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# Hydrological Monitoring with Hybrid Sensor Networks

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## ABSTRACT

*Existing hydrological monitoring systems suffer from shortcomings in accuracy, resolution, and scalability. Their fragility, high power consumption, and lack of autonomy necessitate frequent site visits. Cabling requirements and large size limit their scalability and make them prohibitively expensive.*

*The research described in this paper proposes to alleviate these problems by pairing high-resolution in situ measurement with remote data collection and software maintenance. A hybrid sensor network composed of wired and wireless connections autonomously measures various attributes of the soil, including moisture, temperature, and resistivity. The measurements are communicated to a processing server over the existing GSM cellular infrastructure.*

*This system enables the collection of data at a scale and resolution that is orders of magnitude greater than any existing method, while dramatically reducing the cost of monitoring. The quality and sheer volume of data collected as a result will enable previously infeasible research in hydrology.*

## I. INTRODUCTION

The data collected by current hydrological monitoring systems is limited in spatial and temporal resolution, due to both cost and lack of autonomy of the systems. Site visits by experts are required for data collection, as well as maintenance of the system. If the problems of travel costs and site disruption were alleviated, by using remotely triggered, in situ measurement devices, the data could be updated more frequently. Creating low cost measurement systems, along with the ability to leave the equipment in the field for extended periods of time, make it possible to increase the spatial resolution, or alternatively, cover a larger area. This gives a more complete picture of the processes at work in the soil and enables the construction of a hydrological snapshot of a large area. Remotely triggered, in situ measurement devices also decrease the delay between measurements that are required to occur concurrently over an entire area being monitored.

While there exist measurement systems that can be left on site, they are expensive and fragile. Current systems usually use a data logger wired to probes. The data logger must be placed in a protective structure to keep it from being damaged

by the environment, because it has not been specifically designed to remain in the field for long periods. The majority of existing systems have high power consumption, which necessitates expensive wiring and easy access to the power grid.

The aforementioned shortcomings in cost, site disruption, and accuracy can be solved by applying a hybrid sensor network, which includes both wireless and wired connections among the nodes. In this approach, a sensor network is installed at the site and the location of each sensor recorded, either by hand, via GPS, or through a location discovery method. The sensors self-organize into an ad hoc network. The system can be accessed from any computer connected to the Internet. Remote data collection and maintenance considerably reduce the number of site visits required, which in turn reduces the cost of monitoring. Also, in situ sensors do not disturb the site, allowing for more accurate measurements, when compared to methods that must remove a sample from the site.

The network is comprised of three types of nodes: sensor nodes, cap nodes, and base stations. The sensor nodes, which perform the measurements at different depths of the soil, are wired together to form a sensor string. This string is buried in the ground, with the top-most node, designated as the cap node, above the surface. The cap node is connected wirelessly to other cap nodes and a base station that is used as a gateway between the sensor network and the external world. Short-range wireless communication among the cap nodes and base station eliminates the considerable cost and effort of installing the cables required for lateral coverage. The long-range communication between the base station and the external world is also wireless, as it utilizes the existing cellular phone infrastructure. All devices use battery power, which eliminates the need for power cables.

The sensor measurements can be taken on an event-driven or time-driven basis, i.e., they can be programmed to take measurements on a specific, pre-programmed schedule, when a specific environmental event occurs (e.g., rainfall), or at the remote request of a user. In any case, the sensors remain in sleep mode until the time they are required to take a measurement. They briefly activate, collect the data, and return to sleep mode, which greatly reduces their power consumption.

Similarly, communication of the collected data can be either time- or event-driven.

The nodes can be programmed to take measurements on a periodic basis. For a parameter such as temperature, a longer period could be used, because the temperature does not change quickly. In contrast, in event-driven schemes, measurements are taken in response to a pre-specified external event. For example, if there were precipitation sensors on the network, one could program the network to take a temperature measurement while it is raining [1].

