Research Article

COMMONSense Net: A Wireless Sensor Network for Resource-Poor Agriculture in the Semiarid Areas of Developing Countries

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Abstract

COMMONSense Net (CSN) is an ongoing research project that focuses on the design and implementation of a sensor network for agricultural management in developing countries, with a special emphasis on the resource-poor farmers of semiarid regions. Throughout the year 2004, we carried out a survey on the information needs of the population living in a cluster of villages in Southern Karnataka, India. The results highlighted the potential that environment-related information has for the improvement of farming strategies in the face of highly variable conditions, in particular for risk management strategies (choice of crop varieties, sowing and harvest periods, prevention of pests and diseases, efficient use of irrigation water, etc.). Accordingly, we advocate an original use of information and communication technologies (ICT). Our demand-driven approach for the design of appropriate ICT tools that are targeted at the resource-poor, we believe, is relatively new. In order to go beyond a pure technocratic approach, we adopted an iterative, participatory methodology.

Introduction

To this day, and despite an economic boom centered essentially on the service sector of large cities, India has remained a mainly rural society. The share of agriculture in employment is still about 67% (Barker & Molle, 2004), with a majority of small land holdings. In Karnataka, 87% of the farming families own farms of less than 4 ha, accounting for more than 50% of the total cultivated area. Families with very small farms (less than 1 ha) constitute 39% of the total. They usually lack access to irrigation facilities and depend on rain-fed farming for their livelihood. Their crop yields are highly unreliable due to the variability in rainfall in both amount and distribution (Gadgil, Abrol, & Rao, 1999). For all these reasons, we refer to this group as resource-poor farmers.

Since 2001, drought has hit India repeatedly. A wave of farmers' suicides ensued, claiming probably tens of thousands of lives throughout the country, although official figures are lacking (Mishra, 2006; Zubair, 2006). What is certain, however, is that the principal cause is a vicious circle of borrowing money to buy seeds and then getting into increasing debt because of crop failure (Sainath, 2005). This happens not only because of

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adverse climatic events but also because farmers, for economic reasons, tend more and more to replace traditional crops with cash crops: sometimes ill-adapted to the local conditions, sometimes inefficiently grown due to lack of knowledge and experience. Improved environment monitoring may be part of the answer. Although it cannot prevent drought or replace a political solution to the decline of Indian agriculture, environment monitoring can help to improve the lives of resource-poor farmers by mitigating the effects of extreme events, allowing the farmers to adapt their strategy to abnormal or changing climatic features when they occur. Information on the temporal and spatial variability of environmental parameters—their impact on soil, crops, pests, diseases, and other components of farming—plays a major role in formulating farmers' strategies (Hammer, Nicholls, & Mitchell, 2000; Gadgil, Rao, & Rao, 2002; Glanz, 2003). Today, large mechanized farms in developed countries take this factor into account and utilize the convergence of several technologies, including in-field sensors, the geographic information system (GIS), remote sensing, crop simulation models, prediction of climate, and advanced information processing and telecommunications. Similar techniques can be highly useful to farmers in the semiarid regions of developing countries. However, the techniques developed so far are difficult to apply to small land holdings and labor-intensive, low-productivity agriculture. Moreover, the implications of climatic variability in developing countries are a largely unexplored area for agriculture research (Sivakumar, Gommes, & Baier, 2000).

It is generally admitted that the emergence of wireless sensor networks in the near future will represent a window of opportunity to perform efficient environment monitoring at a fraction of the current price. This article presents the ongoing design and implementation of COMMONSense Net (CSN), a decision support system for resource-poor farmers using the wireless sensor networks' technology for environment monitoring. Because of the novelty of the issues that this project addresses, we use extensively a participatory and iterative design. In addition to providing direct support to farmers for yield improvement at the local level, the system will allow for the collection of extensive data that will be used to validate and adapt existing crop models for particular soil and climate conditions. The long-term goal of the project is to help develop replicable strategies for agricultural practices.

Use of Environmental Data for Marginal Agriculture: A Survey

The results and discussion of this section are based on a field survey conducted over a period of 10 months from August 2003 to May 2004 in three villages of the Pavagada region (Southern India): Chennakeshavapura (CKPura), Venkatapura and Ponnasamudra (Rao et al., 2004). The goal of this inquiry was to identify and categorize the information needs of the population living in the semiarid regions of India and to assess the relevance of environment monitoring in such a context.

Background

The Pavagada region is a part of the large semiarid tract of Southern India. It is centered at 14^o N and 77^o E and is situated in the eastern part of Karnataka state. The central part of the region is a plateau with an elevation of about 600–700 m, and several chains of rocky hills found in the landscape form a series of watersheds.

The upper catchment areas of the watersheds are utilized for rain-fed groundnut cultivation. Hills and rocky outcrops constitute the grazing lands for the livestock. In the lower reaches of the watersheds, manmade tanks storing runoff for irrigation were constructed several centuries ago. In addition, large open wells, as well as tube wells, support small patches of irrigated farms. For economic reasons, however, about 85% of the total cultivated area depends exclusively on rainfall for the growing of groundnut during the rainy season (June–November).

Indeed, water for irrigation is too costly for the resource-poor farmers. Their farms are usually located on the upper reaches of the local watershed and thus cannot benefit from the water stored in traditional surface storage reservoirs in the valleys below. As the drilling of bore wells is costly and has a history of a high failure rate, the risk of investing in them is too high to take.

The major climatic feature of the region is the low amount of rainfall and its high variability. The annual average is 561 mm, with a standard deviation as high as 190 mm. The distribution of the rainfall within the year is bimodal (Rao et al. 2004). The maximum rainfall occurs during the second half of

Table 1. User Survey Participation

User Group	Number of Families	Meetings Held	Participants (Average)
Rain-fed farmers	160–200	11	29
Irrigated farmers	40–60	4	18
Irrigated orchards owners	10–12	2	10

September. The second mode is between the last week of May and the first week of June.

Another major characteristic of the climate of the region is the frequent occurrence of long dry spells. Consequently, the crop is highly prone to moisture stress, a risk enhanced by the low moisture retention capacity of the shallow, sandy loam soils. As a result, for 60% of the harvests the cost of cultivation is not recovered (Rao & Gadgil, 1999).

