COMMON-Sense Net: Improved Water Management for Resource-Poor Farmers via Sensor Networks

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***Abstract*— We describe the on-going design and implementation of a sensor network for agricultural management targeted at resource-poor farmers in India. Our focus on semi-arid regions led us to concentrate on water-related issues. Throughout 2004, we carried out a survey on the information needs of the population living in a cluster of villages in our study area. 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.). This leads us to advocate an original use of Information and Communication Technologies (ICT). We believe our demand-driven approach for the design of appropriate ICT tools that are targeted at the resource-poor to be relatively new. In order to go beyond a pure technocratic approach, we adopted an iterative, participatory methodology.**

I. Introduction

This paper presents an on-going project that uses sensor networks to meet the information needs of the rural poor living in the semi-arid regions of developing countries. Our test case is situated in rural Karnataka (India).

To this day, it remains uncertain whether the resources and technologies available in developing countries will be sufficient to satisfy a growing population's demands for food and other agricultural commodities [1]. Worldwide, nearly one billion people suffer from hunger. The most affected regions are by far the semi-arid tropics, where precipitation is scarce and unpredictable. The rural poor are the most vulnerable to this climatic variability, because they lack the resources to adapt to adverse conditions.

In India today, the share of agriculture for employment is about 67% [2], 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 [3]. 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 both rainfall amount and its distribution [4], [5]. For all these reasons, we refer to this group as resource-poor farmers.

Information on the temporal and spatial variability of environmental parameters, their impact on soil, crop, pests, diseases and other components of farming play a major role in formulating the farmers' strategy [6], [7], [8]. Today, large mechanized farms in developed countries take this factor into account and utilize the convergence of several technologies, including in-field sensors, geographic information system (GIS), remote sensing, crop simulation models, prediction of climate and advanced information processing and telecommunications. Similar information can be highly useful to farmers in the semi-arid 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 [9]. This is a gap that we are trying to bridge.

In the following sections of this paper, we present the on-going design and implementation of a decision support system for resource-poor farmers, which uses the wireless sensor network technology for environment monitoring. Because of the novelty of the issues that we address, our project is demand-driven and uses extensively a participatory and iterative design. In addition to providing direct support to farmers for yield improvement at the local level, the system allows the collection of extensive data that will be used to validate and adapt existing crop models for particular soil and climate conditions. Our long-term goal is to help developing replicable strategies for agricultural practices.

In section II, we summarize the results of a participatory survey about the information needs of the rural population, which we conducted in three villages of Karnataka in partnership with the Center for Atmospheric and Oceanic Studies (CAOS) of the Indian Institute of Science in Bangalore. Section III describes the use cases of our system and positions

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wireless sensor networks (WSNs) in comparison with other technologies such as remote sensing and cellular networks, in order to explain where - and under what conditions - WSNs can be used in our context. In section IV, we describe the different elements of our system. In section V, we present the early results derived from our first prototype deployment in Karnataka. In section VI, we challenge our design using the usual criticisms made to ICT projects for development, such as affordability, sustainability and scalability. Finally, we present related research projects in section VII, before drawing a conclusion and outlining some future work perspectives in section VIII.

II. 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 ten months from August 2003 to May 2004 in three villages of the Pavagada region in Karnataka (Southern India): Chennakeshavapura (CKPura), Venkatapura and Ponnasamudra [10]. The goal of this enquiry was to identify and categorize the information needs of the rural population living in semi-arid regions.

A. Background

The Pavagada region is a part of the large semi-arid tract of Southern India. It is centered on 14 °N and 77 °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 to 700m, 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 watershed, man-made 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. Since the drilling of bore wells is costly and has a history of high failure rate, the risk is too high for them to take.

The major climatic feature of the Pavagada region is the low amount of rainfall and its high variability. The annual average is 561mm, with a standard deviation as high as 190mm. The distribution of the rainfall within the year is bimodal. The maximum rainfall occurs in the second half of 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 [11].

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

TABLE I
Population involved in the CKPura User Survey

B. Survey Methodology

Before beginning the assessment of information needs, we 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) we identified a set of knowledgeable individuals. Through discussions with these people, we were able to determine the major livelihood and other livelihood options of the families belonging to the relevant user group.