While each node takes measurements from its immediate vicinity, the network of nodes together can measure a much larger area. Measurement methods such as time domain reflectometry (TDR) [2], time domain transmission (TDT) [3], dielectric, and electromagnetic induction [4], can be taken over an area only limited by the number of nodes, instead of being limited by the physical properties of a sensor. A single TDR measurement can cover a volume less than  $0.01 \text{ m}^3$  [2], while an array of nodes, all taking simultaneous TDR measurements, can cover a much larger area, on the order of kilometers, in the same amount of time. This greatly improves the spatial resolution of hydrological measurement methods based on electromagnetic properties of the environment.

The remainder of this paper is organized as follows. Section II provides a background on hydrological monitoring, and describes a number of related studies. In Section III, the design and operation of the proposed hydrological monitoring network is discussed in detail. Section IV concludes the paper and discusses a number of avenues designated for future research on the topic.

## II. BACKGROUND AND RELATED WORK

The idea of measuring physical processes with sensor networks is not new, and has been described in other studies [5]–[9]. Doolin and Sitar [5] describe two field tests of wildfire monitoring with wireless sensor networks (WSNs). The sensors used were based on Mica2<sup>®</sup> motes interfaced with a sensor board containing temperature, relative humidity, barometric pressure, light, and acceleration sensors. For each test, the motes were mounted on poles above the tall grass fuel. A fire was started and the motes recorded the temperature, barometric pressure, and relative humidity of the front of the fire as it passed them. Each mote failed to transmit data at some time during the tests, but due to the large number of motes, reliable data was still collected. These tests show that useful data can be collected despite the failure of many nodes. The system proposed in this paper also benefits from this feature.

In [6], two experiments are described that compare the performance of WSNs to traditional measurement methods for structural monitoring. The two experiments, namely, the structural integrity sensor test and the ground liquefaction sensor test, show that even with a high rate of node failure, the network returns results on par with traditional wired sensors. The author also states that the software for the motes is hard to use and does not provide all promised features. Even though

the devices performed admirably, there is still significant work to be done on both the hardware and software sides of WSNs.

The design and field testing of a sensor network for measurement of soil moisture is described in [1]. The system is based on Mica2<sup>®</sup> motes and employs various sensor types that coordinate with the network to react to external stimuli such as precipitation. When the network detected that it was raining, it would increase the sampling rate of the soil moisture sensors, returning it to normal when the rain stopped. The network routing is static, with some motes dedicated to routing messages. The network's base station was connected to a remote database server via the GSM network.

While the network met the goal of being reactive, improvements can be made, such as generalizing the event-condition-action framework [1] and generalizing the network structure, allowing for ad hoc removal and insertion of nodes into the network. The most significant difference between [1] and the method proposed in this paper is the depth of the measurements. The system described in [1] only measures soil moisture at the surface, while the system of this paper can measure below the surface, using buried sensors.

Current WSNs only measure properties on or above the surface. Geophysical processes happen both on and below the surface. Current methods of measuring subsurface processes include gravimetric, dielectric, ultrasonic, spectroscopic, electromagnetic induction, thermal, and nuclear methods [4]. These methods are labor intensive, power hungry, and expensive.

Another shortcoming of existing methods is the requirement that a site sample be removed and analyzed. For example, in gravimetric methods [4], a soil sample is removed, weighed, dried, and then weighed again. The difference in weight is assumed to reflect the moisture in the soil. This process of removing a sample from the site is disrupting the very property that is being measured. Since the soil was removed, the measurements of the sample reflect the state of the site before the sample was taken, instead of its current state. The disruption also limits the rate at which useful measurements can be taken. In situ testing methods, such as techniques employed in the system proposed in this work, eliminate the need for taking samples and facilitate a considerable increase in the rate of soil property measurements.

