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L^{3}SN: A Level-Based, Large-Scale, Longevous Sensor Network System for Agriculture Information Monitoring*

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Abstract

We developed L^{3}SN, a scalable, longevous, adaptive, and internet accessible wireless sensor network system for agriculture information monitoring, which is meticulously designed to meet the requirement of thousands hectares coverage, years of time monitoring and the adverse environment. The system architecture, the agriculture sensor device, the mesh protocol, and the web-based information processing platform are introduced. We also presented some implementation experience. The mesh protocol (LayerMesh) is highlighted, in which "stair scheduling" and "distributed dynamic load-balancing" are proposed to response the scalability, longevity and adaptivity requirements. We believe the design of L^{3}SN is useful to many other large-scale, longevous applications such as hydrologic monitoring, geological monitoring etc.

Keywords: Wireless Sensor Network, Agriculture Information Monitoring, Large-scale, Longevity, Adaptivity

1. Introduction

Agriculture Informatization is an important area, related to people life and national interest, is proposed to be empowered by wireless sensor network technology. For agriculture information monitoring, the water, soil conditions, the crops, fruits conditions, as well as the conditions of livestock are required to be monitored in real-time by many spatially distributed wireless sensors. These wireless sensors are battery or solar energy powered, equipped with wireless radio, storage unit, data processing unit and various sensing units. They are desired to be easily deployed into the large-scale farmland, to self-organize to a functional distributed multi-hop network via wireless communication, to work for years of time to collect data, and to be self-maintenance against the environmental dynamics of the four seasons.

If such systems are available, they can bring many economic and social benefits. However, although the wireless sensor network technology has been fast developed in the past ten years [1], it is still very challenging to realize such an agriculture information monitoring system. The difficulties come from three aspects.

1. Extremely large in scale. The farmland is often in the scale of millions hectares. The complexity of network organization and routing will turn to a qualitative change when the network scale becomes very large.

2. Extremely long lifetime. Agriculture applications need the network be functional for years of time, but the scarce energy on the sensor node can hardly afford this, especially when the network is large and the sensor has many data to forward.

3. Adverse environment. The adverse weather will challenge the durability of the hardware. The growth of crops will block or affect the wireless links, causing the network working in a highly dynamic radio environment.

Existing studies have presented some implementation trails, but seldom results have been presented to thoroughly investigate and solve above challenges. In this paper, we propose and demonstrate L^{3}SN: A Level-Based, Large-Scale, Longevous Sensor Network for Agriculture Information Monitoring. We focus on the design and implementation issues to show how the above challenges are handled. Our main contributions are two

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folds.

1. The design and development of the L^3SN system, including system architecture, interfaces, hardware, mesh protocol, and the web-based information processing platform.

2. The level-based mesh protocol, which is named as LayerMesh is highlighted. We specially designed "stair scheduling", and "distributed dynamic load-balancing" to handle the above challenges.

To our best knowledge, it is the first time that the following key points are developed and demonstrated for the large scale sensor network.

1). Load-balancing problem in large scale network is solved and implemented by a fully distributed algorithm.

2). The two-tiered architecture and the open interface design provides infinite scalability.

3). The "stair scheduling" and "adaptive routing" provides novel solutions for energy efficient and adaptive longtime maintenance.

With these key issues, we designed and developed the L^3SN system. The following sections of this paper are organized as follows. In Section 2, related work will be introduced. In Section3, the architecture and interfaces of L^3SN system will be presented. The LayerMesh protocol will be introduced in Section 4. Some implementation results and experience are discussed in Section 5. We conclude the paper in Section 6.

2. Related Works

2.1. Agricultural Information Monitoring Using Wireless Sensor Network

Wireless sensor network system for agriculture information monitoring has attracted great research attentions. Some preliminary experimental systems have been reported. Jenna Burrell, *et al*., investigated different sensor network configurations in vineyard application [2], and summarized some design guidelines for agricultural monitoring system. Murat Demirbas, *et al*. [3] deployed a small scale sensor monitoring system in a green house and drew suggestions that single-hop cluster should be a better solution for easy-to-use and network longevity. A mobile field data acquisition system was developed by Gomide *et al*. [4] to collect data for crop management and spatial-variability studies. Mahan and Wanjura [5] cooperated with a private company to develop a wireless, infrared thermometer system for infield data collection. Cross-bow developed eKo system [6], which involves solar-powered "eKo node" with zigbee radio and "eKo view" for real-time data rendering. It uses Xmesh protocol to make the eKo system easily setup.

