AgriSens: IoT-Based Dynamic Irrigation Scheduling System for Water Management of Irrigated Crops

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***Abstract*—In this paper, we present the design of an IoT-based dynamic irrigation scheduling system (AgriSens) for efficient water management of irrigated crop fields. The AgriSens provides real-time, automatic, dynamic as well as remote manual irrigation treatment for different growth phases of a crop's life cycle using Internet of Things. A low-cost water-level sensor is designed to measure the level of water present in a field. We propose an algorithm for automatic dynamic-cum-manual irrigation based on farmer requirements. The AgriSens has a farmer-friendly user interface, which provides field information to the farmers in a multi-modal manner — visual display, cell phone, and Web portal. It achieves significant results with respect to different performance metrics such as data validation, packet delivery ratio, energy consumption, and failure rate in various climatic conditions and with dynamic irrigation treatments. Experimental results show that the AgriSens helps improve the crop productivity by at most 10.21% over the traditional manual irrigation method, expands the network's lifetime 2.5 times more than the existing system yet achieving a reliability of 94% even after 500 hours of operation.**

***Index Terms*—Internet of Things (IoT), Water Management System, Irrigated Crop, Precision Agriculture, Smart Irrigation, Wireless Sensor Node.**

I. INTRODUCTION

WATER management of irrigated crops is one of the key parameters governing precision agriculture. Low irrigation in terms of water management and scheduling causes crop stress and ultimately reduces crop yield. Hence, there is a great demand for efficient irrigation that necessitates the availability of precise information about irrigation demand in near real-time. The goal of water saving and precise water management can be achieved using Internet of Things (IoT) [1], [2]. Indeed, using IoT, it is possible to achieve smart and intelligent connectivity of physical devices embedded with sensors, actuators, and network connectivity modules that exchange data among themselves, machines, and humans in a collaborative manner from anywhere and anytime [3]–[5]. Empowered by these features, IoT finds its major application in agricultural sector for irrigation management, greenhouse gases monitoring, and remote controlling. Thus, IoT has the potential for transforming agriculture, thereby increasing the crop productivity while enhancing the quality of production, by managing and controlling many activities used in the agriculture sector [2].

In the existing works, researchers [6]–[8] mostly focused on water saving methods for water management of irrigated field, with the help of automated irrigation system using wireless sensor networks (WSN), where the irrigation condition is a predefined static value for the entire crop duration. Specifically, a sprinkler-based irrigation system is [6], which is site-specific and variable rate, but is limited in its applicability to multiple crop fields. On the other hand, in the irrigation procedure proposed in [8], the whole field is irrigated with water even if the sensed value of any deployed sensor falls below a predefined threshold. The entire field may not require irrigation at that point.

In agriculture, every growing stage of a crop requires different irrigation treatments. This method of treating the crops is termed as dynamic irrigation, which is performed in terms of time schedule and volume of water [9]. In the case of paddy (rice) fields, for example, the growing cycle is divided into three growth stages: vegetative, reproductive, and maturity. These stages require different irrigation treatments which necessitates dynamic irrigation [9]. Additionally, remote manual irrigation is an add-on requirement in various cases such as climate change, crop health, and geographic area, which is based on farmer's experiential inputs. Existing works [6]–[8] focus on either automatic or manual irrigation. However the idea of proposing a complete system providing *automatic dynamic* as well as *remote manual* irrigation treatment in the different growing stages of a crop is still far-fetched. This motivates our AgriSens work.

In addition, there is a need for a versatile irrigation system for managing water in the heterogeneous crop fields (e.g., rice, sesame, and sweet corn), where each crop has different irrigation requirements. Apart from water management, farmer-field communication is also required for providing field information to the farmers in order to manage and control the field's on-going activities in real-time without going to the field. The existing works [6]–[8] did not address the provision of farmer-field interaction, remotely and conveniently. As agricultural applications totally depend on the farmer's activities, where farmers may lack expertise to use the current technologies, a simple solution is highly desirable from the farmer's point of view.

To address the above-mentioned issues, in this paper, we

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present the design of an IoT-based dynamic irrigation scheduling system (called AgriSens) for irrigated crop fields. In summary, the *contributions* of this paper are as follows.

1) We design a *real-time automated irrigation system* for crop fields using IoT.
2) We propose an *algorithm* for *automatic dynamic* irrigation treatments in the different phases of a crop's life cycle.
3) In addition to automatic irrigation, the proposed AgriSens system offers *manual irrigation*, *remotely*, which is based on the farmer experience or expert inputs.
4) We design a low-cost *water-level sensor* that generates discrete values according to the level of water present in a field.
5) AgriSens provides field information to the farmers in different ways, such as *visual display, cell phone, and Web portal* using General Packet Radio Service (GPRS)-enabled Light-Emitting Diode (LED) array and Liquid Crystal Display (LCD), Global System for Mobile communication (GSM) technology, and the Internet.

II. RELATED WORKS

This section summarizes existing works on manual and automatic water irrigation using advanced technologies, such as WSNs and IoTs, towards water saving and precision agriculture.

