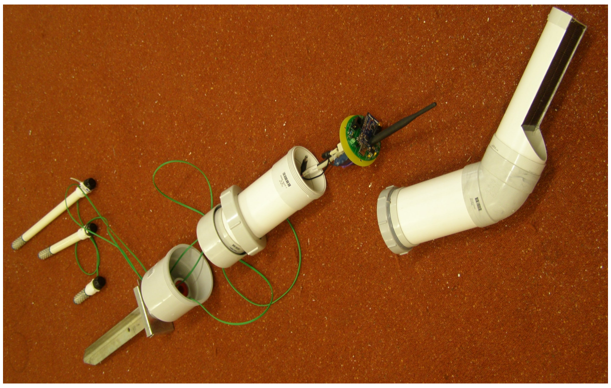

Figure 1. Different sections of the sensor pod.

The sensor pod can be separated into two sections, the base section and the Tmote enclosure. The base section, shown in Figure 2 includes a 35 cm metal star picket, a flexible polyurethane coupling and a PVC receptacle. The flexible coupling is a low torque coupling that will allow the sensor pods to be pushed 90° to the ground in any direction and then fully recover to the default vertical position. The use of a flexible coupling allowed us to use a much lighter structure for the sensor pod design as it prevents the cattle from applying large forces on the structure. The star picket is driven into the ground around 1 meter from the location of the GMS.

GMS wiring runs underground and vertically up out of the ground and into the base of the PVC receptacle. There is approximately 10 cm of cable between the ground and the receptacle that is

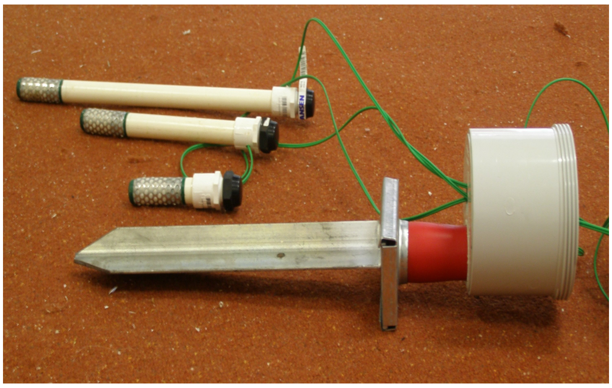

Figure 2. The base section of the sensor pod.

protected by conduit. The receptacle is a standard 10 cm PVC coupling that allows either a cap to be directly screwed on or a sensor node to be mounted. The ability to protect the sensor plugs from the environment using the cap when sensor nodes are not present is quite useful during repair and maintenance of the system.

The Tmote enclosure can be unscrewed into two sections. The lower section contains batteries and interface wiring. The upper section contains a solar panel, a LED and reed switch for diagnostics. The Tmote is plugged into the lower section. An 8dB gain antenna is connected to the Tmote to provide a larger communication range. The Tmote and antenna sit inside the upper section when assembled. A flexible "telephone" cord allows the solar panel, LED and switch to be connected to the remainder of the electronics, and still allows the two sections to be screwed together.

A small motherboard is used to implement the custom GMS interface and to provide circuitry for solar battery charging and power regulation. The motherboard has a single connector to the battery and sensors on its underside. The Tmote and solar panel connector are plugged into its upper side. The entire assembly process is toolless; this allows for simple replacement of any part of the system.

It is essential to use AC stimulation when measuring a GMS's resistance; a net DC current would cause electrolytic damage within the sensor. Normally, this requires purpose built interfacing circuits. For the purpose of this sensor network deployment, we have developed a unique simple interface using only passive components and the TMote Sky's I/O and ADC pins. The GMS is placed in series with a fixed resistance to form a simple voltage divider. A current is driven through it by alternately toggling two digital I/O pins on the Tmote's microcontroller (these are set to high impedance between readings). The Tmote's ADC pins are used to measure the stimulus and response voltages, so the GMS's resistance can be calculated.