Current systems for measuring properties of soil are large in size and require on-site expert personnel to operate. For example, Jackson et al. [10] used an airborne electronically-steered L-band radiometer (ESTAR) to measure surface soil moisture, and compared it to ground observations (gravimetric method) and L-band push broom microwave radiometer measurements. All three of these methods require on-site personnel. The ESTAR system also requires the use of a C-130 aircraft. The system proposed in this paper eliminates the need for such large and costly equipment. Moreover, it utilizes long-range data communication and remote maintenance, which considerably reduces the need for intervention by skilled personnel.

Two other soil property measurement techniques, specific

potential and resistivity measurements [11], also require on-site personnel and may require large equipment, depending on the measurement requirements. The measurements can be taken manually with a multi-meter, or the probes can be connected to a large data logging device that is typically vulnerable to the elements and requires that a shelter be built for it and its external power supply.

The aforementioned studies underscore the need for novel environmental monitoring systems that are low-cost, perform in situ testing and collect and report accurate data without the intervention of onsite experts. Low power consumption is a very desirable feature, as it increases the unattended field life of the device. A small, inconspicuous, and rugged device can considerably lower costs, as it survives exposure to the elements without requiring protective housing. The remainder of this paper elaborates upon a novel approach to meeting these specifications.

### III. SYSTEM DESIGN AND OPERATION

This section describes the general design of the sensor network being proposed for hydrological monitoring. The main components are introduced and the sensor string is presented in detail. The main objective of the sensor network is to measure soil properties at varying depths. Each sensor takes measurements based on a schedule, or when prompted by an event. Events could be a measurement value exceeding a threshold, or simply at the user's request. The measurements must be stored and transmitted back to a database for archival and use by a scientist. The focus of this work is the sensor network, not the database server, which will only be mentioned in passing.

The sensor network is comprised of a collection of sensor strings and at least one base station. Each sensor string connects a series of subsurface sensor nodes and a cap node at the surface. An estimate for the average number of nodes on a string is 25, with less than 1 meter between the nodes. Sensor strings capture a vertical snapshot of soil properties from their sensor nodes. The strings are distributed laterally over the site, covering the required area. With 36 sensor strings, roughly 600 square meters can be covered, based on the maximum range of the wireless transceiver. The area covered can be easily increased by adding sensor strings. The vertical and lateral coverage of sensors creates a three-dimensional view of the soil properties. This three dimensional view of the soil is one of the primary accomplishments of this system.

Figure 1 describes the proposed system in three levels of abstraction. The sensor node and its major components are depicted in Figure 1(a). In Figure 1(b), the sensor string is shown as a variably-spaced series of sensor nodes connected to a cap node that houses a wireless transceiver. The sensor nodes are buried under ground and communicate with the rest of the network through the cap node. Figure 1(c) shows the layout of the system as a whole.

The sensor strings form an ad hoc network, using the base station as a gateway to the Internet. The base station and other networking aspects of the system are presented

in detail in [12]. The most important modules that the base station houses are the two different wireless transceivers. One transceiver connects to the ad hoc network of the sensor strings, while the other connects to the cellular phone network, allowing the sensor network to connect to the Internet. The base station communicates over the Internet with a dedicated server running database and application interface software. The database server is used to archive the collected data and provide an interface for client applications, so the base station does not need to have as much memory to store data or consume power every time data is needed.

Each sensor string is comprised of a vertical array of serially connected sensor nodes that take soil measurements at different depths. The topmost node is designated as the cap node. All of the nodes in the string, except for the cap node, are buried, making the cap node the only visible node once the string is installed. Each sensor node measures only a small area of the soil. Since it is desirable to measure a large area, many sensor nodes are used, the exact number of which depends on the desired measurement resolution or coverage area.

The cap node is the data aggregator and coordinator for the sensor string. When a sufficient number of measurements have been taken, the cap node collects the readings of all sensor nodes in the string. If surface soil measurements are required, the cap node itself will include sensors that take measurements on a schedule, just like any of the buried sensor nodes. The cap node combines the sensor node's measurements with any measurements of its own, applies data aggregation techniques, and transmits the information to the base station.