Survey Methodology

Before beginning the assessment of information needs, Rao et al. classified the different user groups, with the family as the basic unit. Each family can have more than one livelihood activity (e.g., farming, sheep keeping, trade, fuel wood gathering, etc.). The various livelihood activities of the families are listed on the basis of effort allocated by the family for the activity. Livelihood activities with maximum allocation of effort are categorized as major livelihood activities. During the initial survey and mapping of the village, for each neighborhood (cluster of houses) or caste group (endogamous group signifying social status) the authors of the survey identified a set of knowledgeable individuals. Discussions with these people allowed the authors to determine the major livelihood and other livelihood options of the families belonging to the relevant user group.

In the second phase, Rao et al. collected the information needs of various groups (see Table 1). For this part, they held group meetings and complementary semistructured interviews. For the group meetings, the resident families were grouped along patterns of resource use (such as irrigated agriculture, rain-fed agriculture, animal grazing, daily labor, etc.). During the group discussions, the farmers identified relevant issues and prioritized them. Several group discussions with the members of the user group were held to determine focal issues of their information needs. The identified focal issues were prioritized by consensus. Any disagreements in choice of focal issues or assignment of priorities were also documented. Separate discussions were then held with interested individuals, in order to gather more details. These discussions typically lasted for 2–4 hours with 3–6 users and usually took place at the farms or houses of user group members.

The following section focuses on the analysis of the different farming groups, at the expense of shepherds, shop owners, craftsmen, and so forth. Special emphasis is given to the resource-poor farmers, because they constitute the target population of the COMMONSense Net project. Richer farmers are also considered, as they are likely to be directly affected by a deployment of the system. More information can be found in the survey report.

Summary of Results

The information requirements of the rural families are very diverse. They cover a wide range of needs including weather prediction, market conditions on a particular day, or legal advice on land-holding rights. A significant finding, however, is that environment-related information ranks high in the perceived needs of the rural families. Drawing directly from the user survey document, we constructed a prioritization of information needs per user group, as depicted in Table 2, in which a “1” designates the highest priority.

In Table 2, one can distinguish different types of issues. Concerns about electricity cuts or groundwater and wells are specific to farmers rich enough to afford to pay for irrigation. As for resource-poor farmers, their wish for better weather forecasts or employment opportunities can hardly be satisfied by better agricultural practices. Nevertheless, the two themes of crop yield prediction and disease control stand out prominently in all the farmers’ categories. For these subjects, the management options available and their costs, risks, and benefits are largely influenced by the high variability of environmental parameters.

Interpretation and Motivation

At first glance, the realization that crop yield is an important concern for farmers seems obvious. How-

Table 2. Priority of Information Needs per User Group

	Rain-fed Farm Owners	Irrigated Orchard Owners	Irrigated Farm Owners
Crop yield assessment	1 (groundnut)	4 (areca nut)	1
Plant disease forecast	2	—	—
Rain prediction	3 (groundnut)	2	4
Work-force scarcity	4 (harvest)	—	—
Water level in wells	—	1	2
Groundwater survey	—	3	—
Electricity supply	—	5	3

ever, the nontrivial finding of the survey is the fact that crop yield *prediction* is critical mainly for poor farmers, because their lack of resources forces them to constantly adapt their strategies to the evolution of the environment. Hence, expected yield plays an important role in the choice to invest or not in an agricultural practice, such as buying fertilizer or pesticides.

As we showed in the previous subsection, environment monitoring and understanding the impact of variability constitute a leitmotiv for farmers. This calls for an extension of the usual paradigm of rural development projects centered on ICT (Prahalad & Hammond, 2003). Whereas projects currently consider primarily interpersonal communications such as rural phone and Internet connectivity, the COMMONSense Net project seeks to advocate a different category of applications that will allow the farmers to connect to and act on the constraints of their own environment in a more precise way.

In semiarid regions, the amount of rainfall and its distribution during the season influence most of the farming: crop yields, disease and pest incidence, farming operations, level of inputs, and so forth. Because they are farming under such a high-risk situation (uncertainty of expected benefit), poor families try to minimize their risk by investing as little as possible, be it for soil fertilizers, soil water conservation, or spraying for pest and disease management. The downside of such a strategy is that in good rainfall years their crop yields are much lower than the potential. Experience shows that they usually achieve about half of the yields of the large farmers, who use better soil fertility and pest management. In situations of uncertain output, the use of a decision-support system able to give information on the benefits and risks of all the available options will help resource-poor farmers to make informed choices for the best strategies.

A sensor network can help them in several ways, by making it a tool in the hands of agricultural scientists who work on more sustainable practices and strategies. Simulation models of crops, pests, diseases, and farming operations are important tools for answering several of the farmers' information requirements. The environment monitoring data provided over time and space by sensors can be used to validate and calibrate existing models. In case such models are not available, this data can help develop and validate simple models by using the state-of-the-art expertise available. It can also help assess the efficiency of simple water conservation measures, such as planting trees or mulching.

Used directly in the field, a sensor network can improve farm-level decision making by providing important benchmarks for the impact of moisture deficits and can monitor in real-time the field conditions with regard to these benchmarks, providing the farmers with a decision-support system adapted to their needs and encouraging them to invest in order to get higher profits from their farms.

Resource-poor farmers, in particular, resort to rain-fed farming not out of choice but out of necessity. Irrigation practices in the semiarid areas of developing countries are usually inefficient and require large quantities of water. This necessitates drilling wells, which is either too risky or unaffordable for them. A reliable decision-support system is a component of a deficit irrigation system that seeks to maximize the effects of irrigation on crop yield while

Table 3. Environmental Data for Marginal Agriculture

Theme	Parameters	Model
Pest & disease	Temperature, humidity, precipitation	HEURISTICS
Crop yield	Temperature, humidity, precipitation, solar radiation, soil moisture	DSSAT, APSIM
Water in bore wells	Water level, pumping time and rate	To be determined

Note: *HEURISTICS =*
DSSAT = Decision Support System for Agrotechnology Transfer.
APSIM = Agriculture Production Systems sIMulator.