3 Software Description

The network software is built on the Boomerang operating system, a derivative of TinyOS which is provided by Sentilla. The network is Deluge-enabled, allowing for the propagation of program updates over the air. MultiHopLQI is used for the routing of samples to the gateway. A custom broadcast layer was implemented, allowing the gateway to send requests to a particular node in the network for the retrieval of missed sample entries.

The software includes a diagnosis module, allowing for simple node diagnosis. As an example, a user in the field can send a single-hop message to a particular node, triggering a response containing the most recent sensor readings. Similar functionality can be achieved by triggering the sensor pod's reed switch, which is wired to the Tmote's user button interrupt. When triggered, the Tmote will check its sensor and voltage levels, and respond with a LED pattern indicating its status (e.g. low voltage).

One of the goals of the sensor pod design was a system which allows for easy installation and replacement of the Tmote Sky modules. The traditional method of tightly coupling a Tmote's radio ID to its location was deemed inappropriate, as with the relatively large number of nodes, the potential for making an error during programming, and having duplicate radio IDs was too high. Thus, a process was developed whereby each Tmote is given two IDs; a radio ID, assigned when the Tmote is programmed, and a location ID, assigned when the Tmote is physically installed in the field.

Radio ID duplication is avoided by having a global, continually incrementing radio ID, which is assigned to the next Tmote that is programmed. When the Tmote is installed in the field, it is given a location ID, corresponding to the location at which it is being installed. A location ID is assigned with a simple Java program that can be executed on a laptop or PDA. While this process does not eliminate the potential for existence of duplicate location IDs, there is no possibility of duplicate radio IDs, thus radio communication will not be corrupted. Additionally, there is no need for a constantly changing look-up table mapping node IDs to locations. Rather, a static lookup table mapping location IDs to locations is sufficient. Finally, a TinyOS build environment does not need to be taken into the field; rather, a laptop or PDA with a serial port is all that is required. The network's system architecture is shown

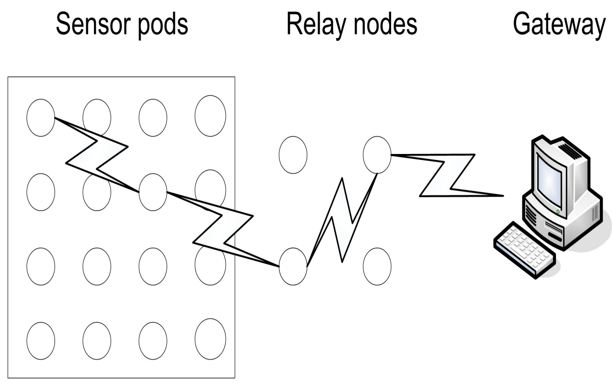

Figure 3. The network's system architecture.

in Figure 3. The sensor pods are deployed in a grid topology; two pairs of relay nodes are used to transmit data to the gateway node. The gateway node is physically plugged into the gateway PC's USB port, which provides power and communication. The distance between the sensor field and the relay nodes is around 60 metres, and another 75 metres from the relay nodes to the gateway node.

Data received from the network is initially archived in a PostgreSQL database running locally on the gateway PC. The database stores timestamped readings from each of the sensor pods. This includes readings from the three GMS, temperature sensor, humidity sensor, Tmote supply voltage, and current battery voltage. The data is collected every 5 minutes. The gateway PC is internet enabled with a 3G connection, allowing the data to be sent to our Hobart site using Java Messaging Service (JMS) over a reverse Secure Shell (SSH) tunnel. A simple listener program running in Hobart receives the JMS messages and saves the data in another PostgreSQL database. The JMS publisher running on the gateway PC buffers readings for a configurable amount of time (typically 2 days), making the system robust against network outages.

4 Sensor Deployment

Water use efficiency can be achieved via a precisely scheduled irrigation plan. Such a plan provides a means of irrigating with an exact amount of water at the targeted dry area to fulfil the needs of pasture evapotranspiration. In order to tackle soil water dynamics in deficit irrigation at high resolution, sensors must be deployed at a high density. We have deployed sensor pods at various densities across the field. The farm has been divided into four paddocks.

