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Review

Wireless sensor networks for agriculture: The state-of-the-art in practice and future challenges

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ABSTRACT

The advent of Wireless Sensor Networks (WSNs) spurred a new direction of research in agricultural and farming domain. In recent times, WSNs are widely applied in various agricultural applications. In this paper, we review the potential WSN applications, and the specific issues and challenges associated with deploying WSNs for improved farming. To focus on the specific requirements, the devices, sensors and communication techniques associated with WSNs in agricultural applications are analyzed comprehensively. We present various case studies to thoroughly explore the existing solutions proposed in the literature in various categories according to their design and implementation related parameters. In this regard, the WSN deployments for various farming applications in the Indian as well as global scenario are surveyed. We highlight the prospects and problems of these solutions, while identifying the factors for improvement and future directions of work using the new age technologies.

Contents

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1. Introduction

Modern day farming demands increased production of food to accommodate the large global population. Towards this goal, new technologies and solutions (Chen et al., 2015; Misra et al., 2015; Goumopoulos et al., 2014; Amaral et al., 2014; Ngo et al., 2014; Ullah et al., 2014; Misra et al., 2014; Qu et al., 2014; Misra et al., 2013; Riquelme et al., 2009; Garcia-Sanchez et al., 2011; Camilli et al., 2007) are being applied in this domain to provide an optimal alternative to gather and process information (Behzadan et al., 2014; Dhurandher et al., 2014) to enhance productivity. Moreover, the alarming climate change and scarcity of water (Postel, 1999; Bouwer, 2000; Saleth and Dinar, 2000; Jury and, 2007; Falloon and Betts, 2010; Mueller et al., 2012) demand new and improved methods for modern agricultural fields. Consequently, the need for automation and intelligent decision making is becoming more important to accomplish this mission (ur Rehman et al., 2014; Suprem et al., 2013; Wang et al., 2006; Hart and Martinez, 2006). In this regard, technologies such as ubiquitous computing (Burrell et al., 2004), wireless ad-hoc and sensor networks (Diallo et al., 2015; Srbinovska et al., 2015; Zhao et al., 2013; Karim et al., 2013; Zhang et al., 2013; Krishna et al., 2012; Zhang and Zhang, 2012; Misra et al., 2011; Mirabella and Brischetto, 2011; Lloret et al., 2011; Garcia et al., 2010; Bri et al., 2009; Lloret et al., 2009; Lin et al., 2008; Wang et al., 2006), Radio Frequency Identifier (RFID) (Ruiz-Garcia and Lunadei, 2011), cloud computing (Ojha et al., 2014; Misra et al., 2014; Cho et al., 2012), Internet of Things (IoT) (Atzori et al., 2010; Gubbi et al., 2013), satellite monitoring (Moghaddam et al., 2010), remote sensing (Bastiaanssen et al., 2000; Morais et al., 2008; Ye et al., 2013), context-aware computing (Moghaddam et al., 2010) are becoming increasingly popular.

1.1. Motivation

Among all these technologies, the agriculture domain is mostly explored concerning the application of WSNs in improving the traditional methods of farming (ur Rehman et al., 2014; Zhao et al., 2013; Wang et al., 2006; Akyildiz et al., 2002a,b; Akyildiz and Kasimoglu, 2004; Yick et al., 2008; Ruiz-Garcia et al., 2009). The Micro-Electro-Mechanical Systems (MEMS) technology has enabled the creation of small and cheap sensors. The ubiquitous nature of operation, together with self-organized small sized nodes, scalable and cost-effective technology, enables the WSNs as a potential tool towards the goal of automation in agriculture. In this regard, precision agriculture (Chen et al., 2015; Cambra et al., 2015; Barcelo-Ordinas et al., 2013; Baseca et al., 2013; Díaz et al., 2011; López et al., 2011; Park et al., 2011; Matese et al., 2009), automated irrigation scheduling (Lichtenberg et al., 2015; Reche et al., 2015; Greenwood et al., 2010; Gutiérrez et al., 2014; Moghaddam et al., 2010), optimization of plant growth (Hwang et al., 2010), farmland monitoring (Corke et al., 2010; Voulodimos et al., 2010), greenhouse gases monitoring (Malaver et al., 2015; Yang et al., 2013; Mao et al., 2012), agricultural production process management (Díaz et al., 2011; Dong et al., 2013), and security in crops (Garcia-Sanchez et al., 2011), are a few potential applications. However, WSNs have few limitations (Akyildiz et al., 2002a; Yick et al., 2008) such as low battery power, limited computation capability and small memory of the sensor nodes. These limitations invite challenges in the design of WSN applications in agriculture.

In agriculture, most of the WSN-based applications are targeted for various applications. For example, WSNs for environmental condition monitoring with information of soil nutrients is applied for predicting crop health and production quality over time. Irrigation scheduling is predicted with WSNs by monitoring the soil moisture and weather conditions. Being scalable, the performance of an existing WSN-based application can be improved to monitor more parameters by only including additional sensor nodes to the existing architecture. The issues present in such applications are the determination of optimal deployment strategy, measurement interval, energy-efficient medium access, and routing protocols. For example, a sparse deployment of nodes with a long data collection interval is helpful for enhancing the lifetime of a network. However, challenges may emerge from the choice of the deployment region. As an example, if the field area is separated by obstructions then it will lead to attenuation of signal, thereby affecting the inter-node communication.

In the Indian scenario, the WSN-based farming solutions need to be of very low cost to be affordable by end users. However, with the increasing population, the demand of food-grain is also rising. Recent reports warns that the growth in food grain production is less than the growth in population (Shanwad et al., 2004). Also, India is one of the largest exporters of food grains, and thus, researchers (Shanwad et al., 2004; Mondal and Basu, 2009) demand to boost production by incorporating advanced technologies. Consequently, new and modern technologies are being considered in many agricultural applications to achieve the target (Mondal et al., 2004). The current state of development in the Indian scenario comprises of technologies such as WSNs, General Packet Radio Service (GPRS), Global Positioning System (GPS), remote sensing, and Geographical Information System (GIS).

1.2. Contributions

In this paper, we surveyed the variants of WSNs and their potential for the advancement of various agricultural application development. We highlight the main agricultural and farming

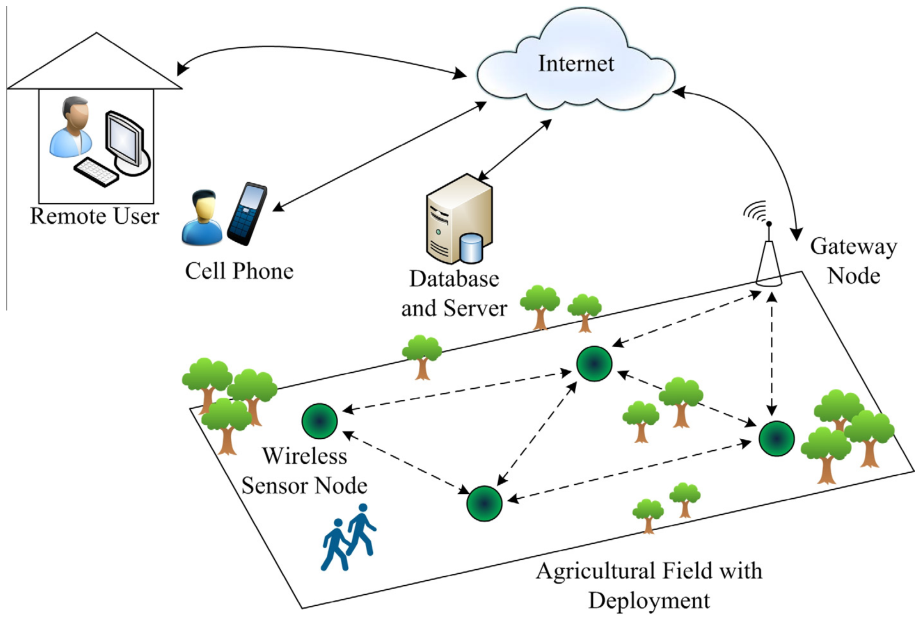


Fig. 1. A typical wireless sensor network deployed for agricultural applications.

applications, and discuss the applicability of WSNs towards improved performance and productivity. We also classify the network architecture, node architecture, and communication technology standards used in agricultural applications. The real-world wireless sensor nodes and various sensors such as soil, environment, pH, and plant-health are also listed in this paper. In Section 5, we study and review the existing WSN deployments both in the global as well as the Indian scenarios. In summary, the *contributions* of this paper are listed as follows.

- We study the current state-of-the-art in WSNs and their applicability in agricultural and farming applications.
- The existing WSNs are analyzed with respect to communication and networking technologies, standards, and hardware.
- We analyze the prospects and problems of the existing agricultural applications with detailed case studies for global as well as the Indian scenarios.
- Finally, we present the futuristic applications highlighting the factors for improvements for the existing scenarios.

1.3. Paper organization

The rest of the paper is organized as follows. Section 2 presents the basics of WSNs, its requirements, potentials and different possible application in the agriculture domain. Design of a wireless sensor network for agricultural application is discussed in Section 3. The technologies and standards used in agricultural applications are analyzed in Section 4. We further discuss about the currently existing state-of-the-art and real-world applications in Section 5, and analyze the prospects and problems of the existing solutions. In Section 6, we provide few future direction of work pointing out the factors for improvement. Finally, the paper concludes in Section 7.

2. Wireless sensor networks and its potential for agricultural applications

In this section, we discuss two widely used variants of WSNs—Terrestrial Wireless Sensor Networks (TWSN) and Wireless Underground Sensor Networks (WUSN), specifically used in agricultural applications.

2.1. Terrestrial wireless sensor networks

WSNs are a network of battery-powered sensors interconnected through wireless medium and are typically deployed to serve a specific application purpose (Akyildiz et al., 2002a,b; Akyildiz and Kasimoglu, 2004). In TWSNs, the nodes are deployed above the ground surface. The advancements in MEMS technology has enabled the creation of smart, small sized, although low cost sensors. These powerful sensors empower a sensor node or *mote* to accurately collect the surrounding data. Based on the sensed information, these nodes then network among themselves to perform the application requirements. For example, consider a precision agriculture environment where WSNs are deployed throughout the field to automate the irrigation system. All these sensors determine the moisture content of the soil, and further, collaboratively decide the time and duration of irrigation scheduling on that field. Then, using the same network, the decision is conveyed to the sensor node attached to a water pump. Gutiérrez et al. (2014) proposed one such automated irrigation system using a WSN and GPRS module.