The sensor node measures the soil properties using in situ sensors. The sensors considered for the first prototype measure soil temperature and moisture content. The temperature is measured with a standard temperature sensor, while the soil moisture content is measured by two different sensors, one of which uses TDR, and another that uses TDT to measure electrical properties of the soil, from which the amount of water in the soil can be determined.

The software for all the nodes in the network is interrupt based, with the two sources of interrupts being the network interfaces and the internal timer. The interrupt-driven approach allows the nodes to remain in sleep mode for the greatest amount of time possible, decreasing the amount of power used. Figure 2 is a flow chart of the software for the cap node.

The internal timer is used to govern the schedule, which encompasses all actions the node must initiate. The two most important actions are to take a measurement and upload collected measurement data. Other possible actions, that vary based on node type, are detailed in [12]. The node sets the timer for the next action in the schedule, and when the timer expires, it returns from sleep mode and performs the action. When the action is complete, the timer is set for the next action, and if there are no further actions, the node enters sleep mode.

The network interface interrupts are triggered in response to an incoming message. The primary messages of interest are data being uploaded from other nodes, and configuration

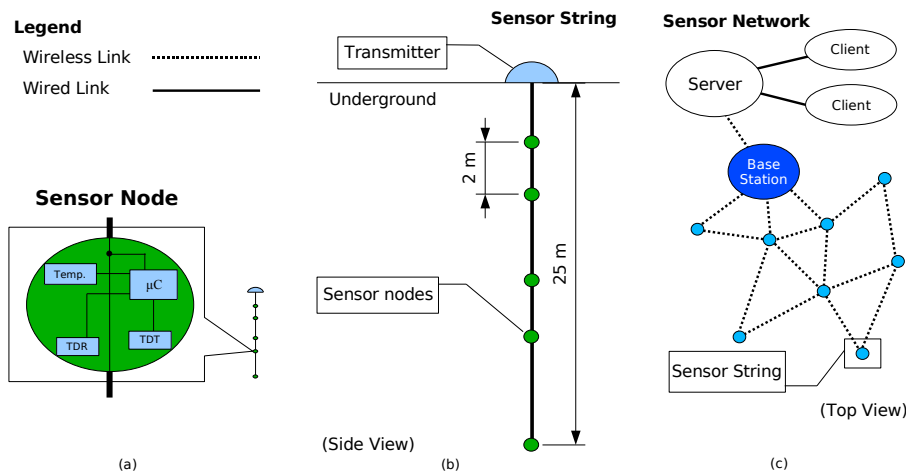


Fig. 1. Proposed sensor network and its components.

changes. With these two message types, the sensor network can upload the collected data to the database server and handle changes to the schedule, in response to user updates or specific events in the sensor network.

Remote updates to the schedule of each node allow the system to respond to events in the network and to changes requested by the user. The user requested changes could be a change to the schedule, or even a request for an immediate measurement. This flexibility allows for fine-grained control of the network, without requiring site visits.

The interaction between the sensor nodes, cap nodes, and base stations is outlined in Figure 3. Each row in the figure represents a task the network must perform, and each column represents the different types of nodes. Arrows that cross a column boundary indicate a message that must be transmitted over the network; arrows within a column indicate interaction among methods inside a single node.

The second row in Figure 3 shows the flow of configuration updates through the network. Configuration updates, which always originate from the base station, are the primary means of control. When the base station finds new configuration information in the database, it downloads it and, if it is relevant to the sensor strings, transmits it to the cap nodes. The local configuration is changed and if necessary, the schedule is updated. When the cap node receives an update, it applies any relevant changes to itself and composes new configuration updates that are pertinent to the sensor nodes on the string.