2.2. Large-Scale Longevious Sensor Network

Studies of Large-scale longevious sensor network can be categorized into two classes: 1) application-oriented and 2) theoretical-oriented. In the first class, an early study of WSNs for habitat monitoring is reported in [7]. In [8], Werner-Allen *et al* deployed a WSN at Ecuador to monitoring the activity of an active volcano. But the system scale is only 16 nodes. GreenOrbs [9] is reported as a large-scale system for canopy closure estimates, which had 120 sensors in 2009. However they used only the built in low power listening mode to conserve energy, which is not very energy efficient.

In theoretical aspect, many results can be found in the literature. Li *et al*. [1] studied the message, energy and time complexities for data collection, query and aggregation in large scale network. Yick *et al*. [10] provided an extensive survey for the main results of this area. However, up to now, few results are found to thoroughly investigate and solve the scalability, longevity and environment dynamics of agricultural wireless sensor network.

3. L^3SN System: Architecture and Interfaces

We designed and developed L^3SN. The system architecture and interfaces are introduced in this section.

3.1 System Architecture

L^3SN is designed with the aim of open architecture and standardized interfaces. **Figure 1** shows the system architecture and the standardized interfaces.

Particularly, the architecture of L^3SN includes a Two-tiered Sensor Network for data collection and an Information Service Platform for data rendering and processing.

1) Two-tiered Sensor Network.

The sensor network in L^3SN is composed by many low-tier energy-limited nodes (LNs), and some high-tier gateways. The LNs in low-tier capture environmental data and report the raw data to the gateway. The gateways organize the neighboring LNs into clusters and work as the cluster head. It collects information in its cluster, aggregates the information, and reports the results to the Internet. Through the Internet, the data captured by the wireless sensors are finally reported to the service platform and utilized by end users.

2) Information Service Platform.

The information service platform contains data logging daemon, database, and web server. It provides data storage, data processing, data querying and other agricultural information services to users.

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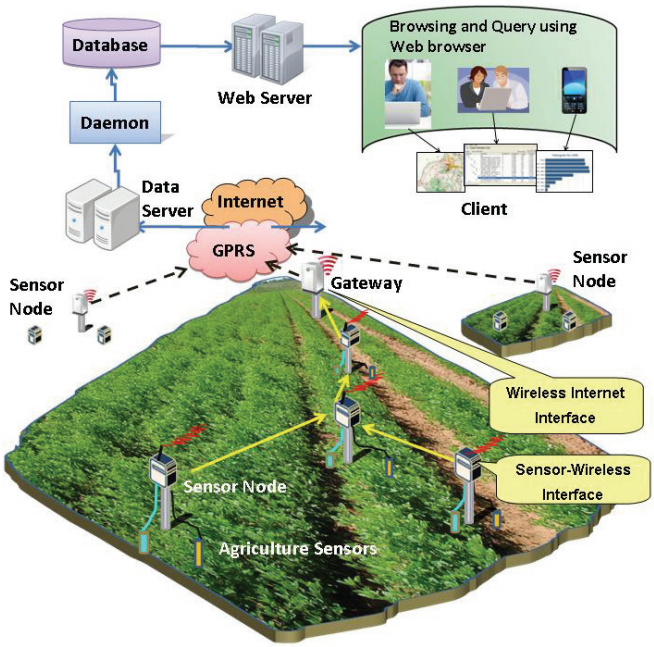


Figure 1. System architecture and the standardized interfaces in L^{3}SN system.