Fig. 1 depicts a typical wireless sensor network deployed on field for agricultural applications. The field consists of sensor nodes powered with application specific on-board sensors. The nodes in the on-field sensor network communicate among themselves using radio-frequency (RF) links of industrial, scientific and medical (ISM) radio bands (such as 902–928 MHz and 2.4–2.5 GHz). Typically, a gateway node is also deployed along with the sensor nodes to enable a connection between the sensor network and the outer world. Thus, the gateway node is powered with both RF and Global System for Mobile Communications (GSM) or GPRS. A remote user can monitor the state of the field, and control the on-field sensors and actuator devices. For example, a user can switch on/off a pump/valve when the water level applied to the field reaches some predefined threshold value. Users carrying mobile phone can also remotely monitor and control the on-field sensors. The mobile user is connected via GPRS or even through Short Message Service (SMS). Periodic information update from the sensors, and on-demand system control for both type of users can also be designed.

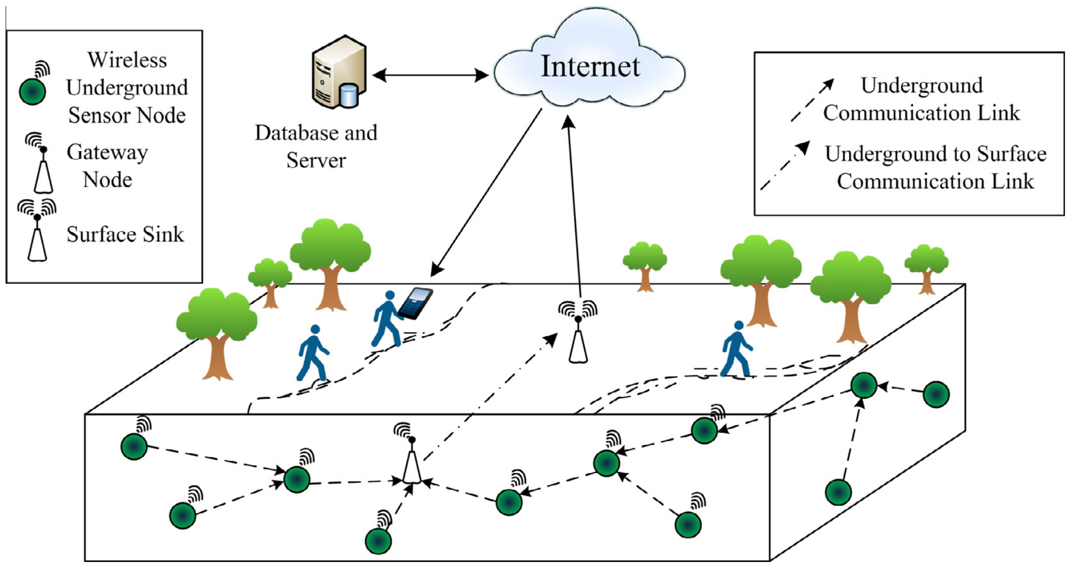


Fig. 2. A typical wireless underground sensor network deployed for agricultural applications.

Table 1
Differences between terrestrial and underground WSNs.

Feature	TWSNs	WUSNs
Deployment	Placed over ground	Buried under-ground
Depth	Anywhere over ground	Topsoil (0–30 cm) and subsoil (>30 cm)[a]
Communication range	≈100 m	≈0.1–10 m
Communication frequency	Higher (868/915 MHz, 2.4 GHz)	Lower (433 MHz, 8–300 kHz)
Antenna size	Smaller	Larger
Energy consumption	Lower	Higher
Cost	Lower	Higher

[a] References Martinez et al. (2004) and Vuran and Silva (2009) reported a glacier monitoring network where underground communications over 30 m distance were possible. Further, using higher transmission power, 80 m distance under ice were also covered.

2.2. Wireless underground sensor networks

Another variant of the WSNs is its underground counterpart—Wireless Underground Sensor Networks (WUSNs) (Akyildiz and Stuntebeck, 2006; Vuran and Akyildiz, 2008). In this version, the wireless sensors are planted inside soil. In this setting, higher frequencies suffer severe attenuation, and comparatively lower frequencies are able to penetrate through the soil (Silva and Vuran, 2010; Yu et al., 2013). Thus, communication radius gets limited and the network requires higher number of nodes to cover a large area. The application of wired sensors increases the network coverage by requiring relatively smaller number of sensors. However, in this design, the sensors and the wires may be vulnerable to farming activities.

A typical agricultural application based on underground sensor networks is shown in Fig. 2. Unlike the TWSN-based applications shown in Fig. 1, in this figure, the sensor nodes are buried inside soil. One gateway node is also deployed to transmit the information collected by the underground sensor nodes to the surface sink placed over the ground. Thereafter, the information can be transmitted over the Internet to store in remote databases, and can be used for notifying a cell phone carrying user. However, due to comparatively shorter communication distance, more number of nodes are required to be deployed for use in WUSNs.

2.3. Differences between TWSNs and WUSNs

We highlight the specific differences between the TWSNs and WUSNs in Table 1.

2.4. Usefulness of WSNs

In the following, we highlight the salient features of WSNs that have enabled themselves as a potential tool for automation in the agricultural domain.

(i) *Intelligent decision making capability:* WSNs are multi-hop in nature (Akyildiz et al., 2002a,b; Akyildiz and Kasimoglu, 2004). In a large area, this feature enhances the energy-efficiency of the overall network, and hence, the network lifetime increases. Using this feature, multiple sensor nodes collaborate among themselves, and collectively take the final decision (Kulkarni et al., 2011; Bhattacharjee et al., 2012; Wu et al., 2012; Yao et al., 2013).

(ii) *Dynamic topology configuration:* To conserve the in-node battery power, a sensor node keeps itself in the 'sleep mode' most of the time. Using topology management techniques (Ren and Meng, 2009; Chu and Sethu, 2012; Li et al., 2013), the sensor nodes can collaboratively take these decisions. To maximize the network lifetime, the network topology is configured such that the minimum number of nodes remain in the active mode.

(iii) *Fault-tolerance:* One common challenge in deploying the WSNs is that the sensor nodes are fault-prone (Younis et al., 2014). Under such circumstances, unplanned deployment of nodes may lead to network partitioning, and in turn, the overall performance of the network is affected. However, in countermeasure, the sensor nodes can 'self-organize' by dynamically configuring the network topology (Misra et al., 2011).

(iv) *Context-awareness:* Based on the sensed information about the physical and environmental parameters, the sensor nodes gain knowledge about the surrounding context. The decisions that the sensor nodes take thereafter are context-aware (Vijay et al., 2011).

(v) *Scalability:* Generally, the WSN protocols are designed to be implemented in any network irrespective of its size and node count. This feature undoubtedly widens the potential of WSNs for numerous applications.

(vi) *Node heterogeneity:* WSNs are often assumed to be comprised of homogeneous sensor attached devices (Misra et al., 2015; Li and Hou, 2005; Ren and Meng, 2009). However, in many realistic scenarios, the devices are heterogeneous in respect of processing and computation power, memory, sensing capability, transceiver unit, and movement capability.

(vii) *Tolerance against communication failures in harsh environmental conditions:* Due to the wide range of applications in open agricultural environments, WSNs suffer the effects of harsh environmental conditions (Misra et al., 2014). The WSN protocol stack includes techniques to withstand the effect of communication failures in the network arising due to environmental effects.

(viii) *Autonomous operating mode:* An important feature of WSNs is their autonomous operating mode (Misra and Jain, 2011) and adaptiveness (Nicopolitidis et al., 2011). In agricultural applications, this feature certainly plays an important role, and enables an easy as well as advanced mode of operation.

(ix) *Information security:* The WSNs carry raw information about on-field parameters. To ensure the security of sensed information, WSNs provides access control mechanisms (Misra and Vaish, 2011) and anomaly detection (Karapistoli et al., 2013) to restrict unauthenticated users.

2.5. Potential applications

We list the possible agricultural and farming applications which can be implemented using WSNs.

- *Irrigation management system:* Modern day agriculture requires an improved irrigation management system to optimize the water usage in farming (Adamala et al., 2014; Greenwood et al., 2010). The alarming reduction of ground water level is another motivation for the requirement of an advanced system. In this context, micro-irrigation techniques are cost-effective and water-usage efficient (Raina et al., 1998; Westarp et al., 2004). However, micro-irrigation efficiency can be further improved based on the environmental and soil information. In this regard, WSNs are applied as the coordinating technology (Lichtenberg et al., 2015; Gutiérrez et al., 2014; Lorite et al., 2013; Moghaddam et al., 2010).
- *Farming systems monitoring:* Currently, various improved systems and devices are used in farming. In this regard, an improved system to manage these devices eases the overall operation, and enable automation in faming (Kim et al., 2014). Also, such remote monitoring systems help towards enabling improved management in large agricultural fields. Further, with the input of additional information such as satellite images and weather forecasts, the system performance can be improved.
- *Pest and disease control:* Controlled usage of pesticides and fertilizers helps increasing the crop quality as well as minimizing the farming cost. However, for controlling the usage of pesticides, we need to monitor the probability and occurrence of pests in crops. To predict this, we also need the surrounding climate information (Matese et al., 2009; Bhave et al., 2013) such as temperature, humidity, and wind speed. A WSN can autonomously monitor and predict these events over a field of interest (Bhargava et al., 2014).
- *Controlled use of fertilizers:* Plant growth and crop quality directly depend on the use of fertilizers. However, optimal supply of fertilizers to proper places in fields is a challenging task. The use of fertilizers for farming may be controlled by monitoring the variation in soil nutritions such as Nitrogen (N), Phosphorous (P), Potassium (K), and pH. Consequently, soil nutrition balance may also be achieved, and hence, crop production quality is also maintained. Gonçalves et al. (2015) studied the effectiveness of mobile nodes to improve agricultural productivity in a smart system with Precision Sprays.
- *Cattle movement monitoring:* A herd of cattle grazing a field can be monitored using WSN technology or Radio Frequency Identifier (RFID) (Voulodimos et al., 2010; Kwong et al., 2012). Thus, real-time monitoring of any cattle is also achieved. This technology can be implemented further to monitor whether any cattle is moving near the vegetation fields or not.
- *Ground water quality monitoring:* The increased use of fertilizers and pesticides lead to decrease in the quality of ground water. Placing sensor nodes empowered with wireless communication help in monitoring the water quality (Lin et al., 2008; Zia et al., 2013).
- *Greenhouse gases monitoring:* Greenhouse gases and agriculture are closely related to each other. Greenhouse gases are responsible for increasing the climate temperature, and thus, has direct impact on agriculture. On the other hand, greenhouse gas emission comes from various agricultural sources. Malaver et al. (2015) presents the development of a system of solar powered Unmanned Aerial Vehicle (UAV) and WSN to monitor greenhouse gases – CH_4 and CO_2.
- *Asset tracking:* Wireless technology enabled farming equipments attract the possibility of remote tracking (Misra and Singh, 2012) of these assets. A farmer can track the position of the farming vehicles and irrigation systems from his home.
- *Remote control and diagnosis:* With the advent of internet of things, remote control and diagnosis of farm equipments such as pumps, lights, heaters, valves in machinery are also possible (Fukatsu et al., 2011; Coates et al., 2013).