1) WSN-based Irrigation: With the advancement in WSNs, many studies [6]–[8], [10]–[12] have been carried out in the agriculture field to make farming operations more accurate and precise in real-time. In [7] an automatic irrigation system is proposed using WSNs for Jew's ear planting. The wireless sensor node, actuators, and weather station are directly connected to the portable controller using ZigBee. The authors only measure the relative temperature and humidity from the experimental field. The irrigation condition is considered based on two methods – manual and automatic. The farmers can manually irrigate their fields by pressing a button on the portable controller placed in the field. Automatic irrigation is based on the expert's input. Remote monitoring and controlling is not considered in this paper.

A lab-scale prototype of irrigation system using WSNs is proposed in [13] for precision irrigation. A graphical user interface using Java is developed for visualizing the field information. But the proposed system is dedicated to a field and is applicable to only a small field. On the other hand, Web-based irrigation systems using WSNs are proposed in [10] and [6]. The authors [10] use Web interfacing with WSNs and Raspberry Pi to control and monitor irrigation of the field, remotely. The irrigation pattern is scheduled on the basis of the soil moisture and soil temperature. In [6] a water saving irrigation system is proposed using a distributed WSN for the arid or semiarid area, where the proposed system does site specific and variable rate irrigation with the help of global positioning system and programmable logic controller. However, this system is not applicable to large-scale and/or multiple fields. As Bluetooth is used as a communication protocol between the sensor node and the base station, the system suffers from the problems of communication range of intra-band (max 10 m), a number of sensor nodes with a base station (max 7 slaves), energy consumption, and reconnectivity. Additionally, sprinklers are used as actuators to irrigate the field limiting its application to multiple crop fields.

In [8] a Web-based irrigation system is proposed using WSNs, where the authors used soil moisture and soil temperature sensor for water management. The proposed system irrigate the whole field when sensed value of a node falls below a predefined threshold. The entire field may not require irrigation at that point. The irrigation procedure is also not suitable for all types of crops. Furthermore, the proposed solution presents field information on the designed Web portal, which may not be suitable for farmers to monitor and control the system. Finally, the system suffers from flexibility and heterogeneity in terms of applications.

2) IoT-based Irrigation: In [14]–[16], IoT is applied to modernize the irrigation system in the agricultural fields. The authors in [14] designed a lab-scale prototype of an automated irrigation system using IoT. In this architecture, IP-enabled Wi-Fi is used for local communication between a sensor node and a central unit, and GSM is used for remote communication between the central unit and the administrator. However, in real life deployments, Internet-based Wi-Fi service may not be available in the remote agricultural field. To irrigate the field, the values of daylight, soil moisture, and water-level sensor are used. In addition, the proposed system sends an SMS alert to the administrator if water shortage arises in the main water supply.

In [15] is proposed an overview automated irrigation system of Cloud of Things, which is combination of IoT and CPS. This system uses thermal imaging technology to measure the irrigation temperature distribution of a field, which provides accurate irrigation scheduling. However, the proposed solution does not consider dynamic irrigation for different growth phases of a crop's life cycle. Similarly, in [16] is proposed a lab-scale prototype of an IoT-based irrigation system, which uses regression algorithm to determine the amount of water required for daily irrigation based on the collected sensor data of soil moisture, temperate, and rain drop sensors. In this system architecture, IP-enabled Wi-Fi is used for local communication between a sensor node and cloud server. However, in real life deployments, Internet-based Wi-Fi service may not be available in the remote agricultural field.

Synthesis: A critical analysis of the existing works reveals that there exists a research gap in automatic irrigation to meet dynamic irrigation treatments in a crop's life cycle. The existing works primarily focus on either automatic or manual irrigation with same level of water treatment in the entire crop session, and are mostly designed for a particular crop field. In this paper, we present an IoT-based irrigation system that provides real-time, automatic, dynamic as well as remote manual irrigation treatment for different growth phases of a crop's life cycle. Our system is applicable to heterogeneous crop fields and offers a farmer-friendly interface. This work led to an Indian patent filing (Filed No. 201731031610, on September 6, 2017).

III. THE AGRISENS ARCHITECTURE

In this section, we present the proposed AgriSens architecture as illustrated in Fig. 1. We follow the traditional conceptual architecture of WSNs, towards the architecture of IoT, in order to design the AgriSens proposed system.