Table 4. Environmental Data for Marginal Agriculture: Crop Yield

Information Needs	Specific Questions of Marginal Farmers	Strategy to Provide Information	Role of Sensors	Other Analytical Tools
Soil Fertility	Benefits, costs and constraints in adding soil amendments instead of fertilizers.	Assess expected benefit over next 4–7 years.	Measure soil moisture increase by treatment.	Groundnut simulation model, rain fall pattern based on climatologic prediction.
	Given the variability of rainfall, optimal choice and quantity of fertilizer.	Cost/benefit analysis of fertilizer input levels using crop model runs over 100 years.	Soil moisture measurements to validate groundnut crop model.	Groundnut simulation model and long-term climate data.
Timing of Farming Operations	Provide forecasts of rains during weeding and harvest.	Determine specific soil moisture ranges that have an impact on farming operations for different soil textures and monitor them.	Correlate soil moisture to farming outputs. Real-time monitoring of the soil conditions for deficit irrigation.	Forecast of rain 7–10 days in advance.
Water Conservation Measures	Cost/benefit analysis of using bunds and trees.	Using existing models and historical data.	Soil moisture data to validate models.	DSSAT, water shed models.

Note: *DSSAT = Decision Support System for Agrotechnology Transfer.*

minimizing the intake of water. For poor farmers, this could mean applying new strategies of partial irrigation, such as transporting water from community tanks on carts, renting rich farmers's wells, and other strategies.

Data Requirements

Table 3 summarizes the parameter set that was isolated and the corresponding prediction models. Drawing on the survey's analysis of the needs of small-farm families in terms of environmental data (Rao, 2006), we extract the most promising and rapidly implementable applications and analyze them (Table 4).

System Functionalities and Use Cases

At this early stage of the project, it seemed easier to collaborate with agriculture scientists in order to design our application, because we feared that a direct interaction with the farmers would generate either incomprehension (their immediate attention being more focused on loans) or high expectations leading to disappointment and disinterest, as our prototype will take time to be fully operational. As a consequence, we defined system functionalities and use cases jointly with a crop physiologist from the University of Agriculture Sciences, Bangalore, and a farmer with higher-education training in agronomy.

Crop Modeling

Several crop simulation models are available for simulating the growth of various crops and crop mixes with different environmental constraints such as moisture stress, nutrient stress, and water logging. These models are an important component of the decision-support system (see Table 3 and Table 4). In this case, we identified DSSAT (Decision Support System for Agrotechnology Transfer; Matthews & Stephens, 2002) and APSIM (Agricultural Production Systems sIMulator; Keating et al., 2003) as the most promising models for the Pavagada region. They have, however, certain limitations.

Both DSSAT and APSIM have a deep but narrow focus on certain components of decision making—crop growth and yield—and they neglect other pertinent areas (McCown et al., 1996; Mathews & Stephens, 2002). In decision making for farmers, precision should not be provided at the expense of relevance. In other words, it is more important "to be roughly right than precisely wrong." Making effective use of the models as a tool in order to serve the needs of farmers would require building additional components to measure (or "for elements") such as the impact of pests and diseases, the timing of farming operations, and the like. Data from a sensor network will help to develop, design, and test simple models for a better application of the—more complex—crop models.

A specific criticism of DSSAT is that it is highly "crop-plot centric," whereas the users consider farming processes at the higher scale of a whole agricultural ecosystem (Walker, 2002). A sensor network with wide deployment and high data availability for several environment parameters has the potential to validate models of the ecosystem and farm-scale processes or develop simple ones.

Finally, both models do not take into account the most recent developments in environmental monitoring technology. They are based on a daily timescale for assessing temperature and air humidity. Moreover, a fundamental parameter such as soil moisture is assessed indirectly, based on soil characterization and rainfall measurements. Such limitations no longer apply. Sensor networks can both improve the sampling time-scale and use direct parameters relevant to crop yield, such as soil moisture.

The use case for this part is as follows. Once the sensor network is deployed, the data are gathered repetitively, saved into a database, and uploaded regularly by crop modeling specialists, who tune the model coefficients to the relevant parameter space in the region of interest; validate the model with the new set of data; and complement or modify it as improved environmental data become available.

Water Conservation Measures

Comparative readings of soil moisture can be used to assess the efficiency of different water conservation measures, such as building bunds and planting trees to trap water in the shallow layers of the soil, or using mulch and gypsum to reduce evaporation. This use case is similar to the previous one, except that here, soil moisture readings are used directly. Sensors are placed in fields that are comparable from a physical point of view, but where different water conservation measures are used.

The two first use cases do not take direct advantage of the possible real-time features of a sensor network, because the response time is not critical. The following subsection presents a real-time application in the form of an empirical decision support system for marginal farmers.

Prediction of Crop Water Requirements for Deficit Irrigation

Because water is scarce to resource-poor farmers, they can benefit from the technology of deficit irrigation, an agricultural water management system in which the water needs of the crop (potential evapotranspiration) during the growing period can only be met partially by a combination of soil water, rainfall and irrigation (Upchurch et al., 2005). Deficit irrigation management requires optimizing the timing and degree of plant stress within restrictions of available water. Of particular use to the farmers is the knowledge of benchmark points for crop/trees water requirements (those points are specific to a particular crop). Using the recent trend of soil moisture values recorded by sensors and the knowledge of these points, the farmer can predict the behavior of his crop and use simple water management techniques.

For such an application, in addition to deploying soil-moisture sensors, other parameters are needed. Climatic parameters such as daily rainfall, sunlight hours, wind speed, and air humidity are homogenous enough to necessitate the deployment of only one weather station every few square kilometers.

Soil characteristics, however, can vary significantly because of composition and situation. This means that the soil moisture retention capability has to be assessed every few hectares at least.

Concretely, it is reasonable to deploy one pair of sensors (for cross-checking) per homogenous parcel, to compute the model coefficients for this parcel over a calibration phase and retrieve them from a table when a prediction has to be made. In order to assess the influence of a particular feature of the landscape (such as trees, bunds, etc.) on the soil conditions, a sensor is added at this particular location.

The use cases are as follows.