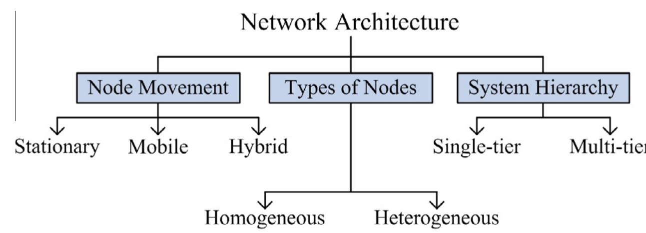


Fig. 3. Classification of network architectures with respect to different parameters.

3. Design of a wireless sensor network for agricultural applications

3.1. Network architecture for agriculture applications

In this section, we discuss the network architecture considered in various agricultural applications. We classify the architectures in various categories and highlight the potential agricultural applications suitable for each one. Fig. 3 provides a visual depiction of the architectures classified with respect to different parameters.

Based on the *movement* of the networked devices and nodes, we classify the existing architectures in the following categories:

- *Stationary architecture:* In the stationary architecture, the sensor nodes are deployed at a fixed position, and during the application duration, they do not change their position. Typically, applications such as irrigation management system, ground water quality monitoring, and controlling the use of fertilizers require stationary architectures. In such applications with TWSNs, the data logger (data collector) sensor nodes are

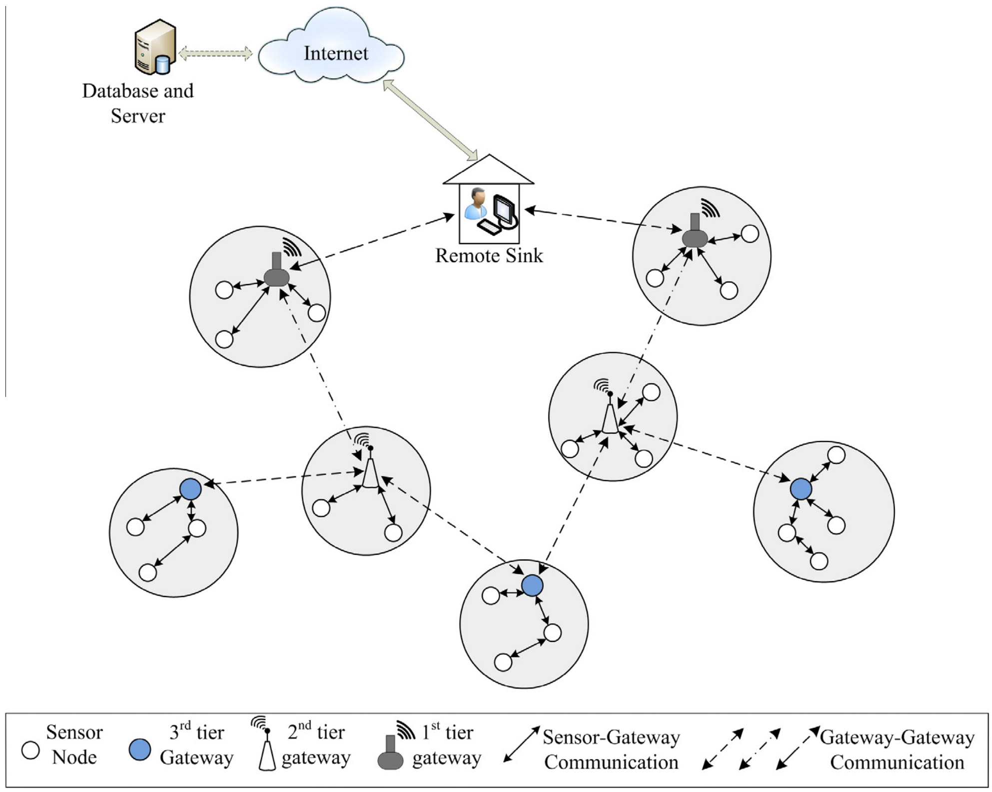


Fig. 4. One application based on multi-tier architecture.

typically placed over the field. However, in WUSNs, the data collector sensor nodes are placed under-ground. Also, as shown in Fig. 2, aggregator nodes may be placed under-ground to collect all the data of the underground sensors and communicate with the outside TWSNs.

- *Mobile architecture:* Mobile architectures comprise of devices which change their position with time. An example of applications based on such architecture will be an autonomous network of tractors and cell phone carrying farmers serving the purpose of ubiquitous farming operations.
- *Hybrid architecture:* In the hybrid architecture, both stationary and mobile nodes are present. For example, this type of architecture is applicable to farming applications consisting of stationary field sensors, mobile farming equipments, cell phones carrying users, and moving cattle.

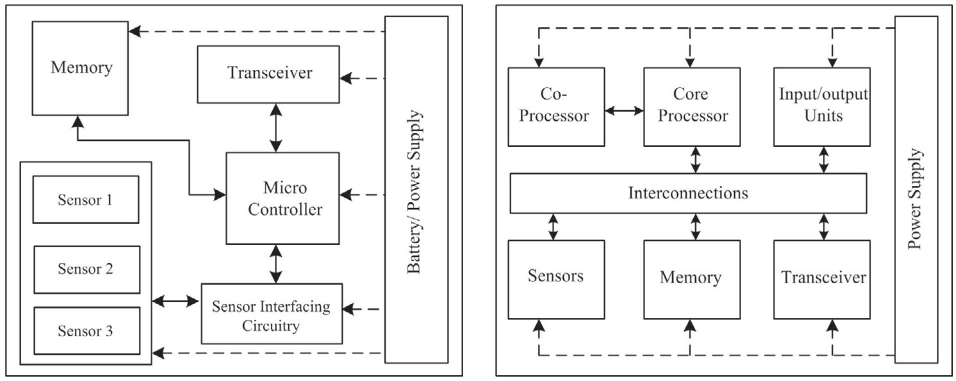
Based on the *types* of sensor nodes and associated devices, the existing architecture used in agriculture are classified as follows:

- *Homogeneous architecture:* As the name suggests, homogeneous architecture comprises of sensor equipped devices of similar potential. This type of framework is typically used in applications based on the unplanned deployments. In such circumstances, the network is deployed mainly for *in situ* monitoring of the desired agricultural parameters. However, this type of architecture lacks variety in terms of communication hardware. Consequently, the schemes and communication protocols are designed keeping this limitation in mind. One example application of this type of architecture is agricultural data collection application on the use of pesticides and changing quantity of soil nutrients.
- *Heterogeneous architecture:* In this type of architecture, various types of sensor nodes, and devices are present. These devices vary in terms of computation power, memory, sensing capability, and transceiver units. For example, in any irrigation management application, the on-field sensor nodes communicate their sensed information to a master or sink node, which again transfer the information to remote user. In this case, the sink node is capable of communicating in multiple modes—RF and GSM. Another possible application may be the farming systems monitoring and agricultural asset tracking. In this application, multiple heterogeneous devices are included with on-field sensors. The application model shown in Fig. 1 depicts a heterogeneous architecture. In Fig. 1, the field sensor and gateway nodes are of different configurations.

The architectures are classified into various categories based on the *hierarchy*.

- *Single-tier architecture:* This type of architecture is most common among the agricultural applications, specifically small-scale ones. In this type of architecture, the on-field devices and sensor nodes directly communicate their data to a sink node placed near the application area. This type of architecture is also referred to as the *single clustered architecture*.
- *Multi-tier architecture:* In a multi-tier architecture, there are multiple levels in the overall application hierarchy. The on-field sensor nodes remain in the lower level of hierarchy, and form the basic clusters. Thereafter, the next levels of hierarchy include multiple clusters to reach the gateway nodes. Typically, multi-tier architectures consist of heterogeneous nodes.

Fig. 4 shows a multi-tier architecture with three levels of gateways. The basic unit of the network is formed by a cluster comprised of sensor nodes and a cluster head, referred to as the 3rd tier gateway in the figure. These gateways again form a cluster with the 2nd tier gateways as the cluster head, and thus, the hierarchy is followed iteratively until the remote sink is reached.



(a) Architecture of a typical embedded multi-chip sensor node

(b) Architecture of a typical system-on-chip based sensor node

Fig. 5. System components: embedded multi-chip vs system-on-chip sensor nodes.

3.2. Architecture of sensor nodes

3.2.1. Embedded multi-chip sensor nodes

The components of a typical multi-chip sensor node are shown in Fig. 5(a). Typically, a sensor node consists of an application-specific sensor array with a transceiver unit for communication. A processor or micro-controller unit is used as the "brain" of the node. Optionally, a sensor board includes memory units to store data. Depending on the application demand, the architecture of the sensor nodes varies to meet the demands. For example, the processing power and on-board memory size are increased to meet the requirements of more intense or intelligent processing.

In this respect, another important technology is System-in-Package (SiP), which is defined as any combination of multiple chips including passive components (such as resistors and capacitors) mounted together keeping provision to attach external components later. SiP reduces the product cost with optimized size and performance. Thus, the SiP technology has potential for applications in agricultural scenarios. SiP based agricultural systems can be applied in different applications simply by attaching different sensors with the main package.

In the following, we discuss the associated factors in the selection of the components of a sensor node as per the requirement of agricultural applications.