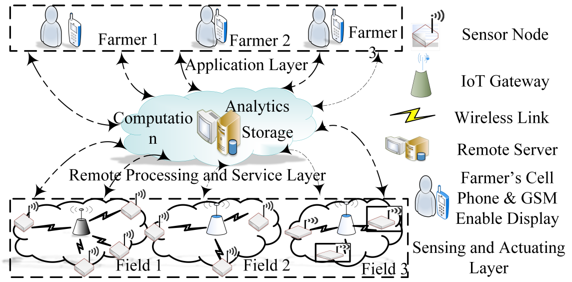


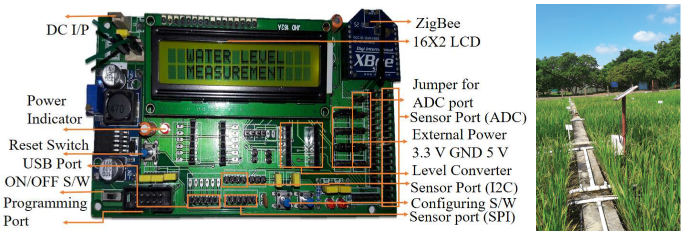
Fig. 1. Proposed AgriSens architecture

To generalize the system, let us consider M number of IoT gateways in the proposed architecture. Each IoT gateway $q \in M$ is equipped with N sensor nodes, where each sensor node $i \in N$ is equipped with K and L number of sensors and actuators, respectively.

1) Sensing and Actuating Layer: In this layer, sensor nodes are deployed in the field to sense the parameters of the environment and forward the data to the gateway nodes using ZigBee. The gateway nodes transmit the data to the remote server in the packet format of GPRS. ZigBee and GPRS provide the underlying communication of the IoT architecture to enable the integration and interconnection of physical and virtual things [17]. The sensing data are compared with the preset threshold values stored in *Electrically Erasable Programmable Read-Only Memory* (EEPROM) of the node. For any deviation from the threshold, the processor of the node will send a signal to the actuator connected to the node in order to activate the solenoid valve that irrigates the field on demand. The design details of the sensor node are presented in Section IV.

2) Remote Processing and Service Layer: This layer processes data as well as the requests coming from the top-most and bottom-most layers of the AgriSens. The remote processing layer provides an advantage of controlling operations in the field from a remote location. If there is a need for irrigating the field when a farmer requires, then this layer will be executed without the physical presence of the farmer in the field. The details of remote server is described in Section IV-4.

3) Application Layer: This layer is designed in such a way that a farmer can easily visualize the information and ongoing activities of the field. Farmers are provided with GSM capability that is used to send data to the farmer's cell, and GPRS-enabled LCD display and LED array indicator placed in the farmer's house to monitor their field information conveniently. Also, using the Internet, the farmers can access their field information through the Web server at any time. The farmers can also control the operations taking place in the field according to the requirement through GSM and the Internet.



(a) (b)

Fig. 2. (a) Designed sensor node. (b) Deployed sensor node.

IV. DESIGN OF AGRISENS

In this section, we present the design of our proposed AgriSens system, and also describe in detail different components such as sensor node, water-level sensor, IoT gateway, and remote server.

1) Integrated Design of Sensor Node: We design an in-house *energy-efficient*, *reliable*, and *low-cost* wireless sensor node, as shown in Fig. 2(a). The detailed pin diagram of the components of the designed sensor node is presented in Fig. 3, while describing the interfacing connection of different components with the processor of the node. LCD is only used for debugging the ongoing activities of the designed node, but not used in the experiments to minimize the energy consumption of the node as it is energy hungry component. More details of the sensor node is available in our published paper [18]. The practical deployment of the designed nodes in an agricultural field is shown in Fig. 2(b).

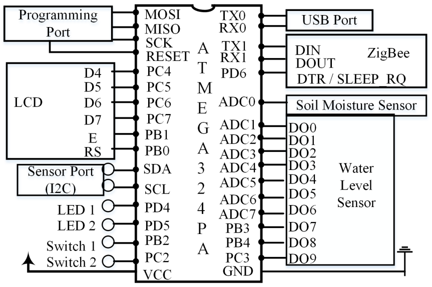
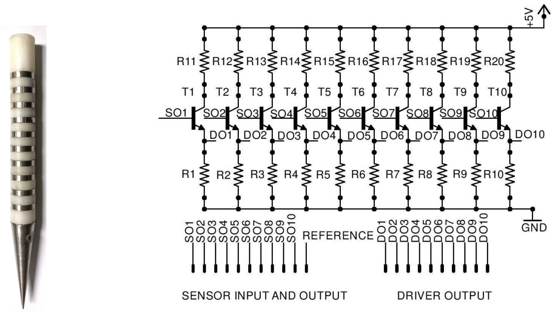


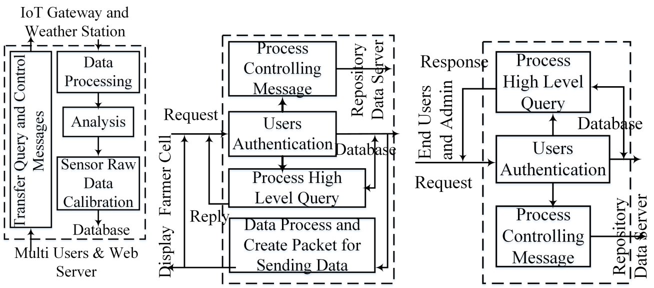
Fig. 3. Pin diagram of the proposed sensor node

2) Integrated Design of Sensors: In the AgriSens, we use two different types of sensors for water management of irrigated crops — soil moisture (EC-5) and water-level sensors. We design in-house a low-cost water-level sensor, which generates discrete value according to the level of water present in the field, as shown in Fig. 4(a). The simplest circuit to drive the water-level sensor is given in Fig. 4(b). This sensor measures maximum 10 cm water levels by using the electrical conductivity property of water. When water reaches a certain height, the corresponding transistor switches to the 'ON'state. The value of highest level, among all conducting levels, is taken into account and is the indication of the present value of water in the field. As the water-level sensor comprises of only a few components, it is very cheap and robust. The farmers can easily operate and install this device in their field.