In the second phase, we collected information needs of various groups. For this part, we held group meetings and complementary semi-structured 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 group discussions, we identified relevant issues and prioritized them with the farmers. 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 the details of information on focal issues. These discussions typically lasted for 2 - 4 hours with 3 to 6 users and usually took place at the farms or houses of user group members.

In the following section, we concentrate our analysis on the different farming groups (at the expense of shepherds, shop owners, craftsmen etc.) : the resource-poor farmers, since they constitute our target population, and the other farmers, who are the most likely to be directly affected by a deployment of our system.

More information can be found in the survey report [10].

C. Results

The information requirements of the rural families were very diverse. They covered 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 [10] , we were able to construct a prioritization of information needs per user group, as depicted in Table II, in which a '1' designates the highest priority.

In summary, one can see from the list of issues at stake for farmers that themes of pest and disease control, crop yield and water levels in bore wells stand out prominently. For each of these subjects, the management options available, their costs, risks and benefits are largely influenced by the high variability of environmental parameters.

D. Interpretation

At first sight, the realization that crop yield is an important concern for farmers seems obvious. However, the non-trivial finding of the survey is the fact that crop yield *prediction* is extremely important to 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. This means that the kind of environment monitoring systems that they cannot afford is precisely what they would need to improve their livelihood.

As we showed in the previous subsection, environment monitoring and assessing the impact of variability constitute a leitmotif for farmers. This calls for an extension of the usual paradigm of Rural Development projects centered on ICT [12]. Whereas current projects consider primarily interpersonal communications such as rural phone and Internet connectivity, we want to advocate a different category of applications that will allow the farmers to connect to- and act on the constraints of their own environment and livelihood in a more precise way.

In semi-arid 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, etc. 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 an informed choice for the best strategy.

It is in this area that a sensor network can help such farmers in several ways. Simulation models of crops, pests, disease and farming operations are important tools to answer several of their information requirements. The environment monitoring data provided over time and space by sensors can be used to validate and calibrate existing models. In the case where such models are not available, it can help to develop and validate simple models by using the state-of-the-art expertise available. Finally, it can improve farm-level decision making by providing important benchmarks for the impact of moisture deficits, and monitor in real-time the field conditions with regard to these benchmarks, providing the farmers with a decision-support system adapted to their needs, encouraging them to invest in order to get higher profits from their farms.

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 -

TABLE III

ENVIRONMENTAL DATA FOR MARGINAL AGRICULTURE

In particular, resource-poor farmers resort to rain-fed farming not out of choice, but out of necessity. Irrigation practices in the semi-arid 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 impact of irrigation on crop yield while 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, etc.

E. Data Requirements

Tables III and IV summarize the parameter set that we isolated and the corresponding prediction models:

Drawing on the survey coordinator's analysis of the needs of small-farm families in terms of environmental data [13], we were able to extract the most promising and rapidly implementable applications and analyze them (Table IV).

III. SYSTEM FUNCTIONALITIES AND USE CASES

The testbed that we chose is the region where the survey was run, the Pavagada region. The first location for operating our prototype is the village of Chennakeshavapura.

A. 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 Tables III and IV). In our case, we identified DSSAT (Decision Support System for Agrotechnology Transfer) [14] and APSIM (Agricultural Production Systems sIMulator) [15], [16] as the

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

TABLE II

PRIORITY OF INFORMATION NEEDS PER USER GROUP

Information Needs	Specific Questions of Marginal Farmers	Strategy to Provide Information	Role of Sensors	Other Analytical Tools / Data Needed
Soil Fertility	1) 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.
	2) 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 and climatic parameters 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 and other climatic parameters 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 strategies	DSSAT, water shed models.

TABLE IV

ENVIRONMENTAL DATA FOR MARGINAL AGRICULTURE: CROP YIELD

most promising models for our region. They have, however, certain shortcomings in our context.

Both DSSAT and APSIM have a narrow and deep focus on certain components of decision making - crop growth and yield - and neglect other pertinent areas ([17], article of Stephens and Middleton in [14]). In decision making for farmers, precision should not be provided at the expense of an integrated answer. It is more important "to be roughly right than precisely wrong". Making effective use of the models as a tool to serve the needs of farmers would require us to build additional components such as impact of pests and diseases, timing of farming operations etc. Data from a sensor network will help us 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 [18]. A sensor network with wide deployment and high data availability for several environment parameters has the potential to validate models of ecosystems and farm scale processes and/or develop simple ones.