Calibration: As a one-time effort, soil moisture probes need to be calibrated with measurements from the gravimetric method, an accepted standard procedure for determining soil moisture. Climatic probes are also calibrated. Then, in the normal mode of operation, the calibration continues to take place, in a feedback loop based on the difference between the predicted and measured value in order to take local variations into account.

Alert: Real-time alerts are given whenever the measured soil-moisture of a parcel reaches a threshold in the benchmark values. These alerts are automated, but farmers have to be notified by the system operator. Once the alert is given, the farmer should be able to look at weather forecast data and know, based on historical climatic data for the region, the probability of rain in the near future.

Soil Moisture Prediction: Based on the model and the actual measurements, the system uses a real-time learning process to give predictions on soil-moisture values over time.

Water Requirements Assessment: Based on the same type of request as above, the system gives an estimate of the minimum irrigation water needed according to the benchmarks.

Open Functionalities

At a nontechnical level, we plan to organize collaborative discussions with the farmers about the raw data obtained and to give them fully open access to the data collected in the form of graphs and preprocessed data.

System Outline

Technology Choice

General characteristics of the use cases detailed in the previous section are spatial variability of the data, temporal variability of the data, and a real-time component in the deficit irrigation case. In such a situation, the advantage of using a sensor network instead of stand-alone sensors with data-loggers was underlined by Beckwith, Teibel, and Bowen (2004). Although the network they use is a dense network spanning a small area of 2 acres (approximately 0.8 ha), they observe significant gains in deployment time, data gathering and maintenance efficiency.

Another possibility would be the use of remote sensing. The MODerate-resolution Imaging Spectrometer (MODIS), for instance, provides raw images on a daily basis, although their use involves considerable extra processing. MODIS's spatial resolution is around 500 m. Such a solution is minimally intrusive and scales excellently, but it only works for the shallow layers of the soil (down to 10 cm at most). The deeper layers (the root zone) are beyond the reach of such a system. For this reason, and because in remote sensing the physical parameters are assessed *indirectly*—through interpretation of the electromagnetic spectrum—the data are less accurate than for ground sensors.

The frequency and delay of data depend on the satellite's orbit. As a consequence, remote sensing is not ideally suited for a real-time application if one wants to monitor a parameter continuously.

Ground-based sensors operating wirelessly are more appropriate. But the right technology must be chosen accordingly. Telemetry using cellular networks such as GSM is widely used today. It presents the advantage of wide and rapidly expanding coverage. There are two main limitations to the use of such systems. The first is recurring communication costs, which are prohibitive for messages sent several times per hour over a long period of time. The second is the network coverage in rural areas outside of the villages. In the COMMONSense Net (CSN) test-bed, for instance, although there is limited GSM connectivity within the village, the fields nearby are not covered.

Wireless sensor networks (WSNs) are, however, fully scalable. They do not depend on any preexisting infrastructure and can be redeployed or expanded easily. Because of the ability of their

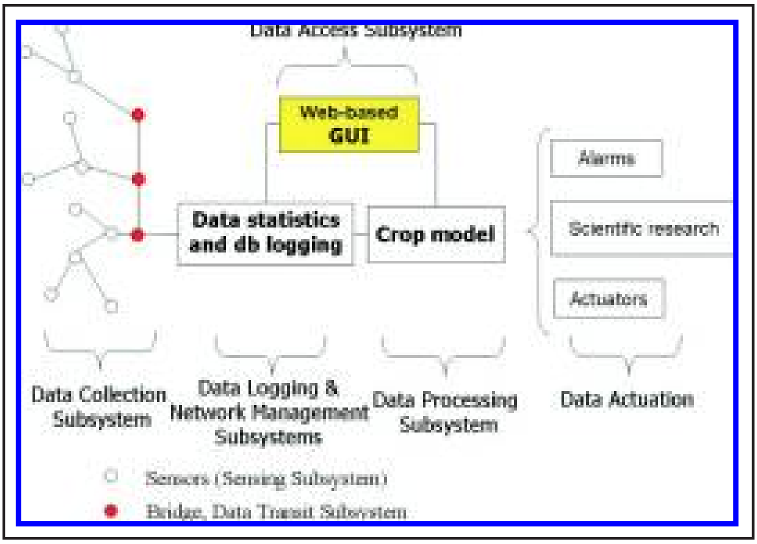

Figure 1. System overview.

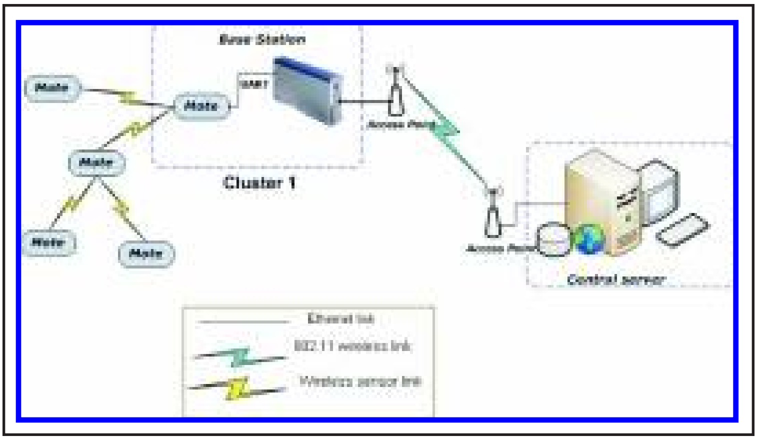

Figure 2. System architecture.

elements to reorganize spontaneously when the conditions change, they are resilient to partial failures. The communications, being independent from any operator, do not cost anything. As this technology is inherently meant to be deployed unattended for extended periods of time, it includes by-default low-power radio and the possibility to develop power management mechanisms that extend the lifetime of the elements and the network as a whole.

Our agricultural specialists are still debating what would be the appropriate time and space resolution for the data they need to collect. Faced with this uncertainty, we decided to begin by providing data at a high rate and spatial resolution in order to be able to filter out redundant values. The result of such a test will determine whether our hypothesis is correct (i.e., if a sensor network is the appropriate technology for the kind of applications we envision).

System Overview

The system design is as shown in Figure 1. This corresponds to a logical architecture summarized in Figure 2, the subsystems of which we detail in the following subsections.