(a) (b)

Fig. 4. (a) Designed water-level sensor. (b) Driver circuit of water-level sensor.



(a) (b) (c)

Fig. 5. Functional block diagram of different severs. (a) Repository data server. (b) Multi-user server. (c) Web server.

3) Integrated Design of IoT Gateway: The design of IoT gateway is based on the purpose of solving the need for data transmission using two different protocols, namely ZigBee and GPRS. Every gateway is given a unique user ID, which is randomly generated after sign up in the designed Website portal. We use rechargeable battery and solar panel in the power section of the gateway to ensure uninterrupted service.

4) Implementation of Remote Server: In our design, we develop three different types of servers such as Multi-user, Repository, and Web servers to serve different functionalities of the AgriSens. Java and *Java Server Pages* (JSP) are used for developing the remote server. The detailed functionalities of the remote server are presented in Section V-B2.

V. IMPLEMENTATION OF AGRISENS

We implemented and deployed AgriSens in two crop fields: Indian Institute of Technology Kharagpur's (IIT KGP) and Benapur's agriculture field, India. In this section, the field irrigation scheduling is described by dividing the whole management framework into two different categories: data sensing and aggregation, and data transmission.

A. Data Sensing and Aggregation

Let $S_{q,i,j}$ be the sensed data for sensor $j \in K$ of the node $i \in N$ under the IoT gateway $q \in M$ at T_{sens} time interval. Therefore, the total sensed data $S^{total}_{q,i,j}$ for time T_{send} is calculated as:

$$S^{total,t}_{q,i,j} = S^{total,(t-1)}_{q,i,j} + S_{q,i,j}, \quad \text{if } T = T_{sens} \qquad (1)$$

where T_{sens} and T_{send} are the sensing and sending time interval, respectively. T is the calculated time in minutes using the internal timer of the node.

B. Data Transmission

1) Localized Communication: We use ZigBee for establishing localized communication between the sensor node and the IoT gateway. *Time Division Multiple Access* protocol is used to make collision-free transmission among sensor nodes with the gateway. To make the system work efficiently and effectively, we put microcontroller of each sensor node in the active mode at all times. We assume that the energy consumption of the microcontroller is negligible. We only control the energy of the ZigBee module. By default, the ZigBee is in the sleep condition. When time T is equal to the sending time T_{send}, the node $i \in N$ activates the ZigBee and calculates the average value $S^{avg}_{q,i,j}$ for each sensor $j \in K$ in Equation (2).

$$S^{avg}_{q,i,j} = \frac{S^{total,t}_{q,i,j}}{C^{sens}_{q,i}}, \quad \text{if } T = T_{send} \qquad (2)$$

where $C^{sens}_{q,i}$ is the number of samples for T_{send}. The calculated average value is transmitted to the nearest gateway using the packet format of ZigBee. We discuss the actuation and control in Section V-C.

2) Remote Communication: The remote communication architecture of the AgriSens is implemented using three servers: (a) repository data server, (b) multi-user server, and (c) Web server.

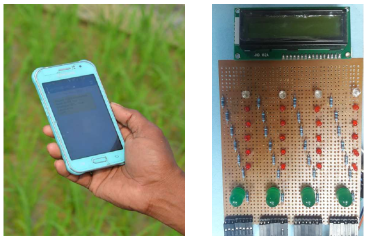
a) Repository Data Server: The gateway node from each monitoring area establishes a connection with the remote repository data server using GPRS. The overall functions performed by the repository data server are shown in Fig. 5(a). For data processing, the server extracts the meaningful information from the incoming packets and the sensed raw data is calibrated. As an example, we formulate a calibration equation for soil moisture sensor (EC-05), according to the type of soil used in our fields, as shown below:

$$S^{sens}_{q,i,j} = \xi \times S^{avg}_{q,i,j} - \delta \qquad (3)$$

where $S^{sens}_{q,i,j}$ is the percentage of soil moisture available in the soil. The values of ξ and δ (0.1087 and 50.059 respectively) are calculated using the curve-fitting method.

b) Multi-user Server: The working principle of this server is described in Fig. 5(b). To solve the data privacy issue, we introduce user authentication using cell phone number verification. If the farmer finds the data produced by a sensor to be irrelevant, they can control the node as well as the sensor by sending a control message to this server, remotely. The server is responsible for communication establishment with the farmer's cell phone through SMS. The LCD and LED displays are shown in Fig. 6, which are placed in the farmer's house, do the same using GPRS.

c) Web Server: We design a Web server using REST Web services. The working principle of the server is shown in Fig.5(c). A secret key is generated for every user in the sign-up phase, which is used to see the ongoing activities of their field



(a) (b)

Fig. 6. Information sending. (a) At cell phone. (b) At farmer house.