- *Processor:* The computation power of the sensor node solely depends on the choice of the processing unit. A micro-controller provides few advantages such as low cost, flexibility to communicate with other nodes, ease of programming, and low power consumption over the traditional processors. Mostly, these micro-controllers work on 3.5–5 V. However, power consumption is one of the most important factors in sensor nodes. Considering this fact, micro-controllers are preferred over general purpose processors.
- *Transceiver:* Transmission and reception are the two major reasons of energy consumption in sensor nodes. In agricultural applications, the network planner chooses the deployment to ensure optimal power consumption of the sensor nodes.
- *Memory:* The sensor nodes have two types of on-board memory—memory associated with processor and external memory. Depending on the application requirement, sensor nodes need to store historical data for intelligent decision making. In this regard, flash memories are used for additional storage.

Table 2
Differences between the embedded multi-chip nodes and SoCs.

Attribute	Embedded multi-chip	System-on-chip
Processor	Few & homogeneous	Multiple & heterogeneous
Power consumption	High	Low
Cost	High	Low
System size	Bigger	Smaller
Memory	Separate chip	Integrated

- *Power:* It is also an important factor for selecting the sensor nodes, as the battery power of the sensor nodes is limited. In many agricultural applications, the nodes possess alternate energy sources such as solar power. However, solar power is available during the day time only, and at other times, the nodes rely on battery power. Also, frequent change of battery increases the cost of maintenance. Thus, we need energy-efficient algorithms such that the energy consumption of the sensor nodes are reduced.
- *Cost:* One very important selection factor of the sensor nodes is the total hardware cost. A low cost application design is always preferred for any application level, and consequently, it is the most important issue in terms of applications targeting the low and middle income country (LMIC) markets.

3.2.2. System on Chip (SoC) sensor nodes

The System-on-Chip (SoC) architecture, on the other hand, follows more application specific design targeting minimization of the power requirements and design cost. SoC provides an integration of multiple programmable processor cores, co-processors, hardware accelerators, memory units, input/output units, and custom blocks. Fig. 5(b) shows the components of a typical SoC based sensor node. The envisioned applications for SoC is mainly in designing Network on Chips (NoCs) (Koch et al., 2006), systems for multimedia and streaming applications (Karim et al., 2003) which are computationally intensive.

Currently, in agricultural applications, the use of SoCs are very rare. However, the advent of SoC has a lot of potential for the agriculture and farming domain. Firstly, the use of SoCs based sensor nodes instead of current day embedded multi-chip sensor nodes will increase the computation power, and decrease the energy-consumption. Also, the size of the nodes will be less and thereby, portability of the overall system increases. Compared to multiple silicon dies in SiP, SoC is single die based, and thus, SoCs result in lesser size, but, higher cost.

Table 2 briefly lists the differences between the embedded multi-chip nodes and SoCs.

4. Technologies and standards used in agriculture

In this section, we discuss the details of the wireless communication technologies, and the standards used in various agricultural applications. Also, we study the different wireless sensor nodes available in the market for use in these applications.

4.1. Wireless communication

- *ZigBee:* (ZigBee Specifications; Baronti et al., 2007; Guo et al., 2012); technology defines the network and application layer protocols based on the IEEE 802.15.4 standard (IEEE Standard for Information technology, 2006) physical and MAC layer definitions required for designing a wireless personal area network (WPAN) using low power radio-enabled devices. Being energy-efficient, low cost, and reliable, the ZigBee technology is preferred for WSN-based applications in the agricultural and farming domains. ZigBee also supports short-distance (10–20 m) data communication over multi-tier, decentralized, ad-hoc and mesh networks. The ZigBee-enabled devices have a low-duty cycle, and thus, are suitable for agricultural applications such as irrigation management, pesticide and fertilizer control, water quality management, where periodic information update is required. However, ZigBee applications yield low data rates of only 20–40 kbps and 250 kbps at 868/915 MHz and 2.4 GHz frequencies of ISM band, respectively. Typically, this standard requires low specification hardware (such as microprocessor with 50–60 kb memory) and includes security encryption techniques.
- *WiFi:* WiFi is a wireless local area network (WLAN) standard for information exchange or connecting to the Internet wirelessly based on the IEEE 802.11 standards family (IEEE 802.11, 802.11a/b/g/n) (IEEE Standard for Information technology, 2005, 2012a). Currently, it is the most widely used wireless technology found in devices ranging from smart phones and tablets to desktops and laptops. WiFi provides a decent communication range in the order of 20 m (indoor) to 100 m (outdoor) with data transmission rate in the order of 2–54 Mbps at 2.4 GHz frequency of ISM band. In agricultural applications, WiFi broadens the use of heterogeneous architectures connecting multiple type of devices over an ad-hoc network.
- *Bluetooth:* Bluetooth (IEEE Standard for Information technology, 2012b; Bluetooth Technology Special Interest Group), which is based on the IEEE 802.15.1 standard, is a low power, low cost wireless technology used for communication between portable devices and desktops over a short range (8–10 m). The Bluetooth standard defines a personal area network (PAN) communication using the 2.4 GHz frequency of the ISM band. The data rate achieved in various versions of the Bluetooth ranges from 1 to 24 Mbps. The advantages of this technology are its ubiquitous nature, and therefore, it is suitable for use in multi-tier agricultural applications. The ultra low power, low cost version of this standard is named as Bluetooth Low Energy (BLE) (Xhafa and Ho, 2013, 2015; Linde and Tucker, 2013), which was initially introduced by Nokia in 2006 as Wibree (Nokia, 2006). However, in 2010, BLE was merged with main Bluetooth standard version 4.0. BLE also uses the 2.4 GHz ISM frequency band with adaptive frequency hopping to reduce interference. Also, BLE includes 24 bit CRC and AES 128 bit encryption technique on all packets to guarantee robustness and authentication. BLE topology supports one-to-one as well as one-to-many connections between devices.
- *GPRS/3G/4G:* GPRS (General Packet Radio Service) is a packet data service for GSM based cellular phones. A data rate of 50–100 kbps is achieved in the 2G systems. However, in GPRS, throughput and delay are variable, and they depend on the number of other users sharing the same resource. Although the biggest advantage that GPRS brings is in relieving the range limitation of wireless devices. Any two devices can communicate provided they both are in the GSM service area. However, it is better suited for the periodic monitoring applications than to the real-time tracking-type applications. The advanced version of GPRS is Enhanced Data rates for Global Evolution (EDGE), which offers increased data rate with no hardware/software changes in the GSM core networks.
  3G (Goodman and Myers, 2005) and 4G (Parkvall et al., 2008) are the *third* and *fourth* generations of mobile communication technology. The corresponding data transfer rate achieved in these technologies are 200 kbps and 100 Mbps to 1 Gbps in 3G and 4G, respectively.
- *WiMAX:* WiMAX is the acronym for Worldwide Interoperability for Microwave Access, a wireless communication standard referring to the inter-operable implementations of the IEEE 802.16 standards (IEEE Standard for Local and metropolitan area networks, 2011) family. WiMAX is targeted to achieve 0.4–1 Gbps data rate on fixed stations, and the maximum transmission range using this technology is 50 km. The Mobile WiMAX (IEEE 802.16e standard) provides data rates in the order of 50–100 Mbps. Also, WiMAX is stated to be energy-efficient over the pre-4G Long-Term Evaluation (LTE) and Evolved High-Speed Packet Access (HSPA+) (Deruyck et al., 2010; Louta et al., 2014). The long range support together with high speed communication features place WiMAX as the best suitable technology for agricultural applications involving asset monitoring such as farming system monitoring, crop-area border monitoring, and real-time diagnostics such as remote controlling of water pumps, lights, gates, remote diagnosis of farming systems.

In Table 3, we compare the different communication technologies with respect to various parameters. We also mention the suitable agricultural applications of each technology.

4.2. Wireless sensor nodes

There exists a number of different wireless sensor platforms for use in the agricultural domain (ur Rehman et al., 2014). In Table 4, we analyze the existing wireless sensor nodes by classifying them according to different features and parameters.

4.3. Application specific sensors

In this section, we discuss the various application specific sensors which empower the wireless sensing platforms. For better classification, we divide these sensors in three main categories—soil, environment, and plant related.

4.3.1. Soil related

In Table 5, we compare the sensors along with different soil-related measurement parameters—suitable for different potential agricultural applications.

4.3.2. Environment related

Environmental sensors such as humidity, ambient temperature, and wind speed are deployed with the application-specific soil and plant sensors in various agricultural applications. Such kind of heterogeneous placement ensures intelligent and improved

Table 3
Comparison of different communication technologies.

Parameter	ZigBee	WiFi	Bluetooth	GPRS/3G/4G	WiMAX
Standard	IEEE 802.15.4	IEEE 802.11a,b,g,n	IEEE 802.15.1	–	IEEE 802.16a,e
Frequency band	868/915 MHz, 2.4 GHz	2.4 GHz	2.4 GHz	865 MHz, 2.4 GHz	2–66 GHz
Data rate	20–250 kbps	2–54 Mbps	1–24 Mbps	50–100 kbps/200 kbps/0.1–1 Gbps	0.4–1 Gbps (stationary), 50–100 mbps (mobile)
Transmission range	10–20 m	20–100 m	8–10 m	Entire GSM coverage area	$\leqslant$50 km
Energy consumption	Low	High	Medium	Medium	Medium
Cost	Low	High	Low	Medium	High

Table 4
Comparison of the existing wireless sensor platforms.

Feature	MICA2	MICAz	TelosB	IRIS	LOTUS	Imote2	SunSPOT
Processor	ATmega128L	ATmega128L	TIMSP430	ATmega128L	Cortex M3 LPC 17xx	Marvell/XScalePXA271	ARM 920T
Programming							Java
Clock speed (MHz)	7.373	7.373	6.717	7.373	10–100	13–416	180
Bus width (bits)	8	8	16	8	32	32	32
System memory (kB)	4	4	10	4	64	256	512
Flash memory (kB)	Program:128 Serial:512	Program:128 Serial:512	Program:48 Serial:1024	Program:128 Serial:512	Program:512 Serial: 64×1024	Program: programmable Serial: 32×1024	Program:4096 –
Operating frequency band (MHz)	868/915	2400	2400	2400	2400	2400	2400
Transceiver chip	CC1000	CC2420	CC2420	Atmel RF230	Atmel RF231	CC2420	802.15.4
Number of channels	4/50	Programmable	Programmable	Programmable	–	In steps of 5 MHz	–
Data rate (kbps)	38.4 (Baud)	250	250	250	250	250	250
I/O connectivity	UART, I2C, SPI, DIO	UART, I2C, SPI, DIO	UART, I2C, SPI, DIO	UART, I2C, SPI, DIO	3xUART, SPI, I2C, I2S, GPIO, ADC	UART 3x, I2C, GPIO, SPI2x, DIO, JTAG	DIO, I2C, GPIO

Table 5
Comparison of different sensors: soil related.

