Emerging Technologies, Sensor Web

Synonyms

Wireless Sensor Network, WSN, Environmental Sensor Network, ESN

Definition

Sensor webs are networks of sensors that can operate in a coordinated fashion, for example throughcentralized or decentralized control centers. The controller can command the sensor nodes to modify their measurement schedule or configuration in response to environmental factors or to achieve certain measurement goals. Sensor webs are envisioned as a means of providing spatially and temporally adaptive in-situ measurements for validation of remote sensing observations.

Introduction

Satellite remote sensing often results in data and retrieved geophysical products with resolutions that are significantly coarser than the scale of variations of the phenomena they represent. As an example of a geophysical variable, soil moisture fields retrieved from satellite observations using microwave instruments have resolutions on the order of kilometers if not coarser. However, the soil moisture fields themselves have spatial dynamics at the scales of several meters (e.g., because of topographic and landcover variations), hundreds of meters (e.g., because of land cover and soil texture variations), and kilometers (e.g., because of precipitation). Therefore, the coarse-resolution retrievals at the satellite pixel scale may not accurately represent the true mean of the soil moisture field.

The validation of satellite retrievalsis therefore a challenging task. It requires the use of in-situ sensor networks, whose node placement has to be such that the proper spatial statistics are represented, and such that the in-situ estimate of the mean soil moisture within the coarse-resolution pixel is close to the true mean. Furthermore, the measurement schedule of the sensor nodes has to be such that the temporal variations of soil moisture are properly captured. At the same time, it has to be dynamic so that, if necessary, only the minimumnumber of measurements are taken so that energy usage is optimized by the network.

A large number of sensor nodes may be necessary to sufficiently represent the spatial variations of the coarse-resolution field. For example, for the NASA Soil Moisture Active and Passive (SMAP) satellite mission, scheduled for launch in 2014, the primary soil moisture product will have a resolution of 10km (Entekhabi et al., 2010). Depending on the topographic, vegetation, and soil texture heterogeneity present in various pixels, tens or hundreds of sensors might be needed for proper retrieval validation. However, it is not feasible to deploy such large number of sensor nodes with conventional data loggers and manual data collection schemes. Instead, wireless network concepts have to be used that allow near-real-time data upload.There are many challenges with such large-scale outdoors networks, including energy management, lifetime, environmental robustness, network capacity, and costs. Such challenges are illustrated by the following discussion involving the design of the sensor web for the SMAP mission.

Global architecture of the sensor web

The global architecture of the in-situ sensor network is shown in Figure 1. The system consists of a field element and a home/office element. A wireless sensor network is deployed over a target field, along with a base station that performs data collection and sensing control, and a database collocated with the base station for local data storage. At each sensing site, several sensors (for example, soil moisture sensors) are deployed at different depths and connected to the sensor node (i.e., a ground wireless module). The base station receives data wirelessly from each sensor node; it can also control their measurement schedules on demand. It also periodically (every half an hour) uploads the collected sensor data through a long-range link, such as a 3G connection, to a database server located in the home base.