Figure 4. Paddock 2, containing 45 sensor pods.

The sensor pods are deployed in each of these paddocks at different densities. Each paddock receives the same irrigation treatment. The treatment regime is described in Figure 5. The white area in the Figure 5 is an overlapping area which gets water from the sprinkler from either side. In paddocks 1 and 4, ten sensor pods are deployed across five treatment regimes. Hansen soil moisture data loggers are installed in paddock 1, in each treatment regime, to allow for verification of the results from the sensor pod readings. Figure 4 shows paddock 2, containing 45 sensor pods deployed seven metres apart. This paddock contains the highest sensor pod density. The sensor layout in paddock 2 is further clarified in Figure 5. The sensor pods are deployed in a uniform grid under the assumption that there is no a-priori knowledge about the irrigation treatment. In paddock 3, one sensor pod is deployed in each treatment regime. The different levels of irrigation practiced in each paddock enable us to study the impact of different soil moisture levels in the field. From the

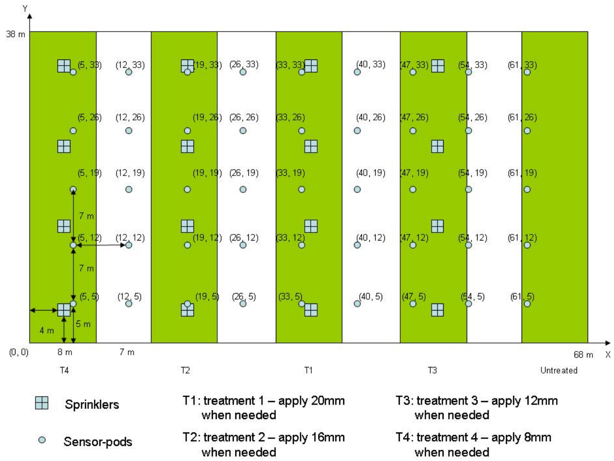

Figure 5. Paddock 2 sensor pod layout, and the irrigation treatment practiced in each paddock.

deployed network, our aim is to measure the pasture's root zone soil moisture, which is a major indication of when irrigation should occur. For local pastures, the significant root zone is at a depth between 0 cm and 30 cm, where over 60% of root mass density, root length density and root volume density occurs [6]. Therefore, two GMSs are installed in each sensor pod to measure soil moisture at depths of 15 cm and 30 cm. The third GMS is deployed to measure the soil moisture at a depth of 45 cm in order to capture water penetration beyond the significant root zone. This allows us to monitor and minimise over-irrigation which may result in soil water deep drainage. An example of three GMSs ready for deployment is shown in Figure 6.

Figure 6. Three Granular Matrix Sensors are installed at depths of 15 cm, 30 cm and 45 cm

5 Preliminary Results

Overall, 70 sensor pods have been deployed at the farm, in addition to four relay nodes and one gateway node. The sensor pods were deployed at the end of December 2007. Apart from a night-time power outage issue still being resolved, the network is now providing continuous data. Data from each sensor pod is collected every 5 minutes. For brevity, in this paper, we show an analysis of soil moisture data collected from two sensor pods from paddock 2, which have been subjected to the same irrigation treatment. GMS readings are stored in the database as resistance in ohms. For this analysis, these resistances were converted into soil water tension (moisture potential) in kPa using three different equations based on soil resistance [1]. High soil water tension level (i.e. moisture potential) corresponds to dry ground, and vice versa. Soil