3.2 Standardized Interfaces

In order to easily integrate more kinds of agriculture sensors into the system, and in order to standardize the connection from the sensor network to the internet service platform, we propose two standard interfaces in L^{3}SN:

1) Sensor-Wireless Interface

The "Sensor-Wireless Interface" defines mapping functions, which transform the sensory data that is captured by the sensor devices to the meaningful data which is easily interpreted by the LN nodes. For a sensor type S_i, which provide raw data X, the interface is defined as:

$$S_i(X)=\{Y = f(X); (Y_{min}; Y_{max}); Y_{precision}\} \quad (1)$$

where f(X) is a mapping function which transforms the raw data X to meaningful value Y. The variables (Y_{min}; Y_{max}) characterize the measuring range of the sensor S_i, and $Y_{precision}$ is the measurement accuracy. With this interface, the raw sensory data of diverse format can be transformed to the regularized format. Therefore, data from different kinds of sensors can be easily interpreted by the LN nodes.

2) WSN-Internet Interface

The "WSN-Internet Interface" performs the task of *data aggregation*. Since the gateway collects data from all the LNs in its cluster, the data at the gateway is large in amount and has some redundancy. In addition, the message collected from a LN contains both the sensory information and the routing information. The sensory information is the agriculture data, and the routing information represents the multi-hop route that the message has traveled. The data aggregation at the gateway is performed in the following way:

1. *Non-compressive aggregation to the sensory data.* The agriculture data from different sensor is accumulated and forwarded to Internet in bulk for avoiding of information loss.

2. *Compressive aggregation to the routing data.* The routing information is mainly used for topology construction and maintenance at the service platform. If all the routing information from all the messages is transmitted to the service platform, it will be very redundant. A light weight compressive aggregation algorithm is developed. If the received routing information at the gateway is: $R = [R_1, R_2, \ldots, R_n]$, where n is the number of sensors in the cluster. R_i is the route from the node i to the gateway. We find that *the routes of leaves are enough to construct the routing tree*, so the routes from the intermediate node will be filtered out during the aggregation. A white list based searching algorithm is developed to carry out data aggregation. The compression rate is n_l/n, where n_l is the number of leaf nodes.

Once finishing the aggregation, the sensory information and the routing information are formatted by the Wireless-Internet interface into standardized message types by adding preamble and ending marks, so that the information platform can easily interpret the received information.

Using the above two standardized interfaces, the L^{3}SN system can integrate different kinds of hardware, including sensors and gateways. So user can focus on their application-oriented development and hardware, and easily access the wireless sensor network protocols and the information platform of L^{3}SN, which support the scalability and easy-to-use features.

3.3. Mesh Protocol

For the two-tiered sensor network, sensors in the different clusters use different radio channel and are assigned different GroupIDs, so that sensors in one cluster will not affect the sensors in the other clusters. A LayerMesh protocol is meticulously designed within one cluster to organize the large amount low-tier sensors to work in energy efficient way, to smartly select multi-hop route and to be adaptive to the environmental dynamics. The key feature of LayerMesh is that routing and scheduling are based on the level information.

The basic functions of the LayerMesh can be separated into two phases:

1). Setup phase. When the sensors are initially deployed, they have no knowledge about the neighbor sensors and environment condition. All sensors are initially

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active. The mesh protocol is designed to let the cluster head broadcast self-organization messages periodically, and let the LNs forward the messages. Via this CH broadcasting and LN forwarding process, all the LNs finish the tasks of:

1) *time synchronization to the cluster head;*
2) *neighborhood survey;*
3) *local-level determination;*
4) *transmission route selection.*

2) Runtime phase. After the setting up phase, LNs are turned to online data collection status by receiving a command broadcasted from the CH. Once entering this status, each LN calculates and schedules its wakeup time based on its local-level, and turns to sleep mode immediately. Each LN sleeps for most of time to save energy and wakes up in the assigned slot to collect data and to transmit data to its parents along the transmission route. Its parents must have waked up to receive the message to work in cooperation. Therefore, the tasks in working phase include:

1) *Energy efficient scheduling;*
2) *Cooperative multi-hop communication;*
3) *Longtime route maintenance.*

To efficiently carry out above tasks to meet the requirements of scalability, longevity and adaptivity, two key innovative designs were proposed and developed in LayerMesh.

3.3.1. Distributed Dynamic Load-Balancing

Load-balancing is one of the keys to deal with the scalability and longevity challenges. **Figure 2** illustrates the load unbalance problem in multi-hop sensor network. The load of node A is six times of the load of node B, caused by the multi-hop load accumulation. Node A will die much quickly than the node B, although they are in the same level. This problem is general and serious when the network scale is large. Previous research has proved that the load-balance tree construction problem with deterministic link is NP-complete [11].