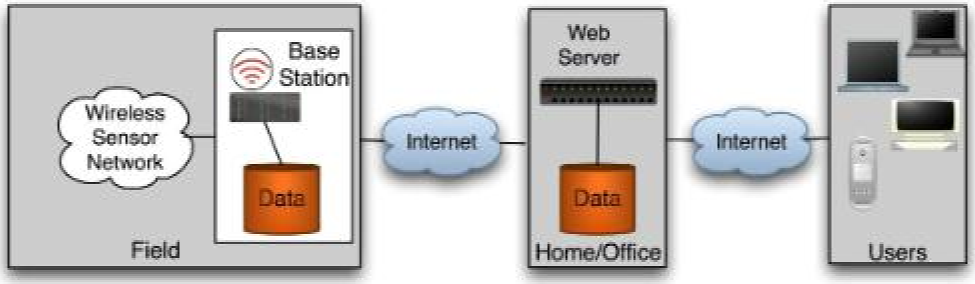

Figure 1. Global architecture of the wireless sensor network system

Initially, this networkwas built using the ZigBee (IEEE 802.15.4 plus higher layer specifications) standard (Moghaddam et al., 2010). The first deployment of this network was in a field near Canton, Oklahoma. ZigBee was chosen as it allowedthe formation of a multi-hop network, and due to its mature technology that could significantly shorten the development and production cycle. The disadvantage was that a router node under the ZigBee specification could not be put to sleep mode, thus consuming significantly more energy and requiring large batteries and large solar panels.It also was proven to be rather unstable for outdoor field environment due to poor router-base station connection, causing end devices (or nodes) to switch parent-child association. Therefore, the architecture was modified to adopt a two-tiered hierarchy: the lower layer consists of a local coordinator (LC) node and multiple sensor nodes or end devices (ED) associated with the LC node.The upper layer consists of LC node(s) and a base station. In contrast to existing network routers, the LC node can sleep and its energy requirements are significantly reduced. The LC node may be equipped with two radio interfaces, allowing it to communicate within the two layers using different radio technologies, effectively making the two layers logically separate. The lower layer uses the IEEE 802.15.4 standard but not the ZigBee suite.The advantages of this design include: (1) flexibility in developing an open protocol on top of 802.15.4 for the lower layer and multiple candidate solutions for the upper layer; (2) the logical separation between the two layers, making sleep scheduling of the ED nodes much easier to control; (3) a different radio solution for the upper layer, allowing the system to span over much longer distances; and (4) ease of scaling up of system architecture. Using this design, the network can be scaled up (Figure 2) to contain multiple local coordinators that can be deployed in multiple landscape types and to cover a span of several kilometers.

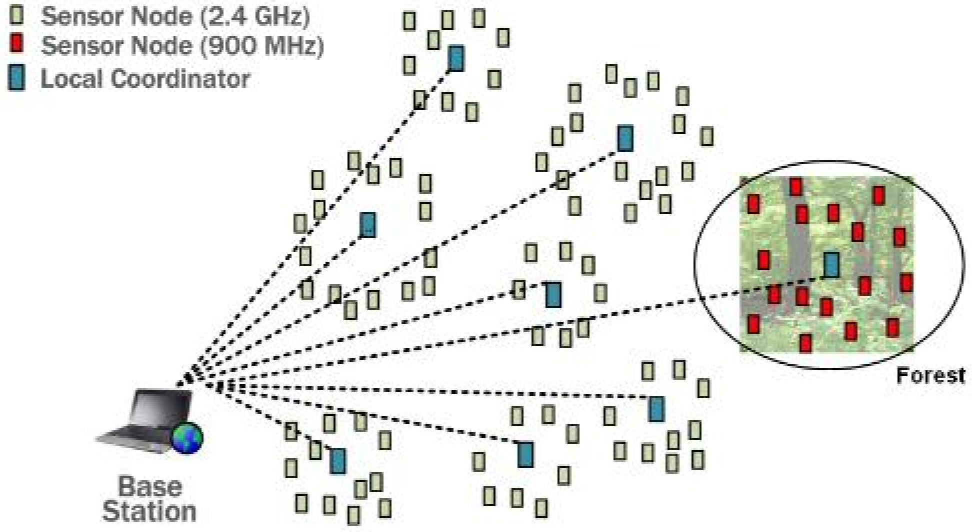

Figure 2. A large wireless sensor network may have multiple local coordinators servicing a variety of different landscape types. Choice of local transceivers should be transparent to the network for extensibility.

Sensor placement, scheduling, and field mean estimation

The true mean of geophysical variables such as soil moisture fields is a function of time and of the state of the soil surface. Its determination ideally would require a very fine sampling of the remote sensing satellite footprint, both spatially and temporally. This, however, is cost prohibitive; manually installing these sensors is expensive, and their battery power does not allow us to continuously sample, as we need them to last a reasonably long period of time (months or even years). These considerations pose severe limitations on how many sensors can be made available, and how frequent they can be used/activated. The overall objective is thus to place and activate sensors such that the field mean may be estimated to a desired accuracy subject to budgetary constraints, e.g., the total number of sensors available, the total amount of available energy at each sensor, and bandwidth.

There are two elements to the above problem; one is the determination of the best set of locations within the sensing field to place a limited number of sensors (sensor related cost constraint), and the other is the optimal dynamic operation of these sensors (when and which to activate) once they are placed (energy constraint).

These two elements are coupled. For instance, if energy of operation is a bigger concern than placement costs, then one can choose to place more sensors to compensate for a desired, reduced sampling rate. The reverse holds as well. In addition, activation and sampling decisions can influence where sensors should be placed and vice versa. But jointly considering and optimizing both elements leads to a problem whose complexity is prohibitive both analytically and computationally.