Finally, both models were taking into consideration for the collection of parameters the actual technical limitations at the time of their conception. They are based on a daily time-scale 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 do not apply anymore. 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:

1) tune the model coefficients to the relevant parameter space in the region of interest;
2) validate the model with the new set of data;
3) complement or modify it as improved environmental data become available.

In this subsection we did not take direct advantage of the possible real-time features of a sensor network, because the response-time is not critical. In the following subsection, we present a real-time application in the form of an empirical decision support system for marginal farmers.

B. 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.

In this case, soil moisture readings are used directly. Sensors are placed in comparable fields, where different water conservation measures are used.

C. 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 [19]. 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 due to 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, compute the model coefficients for this parcel over a calibration phase, and retrieve them from a table when we want to make some prediction.

When we want 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.

1) Input to the system: **Calibration** : As a one time effort, we need to calibrate soil moisture probes with measurements from the gravimetric method, an accepted standard procedure of determining soil moisture. **Climatic probes are also calibrated.** Then, in 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.

2) Outputs from the system: **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. 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, what is the probability of rain in the near future. Because the complexity of statistical forecast is high, we will address this part in the second phase of the project only.

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.

Irrigation Support : This use case takes place during irrigation. Based on high-frequency readings from soil moisture probes, the system gives a hand-held device a real-time feedback on the adequacy of the water volume applied, allowing for fine-tuning of the irrigation process.

D. Open Functionalities

At a non-technical 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.

IV. System Outline

A. Technology Choice

The advantage of using a sensor network instead of stand-alone sensors with data-loggers was underlined by Beckwith et al. [20]. Although the network they use is a dense network spanning a small area of 2 acres (approximately 0.8 ha), they observed 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' spatial resolution is around 500m [21]. Such a solution is minimally intrusive and scales excellently. But, it only works for the shallow layers of the soils (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 electro-magnetic spectrum - the data are less accurate than for ground sensors.

The frequency and delay of data depends on the satellite's orbit. It is not suitable for a real-time application if we want to monitor a parameter continuously (as is the case when irrigation is taking place and we want to fine-tune the intake of water).

Ground-based sensors operating wirelessly are more appropriate. But one still has to choose the right technology.

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 villages. In our testbed, for instance, although there is limited GSM connectivity within the village, the fields nearby are not covered.

Wireless sensor networks (WSNs), on the other hand, are fully scalable. They do not depend on any preexisting infrastructure and can be redeployed or expanded easily. Due to the ability of their elements to reorganize spontaneously when the conditions change, they are resilient to partial failures. The communications, being independent from any operator, do not

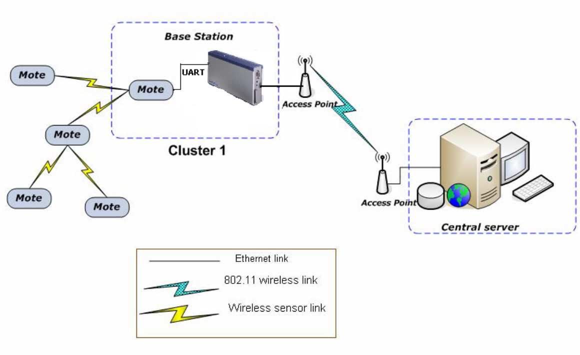

Fig. 1. System overview

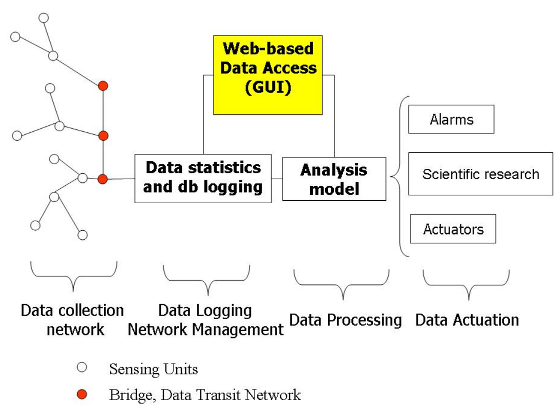

Fig. 2. System architecture

cost anything. Since 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.