Sensor	Soil moisture	Rain/water flow	Water level	Soil temperature	Conductivity	Salinity
Pogo portable soil sensor (http://www.stevenswater.com)	✓	✓	✗	✓	✓	✓
Hydra probe II soil sensor (http://www.stevenswater.com)	✓	✓	✓	✓	✓	✓
ECH_2O EC-5 (http://www.decagon.com)	✓	✗	✗	✗	✗	✗
VH-400 (http://www.vegetronix.com)	✓	✗	✓	✗	✗	✗
EC-250 (http://www.stevenswater.com)	✓	✓	✓	✓	✓	✓
THERM200 (http://www.vegetronix.com)	✗	✗	✗	✓	✗	✗
Tipping bucket rain gage (http://www.stevenswater.com)	✗	✓	✗	✗	✗	✗
AquaTrak 5000 (http://www.stevenswater.com)	✗	✗	✓	✗	✗	✗
WET-2 (http://www.dynamax.com)	✗	✗	✗	✓	✓	✓

Table 6
Comparison of different sensors: environment related.

Sensor	Humidity	Ambient temperature	Atmospheric pressure	Wind speed	Wind direction	Rain fall	Solar radiation
WXT520 compact weather station (http://www.stevenswater.com)	✓	✓	✓	✓	✓	✓	✗
CM-100 compact weather station (http://www.stevenswater.com)	✓	✓	✓	✓	✓	✗	✗
Met Station One (MSO) weather station (http://www.stevenswater.com)	✓	✓	✓	✓	✓	✗	✗
All-In-One (AIO) Weather Sensor (http://www.climatronics.com)	✓	✓	✓	✓	✓	✗	✗
XFAM-115KPASR (http://www.pewatron.com)	✓	✓	✓	✗	✗	✗	✗
RM Young (model 5103) (http://www.stevenswater.com)	✗	✗	✗	✓	✓	✗	✗
Met One Series 380 rain gauge (http://www.stevenswater.com)	✗	✗	✗	✗	✗	✓	✗
RG13/RG13H (http://www.vaisala.com)	✗	✗	✗	✗	✗	✓	✗
LI-200 Pyranometer (http://www.stevenswater.com)	✗	✗	✗	✗	✗	✗	✓
CS300-L Pyranometer (http://www.campbellsci.com)	✗	✗	✗	✗	✗	✗	✓

decision making. Table 6 lists the sensors specific to the measurement of environmental parameters.

4.3.3. Plant related

The sensors deployed or attached to a plant are also an integral part of modern farming applications. The potential applications include controlled use of fertilizer, crop quality monitoring, pest control, and cattle movement monitoring. The plant related agricultural sensors are listed in Table 7.

5. Existing real-world applications

In Section 5.1, we discuss the different categories of agricultural applications in detail, and also, bring on the real-world counterpart of the same application deployment as a case study. These applications are designed with both the TWSNs and the WUSNs. Also, we mention the developments in the Indian scenarios in Section 5.2. Although, the number of such developments is very small compared to the global scenario. In Section 5.3, we analyze the

Table 7
Comparison of different sensors: plant related.

Sensor	Moisture	Temperature	Hydrogen	Wetness	CO_2	Photosynthesis
Leaf wetness sensor (http://www.decagon.com)	✓	✗	✗	✗	✗	✗
237-L, leaf wetness sensor (http://www.campbellsci.com)	✓	✓	✗	✓	✗	✗
LW100, leaf wetness sensor (http://www.globalw.com)	✓	✓	✗	✓	✗	✗
SenseH2™ hydrogen sensor (http://www.ntmsensors.com)	✓	✓	✗	✓	✗	✗
TPS-2 portable photosynthesis (http://www.ppsystems.com)	✓	✓	✗	✓	✓	✓
CI-340 hand-held photosynthesis (http://www.solfranc.com)	✓	✓	✓	✓	✓	✓
PTM-48A photosynthesis monitor (http://phyto-sensor.com)	✓	✓	✗	✓	✓	✓

Table 8
Deployment parameters: Gutiérrez et al. (2014).

Parameter	Value
Soil moisture sensor	VH400 (http://www.vegetronix.com/)
Soil temperature	DS1822 (http://www.maximintegrated.com/)
ZigBee module	XBee-PRO S2 (http://www.digi.com/)
GPRS module	MTSMC-G2-SP (http://www.multitech.com/)
Photovoltaic cell	Solar panel MPT4.8-75
Micro-controller (WSUs & WIU)	PIC24FJ64GB004 (https://www.microchip.com/)
Electronic relay for pumps	12 V DC
Solid state memory	24FC1025 (https://www.microchip.com/)
Architecture	Single-tier heterogeneous
Deployment area	600 m^2
Transmission range (WSU)	$\leqslant$1500 m
Data upload interval (WIU to server)	60 min
WSU–WIU communication	ZigBee-based (2.4 GHz)
WIU–server communication	GPRS-based

challenges, problems, and prospects of the existing solutions both in the global as well as the Indian scenarios.

5.1. Global scenario

5.1.1. Irrigation management

The recent years have witnessed an upsurge in the deployment of WSNs, specifically in the irrigation management applications (Gutiérrez et al., 2014; Kim et al., 2011, 2009, 2008; Moghaddam et al., 2010; Erdem et al., 2010; Kim and Evans, 2009; Pierce and Elliott, 2008; Vellidis et al., 2008; Nemali and Iersel, 2006). This is mainly because of the importance of water in crop production (Postel, 1999; Bouwer, 2000; Saleth and Dinar, 2000; Jury and, 2007; Falloon and Betts, 2010; Mueller et al., 2012). In the following, we survey two such deployments as case studies.

□ *Case Study—San Jose del Cabo, Baja California Sur (BCS), Mexico:* Gutiérrez et al. (2014) described the development and deployment of an automated irrigation system comprising of a distributed WSN, a gateway, and remote server. The project was dedicated to implement a WSN system capable of reducing water use. The WSN consists of soil moisture and temperature sensors buried in ground for taking measurement in different depths. The gateway node has on-board facilities supporting both ZigBee (IEEE Standard for Information technology, 2006; Baronti et al., 2007; Guo et al., 2012) and GPRS communications. It is also empowered with intelligent decision making such as automated irrigation activation based on soil moisture and temperature values exceeding a certain predefined threshold value. The remote server is used for storing all the information, and displaying the information in a graphical user interface (GUI). The advantage of this application design is its real-time data analysis feature. The system components are explained in the following:

- *Wireless Sensor Units (WSUs):* Each WSU, deployed on-field, has four different type of components—application specific sensors, processing unit, radio transceiver, and battery power. Table 8 lists the details of each of the components (sensors and actuator devices) used in reference (Gutiérrez et al., 2014). For energy saving, the micro-controller often remains in the sleep mode. A solar panel is attached with each of the WSUs to recharge their batteries.
- *Wireless Information Unit (WIU):* The WIU acts as the master node, and collects information from the WSUs using the ZigBee technology. All the information received about soil moisture and temperature are compared with a predefined threshold values, and consequently, the pumps are activated for an estimated period. The received information and irrigation related data are saved in the attached solid state memory, and are transmitted to the remote server via GPRS using the Hypertext Transfer Protocol (HTTP). The pumps are driven by two electronic relays of 40-A, 12 V DC. The WIU can be commanded to changed the irrigation scheduling from the remote server, and is also equipped with a button to perform manual irrigation. Four different irrigation actions (IAs) are considered—manual irrigation, predefined irrigation, and automated irrigation with soil moisture of at least one sensor dropping below threshold, and automated irrigation with soil temperature of at least one sensor exceeding past the threshold.
- *Remote web server:* The server shows a specific GUI, which visualizes the data from each WSU, total water consumption, and IA type. The web application also enables the user with direct programming facility of the scheduled irrigation schemes, and changing the threshold values based on the crop type and season.

□ *Case Study—Smart Sensor Web:* The Smart Sensor Web (SSW) system proposed by Moghaddam et al. (2010) introduces a new technology for smart sensor web system measuring the surface-to-depth soil moisture profile of on-field sensors. The University of Michigan Matthaei Botanical Gardens in Ann Arbor, Michigan was chosen as the deployment region of the on-field sensors. The *in situ* sensors were deployed to model the spatio-temporal variations in soil moisture serving the future goal of enabling satellite observation of soil moisture. To minimize the overall cost and energy conservation, the authors plan to sparsely sample the sensor data.

The Sensor Web, is guided by the intelligence of a control system envisioned to determine an optimal sensor selection strategy to decide sensor configurations over time, and an estimation strategy based on the information of 3-dimensional soil moisture values. The problem of finding an optimal strategy and estimating a parameter are modelled using Partially Observed Markov Decision Process (POMDP) (Lovejoy, 1991). In a real deployment, multiple actuator nodes are placed with multiple sensors placed at different depths. One central coordinator node is deployed to schedule the data transmission events of the actuators. Upon receiving the readings from the *in situ* actuators, the central coordinator estimates the spatial variation of soil moisture. Then, the coordinator decides the time schedule of future measurements. In this manner, the coordinator node leverages the spatio-temporal correlation of soil

Table 9
Deployment parameters: Moghaddam et al. (2010).

Parameter	Value
Soil moisture sensor	ECH_2O EC-5 (http://www.decagon.com/)
ZigBee module	XBee-PRO ZB (http://www.digi.com/)
Photovoltaic cell	Solar panel 700-11347-00 (http://www.sundancesolar.com/)
System-on-chip	EM-250 (https://www.silabs.com/)
Electronic relay for pumps	12 V DC
Node battery	HR-4UTG (http://www.sanyo.com/)
Architecture	Multi-tier heterogeneous mesh
No. of nodes	30
Transmission range	⩽1600 m
Coordinator–server communication	3G

moisture, and optimally estimates with reduced number of measurements.

The system description is presented in the following.