For a given placement plan, the sensor measurement scheduling problem becomes one that aims to minimize the estimation error (for the reconstructed soil moisture process using measured samples) subject to a certain energy/sampling rate constraint, or to minimize the sampling rate subject to an estimation accuracy criterion, or to minimize certain weighted sum of both. The estimation can be done both in a closed-loop fashion and an open-loop fashion. Under a closed-loop approach, temporal and spatial statistics of the soil moisture evolution is first learned using training data (either real or simulated). This knowledge, which describes what is likely to happen given what has already happened, together with samples already collected, i.e., what we know has happened, can help predict the future and thus make judicious decisions on the best time to take the next measurements. This is essentially the idea behind a partially observed Markov decision process (POMDP) formulation of this problem (Shuman et al., 2010).

Under an open-loop approach, recent results from the theory of compressive sensing can be applied. This technique exploits an underlying sparsity feature of the measured signal, and is able to reconstruct the soil moisture process from a very small number of samples to great accuracy. Advantages of this approach include (1) it does not require training or a priori statistical knowledge of the soil moisture process, (2) the sampling sequence (measurement times) can be completely determined offline, and in its simplest form can be a periodic sequence, therefore making implementation very easy, and (3) the same signal reconstruction technique can be used if we augment the sampling sequence with exogenous information like rainfall (e.g., take more samples during a rainfall event and less during dry periods). The figures below shows the recovery accuracy of this approach under three types of measurement schedules (US: uniform/periodic sampling; RS: random sampling; GS: Gaussian sampling; TV: true value) (Wu and Liu, 2012).

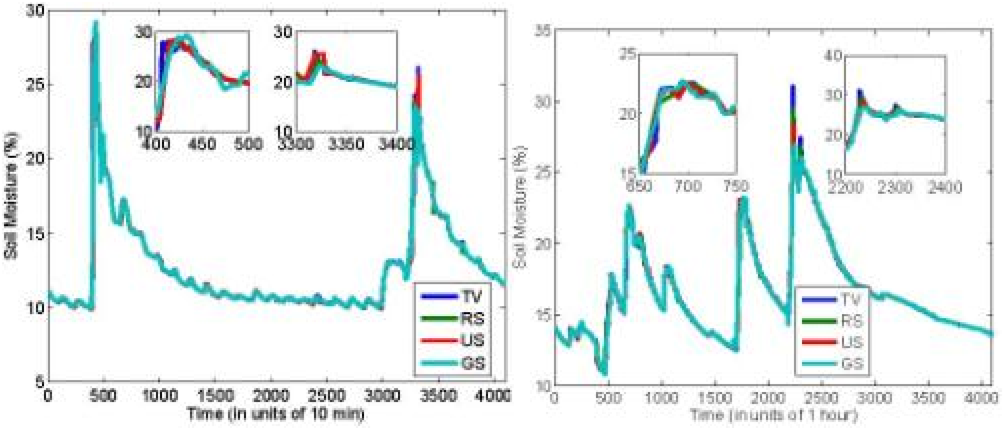

Figure 3.recovery accuracy of compressed sensing approach under three types of measurement schedules (US: uniform/periodic sampling; RS: random sampling; GS: Gaussian sampling; TV: true value)

Energy management schemes

Flexible energy management solutions are needed to meet the lifetime requirements of remote sensing missions such as SMAP. In doing so, increased reliability and reduced cost of wireless sensor network operation, extensibility to a large variety of target environments, and therefore an open and generalized architecture solution are needed.

Past experience has showna significant number of battery failures caused by extreme temperatures as shown in Figure 4. Therefore, for many realistic deployment scenarios, the estimated lifetime of two or more years for a sensor node cannot be realized with rechargeable batteries because of their temperature sensitivity. Non-rechargeable batteries are the best option in this regard because of their tolerance to both high and low temperatures. If the usage of the network is consistently maintained low, such an approach could be very cost-effective and robust. For instance, assuming measurements every 15 minutes, the batteries need only be replaced every 2 to 4 years (depending on the model/type of the battery). No external part, such as a solar panel, is required to be exposed to the environment. This solution has been implemented in the “Ripple-2” system, developed by the authors (Figure 5) as part of the Soil moisture Sensing Controller And oPtimal Estimator (soilSCAPE) project.

Figure 4. Sensor nodes based on solar panels and rechargeable batteries typically have problems associated with sub-zero temperatures.

Site: Canton, OK
Last update of this page: Thursday, August 02, 2012 11:01:23 AM

Technical Report:
* Communication problems (#ED): 12, 19
* Soil moisture probe problems (#ED-#Sensor): E07-01 (bad contact)

Figure 5.A Ripple-2 node powered by non-rechargeable batteries (top) installed in SoilSCAPE field locations such as Canton, OK, USA (bottom).

