

Sensing-cloud: Leveraging the Benefits for Agricultural Applications

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Abstract

The advent of the sensor-cloud framework empowers the traditional wireless sensor networks (WSNs) in terms of dynamic operation, management, storage, and security. In recent times, the sensor-cloud framework is applied to various real-world applications. In this paper, we highlight the benefits of using sensor-cloud framework for the efficient addressing of various agricultural problems. We address the specific challenges associated with designing a sensor-cloud system for agricultural applications. We also mathematically characterize the virtualization technique underlying the proposed sensor-cloud framework by considering the specific challenges. Furthermore, the energy optimization framework and duty scheduling to conserve energy in the sensor-cloud framework is presented. The existing works on sensor-cloud computing for agriculture does not specifically define the specific components associated with it. We categorize the distinct features of the proposed model and evaluated its applicability using various metrics. Simulation-based results show the justification for choosing the framework for agricultural applications.

Index Terms

Sensor-cloud, virtualization, system model of sensor-cloud, sensor-cloud for agricultural applications

I. INTRODUCTION

In precision agriculture, WSNs are used to address different problems (e.g. [1]–[4]). Some of the existing works in this domain with WSN applications are categorized into irrigation management [5]–[10], precision agriculture [11]–[15], farmland monitoring [16], [17], greenhouse gases monitoring [18]–[20], agricultural production process management [13], [21], optimization of plant growth [22], and security and intrusion detection in fields [23], [24]. However, these WSN-based applications primarily target serving single application only, on which WSN is deployed by the users only at their specific interest area. Consequently, only the users (generally the user organization) has access to the data, and, thereby, they are in sole charge of the maintenance of the network. Third party access to this information is generally not enabled in this framework. Alternatively, data sharing may happen between organizations with exchange of money.

In recent times, the sensor-cloud framework has become very popular in various application domains. Compared to traditional WSNs, sensor-cloud provides numerous advantages. The science behind cloud computing empowers the distributed WSNs for enhanced storage and information processing capability. The integrated framework also creates a virtualized platform of sensors, which facilitates efficient and real-time information sharing among multiple users. The virtualization technique also enables dynamic resource management, which, in turn, increases resource utilization. Due to the abstraction of computing resources and efficient access control techniques, the overall architecture also provides information security. All these features the sensor-cloud framework suitable for real-time decision support in multi-user, multi-application scenarios.

The initial works in sensor-cloud focused on defining the infrastructure and its components [25]. Over the recent years, the concept of sensor-cloud and its architecture has matured [26]. In one of the initial works, the concept of physical sensor and its services virtualization was proposed by Evensen *et al.* [27]. Later, Ibbotson *et al.* [28] presented a semantically rich service oriented architecture (SOA), which focuses on simplification of sensor service discovery. Recently, Misra *et al.* [29] presented a theoretical model of sensor-cloud, which mathematically formulates the underlying virtualization technique involved in this technology. The authors promoted the concept of Sensor-as-a-Service (Se-aaS) [29] and showed the benefits of the architecture in terms of cost effectiveness, lifetime of sensor nodes, and fault-tolerance. Madria *et al.* [30] present an architecture for sensor-cloud which define the different part of the protocol stack and interconnections with physical sensors as well as users. In this work, the authors envision the sensor-cloud protocol stack comprised of three vertical layers – *sensor-centric*, *middleware*, and the *client-centric*. The Agriculture Sensor-Cloud Infrastructure (ASCI) [31] shows how various agricultural services can be offered via the sensor-cloud platform. The ASCI framework also devises a layered architecture, which shows the integration of various deployed sensors with different services. Krintz *et al.* [32] proposes an open source, cloud-based agricultural analytics service named SmartFarm. This platform integrates various different technologies such as satellite imagery, weather predictions, and existing data sets with on-farm sensors. One major objective of this platform is to provide a cost-effective platform for data analytics ensuring data privacy.