Sensor-Based Networking System for Improved Water Management of Irrigated Crops

Undertaken by SWAN Lab, Dept. of CSE & AGFE, IIT Kharagpur

Fig. 7. Screenshot of the AgriSens Website

in the Web-portal. Also, using the Web-portal, sensor nodes can be controlled, and the sensor data can be analyzed using statistical tools. The screenshot and Web address of AgriSens server is shown in Fig.7 and *agrisys.iitkgp.ac.in*, respectively.

C. Working Principle of AgriSens

The detailed working principle of each sensor node is presented in Algorithm 1, where we define dynamic irrigation conditions ($S^{act,th}_{p,q,i}$ and $S^{deact,th}_{p,q,i}$) with remote manual irrigation. $S^{act,th}_{q,i}$ and $S^{deact,th}_{q,i}$ are the solenoid activation and deactivation threshold values for the node, respectively. T_p is the duration of each phase. In each phase of the crop's lifecycle, the processor reads the particular irrigation condition from the predefined location of the EEPROM, where all irrigation conditions are stored. The proposed algorithms are written in *mikroC PRO for AVR compiler* [www.mikroe.com].

VI. AGRISENS SYSTEM RELIABILITY

The failure of the AgriSens can occur due to the failure of hardware, firmware, energy harvesting, and the network. The time to failure or life length (t) of a sensor node, IoT gateway, and server are random in nature due to the environmental ramification, network fallout, and unavailability of GSM signal. We characterize these random variables as exponentially distributed with mean $\lambda_{q,i}$, λ_q, and λ_s with value $m(\prod_{i=1}^{m} t_i)^{-1}$, where m is number of failures and t_i is the time to failure of the device. The failure cumulative distribution function of the sensor node ($F_{q,i}(t)$), IoT gateway ($F_q(t)$), and server ($F_s(t)$) at time t are:

$$F_{q,i}(t) = 1 - e^{-\lambda_{q,i} t} \quad (4) \qquad F_q(t) = 1 - e^{-\lambda_q t} \quad (5)$$

$$F_s(t) = 1 - e^{-\lambda_s t} \quad (6)$$

All sensor nodes N are parallelly connected to one another with the gateway $q \in M$ and are independent. Therefore, the total reliability of all sensor nodes N under the gateway $q \in M$ for period t is expressed as follows:

Algorithm 1 Algorithm for each sensor node $i \in N$

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INPUTS:
  $T_{sens}$, $T_{send}$, $S^{act,th}_{p,q,i}$, $S^{deact,th}_{p,q,i}$, $T_p$
OUTPUT:
  $P^{act}_{q,i}$, $S^{avg}_{q,i,j}$
PROCEDURE:
  $T_1, T_2, T_3, C^{sens}_{q,i} \leftarrow 0$;
  while (1) do
      Calculate time $T_1$, $T_2$, and $T_3$;                ▷ Using node timer
      Follow manual irrigation;
      if $T_1 = T_p$ then
          Read and update: $T_p$, $S^{act,th}_{p,q,i}$, and $S^{deact,th}_{p,q,i}$; $T_1 \leftarrow 0$;
      if $T_3 = T_{sens}$ then
          for $j = 1$ to $K$ do
              Calculate sensor data, $S_{q,i,j}$;              ▷ for each sensor
              Calculate $S^{total,t^{th}}_{q,i,j}$ from Equation (1);
          $C^{sens}_{q,i} \leftarrow C^{sens}_{q,i} + 1$;           ▷ Number of Samples
          $T_3 \leftarrow 0$;
      if $S_{q,i,j} <= S^{act,th}_{p,q,i}$ then
          Node active mode; Pump activation and Send information to gateway;
          Sensor node sleep mode; $P^{act}_{q,i} \leftarrow 1$;
      if $S_{q,i,j} >= S^{deact,th}_{p,q,i}$ and $P^{act}_{q,i} = 1$ then
          Sensor node active mode; Pump deactivation and Send information to gateway;
          Sensor node sleep mode; $P^{act}_{q,i} \leftarrow 0$;
      if $T_2 = T_{send}$ then
          Sensor node active mode;
          for $j = 1$ to $K$ do
              Calculate $S^{avg}_{q,i,j}$ from Equation (2);
              Send information to gateway;
          Sensor node sleep mode; $T_2 \leftarrow 0$;
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$$R^{'}_q(t) = 1 - \prod_{p=1}^{N} (1 - R_{q,p}(t)) \quad (7)$$

where $T_{q,i}$ and $R_{q,i}(t)$ are the time to failure and the reliability of the sensor node $i \in N$ under the IoT gateway $q \in M$, respectively. As each sensor node $i \in N$ under the IoT gateway $q \in M$ is serially connected with the IoT gateway $q \in M$, the total reliability of cluster $q \in M$ is $R^{''}_q(t) = R^{'}_q(t) R_q(t)$, where $R_q(t)$ is the reliability of IoT gateway $q \in M$. All clusters M are connected to each other in parallel and are independent of one another. The total reliability of all clusters is calculated as follows:

$$R_M(t) = \left(1 - \prod_{q=1}^{M} (1 - R^{''}_q(t))\right) \quad (8)$$

Further, each gateway $q \in M$ is serially connected with the server. Therefore, the total reliability of the AgriSens is expressed as follows:

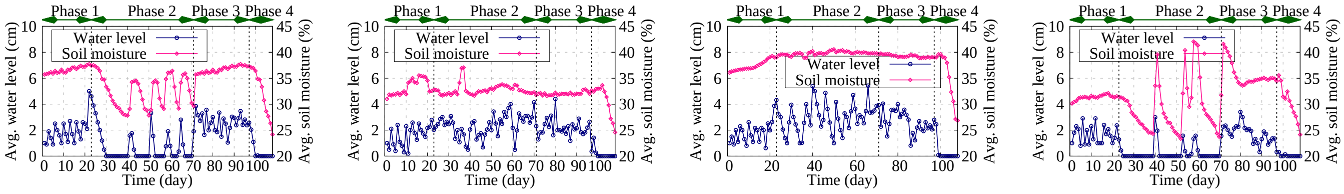
$$R_{sys}(t) = \left(1 - \prod_{q=1}^{M} \left(1 - \left(1 - \prod_{p=1}^{N} (1 - R_{q,p}(t))\right) R_q(t)\right)\right) R_s(t) \quad (9)$$

where $R_s(t)$ is the reliability of the server.

VII. PERFORMANCE EVALUATION

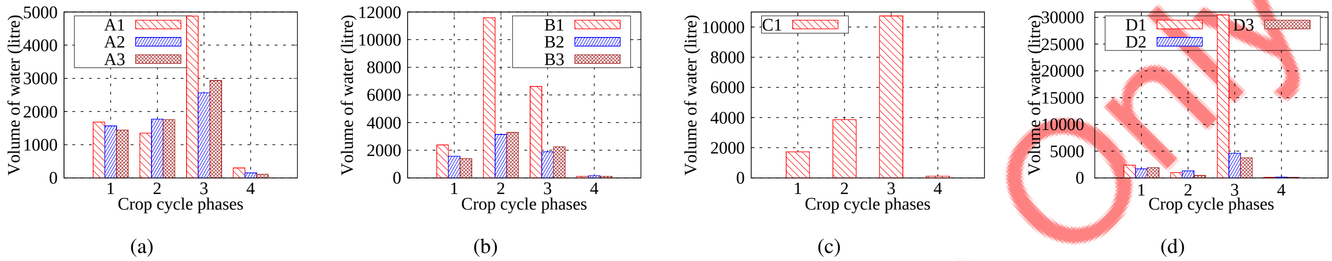
A. Experimental Setup

We experimented AgriSens in the paddy field from January 12, 2017 to April 29, 2017 at IIT KGP's field. The total experimental field is divided into ten equal subfields. Every automated irrigated subfield contains a sensor node and every



(a) (b) (c) (d)

Fig. 8. Soil moisture and water-level of different subfields. (a) Field A1. (b) Field B1. (c) Field C1. (d) Field D1.



(a) (b) (c) (d)

Fig. 9. Water consumption. (a) Treatment T1. (b) Treatment T2. (c) Treatment T3. (d) Treatment T4.

TABLE I
EXPERIMENTAL SETUP

Parameter		**Value**
Area of each subfield		$3X3\ m^2$
Number of sensor nodes		4
Sensing interval		1 min (water monitor.), 15 mins (climate monitor.)
Sending interval		10 mins (water monitor.), 2 hours (climate monitor.)
Intra-band com. range		60 m
Wireless protocols		*ZigBee* (*IEEE 802.15.4*) & *GPRS*
Date rate	*ZigBee*	250 kbps
	GPRS	9.6 kbps

TABLE II
TYPES OF IRRIGATION TREATMENTS CORRESPONDING TO THE DIFFERENT SUBFIELDS (HERE SN= SENSOR NODE)

Type of irrigation	Automated irrigated subfield (Corresponding SN ID)	Manual irrigated subfields
T1	A1 (SN ID 10)	A2 and A3
T2	B1 (SN ID 11)	B2 and B3
T3	C1 (SN ID 12)	—
T4	D1 (SN ID 13)	D2 and D3

node has one soil moisture sensor, one water level sensor, and one solenoid. The experimental setups for water management and climate monitoring is shown in Table I. The types of irrigation treatments for different subfields are shown in Table II. The dynamic irrigation treatment of the paddy's life cycle is discussed in Appendix A-A of the Supplementary file. We use different performance metrics for characterizing the performance of the AgriSens. In case of energy consumption, we consider three modes such as transmitting, receiving, and sleep. Table III presents the unique features and functionalities that differentiate AgriSens from the existing systems [10]–[12], [19]. From the table, we infer that the AgriSens offers greater flexibility, programmability, and versatility.

