Wireless Sensor/Actuator Networks in Precision Agriculture: Recent Trends and Future Directions

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Abstract:

Agricultural production and water has critical importance for socio-economic development of the societies. With population growth and rising affluence, the need for food and thus agricultural irrigation is increasing steadily world-wide. Unfortunately, the underground water level is slowly falling down and forests are being cut down for many reasons which reduces the rainfall amounts significantly. On the other hand, the pollution from pesticides and fertilizers used in agriculture alone remain a major cause of poor water quality. Technological advances in MEMS are leading to the appearance of wireless sensor/actuator networks (WSANs) in a variety of commercial, industrial and military applications. There is no doubt merging wireless sensor technology into agricultural facilities will make farming activities much easier. In this paper, we look at the role of WSANs in agricultural production. We also investigate the communication architecture of WSAN based large scale irrigation management system and explain the key issues that are faced in the system design. Thanks to the easy installation and maintenance of WSANs, lots of water can be saved by giving timely feedback from field to improve the agricultural irrigation efficiency. This kind of solution can greatly help farmers to monitor the amount of water applied to a field.

Key words: wireless network, sensor, actuator, agricultural production, precision agriculture

1. Introduction

In modern agriculture, it is needed to new technologies that will enable to increase the efficiency of production and quality of products while protecting the environment. For this purpose, a large number of parameters that vary with time and location, such as plant/soil characteristics and meteorological conditions, should be kept under control by monitoring them in real time and responding quickly to unexpected changes. In order to increase the efficiency of control, the precision farming techniques are used instead of conventional methods [1]. The precision agriculture includes three main parts: sensing agricultural parameters, transferring them from field to the control station and decision making process, control actions based on sensed data [2].

In agricultural fields, the establishment of the cabling infrastructure for energy and data transmission is often not possible. Therefore, when a central control system is to be formed in order to build a network that enables communication between the sensors and the actuators, the wireless communication becomes inevitable. Recent researches show that the wireless sensor

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networks (WSNs) are the most suitable technology for monitoring and data logging of agricultural applications [3]. A typical WSN is a passive data acquisition system which consists of a large number of sensor nodes (SNs) deployed over a geographical area. The SNs are typically equipped with a low-power radio frequency (RF) transceiver and a low-cost microcontroller together with an energy source, usually a battery. In many practical applications, the SNs' batteries cannot be easily replaced or recharged. Therefore, the SNs have a limited battery energy and finite lifetime whereas it is expected to operate for up to months [4]. The rapid advances in micro-electro-mechanical systems (MEMS) and digital electronic circuits prepare the ground for the production of application specific inexpensive SNs. As a result, the employment of WSNs in agricultural applications has become clearer with each passing day [5].

The next step in the evolution of WSNs is wireless sensor/actuator networks (WSANs) [6]. From a viewpoint of control theory, traditional WSNs are open-loop systems that only detect the physical world, whereas WSANs are closed loop systems that can further interact with it automatically [7]. A WSAN consists of a group of SNs that can measure physical phenomena in the environment and a set of actuator nodes (ANs) capable of affecting the environment. Actuator is a device that programmed to take action in response to sensor measurements [8].

WSANs are emerging as a key technique for precision agriculture to maximize crop yield and quality by optimizing resources such as water, fertilizer and pest control agents [1]. This paper reviews the current scientific literature and discusses recent trends and future directions in the WSAN based applications in agriculture domain such as farm control and monitoring. Within this context, several theoretical advances and underlying methods used to develop a WSAN based system are presented in Section 2. A clustered WSAN architecture to control the irrigation process automatically is proposed in Section 3. Finally, we conclude our paper with a summary and outlook on future work.

2. Background and Literature Review

WSANs are heterogeneous networks that comprise networked SNs and ANs which communicate among each other using wireless links to perform distributed sensing and actuation tasks. The SNs are constrained in terms of memory, processing capability and achievable data rate. On the contrary, the ANs are resource rich devices equipped with powerful computing capabilities, high transmission power and long battery life [9]. The SNs collect physical or environmental measurements within a sensing range and report them to the ANs through direct or indirect way. To fully exploit the potential of WSANs, it is essential to establish a strong architecture that can enable an efficient coordination and communication as well as autonomous decision making capability in a dynamic and unexpected environment.