52 A. Motivation

53 The sensor-cloud framework is strongly founded on the principle of virtualization. The cloud provides the facility for storage
 54 and retrieval of huge amount of sensed data. Using the virtualization concept, the service providers are empowered with the
 55 power of greater sensor utility, while maintaining information security. In this distributed framework, the sensor owner is
 56 responsible for the deployment of sensor nodes. The service provider takes care of the maintenance and deployment overhead
 57 for the deployed nodes. The end-users consume the sensed information through various services offered by the service providers.
 58 Thus, the users are relieved from the task of deployment, maintenance, redeployment, system up-gradation, and any such works.

59 In Figure 1, we depict the structural comparison of the architecture for WSN and sensor-cloud. In this figure, we depict
 60 that WSNs are envisioned to work with single user and single application. On the other hand, sensor-cloud provides a
 61 framework supporting multi-user and multi-applications. The end-users subscribe to these various services which are running
 62 as applications in the framework. Unlike the traditional WSNs, in sensor-cloud we can construct different access levels which
 63 ensures information safety for different levels of users.

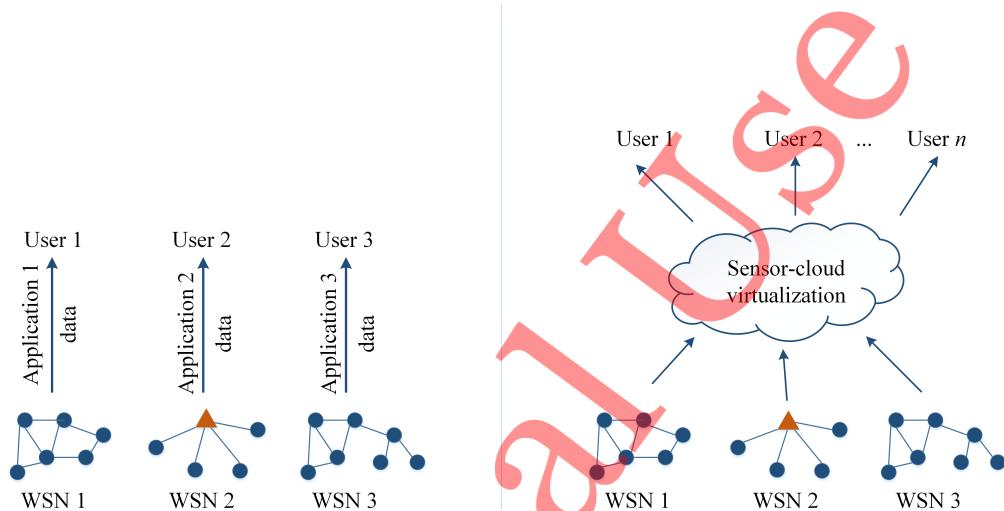


Fig. 1: Comparison of architectures: WSN vs sensor-cloud

64 In agricultural applications, this framework is very helpful due to its cost effectiveness and minimal maintenance requirements.
 65 The end-user, typically a farmer, has no burden of deploying and maintaining the field sensors unlike what would happen if
 66 they had used the conventional WSNs. From the service providers point-of-view as well, the sensor-cloud framework provides
 67 enhanced benefits. Unlike WSNs, in sensor-cloud, the service provider is able to utilize the deployed sensors for multiple
 68 applications and services. In turn, the service providing organization is able to provide the services to more number of people.
 69 The distributed framework also guarantees certain amount of fault-tolerance for the services. This is of great help specifically
 70 for agricultural applications, where sensor nodes face harsh climatic conditions leading to fault-proneness of the nodes. Thus,
 71 the sensor-cloud framework has the potential for leveraging benefits for both the end-users and service providers.

72 B. Contributions

73 In this paper, we present a sensor-cloud architecture for the agricultural applications. We present a mathematical model of
 74 sensor-cloud virtualization specifically targeting agricultural applications. The mathematical model includes details on different
 75 components involved in virtualization. Using case studies, we point out the specific benefits of this new framework over the
 76 existing WSN-based framework. Simulation-based results are presented for both these frameworks. In the following, we list
 77 the major contributions of our work.