B. Results and Discussion

We show the effectiveness of automatic dynamic irrigation treatments and further, AgriSens's performance from the networking perspective is compared with the state-of-the-art WSN system developed by Srijon Microsystems (SM WSN) [19]. We use confidence interval (95%) to show the effectiveness of AgriSens.

1) Evaluation of Climatic Condition: Continuous monitoring of the climatic factors, which include rainfall, temperature, humidity, and wind, that affect the optimal growth of paddy for entire growing stages is shown in Appendix A-B.

2) Dynamic Irrigation Treatment: We used dynamic irrigation treatments of different subfields and followed two irrigation methods, i.e., always standing water (T2 and T3) and alternative dry and wet irrigation (T1 and T4).

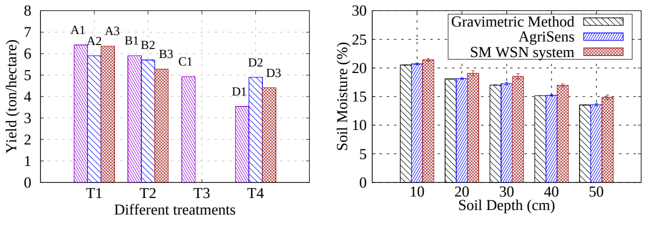
a) Dynamic Water Treatment: Fig. 8 shows the average water-level and soil moisture of subfields A1, B1, C1, and D1 in the different phases of the rice crop's life cycle. The total duration of crop's life-cycle is divided into four phases — Phases 1, 2, 3, and 4. In Phases 1 and 3, the treatment was always standing water for all subfields, which is shown in Fig. 8. In Phase 2, the treatment of A1 and D1 was *alternative dry* and *wet* irrigation, as shown in Figs. 8(a) and 8(d). On the other side, the treatment of B1 and C1 was standing water, as shown in Figs. 8(b) and 8(c). In Phase 4, there was no requirement of any irrigation for all these subfields. As water remains on top of the soil in Phases 1, 2, and 3, the average soil moisture is almost constant for the first 97 days for subfields B1 and C1. The data patterns of Fig. 8 show dynamic irrigation over traditional method, which follows a constant irrigation procedure for the entire crop duration.

b) Water Consumption: Fig. 9 shows water consumption of subfields A1, B1, C1, and D1 compared with the same treatment in manual irrigated subfields. Manually irrigated subfields are irrigated based on the sensor reading at a particular time of a day, which results in less water usage than auto irrigated subfields. Therefore, the rice crop of manual irrigated subfields is affected by water stress due to irregular water irrigation. However, if water usage is very high compared to

TABLE III
COMPARISON OF AGRISENS WITH OTHER SYSTEMS

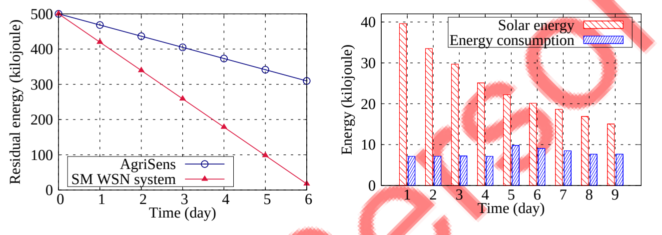
Features			AgriSens	SM WSN [19]	Tarange *et al.* [10]	Sales *et al.* [11]	Pfitseher *et al.* [12]
Sensor node		Multi sensors	Yes	Yes, but no of sensors fixed	No	Yes	No
		Actuator	Yes	Yes	No	Yes	Yes
		Support multiple comm. protocols	**Yes**	No	No	No	No
		Programmable	**Yes**	No	No	No	No
Communication protocols			ZigBee and GPRS	ZigBee and GPRS	ZigBee	ZigBee and GPRS	GPRS
Energy harvesting			**Yes**	Yes	No	No	No
Farmer-friendly interface	Remote monitoring	GSM	**Yes**	No	No	No	No
		Web server	Yes	Yes	Yes	Yes	Yes
	Remote controlling	GSM	**Yes**	No	No	No	No
		Web server	**Yes**	No	No	Yes	No
	Display unit	LCD	**Yes**	No	No	No	No
		LED	**Yes**	No	No	No	No
Applicable for heterogeneous crops			**Yes**	No	No	No	No

other automated irrigated subfields, as in case of subfield D1 shown in Fig. 9(d), it is due to water leakage which was not detected.