2.1. Coordination issues

The process of establishing data paths between the SNs and the ANs is referred to as sensor-actuator coordination. As shown in Figure 1, there are two basic architectures for this type of coordination in WSANs. In automated architecture, the ANs initiate appropriate actions based on the directly received data from SNs. In semi-automated architecture, the sensor readings are processed at the sink node as in most applications of WSNs, before transmitted to the ANs. The automated architecture has advantage of low latency in data transfer. Nevertheless, it requires new algorithms and protocols to perform communication and coordination on the field [6].

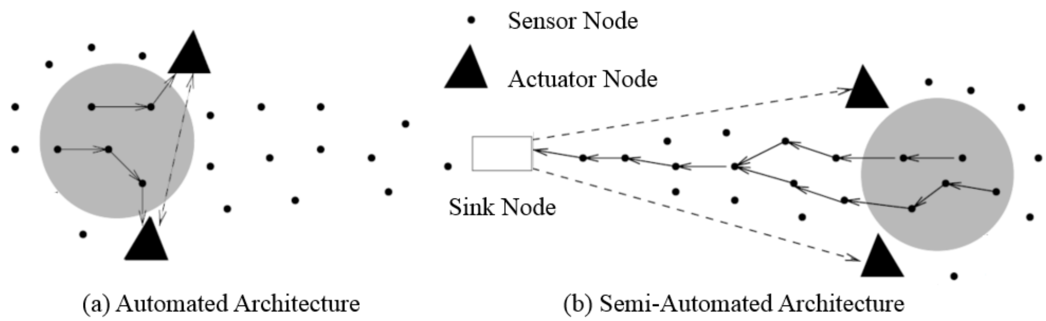

Figure 1. The physical architecture of the WSAN to coordinate sensor and actuator activities

A different approach is introduced by Stojmenovic *et al.* [9] who propose the cooperative architecture for sensor-actuator coordination. Here, the SNs transmit sensing data to the ANs via a single-hop or multiple hops as shown in Figure 2. The ANs analyze the data and may consult the sink node before taking any action. The sink node monitors the overall network and connects the complete WSAN with the task manager node, which is connected to the remote control center by either wired or wireless connection. The operator manages the whole network via task manager node interface.

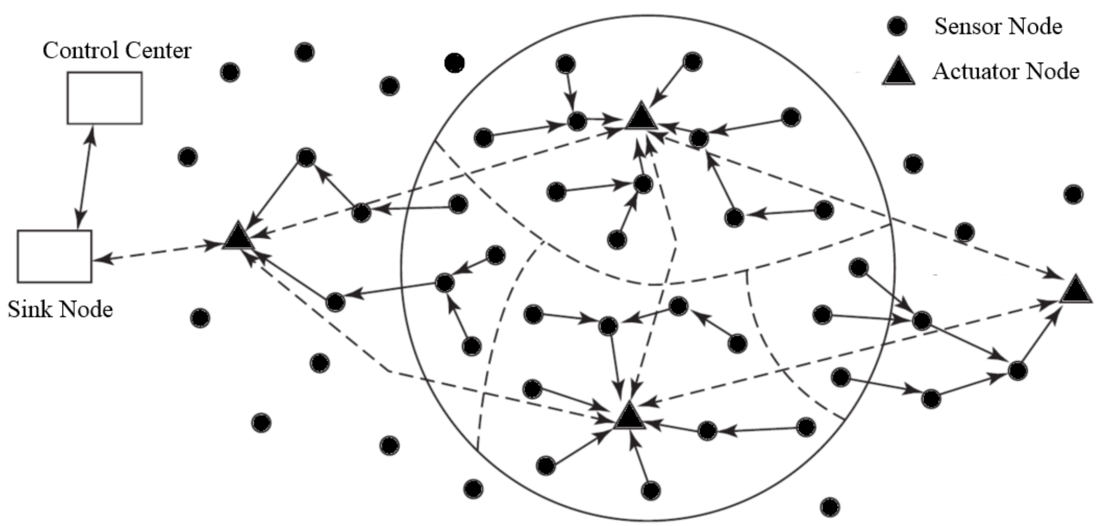

Figure 2. The cooperative architecture for sensor-actuator coordination

Many applications in WSAN require a real time response from the ANs to react to the environments. WSANs usually contain multiple ANs available for reaction, so an efficient actuator-actuator coordination is necessary to provide fast control response [10]. The actuator coordination algorithm allows the ANs to share the event information and enables a collaborative decision on how to perform the proper reactions by selecting the best ANs. This type of coordination splits the whole area among different ANs. They combine the received data and determine how many and which ANs should contribute the closed loop control. The size of the area together with the distance between the ANs determine the actuation strategy.