The last row in Figure 3 represents the primary method of retrieving data from the network. Sensor and cap nodes are scheduled to upload their data periodically, the base station does not initiate the upload. When the sensor node is scheduled to upload data, it removes redundant information from the data and sends it to the cap node on the string. On its own schedule,

the cap node aggregates all the data it has received from the sensor nodes on the string, removing redundant information, and transmits it to the base station. The part not shown on the figure is when the base station uploads the information it has received from the sensor strings to the database server.

While each node is independently capable of taking soil measurements, a system of isolated nodes would not be as effective as a network of nodes that communicate with each other. Networking the components as described in this section allows the system to collect data and deposit it in a database, without requiring human intervention. This feature alone significantly increases the amount of data that can be collected, especially if the desired measurement site is far away from those who wish to measure it. Another benefit of communication among the nodes is the possibility of data corroboration, which can result in elimination of erroneous measurements, increasing the quality of the data collected.

#### IV. CONCLUSIONS AND FUTURE WORK

Among the limitations of existing hydrological monitoring systems are the need for on-site personnel, and the large, expensive support systems required. For example, the ESTAR system described in Section II can measure the soil moisture content of a large area, but requires the use of a C-130 aircraft, which is prohibitively expensive. Another set of existing techniques measures electromagnetic properties of the soil to infer the moisture content. Such systems can be left in the field, but require shelters to be built around the electronics, and in the absence of a local power grid, they need an array of batteries or a generator.

Even with external support, most existing systems require a person to physically visit the device to retrieve the information. All of the sensors are concentrated at the data logger, but their

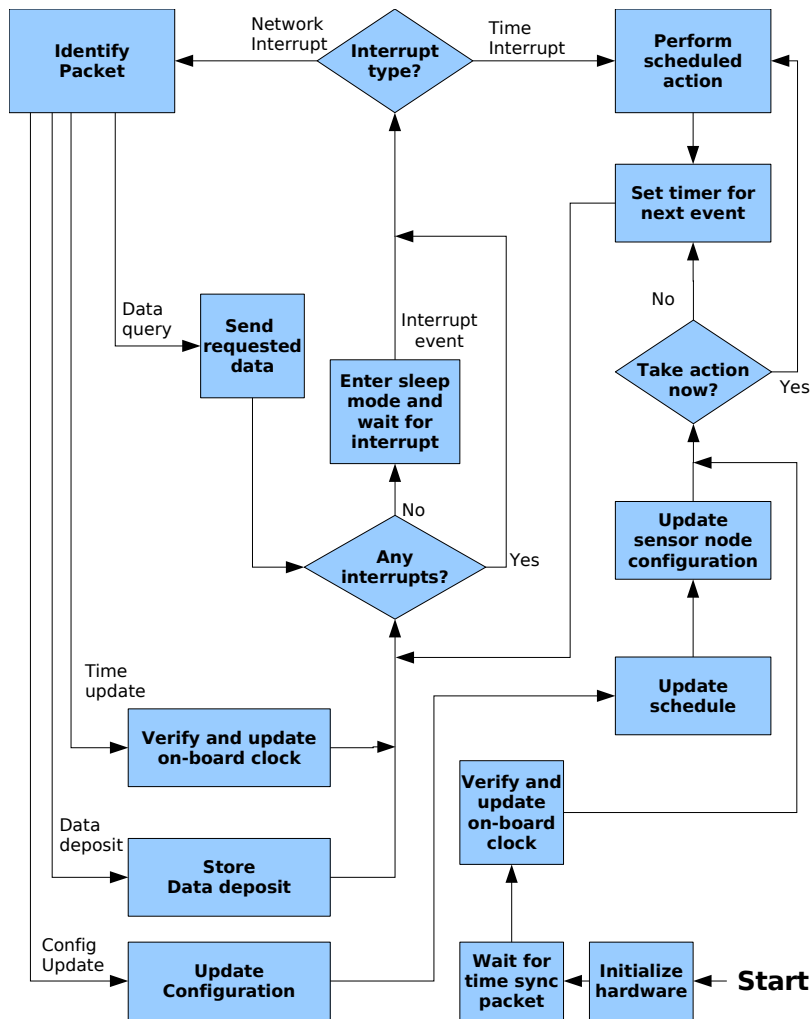


Fig. 2. Flow chart for the software of the cap node.