- *Ripple 1 system:* The on-field sensor nodes, deployed at fixed locations, are equipped with 3–5 soil moisture probes. Communication between the nodes is done using the ZigBee technology built on the IEEE 802.15.4 standard. The nodes are classified into three categories—*coordinator*, *router*, and *end devices*. The specific node level parameters and sensors are listed in Table 9. The sensor nodes are powered with on-board batteries, and solar panels are also installed to recharge them. The coordinate node is attached to the base station computer.
- *Web server:* The base station updates the data to the server using 3G Internet connectivity. The 3G network card is installed on the base station. The server saves all the information, and any home/mobile user is able to visualize the information in real-time, thereby integrating the whole system from the *in situ* sensors to the remote user.

□ *Case Study—Alfalfa Crop Irrigation Cut-off System:* Saha et al. (2011) presented a automatic irrigation cut-off system targeted for eliminating tail water drainage in alfalfa crop. The work is based on Yolo silt loam soil on the UC Davis campus, California, USA, where alfalfa is the largest water consuming crop. Earlier, the flood-irrigation method was used for this crop. However, the water runoff reduces the efficiency of this method. Motivated by this problem, Saha et al. designed a wireless sensor based system which provides the irrigation information from the tail-end of the field. The realization of the system is done by applying a water advance model to the field deployment of wetting-front sensors couple with cellular communication. The irrigator farmer receives a SMS notifying the time to shutdown the irrigation system.

Fig. 6 depicts the application scenario showing the deployment. In the deployment area, 4 out of 48 alfalfa checks are selected for the experiment. Each check is of dimensions 220 m × 15 m with a slope of 0.01%. Wetting-front sensing system was placed at the tail-end of the field.

The system is very useful for a large-scale field with vast area for irrigation.

□ *Case Study—AMI Turf Irrigation System* (Aqua Management): This turf irrigation controller system designed by Aqua Management, Inc. is targeted for the turf irrigation industry to solve the problem of providing efficient water management solutions at an affordable price. It is a cloud-based control system, which considers various on-field parameters such as Evapotranspiration (ET), weather condition, water flow and leak. The application control can be accessed from any computer, tablet, or smartphone.

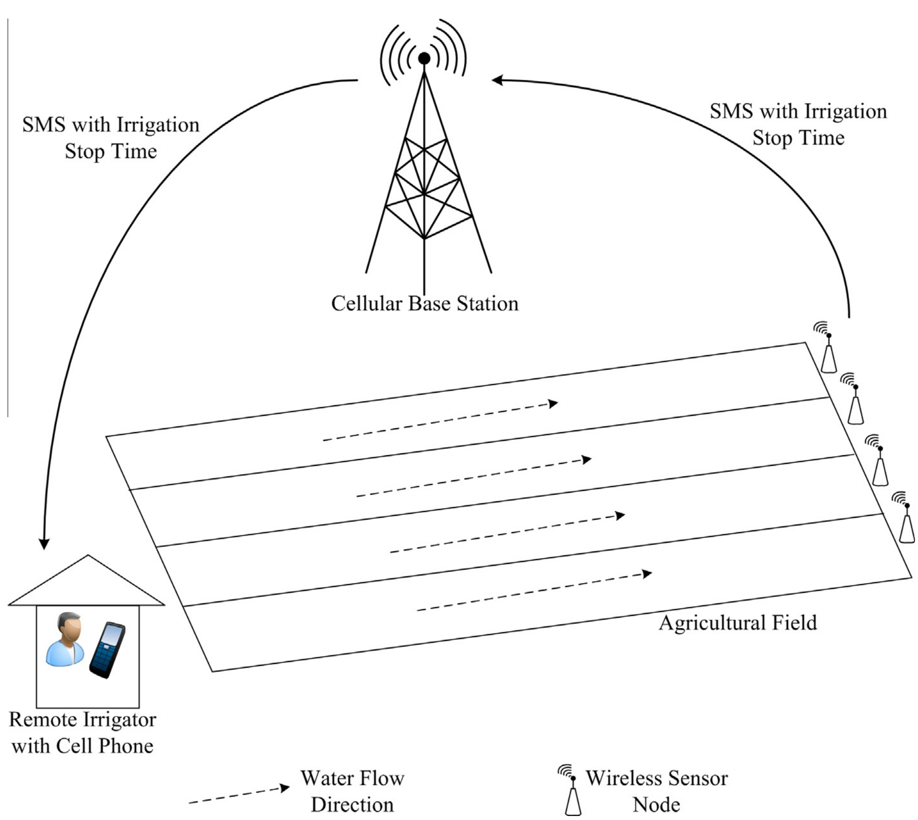


Fig. 6. The deployment of wireless sensor nodes for eliminating tail water drainage in alfalfa crop (Saha et al., 2011).

Table 10
Features: AMI turf irrigation system (Aqua Management).

Parameter	Value
Control capabilities	Central
User interaction	Using simple point and click
Remote programming	Available
Dynamic adjustments	ET and real-time weather based
Flow management	Available
Fault detection	Can detect leak
Alert notification	Automatic
Reaction to faults due to leak and weather related events	Automatic shut down

The features of this system are cataloged in Table 10. The automated decision making framework relies on the following components – local weather value, local ET values from public/private systems, and soil moisture sensors. Alternatively, the AMI data logger (AMI LoggerTM) can also be used to automate irrigation. The AMI Q collects all data from the on-field sensors and flow meters, and upload the information to the cloud.

Overall, irrigation management is based on the actual volume of water, rather than time. Based on the weather condition, irrigation can be stopped or started. The water management facility includes reporting of various analytics such as *water budgeting* on a daily, weekly, monthly, or annual basis.

5.1.2. Vineyard monitoring

Applying pervasive and mobile computing technologies in vineyard monitoring to increase the quality of production and reduce the production cost and the effect of crop related diseases. We review one of the existing works (Burrell et al., 2004) as a case study.

□ *Case Study—Vineyard Production Monitoring* (Díaz et al., 2011): Díaz et al. (2011) presented a design of a precision agricultural system for vineyard production monitoring. The deployment of WSNs help in estimate the variability in agricultural parameters throughout the field. Initially, in the first phase, the authors divide the subject terrain into few different zones (zone A, B, C) based on geographic, weather, and soil maps.

In the network planning phase, the most suitable architecture is chosen based on the application requirement. The subject area dimension was 600 m $\times$ 450 m, and different sensors were placed in different zones. For example, the authors assumed that zone C has temperature, humidity, soil moisture, luminosity, and pH level sensors deployed. In zones A and B, the environmental temperature, humidity and temperature, and luminosity sensors were deployed, respectively. The sensor nodes are assumed to have an transmission range of 75–100 m. The nodes in different zones form a virtual tree structure among themselves, and the sensed information reaches the gateway following a multi-hop path. The detailed deployment parameters are presented in Table 11.

Four types of nodes are considered in the design—*sensor*, *actuator*, *redundant nodes*, and a *gateway*. The sensors can only collect data samples, and information is routed to gateway. The actuator nodes have provision for driving irrigation systems. The actuators can also respond to the given commands about scheduling irrigation. The redundant nodes, as the name suggests, help in information routing, and imitate the functionalities of faulty nodes. The gateway acts as the bridge between the *in situ* network and the base station.

Table 11
Deployment parameters: Díaz et al. (2011).

Parameter	Value
Soil moisture sensor	ECH$_2$O EC-5 (http://www.decagon.com/)
Data acquisition board (zone A & C)	MDA300 (http://www.xbow.com/)
Data acquisition board (zone B)	MTS300 (http://www.xbow.com/)
ZigBee radio module	CC2420 (http://www.ti.com/)
Architecture	Multi-tier heterogeneous tree
No. of nodes	30
Transmission range	75–100 m
Inter-node communication	ZigBee, 2.4 GHz

Information routing is done to select the best neighbor node. The routing scheme can also be executed in an energy conserving manner, and in such a condition, the diagonally placed nodes are not selected for the next hop.

5.1.3. Precision farming

Precision farming is targeted to generate greater productivity with reduced costs. Wireless ad-hoc and sensor networks are utilized in precision farming to gather field data which can then be analyzed to find the best farming conditions.

□ *Case Study—Video Sensing in Precision Agriculture* (Cambra et al., 2015): Cambra et al. proposed video sensing for controlling fertilizer use in agricultural field. Their work is motivated by the objective of maintaining energy-efficiency with reduction of fertilizers in productions as defined Common Agricultural Policy (CAP) 2014/2020.[1] In this work, the AR drones are utilized to capture the video of the field. Based on the video input, a system identifies and geopositions the weeds present in the field. Finally, the fertilizer sprayer system is actuated based on the processed localized information of weeds in fields.

In Fig. 7, we depict the system overview showing the interaction between the AR drones, the central system, and the fertilizer sprays. The AR drones maps the field area in 2D/3D drag and drop waypoint maps. Here, the monitored field area was 17 m by 15 m. These drones form ad-hoc network among themselves and the central system. In this work, Optimized Link State Routing Protocol (OLSR) is applied to route the information from the field drones to the central system in real-time. Also, the drones and other devices are attached with on-board GPS, which enables updating the flight map and calculating the distance between the devices.

The video frames received from the flying drones are processed and geo-referenced in the central system. OpenCV[2] based platform is used to recognize the weeds in the field. In the image processing framework, the authors consider Multilayer Perceptron learning algorithm (Bradski and Kaehler, 2008) with the green and brown color lines which are seen in maize crops. Finally, the locations of the weeds in the field are transmitted to the fertilizer sprayers, which precisely apply fertilizers to the weeds. Thus, using this framework, the overall production efficiency enhances while keeping the fertilizer use at lower levels.

5.2. Indian scenario

5.2.1. Water management

□ *Case Study—Project COMMON-Sense Net* (Project Common Sense Net 2.0; Panchard et al., 2007): The COMMON-Sense Net project was a collaboration project with partners EPFL, Zurich (http://www.epfl.ch/) and the Centre for Electronic Design and Technology (CEDT) at the Indian Institute of Science (IISc) (http://www.cedt.iisc.ernet.in/). The goal of this project was to develop emerging technologies suitable for developing countries. The region of interest was chosen at Chennakeshavapura (CKPura) in the Tumkur district, Karnataka, India. To focus on the specific problems of the chosen region, the targeted goal was to predict and mitigate the effect of adverse environmental changes (Panchard, 2008).

[1] http://ec.europa.eu/agriculture/policy-perspectives/policy-briefs/05_en.pdf.
[2] http://opencv.org/.