2.2. Network architecture

In a large scale WSAN, there is need for energy-efficient data gathering and aggregation protocols to prolong the network lifetime. A basic tenet of energy efficient data transmission is that the network architecture must be scalable. Clustering is the most common technique used to organize the WSN in a hierarchical architecture. It is used to grouping the SNs into different clusters to increase the scalability. Clustering generally achieve high energy efficiency in large-scale WSAN environments and also provides spatial reuse of the bandwidth which is one of the limited resources. In the cluster-based network organization, each cluster has a leader, which is also called the cluster head (CH). The CH is the router of data sent by its members to the sink. Clearly, the CHs perform data aggregation and deliver the fused data toward to the sink node. The advantage of data aggregation is that all raw data can be combined together to extract only the useful information and the network traffic is reduced extensively [11].

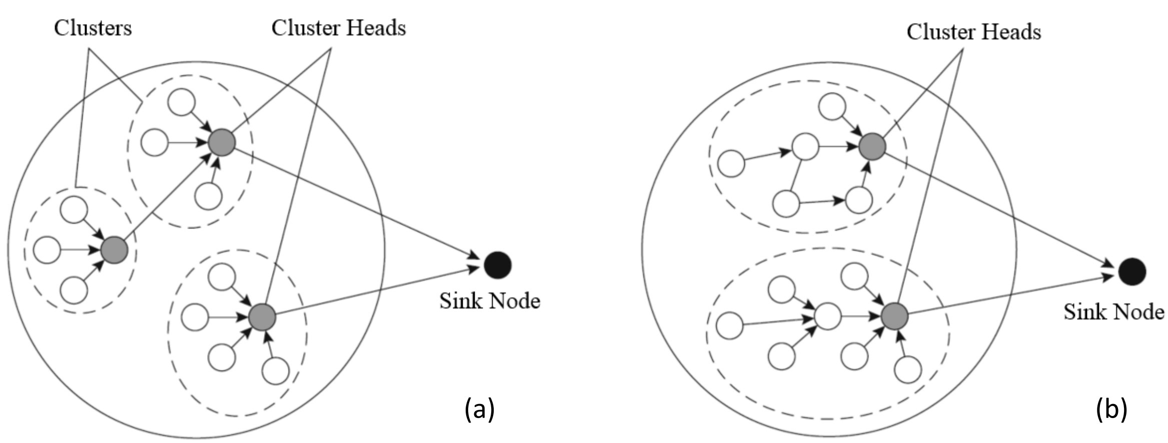

Figure 3. Hierarchical single-tier (a) single-hop (b) multi-hop network architecture

The hierarchical architectures within a clustered WSAN are clearly illustrated in Figure 3. Clustering leads to a two-level hierarchy where the CHs form the upper layer (also called the inter-cluster communication) and the SNs form the lower level (also called the intra-cluster communication). The SNs periodically transmit their data packets to the CHs in intra-cluster communication, while the CHs aggregate and compress the data packets and forward it to the sink node in inter-cluster communication. According to the manner of intra-cluster, all SNs in the same cluster communicate with corresponding CH via single or multi-hop path. Similarly, the CHs transmit data towards the sink node either directly or through the one or more relay CHs [12].

2.3. Communication protocol

In clustered WSAN architecture, the peer-to-peer communication is not supported, so each node within the same cluster can only communicate with its CH. The channel access within the cluster is generally organized with the schedule-based protocols by using Time Division Multiple Access (TDMA) technique in the MAC layer. Each CH defines a TDMA schedule and broadcasts it to the members of the cluster. Hereby, the time-domain is divided into scheduled access periods and the clustered nodes can sleep the most of the time to save energy.

IEEE 802.15.4 supports two operational modes: the beacon enabled mode and the non-beacon enabled mode. In the non-beacon enabled mode, the SNs are allowed to transmit data to their CH at any time. If any SN has no data to transmit, it can go to sleep mode. However, the CHs are not allowed to go to sleep mode, as they cannot predict when the SNs generate data. Thus, the main drawback of the non-beacon enabled mode of IEEE 802.15.4 is the high energy consumption of the CHs. In the beacon-enabled mode, each CH transmits beacon frames periodically, according to its own schedule. Beacons are used to delimit an active period and an inactive period. During the active period, the SNs exchange data with their CH either during a contention access period (CAP) using slotted CSMA/CA or during a contention free period (CFP) where a SN is allocated a guaranteed time slot (GTS) [13].