Sensing Subsystem

For meteorological parameters, CSN uses a weather board designed for use with wireless sensors, integrating temperature and humidity (Sensirion SHT11), ambient light (TAOS TSL2550D), and barometric pressure (Intersema MS5534AM). In the absence of a microclimate, such parameters do not vary significantly over the deployment area, so only two MTS400 equipped nodes are deployed, for redundancy and detection of measurement drifts.

Soil moisture is a parameter of higher variability. We chose the ECH2O probes that can be plugged to wireless sensors via a data acquisition board (MDA300). CSN does not measure solar radiation at this point, although this should be included in the near future, as it is a major input for predicting the productivity of the crop. The leaf area index (LAI) based on the intercepted radiation provides information on the useful biomass of the crop and thus its yield.

Data Collection Subsystem

CSN uses a centralized data-collection model, where individual wireless sensor nodes perform minimal data processing and send back the data via a base station (a node connected to a computer) to a single server where they are processed. As neighboring nodes of the network can be more than 100 m apart, a majority of them are unable to reach the base station directly. They have to resort to multihop transmissions, where nodes can relay data from other nodes in addition to sending their own. This means that every node in the network can perform three tasks: collecting data, sending data toward the base station, and, if needed, relaying data sent by other nodes. As for routing, because there is no mobility in the network and topology changes are rare (node failure, occasional moving or addition of a node), CSN uses a simple tree construction algorithm, based on neighboring radio links quality and hop counts to the base station.

There are two main issues affecting the platform choice for the wireless sensors. The first is radio range. Given the data variability and sparse density of the network, a range of more than 100 m is mandatory, and up to 1 km is desirable. The second important issue is the power consumption, although this characteristic can be mitigated by an appropriate power management scheme such as duty cycling. Ideally, the nodes have to perform autonomously for the duration of the cropping season (roughly 6 months), either on alkaline batteries or with a small solar panel.

Given all these considerations, the most adapted platform available in late 2004 (when the initial choice was made) was the Mica2 (Crossbow, 2002) mote manufactured by Crossbow, because its power consumption is reasonably low and its radio range is the highest among the candidate technologies.

The short range of Zigbee and Bluetooth radios disqualifies them, and technologies such as IEEE 802.11 do not satisfy the power consumption requirements. Still, the radio range of Mica2 is sometimes stretched. Tests conducted in typical landscapes of the deployment area indicated a higher bound of 100 m in the best case with quarter wave antennas connected to a ground plane.

The chosen embedded operating system is TinyOS[1], because it is widely used by the scientific community, quickly becoming a de facto standard. Moreover, this operating system makes libraries of components readily available, such as medium access layer (CSN uses B-MAC) and multihop routing (CSN uses the default route component). In order to save the radio resources as much as possible, the data sampling rate (once every 5 minutes) is higher than the transmission rate, the latter being adjusted automatically at the node level depending on the current variability of the parameters.

Data Transit Subsystem

In order to interconnect disconnected patches to one single server for data logging and network management, CSN makes use of IEEE 802.11 (WiFi) bridges between individual network clusters. Unlike individual sensor nodes, these bridges are connected to the power grid via electric poles that can easily be found in the deployment area. They are not power constrained and expand significantly the scalability of the network, which is then divided into clusters; the cluster head being connected to an IEEE 802.11 access point.

The current solution makes use of classical access points and a rugged PC for the bridge. This solution is both expensive and power hungry. GSM connectivity, which was not satisfactory at the time of the deployment, has since improved considerably in the region of CKPura. Accordingly, we are in the process of implementing a GPRS bridge that will aggregate and transmit the data directly to the central server located at the Indian Institute of Science (IISc) in Bangalore.

Data Logging and Network Management Subsystems

A proprietary Java application, based on an original design by the sensorscope group (Schmid and Dubois-Ferrières, 2005), is used to send commands to the wireless network and to log data and metadata into a database, from which they are extracted for display and processing. The Java application is also used to send commands and queries to the network (such as transmission power and radio channels change).

Data Processing Subsystem

At the moment, the data are processed manually, using the APSIM model in order to check the compatibility of its soil moisture predictions with the readings given by the wireless sensors.

Data Access Subsystem

The system contains a Web-based interface for the display and upload of data. As most of the farmers do not have access to the Web, these data will be made available at a local village center in the form of graphs and spreadsheets. The goal is for this center to become a forum for discussions and a point

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[1] *TinyOS operating system. Documentation available online at http://www.tinyos.net*

of access for searching other useful farming information on the Internet.

Deployment Scenario

Concerning the sensor network itself, the deployment scenario is the same for the three applications described earlier in this document. Wireless sensors are deployed in geographical clusters, each with one base station that is connected to a local server via an IEEE 802.11 (WiFi) link. The sensors are also organized in groups, each group corresponding to a particular application, be it crop modeling, water conservation measures assessment, or deficit irrigation management. Once the wireless nodes are deployed, the data are sent periodically to a centralized database. Sensors from different groups can collaborate for data relaying.

Figure 3. 2005–2006 deployment map.

The placement of sensors and their lifetime depend on the application envisaged for them, but this has no influence on the architecture of the network. The only constraint is to ensure the connectivity of every single wireless sensor with the rest of the network. For this, two test nodes are used, which run a simple Ping-Pong program, one node sending periodically packets that the other one retransmits to its originator upon reception. An LED signals the successful reception of every packet. This way, one can easily check visually that an intended location for a new node is suitable for both packet transmission and reception.

The difference between the different use cases resides on the part of database, as different applications require different computing tools. Data processing, display, and import/export are provided by the Java application and the web-based user interface on a per-group basis.

First Results

The first prototype of the sensor network was developed in late 2004–early 2005 and it has been operating in an controlled outdoor environment on the IISc campus since April 2005. With 10 nodes sending data every 5 minutes in a continuous flow, it proved sufficiently stable for the first deployment in the field to take place.