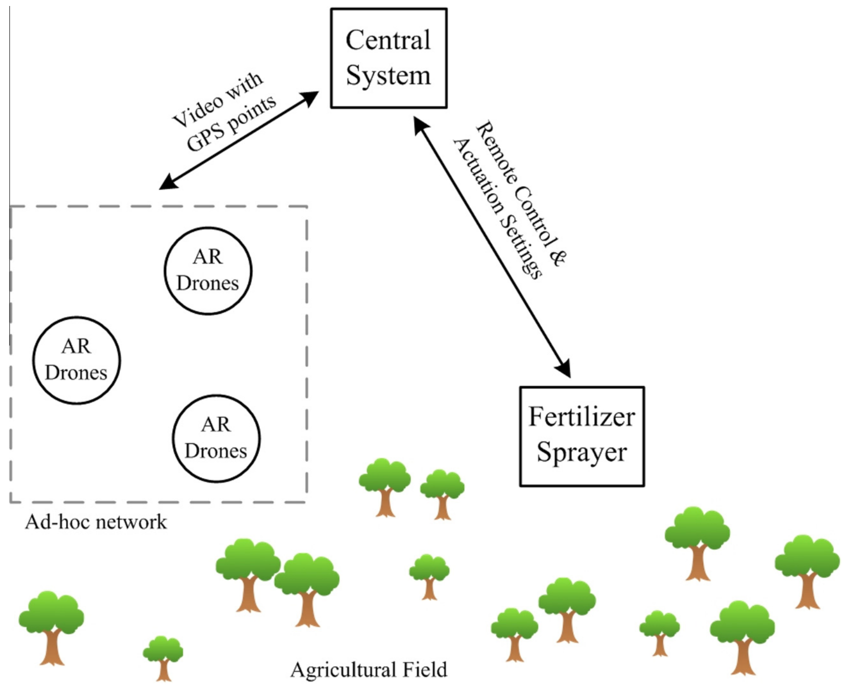


Fig. 7. System overview of video sensing based precision farming system (Cambra et al., 2015).

The actual deployment consists of 9 on-field and 3 backward nodes measuring soil moisture at two different depths of 150 cm and 30 cm. These nodes transmit their data to the base station every 15 min. The base station then transmits the data to the remote server over a GPRS link. In addition to soil moisture, environmental data such as ambient temperature and relative humidity, were also collected. The design of a water management system for deficit irrigation includes the following (Panchard et al., 2006; Prabhakar et al., 2007):

- *Calibration:* First, the soil moisture probes are calibrated using the standard gravimetric method (Reynolds, 1970; Schmugge et al., 1980; Dobriyal et al., 2012; Lekshmi et al., 2014). In the next normal mode, calibration is continued using a feedback loop based on the difference in measured and predicted values.
- *Alert:* Nodes are programmed to issue an alert whenever soil moisture reaches a certain value. The sensed data and historical climate data, together, help in predicting the change of rain in future.
- *Soil moisture prediction:* Real-time prediction of soil moisture is done using a learning method over the predicted and measured data.
- *Water requirements assessment:* The system is also able to estimate the amount of water needed for irrigation at that specific conditions.

The design parameters related to the COMMON-Sense Net project are listed in Table 12.

□ *Case Study—Lab-scale Irrigation Management at IIT Kharagpur, India:* Recently, IIT Kharapur started working on development of low-cost irrigation management system targeted for India. The lab-scale deployment of sensor network was carried out inside IIT Kharagpur campus, a place in the Kangsabati basin.

In this project, four ēKo Pro wireless sensor nodes were deployed over an area of 1440 m^2. Fig. 8 shows the real deployment in the lab-scale facility. Each on-field node embeds four EC-5 soil moisture sensors. In addition to the on-field nodes, another gateway node was placed in the vicinity of the field to receive all the on-field soil moisture data at an interval of 15 min. The gateway node is programmed to run *Crossbow's XServe network management* operations, and provides web services for remote viewing of data and network health. The gateway node also estimates the irrigation requirement of the field, and sends a SMS to the farmer informing this. The system has provision to control the number and recipient of SMS.

Table 12
Deployment parameters: COMMON-Sense Net.

Parameter	Value
Soil moisture sensor	ECH$_2$O EC-5 probes (http://www.decagon.com/)
Relative humidity	Sensirion SHT11 (http://www.sensirion.com/)
Ambient temperature	Sensirion SHT11 (http://www.sensirion.com/)
Ambient light	TAOS TSL2550D
Barometric pressure	Intersema MS5534AM
Architecture	Multi-tier Heterogeneous
Nodes	Mica2 and TinyNode (http://www.tinynode.com/)
Operating system	TinyOS
Transmission range	150–280 m
Packet interval	15 min
Base station – remote server communication	GPRS-based

The different procedural components are described below.

- *Calibration:* The soil moisture sensors are first calibrated using the standard gravimetric method.
- *Irrigation requirements assessment:* The on-field system calculates the amount of water needed for irrigation at that specific conditions. This estimation also depends on the duration between the last SMS update and current time.
- *Update to farmer:* Nodes are programmed to send SMS to the farmers with preprogrammed time and recipient phone number.

The design parameters are listed in Table 13.

Fig. 8. The on-field deployment of the ēKo Pro wireless sensor nodes in IIT Kharagpur lab facility.

Table 13
Deployment parameters: lab-scale irrigation management at IIT Kharagpur.

Parameter	Value
Soil moisture sensor	ECH_2O EC-5 probes (http://www.decagon.com/)
Architecture	Multi-tier
Nodes	eN2100
Radio module	eB2110 ēKo base radio (http://www.xbow.com/eko)
Transmission frequency	2.4 GHz
Transmission range	≈150–450 m
Packet interval	15 min
Base station – remote server communication	GPRS-based

Table 14
Deployment parameters: Sula vineyards (Shah et al., 2009).

Parameter	Value
Soil moisture sensor	ECH_2O EC-5 probes (http://www.decagon.com)
Soil temperature sensor	ECH0 (http://www.decagon.com)
Relative humidity	SHT1x
Ambient temperature	SHT1x
Architecture	Multi-tier Heterogeneous Grid
Transmission range	30 m
Packet interval	60 s
Base station – remote server communication	GPRS-based
Solar cell	Polycrystalline solar modules (6 V, 500 mA)

5.2.2. Precision farming

□ *Case Study—Vineyards Precision Farming:* One of the widely cultivated crops in India is the grapes. Precision farming is applied in this field to reduce the production cost and reach a high turnover. Also, the use of precision farming is justified by the economic value of grapes.

Precision farming in vineyards has to deal with three main issues—optimal water use, disease prediction, and controlled use of pesticides. In this regard, the soil and environment related parameters such as soil moisture, ambient temperature, leaf wetness, relative humidity are most important parameters for measurement. Soil moisture is the controlling factor for the crop production, size and quality of grapes. The quality of grapes and the wine produced from them depend on their size. The area of deployment, i.e., the *Sula vineyards*, Nashik, India, is limited in terms of water resources. Another problem in grapes is the use of pesticides to control diseases such as Downey mildew, Powdery mildew, Anthracnose (NRCG, 2007). Consequently, the overall cost increases, and the crop quality degrades due to the use of harmful chemicals. However, there is another way to reduce the use of pesticides—by predicting the disease. For this purpose, it is needed to integrate the measurement of leaf surface wetness and duration with the existing system of sensors.

Motivated by the above issues, Shah et al. (2009) designed a precision agriculture framework in the Sula vineyards at Nashik, Maharashtra, India. Initially, the lab-based small-scale setup was tested in a greenhouse at IIT Bombay, India with dimensions of 6 m × 9 m. On the other hand, the large-scale deployment at the Sula vineyards consists of wireless sensor nodes equipped with soil moisture, ambient temperature, relative humidity, and leaf wetness sensors. Table 14 lists the various system parameters considered in this project. Based on the on-field sensor data, the Evapotranspiration (ET) and Infection Index were computed.

5.2.3. Crop disease risk evaluation

Crop diseases are the root causes of production and revenue losses. The prediction of crop disease, and taking countermeasures to help farmers ensure sustained revenue generation.

□ *Case Study—Sula vineyards (*Das et al., 2009*):* Das et al. (2009) studied the forecasting of grapevine Downy Mildew disease (Francesca et al., 2006; Caffarra et al., 2012), one of the most common and important fungal diseases in grapes (Madden and Hughes, 1995; Rossi et al., 2010), by deploying a WSN powered with various agro-meteorological sensors. The Downy Mildew disease in grapes is caused by the Plasmapora Viticola virus, which is a weather-related disease. The prediction of such a disease benefits the grapevine industry tremendously—increased revenue with quality enriched food and beverage products. The deployed motes are equipped with ambient temperature, relative humidity, and leaf wetness duration (LWD) sensors. Two different existing models, i.e., the Logistic and Beta models, are adopted in the work (Das et al., 2009). The study was performed for over five months at the Sula Vineyards, Nashik, Maharashtra, India. Following the collected data, the "Infection Index" was computed in real-time using both the Logistic and Beta models.

□ *Case Study—AgriSense (*Tripathy et al., 2013a,b*):* The AgriSense distributed system comprises of wireless sensor nodes with environmental and soil-specific sensors – ambient temperature, relative humidity, leaf wetness, and soil moisture. The actual test-bed was chosen as one semi-arid tropic region located at the Agriculture Research Institute (ARI) of the ANGR Agricultural University, Hyderabad. The target mission was to predict the Bud Necrosis Virus (BNV) disease of groundnut crop. Experiments were executed using different settings of protected and weather-based protection plots with different dates of sowing treatments on three different replicas. The on-field deployment comprises of five MICAz motes with 25 m communication range, transmitting at an interval of 15 min. These nodes communicate among themselves using the ZigBee (IEEE 802.15.4) protocol at the 2.4 GHz RF ISM band. One gateway node sends the collected data to a remote server using GPRS communication.

The remote server converts the raw sensor data to a usable format and saves it in its database for displaying through the graphical user interface (GUI). Based on the data of soil and environmental parameters, various data mining models such as Expectation Maximization (EM), and Gaussian Naive Bayes (NB) classifier were used to predict the pest/disease dynamics. The schematic view of the real-time decision support system (DSS) is illustrated in Fig. 9.