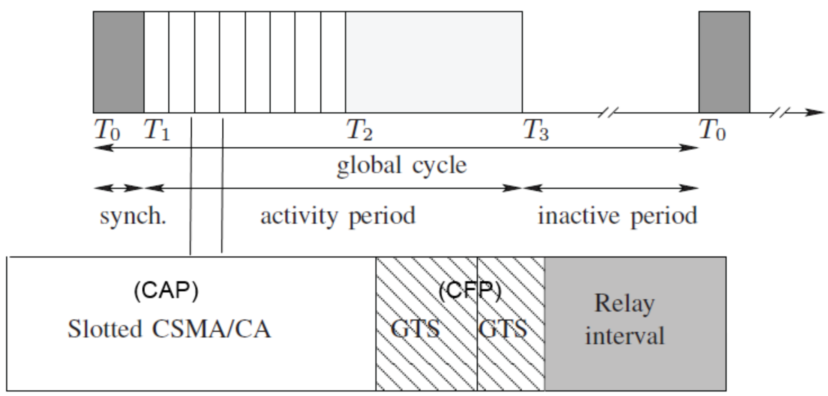

Figure 4. The MaCARI protocol time segmentation

The main drawback of ZigBee is that the cluster tree topology suffers from beacon frame collisions. In [14], the MaCARI protocol is proposed which is guarantees a collision free solution for beacon frames. MaCARI pre-allocates time intervals for CHs to achieve a collision free communication and thus offers a quality of service on the MAC level for high priority traffic. As shown in Figure 4, time is divided into global cycles and each global cycle starts with a synchronization ([T0; T1]) period that can be seen as a beacon-only during which all the CHs transmit their beacon. To avoid collisions between beacon frames, the transmission order is specified by the root coordinator of the WSAN. This transmission order is included in the beacon frame and copied in every beacon frame transmitted. When a CH receives a beacon, it checks the transmission order to know when it should transmit its beacon. Thus, by respecting the transmission order, MaCARI protocol completely avoids beacon frame collisions.

Once all the beacons are sent, a segmentation period ([T1; T2]) starts during which each CH is allocated a time interval to exchange data with its members on one hand and with its parent coordinator on the other hand. During [T2; T3], the CHs use slotted CSMA/CA to exchange data collected from clusters. The SNs are inactive during this period. The durations of [T1; T2] and [T2; T3] depend on the ratio of high priority traffic.

2.4. Related work

In this stage of our study, we reference some of the recent works related to joint problems of control and communication in WSANs to provide a background for our research. Cao *et al.* [7] present a theoretical model of control and communication over WSANs. They focus on two control schemes: a centralized control scheme (CC) in which decisions are made based on global information and a distributed control scheme (DC) that enables distributed actuators to make decisions locally. The centralized controller makes decisions based on the feedback from actuators as well as sensors. But, the distribute control scheme breaks up the centralized control and distribute it each of the actuators so that they can decide by themselves.

Quang and Kim [15] proposed a clustering algorithm to enhance the performance of fixed WSANs. The article concentrates on the investigation of an algorithm for determining the number and position of intermediate nodes, by using information on the positions of the nodes and the energy consumption model. In [16], the authors introduce a paradigm of software product line (SPL) to compose WSAN based systems satisfying different requirements of different farms with shorter term. In order to reduce configuration and modification efforts, this study construct reusable software components shared by different applications that are deployed in different farms and executed on different WSAN platforms with clearly defined interface.

Romdhani *et al.* [17] proposed a hybrid self-organizing data-collection protocol in order to provide energy efficiency, low end-to-end delay and high delivery ratio while taking advantage of the resource available on the ANs in the WSAN. This new self-organization protocol constructs its structure around the actuators and other resource-plentiful nodes. The nature of the structure is different inside and outside of transmission range of these resourceful nodes. Another work [18] on using aperiodic network transmission scheme that reduces the number of transmission instances for the SNs which concentrates on reducing energy consumption and increasing network lifetime without sacrificing control performance. In this context, two new control paradigms are reviewed: event-triggered control and self-triggered control. They also show the possibility of dynamically allocating the network bandwidth based on the physical system state and the available resources.