- 78 • We present the physical node virtualization model for agricultural applications. Mathematically, we justify the advantages
 79 of the sensor-cloud framework over the traditional WSN-based framework.
- 80 • We formulate the sensor node utilization model targeting any agricultural application. The theoretical model presented in
 81 this paper focuses on building up a virtual sensor configuration, which enhances node utilization.
- 82 • We present a model for providing cost effective agricultural computing services to large number of farmers.
- 83 • The theoretical model depicted in this paper is suitable for a multi-organization, multi-user, and multi-application scenario.
 84 This is a significant paradigm-shift from the typical agricultural applications.

85 C. Organization

86 The paper is organized as follows. In Section II, we briefly discuss the existing literature in the area of sensor-cloud. The
 87 proposed system architecture is depicted in Section III highlighting the specific challenges and advantages of the sensor-cloud

framework in the agricultural domain. The energy consumption optimization and virtualization models are presented in Sections IV and V, respectively. We also discuss, in Section VI, two potential applications, as case studies, which can be offered using the sensor-cloud framework. In Section VII, the simulation-based results are presented and discussed. Finally, the paper concludes in Section VIII, citing direction for future works.

II. RELATED WORKS

Over the recent years, the concept of sensor-cloud has drawn lot of attention. A detailed survey of the sensor-cloud framework, applications, and its pros and cons is presented by Alamri *et al.* [26]. One of the initial works by Evensen *et al.* [27] proposed SenseWrap as a middleware for virtualizing any type of physical sensors. They also presented ZeroConf [27], a protocol which lets the applications programmers interact with the sensors without the need of knowing their physical configuration. In this work, the authors mainly focus on sensor abstraction to facilitate the discovery of services and devices using a common interface. However, the virtualization framework presented in this work does not look into various important issues such as security, resource access, and dependency management. Ibbotson *et al.* [28] presented the challenges of various sensor networks connected by heterogeneous communication infrastructures. The authors present a semantically rich service-oriented architecture (SOA) which simplifies the sensor discovery, access control, sensor data consumption, and utilization.

Yuriyama *et al.* [25] presented a detailed description of sensor-cloud infrastructure. This infrastructure enables the on-field sensors in a cloud framework to facilitate the virtualization of resources. Through this infrastructure, the deployed sensors can be accessed and controlled from the end-users' side. Liu *et al.* [33] described a sensor-cloud architecture, which is based on an extended architecture of the CloudMiner [34]. Liu *et al.* [33] envisioned this architecture to be a platform offering various computational, analytical, and storage services. Liu *et al.* [33] addressed the use of virtualization of sensors in the CloudMiner architecture to capture and process sensor data for enabling new applications, and consequently, providing various services that can be availed based on that.

Dynamic duty scheduling for minimizing the energy consumption of the sensor nodes in a sensor-cloud environment is presented in [35]. The authors propose an algorithm to dynamically select a optimal duty interval for each WSN irrespective of the others. Misra *et al.* [36] studied the problem of ensuring Quality of Service (QoS) in a mobile sensor-cloud environment. The authors show that, instead of bandwidth shifting, bandwidth redistribution is required to maintain QoS in such environment. [37] showed how to allocate sensors while maintaining QoS for target tracking applications in a sensor-cloud environment. In an another work, Misra *et al.* [29] presented a theoretical model of sensor-cloud. The authors mathematically define virtualization of sensors in the architecture, and thereafter, the framework is analyzed in detail with respect to various performance evaluation metrics. For virtualization within the sensor-cloud framework, an optimal composition of a virtual sensor and an adaptive data caching method was proposed by Chatterjee *et al.* in [38] and [39], respectively. Chatterjee *et al.* [40] studied the issue of optimal data center selection. A pricing model for the sensor-cloud framework was presented in [41].