For all these reasons, we decided to design and deploy a WSN.

B. System Overview

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

1) Sensing Subsystem: For meteorological parameters, we use the MTS400 weather board designed for use with *Mica2* [22], 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 we only deploy 2 MTS400 equipped nodes, for redundancy and detection of measurement drifts.

Extensive tests of these boards in deployment environment allowed us to assess the precision of the different probes (see section V).

Soil moisture is a parameter of higher variability. We chose the ECH2O probes [23], that can be plugged to *Mica2* motes via a data acquisition board [24].

We do 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.

2) Data Collection Subsystem: We use a centralized data-collection model, where individual nodes perform minimal data processing and send back the data via a base station to a single server where they are processed. As nodes of our network are more than hundred meters apart, a majority of them are unable to reach the base station directly. We have to resort to multi-hop transmissions, where nodes can relay data from other nodes as well as sending their own.

In regards to routing, as there is no mobility in the network and topology changes are rare (node failure, occasional moving or addition of a node), we use 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 our wireless sensors. The first is radio range. Given the data variability and sparse density of the network, a range of more than 100 meters is mandatory, and up to one 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 best platform available in late 2004 (when we made our initial choice) was the *Mica2* mote manufactured by Crossbow, because its power consumption is reasonably low, and its radio range was the highest among candidate technologies.

The short range of *Zigbee* and *Bluetooth* radios disqualified them, and technologies such as 802.11 did not match the power consumption requirements.

Still, the radio range of *Mica2* is sometimes stretched in our case. Our tests conducted in typical landscapes of the deployment area indicated a higher bound of 100 meters in the best case with quarter wave antennas connected to a ground plane.

We use *TinyOS* [25] as an operating system, 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 (we use B-MAC), and multihop routing (we use the default Route component). In our first deployment, tinyOS is used without significant changes to these components, although some issues with topology stability and MAC efficiency make us consider some modifications at this level in the future.

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.

3) Data Transit Subsystem: Because of the sparse nature of the network and since we have to interconnect disconnected patches, we make use of 802.11 bridges between individual network clusters. Unlike individual sensor nodes, these bridges are connected to the power grid via electric poles that can be found regularly 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 a 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. We are investigating a solution based on a serial-to-802.11b embedded module [26].

Alternative solutions include using GSM bridges, or a technology such as the corDECT wireless local loop [27]. Because such solutions were not available in our case, we did not investigate the exact economic impact of using them.

4) Data Logging and Network Management Subsystems: A proprietary Java front-end, developed on the basis of the sensorscope application [28], is used to send commands to the wireless network and to log data and meta-data into a database, from which they are extracted for display and processing.

The Java front-end is also used to send commands and queries to the network (such as transmission power and radio channels change etc.)

5) Data Processing Subsystem: Prediction models are described in section III. This subsystem is still under development; there is no integrated processing of the data for the time being.

6) Data Access Subsystem: We use a web-based interface for the display and upload of both raw and processed data. As most of the farmers do not have access to the web, those data are made available at a local village center in the form of graphs and spread-sheets. The goal is for this center to become a forum for discussions, and a point-of-access for searching other useful farming information on the Internet.

C. Deployment Scenario

On the "sensor network" side, the deployment scenario is the same for the three applications described in section III. Wireless sensors are deployed in geographical clusters corresponding to the assignment to one base station, which is connected to a centralized server via an 802.11 (wi-fi) 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. From then on, the data are sent periodically to a centralized database. Sensors from different groups can collaborate for data relaying.

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 the connection of a single sensor with the rest of the network, which we ensure by using a simple ping-pong application, where two nodes exchange simple data packets and blink upon reception.

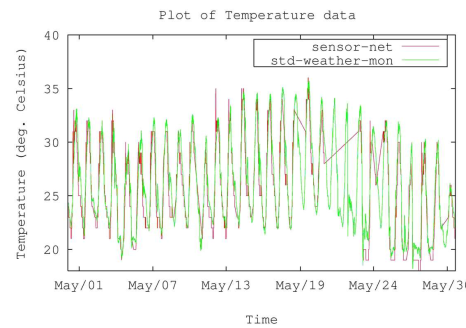

Fig. 4. One-month temperature readings

The difference resides on the database side, since 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.