(a) (b)

Fig. 10. (a) Produced yield comparison of different subfields. (b) Soil moisture data accuracy



(a) (b)

Fig. 11. Energy consumption in different cases. (a) Remaining residual energy. (b) Energy balance.

c) Yield Comparison: Using automated irrigation, we achieve increased yield compared to the same treatment offered in manually irrigated subfields, as shown in Fig. 10(a). From the figure, it is also evident that the AgriSens helps the crop to produce increased yield by at most 10.21% over the traditional irrigation method. The positive affection of yield production is due to real-time water management of subfields A1, B1, and C1. However, due to water leakage, the yield production of subfield D1 is reduced compared to the subfields D2 and D3.

3) Soil Moisture Data Accuracy:

Fig. 10(b) shows the accuracy of the sensed data of the designed node, while comparing with SM WSN system and the standard gravimetric method [20]. The validation of the sensed data is presented in Appendix A-C. Fig. 10(b) signifies that the sensed data are almost the same as the actual soil moisture measured using gravimetry method, which indicates that the system generates accurate data. Also, the sensed data of the AgriSens are more accurate and consistent compared to the SM system. The reasons behind the system generating accurate data are the efficient circuit design and power stability of the node.

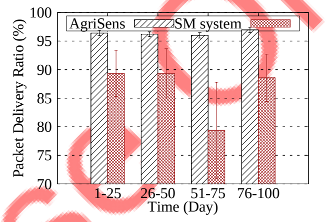


Fig. 12. Packet delivery ratio (PDR)

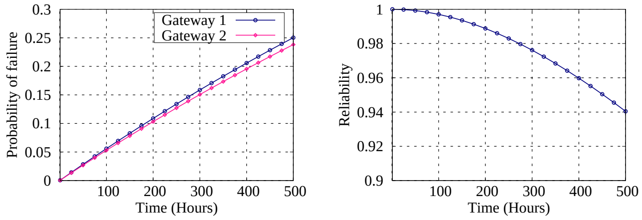
4) IoT Network Performance:

a) Energy Consumption: Fig. 11(a) shows the residual energy of the entire network compared to the SM system. The current consumption of the designed node in the sleep and active modes are 10 mA and 55 mA at 5 Volt, respectively. In this figure, it is shown that the AgriSens minimizes the energy consumption in the network significantly compared to the SM system, which, in turn, increases the network lifetime. This figure depicts that the lifetime of the SM system is 6 days, while the residual energy of the AgriSens is more than 61% even after 6 days. This indicates that the AgriSens expands the network's lifetime 2.5 times more than the existing system. However, it is noticeable that the reasons behind minimum energy consumption are three states and low-power dissipation of the sensor node.

b) Packet Delivery Ratio: Fig. 12 demonstrates that the AgriSens outperforms the SM system. The PDR of the AgriSens always lies between 95.53% and 97.42% due to the higher value of received signal strength indicator, and hence maintains consistency in respect of successful packets transmission to the destination. On the other hand, the PDR of the SM system is highly varying between 70.98% and 93.66%.

5) System Performance Analysis:

a) Energy Balance: Another experiment was performed to monitor the energy steady state condition of the designed sensor node, which represents that the energy consumption of the node is always less than the input energy harvested from the solar panel, which is shown in Fig. 11(b). From this figure, it is evident that even in adverse environmental conditions, the system gives uninterrupted service to the farmers.



(a) (b)

Fig. 13. (a) Failure probability of IoT gateway. (b) The reliability of AgriSens.

b) System Reliability: We evaluate the failure probability distribution and reliability of the sensor node, the IoT gateway, and the server during the experimentation time. During this time, the performance of the sensor node did not reduce, hence, the failure rate $\lambda_{q,i}$ is 0. Fig. 13(a) shows the failure probability of two IoT gateways, where the failure rate per hour $\lambda_{q,1}$ and $\lambda_{q,2}$ are 5.76×10^{-4} and 5.44×10^{-4}, respectively, as calculated in Section VI. In this figure, it is evident that although the failure probability of these gateways increases slowly, these are around 25% and 24% even after 500 hours, which is due to the low failure rate of the gateways. As the server is always in the 'ON' condition and there is no failure of the software, the failure rate of the server, λ_s, is 0. All these components' reliability values affect the overall system performance, which is shown in Fig. 13(b). The figure signifies that the AgriSens has high reliability even after 500 hours, which is around 94%.

6) Cost: The cost of each sensor node is approximately \$20 [18] and that of the water-level sensor is approximately \$4, which shows low-cost due to the requirement of the simplest circuits. Hence, the cost of AgriSens is effectively low.

VIII. CONCLUSION

In this paper, we proposed a real-time automated dynamic and manual irrigation system for heterogeneous crop fields using IoT. The AgriSens maintains dynamically irrigation treatments based on the requirements of different phases of a crop's life cycle, and also considers manual irrigation remotely based on the farmer or expert's inputs. From the experimental results, it is evident that the AgriSens is beneficial for efficient water management of heterogeneous crops, while improving the yield productivity by at most 10.21% over the traditional manual irrigation method, network performance, and system functionalities over the existing systems.

In future, we plan to analyze the effect of weather parameters like wind, humidity, temperature, and UV ray on the yield using machine learning.

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