WSANs constitute an exciting technology with great potential for improving current applications, as far as for opening new ones in precision agriculture. There are many works in the scientific literature describing the main concepts employed in WSAN based agricultural applications that are usually designed to improve the irrigation efficiency. These studies are also effective to help mitigate the effects of adverse weather conditions. Patil *et al.* [19] designed an automatic irrigation control system for precision agriculture. This system regulates the desired moisture level in soil by making pump on/off state based on the sensor readings.

In [20], Ali *et al.* developed a prototype of WSAN for irrigation control in Pakistan which is low cost, ensures proper monitoring of the field, less human involvement, instant and accurate decision making. Zhang and Chang [21] designed a WSAN that uses fuzzy PID control algorithm to achieve the regulation of irrigation water so as to improve the control precision. The overall structure of system is extended over the ZigBee tree topology. Gao *et al.* [22] combined with the advantages of WSNs and fuzzy control technologies and designed an intelligent irrigation system. Here, soil moisture content deviation and the rate of change of deviation are taken as input variables of fuzzy PD controller and the fuzzy control regular database is established for the fuzzy irrigation control system.

Goli *et al.* [23] take advantage of the GSM and SMS to provide the farmer with the ability to handle the water level in the field remotely and in real time WSAN based irrigation management system. The research of Mampentzidou *et al.* [24] provides basic guidelines for deploying WSNs in agriculture and more specifically in applications requiring crop monitoring. Several scenarios were analyzed according to various issues such as power, network, maintenance, etc. to form an overall view.

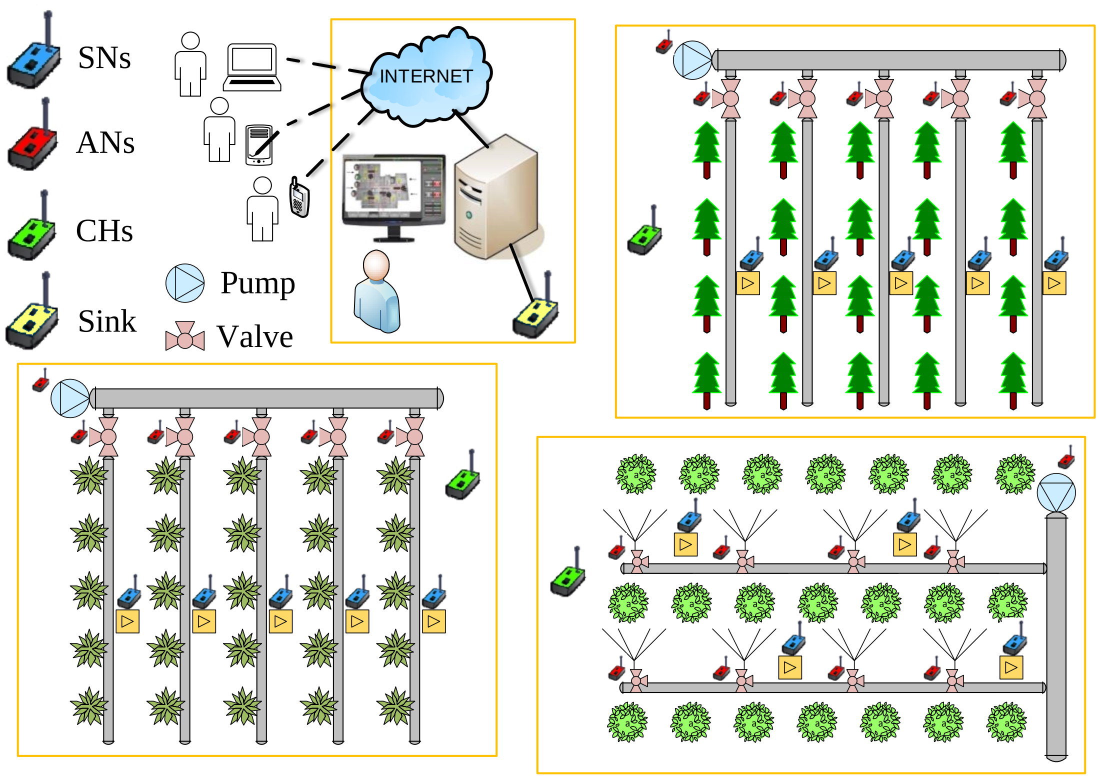

Figure 5. The system model of proposed WSAN based irrigation management platform

3. Proposed System Model

In this section, we describe the WSAN based remote monitoring and control system in detail that can be deployed either in the greenhouse applications or in the open field agriculture. The goal of this system is to monitor the weather conditions with the soil properties and to regulate the flow of water being dispersed to the whole cropland. The methods for measuring soil moisture are out of scope in this paper. In order to optimize the irrigation water use, arrays of actuators (such as pumps and electronically controlled valves etc.) are employed on the field. The system model of proposed network is shown in Figure 5.