Our solution is to propose a distributed dynamic load-balancing algorithm. In this algorithm, the links are no longer deterministic, but probabilistic. At time *t*, a node *i* updates the traffic assignment probabilities to its parent candidates based on the following neighborhood information:

1. $L(t) = [L^t_{k,1}, L^t_{k,2}, \ldots, L^t_{k,n}]$, the current loads of parent candidates.

2. $P(t) = [P^t_1, P^t_2, \ldots, P^t_n]$, the traffic assignment probability from *i* to its parent candidates at time *t*. where *n* is the number of parent candidates. k means the level number. We have developed an algorithm using Equation 2 to update the transmission probabilities of the node *i*. Its convergence and optimality in load balance has been proved [12].

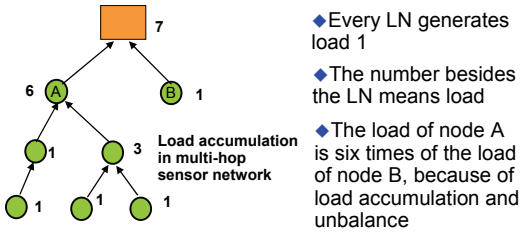


Figure 2. Load unbalance problem caused by load accumulation in multi-hop sensor network.

$$P_i^{t+1} = \frac{P_i^t / L^t_{k,i}}{\sum_{j=1}^{n} P_j^t / L^t_{k,j}} \tag{2}$$

Before transmission, the node *i* generates a random number *x* for route selection. It transmits data to parent candidate *j* if:

$$\sum_{c=1}^{j-1} P_c^{t+1} < x \le \sum_{c=1}^{j} P_c^{t+1} \tag{3}$$

3.3.2. Stair Scheduling

We have developed a level-based stair scheduling scheme to carry out energy efficient data collection and cooperative multi-hop communication. The key idea is to schedule the sensors based on their levels. As shown in **Figure 3**, sensors in each level spend most of time in sleeping. The sensor in level *k* will wake up one slot earlier than the sensors in level *k*-1. After waking up, each sensor will be active for only three time slots:

1) R-Slot, each sensor in level *k* listens to channel to receive data from its children (in level *k* + 1)

2) T-Slot, the sensor transmits the locally collected data and the forwarding data to its parents (in level k-1).

3) Syn-Slot, the sensor listen to the channel to receive the message from its parent and do time synchronization.

From the network point of view, the active slots of the sensors form a stair like scheduling scheme. The key point for stair scheduling implementation is the multi-hop time synchronization. In setup phase of LayerMesh, we use PulseSync[13] MAC stamping method to do multi-hop time synchronization. In stair scheduling, we also use a Syn-Slot to do online time-synchronization. In our experiments, the time synchronization error within 10 hops is less than 1ms. So the stair scheduling can be efficiently implemented. More details of collision avoidance and implementation of stair scheduling can be referred to [14].

4. L^{3}SN System Development

We developed prototypes of the L^{3}SN system, including the LNs, the gateways, and the information service plat-

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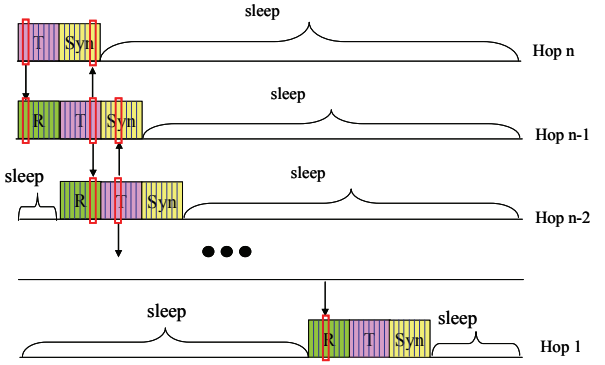


Figure 3. Level-based Stair Scheduling for energy efficient data collection and cooperative multi-hop communication.

form, and we have developed and tested a L^3SN system with 60 LNs and one gateway.