probes must be placed where measurements are needed, necessitating wires between the probes and the data logger. The system proposed in this paper does not have these limitations. The only occasion when the system must be visited by on-site personnel is during installation, when the power cells are depleted, and to collect the equipment if the site no longer needs to be monitored. The site need not be visited to collect the measurement data, as that is autonomously uploaded to the database server.

The original contribution of this research is in the design of the hydrological monitoring system, in particular the sensor strings that enable measurement of soil parameters at various

depths in the soil. This vertical soil coverage, paired with the lateral coverage of sensor strings over the measurement site gives a three-dimensional view of soil properties. This level of site coverage is a considerable improvement over other in situ soil property measurement systems [1], [10].

The sensor network has the ability to measure not only the conditions of the surface soil, but the condition of the soil at different depths below the surface. This feature, coupled with the ability to have all sensors measure concurrently over the entire site, facilitates real-time collection of accurate data on hydrological processes in the soil. This system enables the collection of data at a scale and resolution that is orders of

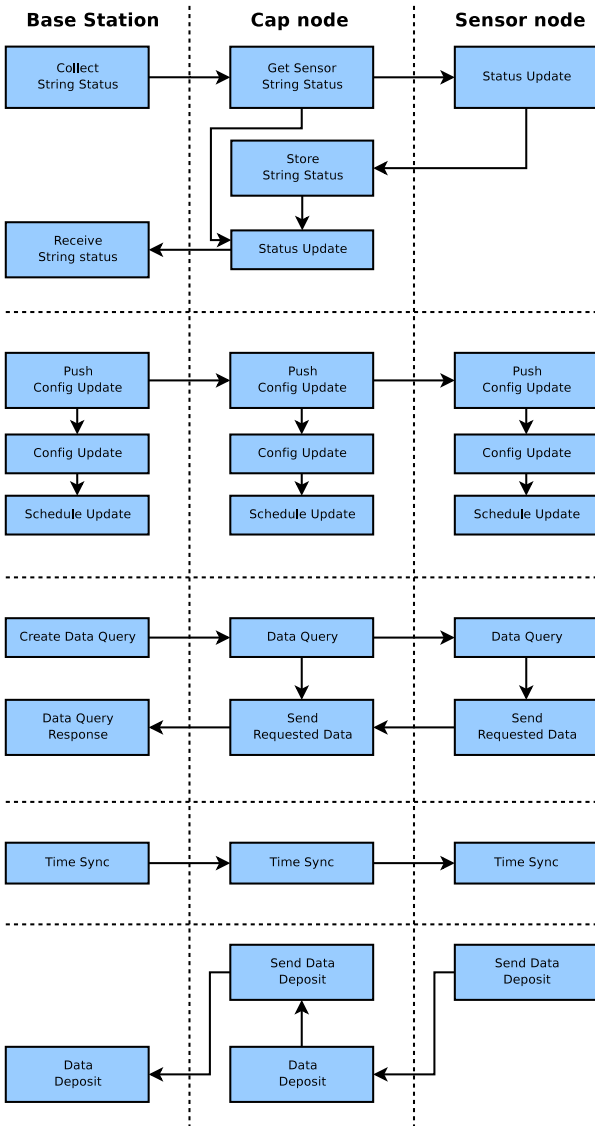


Fig. 3. Flow chart of the node communication methods.

magnitude greater than any existing method, while dramatically reducing the cost of monitoring. The quality and sheer volume of data collected as a result will enable previously infeasible research in hydrology.

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