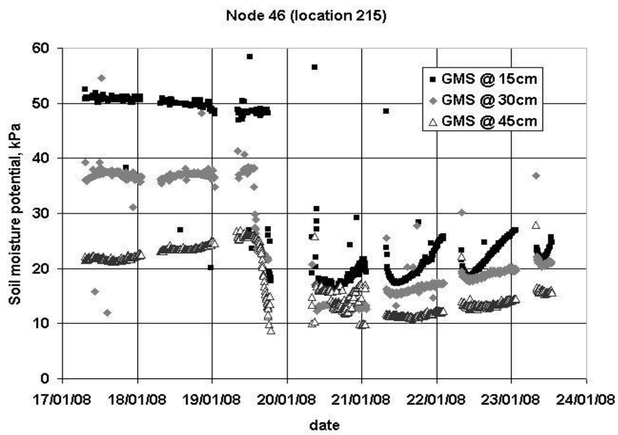

Figure 7. Soil water tension gathered from sensor pod 46 over one week

temperature is required to determine the relationship between soil resistance and moisture potential. The soil temperature probes are not yet installed in our deployment. Thus, the moisture potential is computed for an assumed soil temperature of 20° Celsius. Figure 7 shows the soil moisture of the three GMSs at sensor pod 46. The graph shows the data collected over a one week period. Over the first three days, a clear distinction can be made between the tension at each depth. Tension at 15 cm is highest due to dryness in the soil, whereas the tension at 45 cm is the lowest due to ground moisture. The dramatic drop in tension at all levels corresponds to a rainfall of about 5 mm which occurred on 20/1/2008 at the farm. This clearly shows that the rain affected the surface soil moisture at this location. This pod is located in an area of the field with sparse grass cover, and a high level of irrigation, both of which are conducive to such a change in soil moisture at each depth. Figure 8 shows

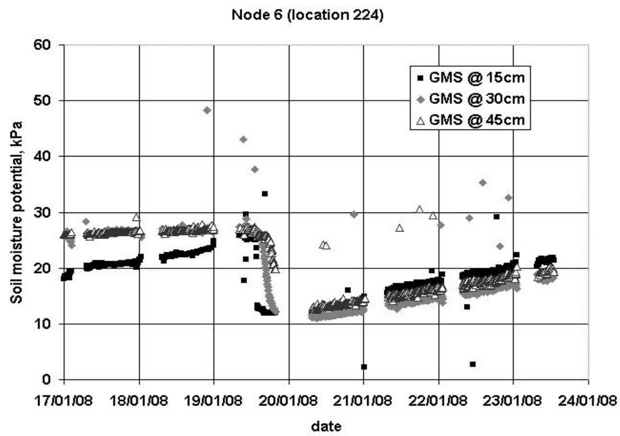

Figure 8. Soil water tension gathered from sensor pod 6 over one week

the results from sensor pod 6. Again, the data clearly shows that the rainfall has affected the soil moisture at this location. Before the rainfall however, the surface at sensor pod 6 had a higher moisture level than at lower depth, which contradicts the data obtained from sensor pod 46. This could be a result of the fact that the grass cover varies throughout the paddock; additionally, the paddock lies on an uneven slope of approximately 6°, which will affect surface runoff in different ways across the field. This may also explain the variation in overall moisture levels between the two pods. After the rainfall, moisture levels at the two pods are more similar.

6 Conclusion and Future Works

In this paper, we describe our experiences in designing, developing and deploying a wireless sensor network with the aim of improving water use efficiency in irrigation. Sensors are deployed in a pasture field at the TIAR Elliott Research Farm near Burnie, in the North West of Tasmania. The developed sensor pods are cost effective, easy to deploy and work in a harsh environment. They are resistant to damage from cattle. GMS are used to measure soil moisture, and are installed at three different depths to study the soil water dynamics and water penetration around the root zone. The aim of this deployment is to aid in the more efficient use water in irrigation.

Currently, we are collecting and validating data from the network. We are in the process of installing soil temperature sensors so that moisture potential can be calculated accurately. The 3G internet connection is relatively unreliable, thus will soon be replaced with a satellite connection. At the paddock scale, we wish to understand plant stress under different irrigation regimes. The ultimate aim of this project is to develop an ideal irrigation regime using real time soil moisture data feeding into a physical soil model.

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