Field Deployment

We proceeded with a first field trial in Chennakeshavapura in December 2005, then with an initial deployment in August 2006. Figure 3 details the settings of this deployment consisting of two separated clusters—note: the water bodies indicated on the map are dry most of the year—from which the network had already collected a wealth of data that were used in three ways: to validate the data collected by the different probes; to assess the performance of the network in terms of range, lifetime and connectivity; and to test and refine the design.

Probe Validation

The results obtained from the sensor network deployed on the IISc campus were compared to the benchmark measurements from the Center of Atmospheric and Oceanic studies (CAOS) from the IISc, in order to determine whether the trends matched. As shown in Figure 4, the results for temperature are an exact match. The same result holds for humidity, which uses the same Sensirion SHT11 probe. The pressure readings are consistently off by around 4 mbar, which merely indicates a calibration error (Figure 5).

We validated the soil moisture readings indirectly

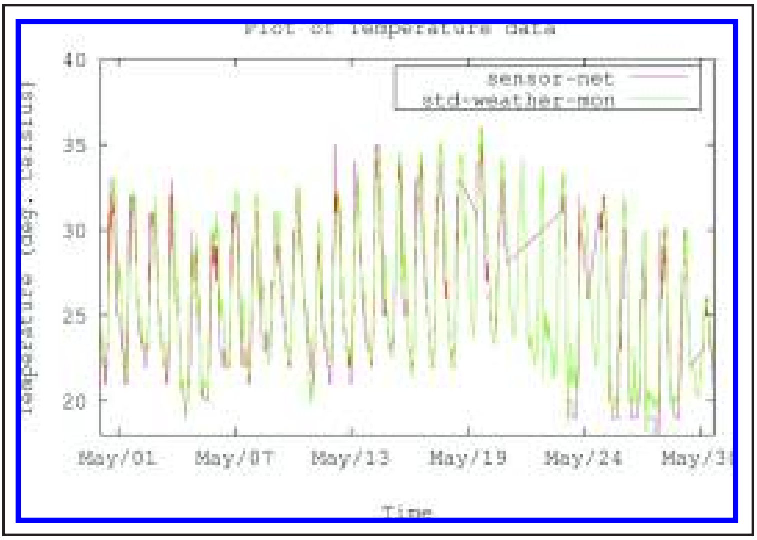

Figure 4. One-month temperature readings (2005).

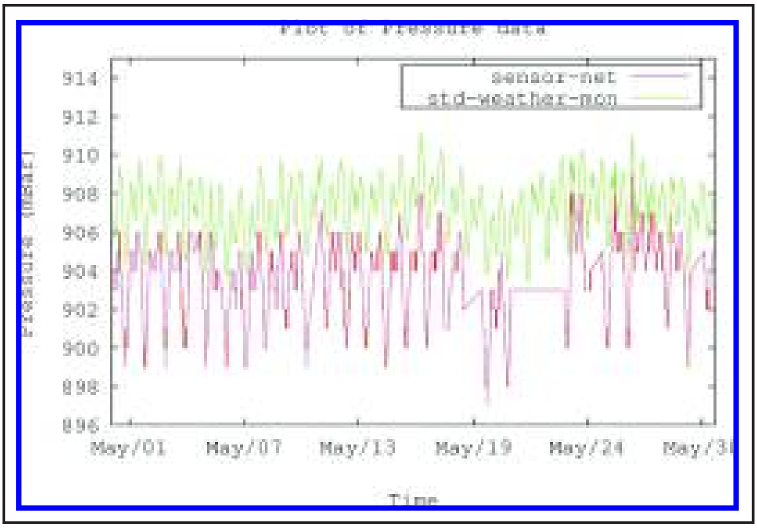

Figure 5. One-month pressure readings (2005).

by superimposing them with rainfall data (Figure 6). As one can see, the trend clearly matches. However, the measurements appear to be noisier than we hoped, although they remain in the 5% range specified in the ECH2O user manual. This problem can be solved by averaging over a larger number of samples, which is done with a traditional data logger, but this will increase the power consumption and decrease the lifetime significantly. This remains an open design issue.

Performance Assessment

We ran extensive real-life tests to assess the performance of the network.

Lifetime of a Node

With a pair of alkaline batteries and a sampling frequency of once every 5 minutes, the lifetime of a node gathering temperature/pressure/humidity is on average 2 months. The nodes sampling soil moisture were found to survive on average half of this time. This prompted us to investigate in detail the software driver for the soil moisture probe and do some optimization by reducing the excitation time from 50 ms to 10 ms, which is the value recommended for the ECH2O probe for a classic data logger.

Radio Range

The shipped Mica2 mote is equipped with a quarter wavelength wire that plays the role of an antenna and has a short communication range of about 100 m (line of sight, 10 dBm radio transmit power). Fortunately, the range can be significantly improved by the use of a quarter wavelength linx antenna and have wavelength ground plane (a square aluminum mesh of size half wavelength). We observed that the motes have a better range of about 200 m line of sight at 1% cutoff, with 10 dBm transmit power. This result was consistent across the deployment area.

Network Connectivity

The multihop routing algorithms that come as standard for TinyOS can cause frequent topology changes. Because of the numerous control messages that are exchanged between the nodes, these multihop routing algorithms end up being power hungry. A single-hop network, where nodes go to sleep and wake up independently to send their data to a base station that is always listening consumes

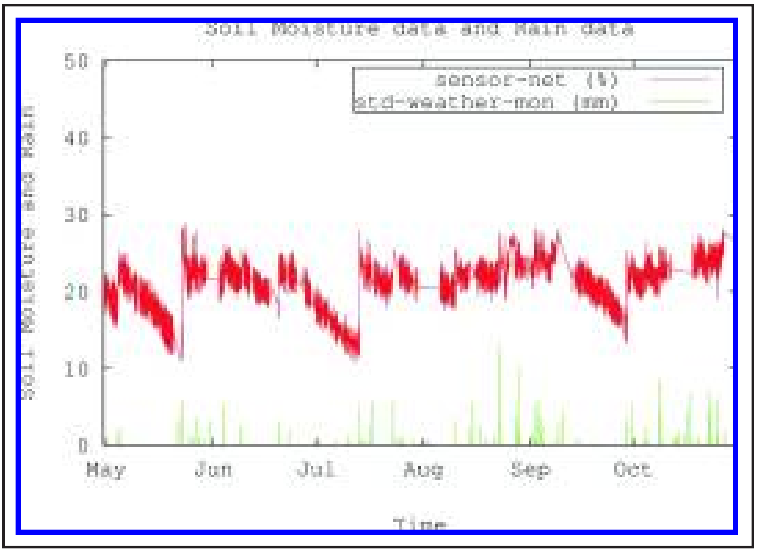

Figure 6. Correlation between rainfall and soil moisture at 30cm into the soil (2005).

less energy. Unfortunately, the wide node distribution rules out this strategy.