It is considered that the clustered WSAN architecture in which the SNs and ANs are regularly deployed over the field and affiliated with the CHs. We assume that every CH knows its location and the list of member nodes associated with it. The ANs are then placed to the appropriate locations that maximize the coverage of CHs. The proposed setup can be applied for controlling drip and sprinkler irrigation. In drip irrigation case, the entire field is divided into laterals such that each lateral contains only one SN/AN pair. So, there are a lot of laterals which are irrigated independently. Conversely, more than one ANs placed on the same lateral in sprinkler irrigation. So, a certain AN can be controlled according to the signal from more than one SNs.

In proposed cooperative architecture, the CH operates as a field coordinator and communicates with all of the ordinary nodes (all nodes that are not CH) in its own cluster. The flow chart of the irrigation control process is shown by Figure 6. We assume that the SNs only transmit data while the ANs only receive data in intra-cluster communication phase. Since the CHs are close to the SN/AN pairs, the single-hop data transfer is available for intra-cluster communication. Obviously, the SNs continuously capture the soil moisture/temperature data and transfer them to their associated CH. In some cases, the ANs can be deployed with external energy sources under available field conditions.

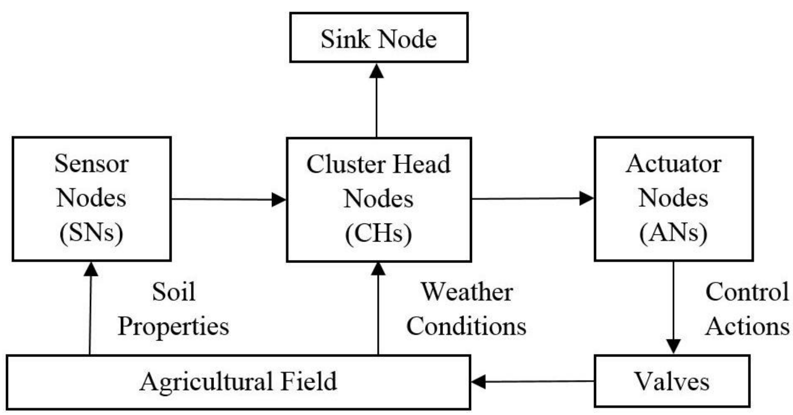

Figure 6. The flow chart of the irrigation control process

In our design, the CHs specifically equipped with meteorological sensors that detect air temperature, relative humidity, barometric pressure, solar radiation, wind speed and direction, rain, soil moisture and temperature etc., so it is possible to gather weather information about sub-zones. After data aggregation process, the CHs inform the sink node at a distant location about the status of their clusters and drive the valves and pumps according to the desired amount of water is applied to the crop. The sink node is connected to the PC of the operator where the collected data is stored for sophisticated analysis. Web based data viewing interface enables not only display the real time soil and irrigation data obtained from the field, but also share other useful information, such as weather forecast and the risks of various plants diseases. Applications for mobile devices can also help improve the convenience of farmers.

The CHs usually send data to higher distances than the SNs and naturally spend energy at higher rates. Therefore, the inter-cluster communication can be achieved by using short-range multi-hop path instead of single-hop direct transmission. Alternatively, the mobile telecommunication infrastructure can be used to send combined information from any CH to the sink node. Hence, besides the ZigBee module, the CHs also include contain a GPRS module in our system design. In many settings, once deployed, it is desirable for CHs to stay awake during for long periods of the data transmission frame. In proposed model, the CHs are equipped with a solar panel to extend the life time. With solar panel, the renewable energy is stored in a bank of batteries.

Conclusions

In this paper, we provide a discussion on the applications of WSANs in the precision agriculture. We also investigate the design of clustered WSAN for agricultural irrigation control. The proposed irrigation system is a model to modernize the agriculture and enables farmers to provide irrigation to larger areas of plants with less water consumption and lower pressure. The advantages of using WSAN are having the reduced wiring and piping costs, easier installation and maintenance in large fields. The system is applicable for different crops with small modifications. It is obvious that the current applications of WSANs are insufficient to meet the need of farmers. Many technical problems of WSANs are still are still under development and researchers are seeking solutions to emerging technical challenges.

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