V. First Results

The first prototype of our sensor network was developed in late 2004 - early 2005, and has been operating in an outdoor controlled environment since April 2005. With 10 nodes sending data every 5 minutes in a continuous flow, it proved sufficiently stable for us to begin the first deployment in the field in December 2005. Fig. 3 details the settings of this deployment consisting of 2 separated clusters. (Note: the water bodies indicated on the map are dry most of the year.)

It is to be noted that integration of the data processing subsystem has not been completed yet. This will begin in early 2006. However, we have already collected a wealth of data that we used in three ways:

1) to validate the data collected by the different probes;
2) to assess the performance of the network in terms of range, lifetime and connectivity;
3) to test and refine our design.

A. Probe Validation

The results obtained from the sensor network were compared to benchmark measurements from CAOS, in order to see if the trend matched. As shown in Fig. 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 (see Fig. 5)

We validated the soil moisture readings indirectly by superposing them with rainfall data (Fig. 6). As we can see, the trend clearly matches.

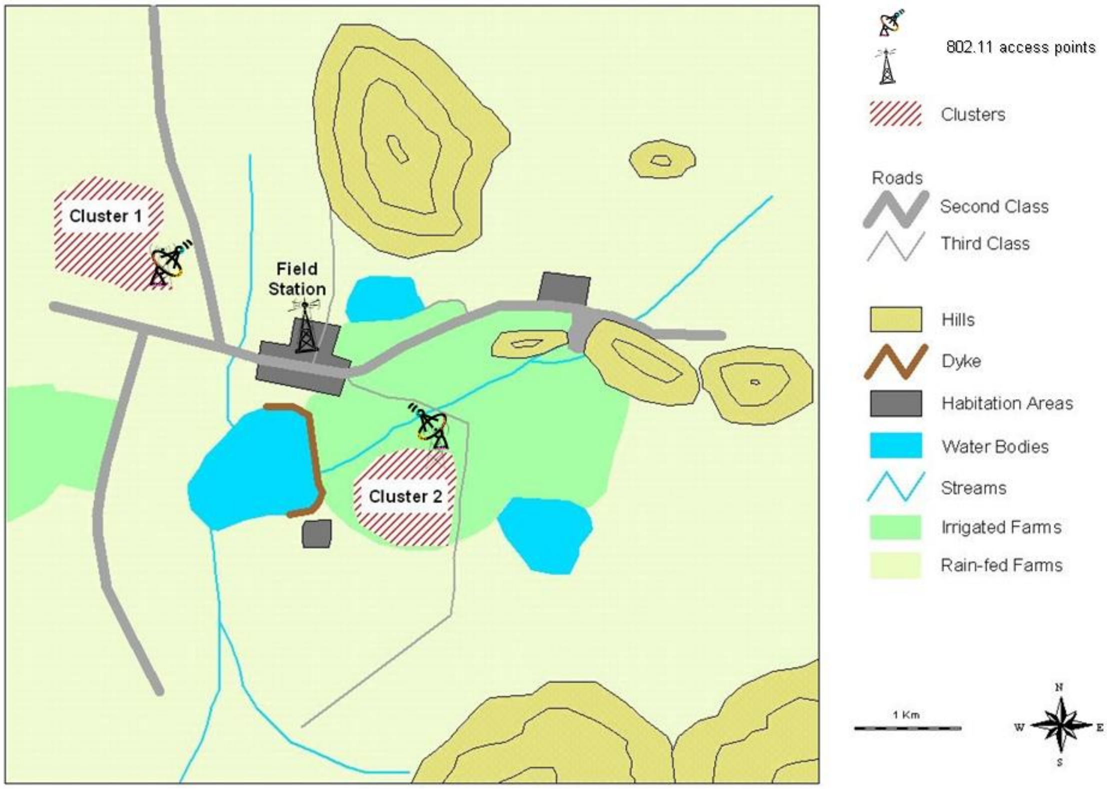

Fig. 3. 2005-2006 deployment map

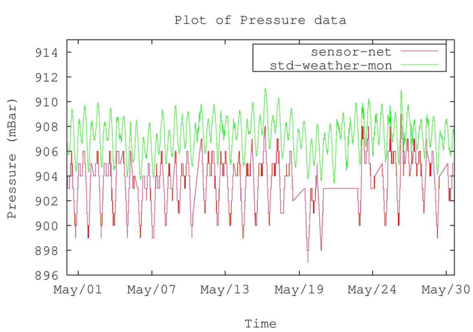

Fig. 5. One-month pressure readings

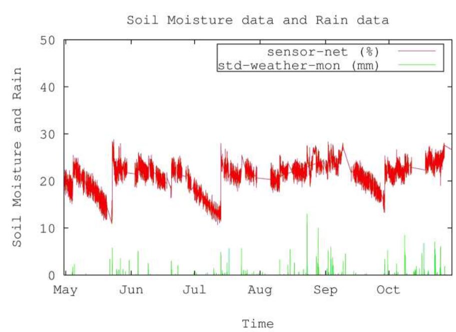

Fig. 6. Correlation between rain-fall and soil moisture at 30cm into the soil

However, the measurements appeared to be more noisy than hoped, at 5% about 2% above the 3 % range specified in the ECH2O user manual. Odds are that such an error interval is sufficient for our application. However, since we do not know with certainty what is the required precision for soil moisture in some use cases (e.g. crop modeling), we are working on minimizing the noise. We can solve this problem by averaging over a larger number of samples (which is what is done in a traditional datalogger), but this will increase the power consumption and decrease the life-time significantly. This remains an open design issue.

B. Performance Assessment

We ran extensive real-life tests for assessing the performance of our network.

Life-time of a node: With a pair of alkaline batteries and a sampling frequency of once every 5 minutes, the life-time 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 datalogger).

Radio range: The shipped *Mica2* mote provides a $1/4$ wavelength whip antenna that has a short communication range of about 100m (line of sight, 10dBm radio transmit power). Fortunately, the range can be significantly improved by the use of a $1/4$ wavelength linx antenna and $1/2$ wave length ground plane (a square aluminum mesh of size $1/2$ wave length). We observed that the motes have a better range of about 200m line of sight at one percent cut-off, with 10dBm transmit power. This result was consistent across the deployment area.