Network Reliability

Memory corruption of motes contributes to the overall unreliability of the system. The experience in live deployment in the backyard with a large, leaf canopy cover resulted in unpredictable node ID changes on at least three occasions. We also experienced a complete freezing of nodes in the field deployment at CKpura. The node ID change is mostly one or two bit flips in the node ID field structure. Although the node ID may be brought back to its original value by a software reboot of the running code, a node freeze has proved to cause a corruption of the flash memory. We suspect high package temperatures to be the cause for the flash corruption seen in the field deployment.

Wi-Fi Link Unreliability

Cluster 1 is about 0.9 Kms, and Cluster 2 is about 2.4 Kms from the field station. Unlike cluster 1, cluster 2 is non-line-of-sight (NLOS) due to very thick vegetation cover. Connectivity from the field station is now possible only by the addition of a 10 dB gain amplifier. Packet losses in excess of 6% in bursts occur in both clusters.

New Design

Because of the issues they face in terms of lifetime, radio range and network reliability led us to undertake major changes in the design of both hardware and software components of our application:

New Platform: We selected and tested a new wireless sensor platform, the Tinynode from Shockfish.[2] This platform presents an average radio range of 300 m with peaks at 1km at full power (15 dBm) and an attractive power consumption profile

New Data Acquisition Board: Designed in-house, this data acquisition board is customized for soil moisture readings and includes a battery case for one 3.6-V lithium battery.

New Software: Based on an ultra-low-power MAC and Routing component, which handles the transmission of the packets over multiple hops, the new application should provide a lifetime of up to 5 years with the low data rates that are used in the CSN application.

This new revision of the wireless sensor network is scheduled for field deployment in February–March 2007 in CKPura.

Human Development Issues

The CSN project deals with an experimental technology: wireless sensor networks. As such, it is likely that it will not lead immediately to concrete "economically profitable" applications. However, as Brewer et al. (2005) reflected about technology needs, "Western market forces will continue to meet the needs of developing regions accidentally at best." In this same spirit, we advocate the importance of exploring the potential of an emerging technology—sensor networks—in the particular case of rural development, in order to take the ecological, social, cultural, and economic conditions of developing countries into account in the design of hardware and software platforms and to develop

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[2] *TinyNode wireless sensor. Documentation available online at http://www.tinynode.com*

applications that are well adapted to this context. These issues are developed in the following subsections, which detail the traps usually associated with the failure of ICT projects in developing countries.

Participatory Iterative Design

The CSN project is built as a set of iterations, all following the same structure and building upon each other in a feedback loop. We begin with the participatory definition of a problem (agricultural water management in semiarid areas of developing countries), propose a technology-based solution, and then develop the appropriate system and evaluate its use and usefulness in the local cultural and social context. Finally, we draw conclusions for improvement, scalability, and the repeatability of the approach, and then pass to the next iteration.

Each iteration uses the evaluation of the output of the previous iteration to redesign correctively the system for the current one. This is done sequentially by extensively using a participatory approach. With meetings and demonstrations, the researchers involve the end users in the design and assessment of the prototype at each step.

Design/Implementation Gaps

Heeks (2001) argues that the failures of information systems projects in developing countries are often caused by design-actuality gaps. Country context mismatches (in terms of institutions, infrastructures, etc.) as well as hard-soft gaps (rational design vs. cultural and political actuality) play a role all the more important if the system was designed in an industrialized context. To summarize, failures can generally be explained by the distance (geographical, cultural, or socioeconomic) between the designers of the system and its intended community of users.

As stated above, the CSN project uses participatory design extensively, which mitigates this risk. Heeks warns, however, that participatory design in itself is no guarantee for success in developing countries, because these techniques have usually been developed in and for industrialized countries organizations. A lesson to be drawn is that a participatory approach in a developing country is instrumental to success if and only if it integrates a tool to bridge the contextual gap between design and use.

In order to bridge this gap, Heeks advocates the usage of *hybrids*—namely, individuals who understand both the alien worlds of the community of users and of the community of designers/builders of the artifact. In the CSN case, the *hybrid* is a local farmer who is also an agronomist and is familiar with information systems for having worked with them for more than a decade.

Ad-hoc networks also present an important feature, in the way that they constitute an emerging technology in constant evolution. This leaves a significant place for experimentation, and in the context of a project such as CSN, presents the advantage of being able to develop a technology specifically for the developing countries, instead of tweaking existing systems made to operate in a different context, which is a criticism made recurrently to projects dealing with ICT for development (Heeks and Brewer, among others).

Computer Literacy and Application Ownership

It is not enough for an information system to satisfy adequately the needs of its intended target population. When this population is living in poor and remote areas with a low level of literacy (not to mention computer literacy), a major issue is the capacity of the user base to understand, use and finally own the system (we define ownership as the ability and willingness to maintain the system in a working state and to integrate it in daily activities).

For this to happen in this case, the project has to meet two conditions: The first is the ability of the sensor network to function autonomously, without the need of skilled maintenance. As we have seen previously, this is a design goal of sensor networks, not yet fully realized, but on which will depend the success or failure of the whole technology. This is reflected in our technology choice. The second is the capacity of the population to learn about the use cases of the system. In order to explain our approach to this part, we developed the concept of capacity building and knowledge creation through apprenticeship (Panchard & Osterwalder, 2005). Our hypothesis is that there are some aspects of apprenticeship that make it particularly suited to the acquisition and integration of radically new paradigms of knowledge. It is a self-organized process in which every individual takes ownership of the knowledge he or she acquires. Not relying on formal teaching, it can be more integrated in the social structure and possibly more equitable, as people without the time, resources, or will to attend classes can be reached through it.