5.3. Prospects and problems of the existing solutions

The existing solutions invent smarter applications for solving multiple challenges existing in the agricultural domain. We discuss

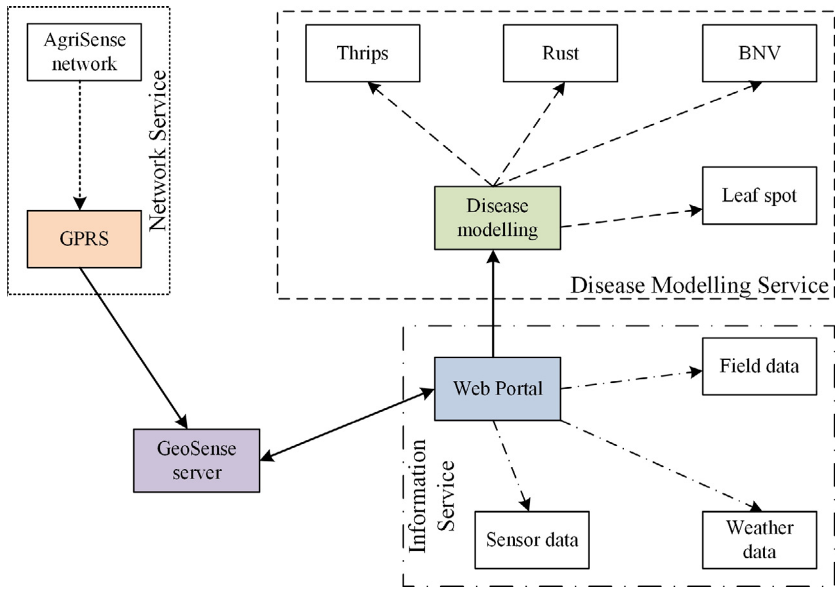


Fig. 9. The components of the real-time decision support system (DSS) used in AgriSense (Tripathy et al., 2013a,b).

the prospects of these application in the following. However, there remains scope to further improve the solutions. We list few points to improve the existing innovations.

- *Cost-effective solutions for LMICs are required:* The existing research and development efforts are targeted at the reduction of hardware and software costs, while maximizing the system output. The overall system cost increases due to the use of foreign imported devices to build the systems. However, for applications in LMICs, we need to reduce the system cost further. Thus, the challenge exist in bringing down the cost further.
- *Scalability of the deployments need to be tested:* For LMICs, we need planned and scaled-up deployment of such agricultural systems. In this way, the average system cost can be reduced down keeping the performance intact. Also, with increased scalability, we need to have design. For a large scale deployment, hierarchical architecture would perform better than the flat single-tier network architecture, as discussed in Section 3.1. For example, in Gutiérrez et al. (2014) and Moghaddam et al. (2010), the on-field WSN deployment in a specific area mostly follows the two-tier hierarchical network architecture with WSUs as end devices and WIUs as the gateway. This type of network architecture can be scaled up by replicating to multiple fields. In this setting, to increase the number of WSUs over a large deployment area, we have to place multiple WIU to provide connectivity to all the WSUs.
- *Fault tolerance:* Fault tolerance is a necessary feature of wireless sensor networks for achieving precision agriculture. Different types of faults (Baljak et al., 2012) that may occur in a WSN based precision agriculture system are – node failure due to depleted battery or any other reason, sensor hardware faults generating erroneous value, faulty sensor calibration, communication failure. In the existing literature, Gutiérrez et al. (2014) presented an irrigation management system which is fault tolerant to nodes (WSUs) and communication failure. In case of any fault, the system follows the default irrigation schedule. To reduce the chances of node failure due to energy depletion, (Gutiérrez et al., 2014; Díaz et al., 2011; Shah et al., 2009) have used solar powered nodes. Also, the topology management and data aggregation schemes should be fault tolerant in a large scale deployment.
- *Energy management and energy harvesting:* Energy management is an important issue in any WSN-based system. System components and algorithms should be designed keeping this issue in mind. Alternatively, the potential energy harvesting solutions such as solar power (Everlast Simjee and Chou, 2008), wind power (AmbiMax Park and Chou, 2006), biomass, and vibration should also be considered while designing WSN based precision agriculture systems. Among the existing works, solar powered WSNs (Gutiérrez et al., 2014; Díaz et al., 2011; Shah et al., 2009) are already in use. Therefore, the future works have scope of working on these non-conventional resource based WSNs.
- *Simplification of the existing solutions are needed:* The end-user of most of the targeted agricultural applications are the farmers. Thus, the designed platforms and solutions are envisioned to be simplified in terms of usability. In this regard, the human–computer interaction issues such as accessibility and usability are required to be taken care of.
- *The present works may further be improved for different climatic conditions, crop and soil types:* Most of the existing developments does not takes care of the real-time climate parameters. However, to enable precision, integration of the environmental parameters are necessary.

6. Future work direction

There are many potential applications of WSNs in the agriculture and farming area. The current state-of-the-art includes most works on irrigation management, vineyard production monitoring, and crop disease prediction.

6.1. Factors for improvement

The factors associated with WSNs that need further attention in the future are listed as follows.

- *Cost:* A low cost solution is always desirable for increasing the scope and outreach of the applications.
- *Autonomous operation:* The future solutions should include the provision for autonomous operations surviving for long time.
- *Intelligence:* An inherent intelligence, which will enable the futuristic solutions to react dynamically to multiple challenges – from conserving energy to real-time response.

- *Portability:* For easy of application, portability of the system is essential. Recent advances in embedded systems, such as System in package (SiP) and System on Chip (SoC) technologies will help in this regard.
- *Low maintenance:* It is essential to design a system which require minimum maintenance effort. This will certainly minimize the average cost in the long run.
- *Energy-efficiency:* To ensure extended lifetime with autonomous operation, the solutions need to be more energy-efficient by incorporating intelligent algorithms.
- *Robust architecture:* A robust and fault-tolerant architecture for the emerging applications is required to ensure sustained operation.
- *Ease of operation:* Typically, the end users of these applications are non-technical persons. Therefore, these applications need to be simple and easy to use.
- *Interoperability:* Interoperability between different components and different communication technologies will enhance the overall functionality of the system.

In addition to the global challenges, there are specific problems in Indian scenarios with respect to the agricultural WSN systems. We list few India specific challenges in the following.

- *Cost:* The high cost of the sensors and associated systems is the major deterrent for these applications in the LMICs.
- *Variable climate & soil:* The most challenging part in designing a WSN-based system for agriculture for India is the different temperature and soil types throughout the country. The application parameters are required to be tuned such as to function properly at different locations.
- *Segmented land structure:* Unlike the USA, India has partitioned farming land, a specific challenge which demands suitable deployment architecture for WSN-based agricultural applications like irrigation management.
- *Average farmer requirement:* In India, the average land holding per farmer is also lower than global scenario. Due to this, smaller and personalized systems are in demand.
- *Overall plan:* An overall planning, considering the segmented land structure and farmer requirement, is required for attaining success in bringing automation in agriculture and farming domain.

6.2. Futuristic applications

In recent times, with the advent of the new technical concepts such as sensor-cloud technology, big-data analytics, Internet of Things (IoT), new applications are envisioned. We briefly describe such concepts, and enlist a few potential futuristic applications in the following.

- *Sensor-cloud computing:* sensor-cloud computing refers to the on-field WSN applications empowered with cloud computing (Ojha et al., 2014; Alamri et al., 2013; Zhu et al., 2014). This integrated framework benefits the WSNs with improved processing power and storage capacity. Furthermore, sensor-cloud improves the data management and access control while increasing the resource utilization. Few potential application for the agricultural domain are,
  - A cloud-enabled storage of spatial variation of soil and environmental profile with respect to different seasons is need to be developed.
  - Crop health monitoring and yield prediction using mobile sensor-cloud services.
  - Designing a sensor-cloud controlled smart irrigation system for large fields.
  - To design a sensor-cloud operated environment control system for off-season production of vegetables and flowers in greenhouse farming.
- *Big-data analytics:* Big-data analytics techniques are applied to find meaningful insight from large volume of data with various data types (Kim et al., 2014; Nabrzyski et al., 2014). Big-data analytics based techniques are helpful for finding hidden correlations, unknown patterns, business trends, customer preferences, detecting crimes and disasters, etc. We list few big-data application for the agricultural domain as,
  - Building crop growth and disease management models based on farm data.
  - Designing a web-enabled analytics service for the farmers to provide improved information on agriculture.
  - Easy farming equipment control system for large-scale agriculture field.
  - Decision support service to improve crop productivity with optimal cost considering a large-scale contextual agricultural and climatic information.
  - Optimal policy determination based on data analytics for government and industries.
- *Internet of things:* IoT extends the ubiquitous computing concepts with heterogeneous smart devices or 'things' integrated with interoperable communication technologies (Atzori et al., 2010; Gubbi et al., 2013; Morais et al., 2008; Ye et al., 2013; Al-Fuqaha et al., 2015). The IoT paradigm defines 'things' which are capable of identifying, communicating and interacting with their surrounding. Empowered by these pillars, IoT provides flexible control mechanism for on-field parameters in real-time. Due to this, IoT is a potential solution for various agricultural applications. Few potential IoT-based agricultural applications are,
  - Cost-effective agricultural supply chain management using RFID tags.
  - Remote monitoring of animal movement in open pastures.
  - Automated pest counting and remote reporting in farms.
  - Remote control and scheduling of pesticide sprays at an user-defined rate and time.
  - Leak detection and remote water flow control in large-scale agricultural field water supply.

7. Conclusion

The inclusion of WSNs is envisioned to be useful for advancing the agricultural and farming industries by introducing new dimensions. In this survey, we present a comprehensive review of the state-of-the-art in WSN deployment for advanced agricultural applications. First, we introduced the variants of WSNs—the terrestrial WSNs and underground WSNs. Then, we highlighted various applications of WSNs, and their potential to solve various farming problems. The consecutive sections of this paper presented the network and node architectures of WSNs, the associated factors, and classification according to different applications. We review the various available wireless sensor nodes, and the different communication techniques followed by these nodes. Then, using case studies, we discussed the existing WSN deployments for different farming applications, globally and in India. Finally, we presented the prospects and problems associated with the existing applications. Finally, we listed several directions for future research with associated factors for improvement.

The survey of the existing works directs us in concluding few remarks. The current state-of-the-art offers WSN-based solutions for irrigation management, crop disease prediction, vineyard precision farming mostly. Simplified, low cost, and scalable systems are in demand, specifically for the LMICs. At the same time, with the advent of modern technologies, there exist a lot of scope for innovating new and efficient systems. Specifically, low cost solution with features like autonomous operation, low maintenance is in demand. Overall, futuristic pre-planning is required for the success of these applications specifically to overcome the problems in global as well as LMICs.

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