Network connectivity: The multi-hop routing algorithms that come as standards for *TinyOS* can cause frequent topology changes. Because of the numerous control messages that are exchanged between the nodes, these multihop routing algorithms tend to consume a lot of power. A single-hop network, where nodes go to sleep and wake-up independently to send their data to a base station which is always listening would consume less energy. Unfortunately, the wide node distribution rules out this strategy.

C. Network Reliability

Memory corruption of motes contributes to the overall unreliability of the system. Our experience in live deployment in the backyard with large leaf canopy cover, has resulted in unpredictable node ID changes in at least 3 occasions. We have also experienced a complete freezing of nodes in the field deployment at CKpura. The node ID change is mostly a one or two bit flip 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 be 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 10dB gain amplifier. We are experiencing from both the clusters over 6% packet losses, which occur in bursts. We think that the off-the-shelf Access Points (APs) have a large drift in the output power and are currently carrying out experiments to select the most suitable AP for our needs.

D. Field deployment

As mentioned earlier, we are proceeding to a first field trial in Chennakeshavapura. We deployed two clusters, and intend to extend the network continuously in the upcoming months. The goal of the field trial is three-fold:

1) Assess the capacity of the sensor network to calibrate and refine existing crop models (cluster 1)
2) Assess the capacity of the soil moisture probes to quantify different water conservation measures (cluster 2)
3) Test a simple deficit-irrigation management system (upcoming clusters)

The system can be accessed on-line at http://www.commonsensenet.in/ckpura/ckpura.php.

VI. Human Development Issues

In this section, we discuss our project in terms of development goals. It should be noted at this point that this project deals with an experimental technology: sensor networks. It is likely that this project will not lead immediately to concrete "profitable" applications. However, as Brewer et al. reflected about technology needs, "(...) Western market forces will continue to meet the needs of developing regions accidentally at best" [29]. In the 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 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.

A. Participatory Iterative Design

Our project is built as a set of iterations, all following the same structure and building upon each other in a feedback loop. We start with the participatory definition of a problem (agricultural water management in semi-arid areas of developing countries), propose a technology-based solution, 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 repeatability of the approach, and 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, we involve the end-users in the design and assessment of the prototype at each iteration.