Solving concrete issues one after another ensures that people are interested in the process and increases the likelihood of their persevering in the endeavor. It allows for unexpected forms of organization to develop and is adaptive. Ultimately, it is empowering.

This being said, it is to be noted that the project will have to rely permanently on computer literate operators for the development and maintenance of the application itself. This support can be assured by the IISc and by one or two literate individuals hired in the village.

Scalability

One main reason a majority of successful prototypes fail once they pass into the operational mode is the issue of scalability (Bhatnagar & Schware, 2000; Bhatnagar, 2004). Given the difficulty of reliably operating networks of a few tens of nodes, it is still unclear today how well sensor networks will scale in the near future. The solution proposed in this project is to rely on a two-tiered network composed of several, possibly disconnected, clusters of sensors linked by an overlay network of IEEE 802.11 access points that use as a power source the numerous electrical poles present even in the most remote rural areas in India. Because they are not energy constrained, the access points can expand their reach over several kilometers and possibly communicate via multiple hops to the sink. For a scale higher than local, multiple sinks interconnected via the Internet may be used.

It is too early to state whether the CSN project will be able to overcome the scalability hurdle. Given the complexity of the water institutions in India, it is likely that this step will represent a major challenge (Saleth, 2004).

Economic Sustainability

It is difficult at this stage of the project to talk about demonstrable gains, as we are using a technology still in its maturation phase and not yet widely available on the market. As a consequence, rather than study economic feasibility, we aim at verifying the hypothesis that resource-poor farmers can take benefit from a system similar to ours.

This being said, it is important to keep in mind the ultimate benefits that local farmers will get from the system. For the research part (i.e., crop modeling and water conservation measures), the involvement of the agronomical scientific community and the ability to disseminate the obtained results to the population in a credible way are the key points. This is no simple task, but leveraging on existing experience and success stories is possible (Sakthivadivel et al., 2001).

The case of deficit irrigation management is trickier. We would have to demonstrate that the investment necessary per year (one-time sensor purchase, changes of batteries, possible service charge for the forecast) can be recovered by the improvement of yield and the increased income that results or that alternative business models can be found. This subject is out of the scope of the present article, but we address it in an upcoming report.

With their mind set on Moore’s law, analysts usually predict that within a few years the market price for a wireless sensor will be a few U.S. dollars, should the technology be adopted (the price of the probes themselves remaining an issue). Relying on the aggregated purchase power of poor communities (Prahalad & Hammond, 2003), we believe that under such circumstances, our system will be affordable for purchase by local communities and public institutions and the results made available to end users for a fee to be determined, its cost/benefit ratio remaining to be demonstrated in the course of the project.

State of the Art

Sensors have been used in precision agriculture for years. Such systems are used in convergence with other high technologies like global positioning system (GPS), geographic information system (GIS), miniaturized computer components, automatic control, remote sensing, mobile computing, and advanced information processing and telecommunications. Because of radical differences in the type of agriculture and economic power of the farmers, these models and experiences are difficult to apply to the CSN setting.

There is extensive on-going work to design and implement concrete applications of sensor networks (Römer and Mattern, 2004). Among the themes widely regarded as promising, there are habitat and wildlife (Juang et al., 2002; Mainwaring et al., 2002; Small & Haas, 2003), cold-chain management (Riem-Vis, 2004), rescue operations (Michahelles et al., 2003), disaster prevention, and precision agriculture.

Burrell et al. (2004) mention the use of sensor networks for the integrated management of a vineyard. However, the article restricts itself to describing potential uses of a sensor network, without any concrete design or implementation to assess the solution proposed. Field work was conducted by Beckwith et al. (2004). About 65 nodes were deployed over a period of more than 6 months in an Oregon vineyard, reporting temperature every 5 minutes. In the CSN case, both the intended target population (marginal farming versus precision agriculture) and the type of network (scarce and wide versus dense and narrow) differ significantly.

Ho and Fall (2004) consider the case where sensor networks are deployed out of the reach of communication infrastructures. In order to solve the connectivity problems and to mitigate communication interruptions, they propose the use of the delay tolerant networking (DTN) architecture. We have not yet explored the feasibility of this solution.

A few applications can be accessed on the web, in order to ensure diffusion and reusability of information. Sensorscope (Schmid & Dubois-Ferrières, 2005) is a sensor networking application developed at LCAV (EPFL). It includes tools for data and network management, a database interface and a user-friendly web-based GUI, which we reused and extended in the course of the CSN project.

Droogers et al. (2001) have worked on the potential for rain-fed agriculture based on satellite remote sensing across the world. To the best of our knowledge, to date no one has formally explored the role of ICT-based environmental monitoring for agricultural management targeted at resource-poor farmers in semiarid regions.

Conclusion and Future Work

In this article, we have presented an ongoing research and implementation work on an environmental monitoring system primarily aimed at resource-poor farmers of developing countries. Using participatory design and a rigorous technical approach, we have developed an integrated sensor-network system that we are in the process of testing in the field. The goal of this project is the improvement of farming strategies in the face of highly variable conditions, in particular for risk management strategies (choice of crop varieties, sowing and harvest, prevention of pests and diseases, efficient use of irrigation water, etc.).

Because the CSN project is participatory and demand driven, it depends on the involvement of the farmers themselves. For this, we focus on the applications that have either direct (deficit irrigation) and indirect (validation of crop models) impact on the livelihood of resource-poor farmers.

Early results from a deployment in a controlled area, as well as in the field, proved encouraging. Precise figures on the impact over yield, as well as user comments, will condition the further evolutions of the project, which will be carried through in two more iterations until the end of 2007.

As for future work, an enhancement of the system is to modify the crop models that currently assess soil moisture indirectly from rainfall and soil characteristics, in order to make use of the direct data obtained from the field. An additional benefit of the project will be an improved Internet connectivity in the village (due to the WSN server), which farmers can use to access agricultural information resources online. We are currently reflecting on possible ways to integrate this opportunity in the project. We also plan to initiate work on ground water in the near future. The evolution of the CSN project can be followed at these URLs: http://commonsense.epfl.ch and http://www.commonsensenet.in ■

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