However, it is not always possible to maintain a low-duty cycle. For instance, one could expect to periodically (and temporarily) modify the schedule of the sensor nodes to make measurements with the full node-density capacity of the network to optimize the scheduling and estimation processes. The main drawback in this case is the high energy cost. By adopting an energy-harvesting model, such as solar panels, one could compensate the additional loss of energy. Accordingly, two additional versions of Ripple-2 node are developed. The Ripple-2B is based on supercapacitors and a solar panel and the Ripple-2C is a hybrid solution with supercapacitors and non-rechargeable batteries.

The usage of non-rechargeable batteries is not the preferred option for conventional sensor web solutions, in particular for outdoors. The main reason is the high cost involved in frequent batteryexchanges(Weddell et al., 2008). Also, typically the energy consumption of the nodes is not uniform among them and multiple maintenance trips are necessary. Under the Ripple-2 development, the reasons behind this scenario are investigated and it is concluded that cooperation among nodes is the main factor for the quick battery depletion. In other words, the average energy spent by a node serving the network node is multiple times the energy spent by a node to periodically take measurements and transmit data to the base station.

The authors envisioned a scenario where the network is segmented into physical clusters and each segment has a data collector node (LC) that can communicate with all the sensor nodes in that segment by means of a single hop (direct link)(Silva et al., 2012).By carefully assigning the location of the LC in relation to the sensor nodes of that area, the collaboration among sensor nodesdue to multi-hopping is not necessary. As a result, the network overhead is drastically reduced from typical 3-10% to less than 1%. Also, a sensor node does not need to periodically wake-up to serve the network (i.e., relaying messages). Therefore, the sleep scheduling of a Ripple-2 nodes is only governed by the application duty-cycle. In other words, the energy consumption of a node has a very deterministic behavior and energy balance among nodes is finally achieved no matter the size of the network.

Because a Ripple-2 node can potentially have a very long and continuous sleeping period (i.e., hibernation mode), it is possible to turn-off many modules, such as the radio transceiver, rather than just put these modules into standby mode. The energy savings achieved by following this approach can be as high as 50%. Combined with the savings related to a reduced network overhead, the lifetime of a non-rechargeable battery of a Ripple-2 node can be realistically extended by multiple folds assuminga low duty-cycle regime, such as soil moisture measurements every 20 min (Menachem and Yamin, 2004).

However, there is an important trade-off in relation to non-rechargeable batteries: the pulse current effect which is the non-linear and drastic energy capacity reductionof a battery when it is discharged by a slight higher current, such as 50mA(Silva et al., 2012). No matter how quick is this pulse current (e.g., a very fast radio transmission), the energy capacity of the battery is impacted andits lifetime can be as small as 10% of the nominal/expected lifetime. In order to solve this issue, Ripple-2 adopts supercapacitors as power-matching components. That is, these capacitors are slowly charged by a low current from the battery and quickly discharged by a high-current (radio). Such approach protects the battery against the pulse current effect but is also creates additional data latency issues when the node needs to transmit data very frequently. However, it is not a problem for a low duty-cycles web sensors used in SMAP.

Summary

To respond to the challenge of validation of coarse-scale remote sensing retrieval products such as soil moisture, a generalized wireless sensor network architecture has been developed. This architecture can be scaled to large-scale outdoors wireless sensor webs with flexible placement, scheduling, and power management schemes. The latest implementation of this architecture has been termed “Ripple-2” (with Ripple-1 being the first generation of this architecture). Due to its advantages, this architecture can be extended not just for soil moisture, but for other sensing applications by making it flexible enough for other processor platforms and wireless technologies. Such applications can include any environmental monitoring application that has an extensive network deployed over a large area.

The high-degree of robustness, energy efficiency, and reliability of Ripple-2 are achieved under the assumption of low-duty cycles (e.g., sensor measurements every 10-20 minutes) and data latencies from seconds to minutes.

The Ripple-2 architecture can be considered a milestone in wireless sensor networks (WSNs) because of its specialization for low-duty cycle and data-centric applications, breaking well established concepts for WSNs. Without increasing the costs, the energy performance of Ripple-2 nodes is significantly superior compared to any similar WSN/telemetry solution. In fact, even non-rechargeable batteries can now be considered as a cost-effective option. However, technological enhancements can provide the path to turn Ripple-2 into a generic WSN solution.

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