B. Design/Implementation Gaps

Heeks [30] 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 versus 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, we use participatory design extensively, which mitigates this risk. Heeks warns, however, that participatory design in itself is no guarantee for success in developing countries, since 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 our case, the *hybrid* is a local farmer who is also an agronomist and who 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 ours, presents the advantage of being able to develop a technology specifically for the developing countries context, 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 (see for instance [30], [29]).

C. 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 our case, we have to meet two conditions :

The first is the ability of the sensor network to function autonomously, without the need of skilled maintenance. As we saw in section IV, 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 (section IV).

The second is the capacity of the population to learn about the use cases of the system. In order to explain our approach of this part, we developed the concept of capacity building and knowledge creation through apprenticeship [31]. Our hypothesis is that there are some aspects of apprenticeship that make it particularly suited in 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 is acquiring. 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 insures that people are interested in the process and increases the likelihood of them persevering in the endeavor. It allows for unexpected forms of organization to develop and is adaptive. Ultimately, it is empowering.

It is to be noted that we 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 Indian Institute of science in Bangalore, and by one or two literate individuals hired in the village.

D. Scalability

One main reason why a majority of successful prototypes fail once they pass into operational mode is the issue of scalability. [32], [33].

Given the difficulty of operating reliably 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 802.11 access points using 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 our project will be able to overcome the scalability hurdle. No institutional contacts have been made beyond the local level, mainly because we feel a proof of concept needs to be made before seeking interest for the project from the political institutions. However, given the complexity of the water institutions in India, it is likely that this step will represent a major challenge [34].

E. Economic Sustainability

It is difficult at this stage of the project to talk about demonstrable gains, since we are working on a system that to our knowledge is without precedent, using a technology still in its maturation phase and not yet available on the market. As a consequence, rather than study economic feasibility, we aim at making a proof of the concept 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 [35].

The case of deficit irrigation management is trickier. One has 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 paper, but we address it in an upcoming article.

With their mind set on Moore's law, analysts usually predict within a few years a market price of a few USD for a wireless sensor, should the technology take up (the price of the probes themselves remain an issue for now). Relying on the aggregated purchase power of poor communities [12], we claim that under such circumstances, our system will be affordable, its cost/benefit ratio remaining to be demonstrated in the course of our project.

VII. State of the Art

Sensors have been used in precision agriculture for years. Those 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. Due to radical differences in the type of agriculture and economic power of the farmers, these models and experiences are difficult to apply to our particular setting.

There is extensive undergoing work to design and implement concrete applications of sensor networks [36]. Among the themes widely regarded as promising, one can mention habitat and wildlife [37] [38] [39], cold-chain management [40], rescue operations [41], disaster prevention, and precision agriculture.

Burrell et al. [42] 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 nor implementation to assess the solution proposed. Field work was conducted by Beckwith et al. [20]. About 65 nodes were deployed over a period of more than 6 months in an Oregon vineyard, reporting temperature every five minutes. In our 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 [43] considered the case where sensor networks are deployed out of reach from communications infrastructure. In order to solve the connectivity problems and to mitigate communication interruptions, they propose the use of the Delay Tolerant Networking (DTN) architecture. We did not explore the feasibility of this solution in our case.

A few applications can be accessed on the web, in order to insure diffusion and reusability of information. Sensorscope [28] 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. Being essentially a research tool on sensor networks, it does not integrate so far data processing intended for a concrete use.

Work on the potential for rain-fed agriculture based on satellite remote sensing accross the world has been done by Droogers et al. [44].

To the best of our knowledge, no one to date has formally explored the role of ICT-based environmental monitoring for agricultural management targeted at resource-poor farmers in semi-arid regions.

VIII. Conclusion and Future Work

In this article, we have presented our on-going 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 our 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 our project is participatory and demand-driven, we depend on the involvement of the farmers themselves. For this, we focus on 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 proved encouraging. The initial results from the first real-life deployment will be known by the end of 2006. 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 end of 2007.

We are currently working on improvements of the system: use of solar energy to power the nodes, enhancement of the 802.11 bridges and integration of the identified prediction models into the software.

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. A side-effect of the project will be an improved Internet connectivity in the village (because of the WSN server), that farmers can leverage on to access information resources worldwide. We are currently reflecting on possible ways to integrate this opportunity in our project. We also plan to initiate work on ground water in the near future.

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