4.1. LN Node

Our LN is shown in **Figure 4**. It is composed by:

1) A solar panel for energy recharge, which can provide up to 200mw/hour energy supply in a sunny day.

2) Waterproof shell and four waterproof interfaces for easily plugging in of different agriculture sensors. The four interfaces are RS232, I^2C, RS485, Analog respectively.

3) A RF230 radio companied with 12dB antenna. The measured maximum transmission range is 300m, and the data rate is 250k bps.

4) The speed of MCU is up to 16MHz when power supply is enough. The MCU has 128K ROM, 8K RAM, and 10bit ADC.

5) We use air-temperature, air-humidity, soil-temperature (RS485), soil-humidity (RS485), light, and CO2 sensors which can be easily plugged into the LN.

The sensor-wireless interface converts the voltage values from sensors to meaningful temperature and humidity data. For example, the scope of voltage reading of the humidity sensor is 0- 1500mv; the measurement accuracy is 3%, and its transformation function is y = f(v) = 0.05071(v -106.9), therefore the interface of the humidity sensor is:

$$S(v) = \{0.05071^* (v\text{-}106{:}9);\ \{0;\ 1500\};\ 3\%\} \qquad (4)$$

4.2. Gateway

The gateway is composed by a sink sensor, a serial converter and a GPRS DTU [14]. The composition of the gateway is shown in **Figure 4**. The sink sensor use the same hardware as the LN, it is connected to GPRS DTU. The GPRS DTU provides transparent data forwarding from the sink sensor to the Internet. It supports standard TCP/IP protocol, and can be always online by heartbeat signal. The WSN-Internet interface is applied to the sink sensor, as explained in Subsection 3.2.

4.3. Weather Station

We have also developed weather station to monitor the weather information including wind speed, temperature, light *etc*. The weather station is built based on Davis's product and we

4.4 Information Service Platform

We developed the information service platform. The platform consists of a data collection daemon, a data base and a web server.

1) The daemon processes data reception from the GPRS DTUs, and stores the received data into the database.

2) We build the database using mySQL[14]. It maintains the sheets of LNs and gateways to store the historical and the real-time data.

3) The web server is implemented by JavaScript and Tomcat. It uses the Google Earth API to render the topology information of the sensor network, and supports graphical rendering of the real-time and historical data of the LNs and the gateways. The web server also supports various query forms for spatial and historical data analysis.

The snapshots of the web pages are shown in **Figure 5** and **Figure 6**.

5. Conclusions

We have design and developed L^3SN, a level-based, large-scale, longevous sensor network for precision agriculture information monitoring. It is composed by a two-tiered sensor network and an information service platform. In the low tier of the sensor network, a large amount of energy-limited sensor nodes (LNs) are deployed to capture and report information of their designated vicinity. In the high tier of the sensor network, some powerful GPRS gateways organize the LNs to form clusters and report the aggregated information to the Internet. The information service platform is de-

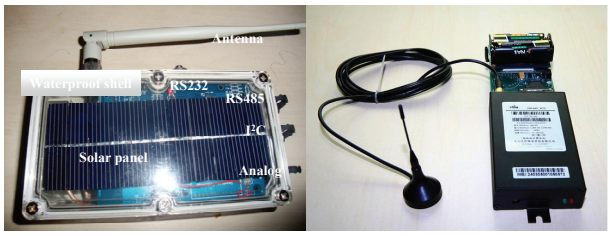


Figure 4. The prototype of LN node and the gateway.

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Figure 5. The prototype of LN node and the gateway.



Figure 6. The prototype of LN node and the gateway.

signed to log, render and analyze the temporal and spatial agriculture information to provide value-created services. We have presented the key design issues of L^{3}SN, including the system architecture, two standardized interfaces and the mesh protocol. Distributed dynamic load balancing and stair scheduling and adaptive routing are proposed to handle the large scale, longevous and adaptivity requirements.

In future work, we will 1) further improve stair scheduling to enhance the energy efficiency performance. The scheduling scheme will be made adaptive to the load of the sensors. So that redundant time slots can be saved to improve energy efficiency. 2) In the second stage, we plan to deploy more 300 LN nodes to Huantai City, Shandong Province to do larger scale field test.

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