Madria *et al.* [30] present a sensor-cloud architecture and described the different parts of the protocol stack. In this work, the protocol stack is divided into three vertical layers – *sensor-centric*, *middleware*, and the *client-centric*. The bottom layer is *sensor-centric*, and as the name suggests, this layer directly interacts with the physical sensors and takes care of the registration, maintenance, and data collection. The *middleware* layer is responsible for handling incoming requests, creating virtual sensors, and computing billing information. Lastly, the *client-centric* layer provides the user interface (UI), manages sessions, checks membership, and manages user repositories. However, this work considers only static sensors to be present in the framework. The integration of WSNs with Mobile Cloud Computing (MCC) was studied by Zhu *et al.* [42], [43]. The authors proposed two different schemes to increase the sensor data reliability in cloud and to minimize the energy consumption of the deployed sensors. In the first scheme, the WSN gateway selectively sends sensory data which is more meaningful to the cloud, by considering the time and priority of requested data. The other scheme is for the sensors to minimize their energy consumption by optimizing the sleep-wake schedule.

Kim *et al.* [31] proposed the architecture of Agriculture Sensor-Cloud Infrastructure (ASCI), which shows how various agricultural services can be offered via the sensor-cloud platform. The ASCI framework devises a layered architecture, which shows the integration of various deployed sensors with different services. Distefano *et al.* [44] argue on the benefits of the device-centric approach of IoT over the data-centric one. In their proposed IoT-A reference architecture, the Sensing-and-Actuation-as-a-Service (SAaaS) approach is presented. In this architecture, various sensors, mobiles and personal devices are abstracted through a unified platform. A smart, cloud-controlled irrigation management system was proposed by Sales *et al.* [45]. The field implementation consists of a set of sensors and actuators deployed for monitoring plants' water requirements. On the other hand, the cloud-based framework hosts a weather forecast application, which helps in making optimal irrigation decision. Whenever the on-field sensor system determines the soil moisture of the field to be lower than the threshold value, the next 6 hour's weather forecast is checked, and then the decision on whether or not to irrigated is made. An open source, cloud-based agricultural analytics service named SmartFarm was proposed by Krintz *et al.* [32]. This platform integrates various different technologies such as satellite imagery, weather predictions, and existing data sets with on-farm sensors. One major objective of this platform is to provide a cost-effective platform for data analytics ensuring data privacy. Additionally, the authors propose an app named RootRApp, which analyzes the SmartFarm sensor data to find the cause of wine grape quality difference.

III. PROPOSED SYSTEM ARCHITECTURE

In the sensor-cloud framework, we consider n number of on-field sensor networks (\mathcal{W}), which are deployed at different locations. For example, the set of all the on-field WSNs is represented by $\mathcal{W} = \{W_1, W_2, \dots, W_i, \dots, W_n\}$. In any such WSN, say $W_i \in \mathcal{W}$, the on-field sensor nodes and the gateway are denoted by S_i and G_i , respectively. The set of all the gateway nodes is denoted by \mathcal{G} . Any sensor node $j \in S_i$ communicate with the cloud through the gateway node G_i . Consequently, the sensor-cloud renders efficient and smart decisions based on the sensed data. We consider any on-field WSN to be represented by a graph $G(S_i, E)$, where S_i and E represent the set of sensor nodes in any WSN W_i and the set of communication links between the nodes. For example, in this graph G , node i and j are connected, e.g. $\overrightarrow{i,j} \in E$, iff $d_{ij} \leq r$, where r is the transmission range of nodes i and j . Here, we assume that the on-field nodes have similar transmission range. The on-field nodes $j \in S_i$ follow the duty values ($\tau_{i,t}^*$) computed by the cloud, and communicate their sensed information to the gateway G_i at specific times. The dynamic duty values are computed by sensor-cloud framework using the dynamic duty selection scheme discussed in Section IV.

We depict the system architecture in Figure 2. In this figure, we show how these n number of on-field WSNs communicate with the cloud via their local gateways. In each of these WSNs, actual topologies are formed by the deployment of sensor nodes at that area. The local topology can also support multi-hop communication between the sensor nodes and the gateway. Needless to say, the end-users are unaware of the actual topology and connectivity. They are able to monitor the information of the nodes, which are pertinent to their subscribed services. On the other hand, the sensor owners can access status/maintenance related information about their deployed nodes in various locations. In Section V, we present the detailed discussion on the components of each of these various entities and the relations among them.

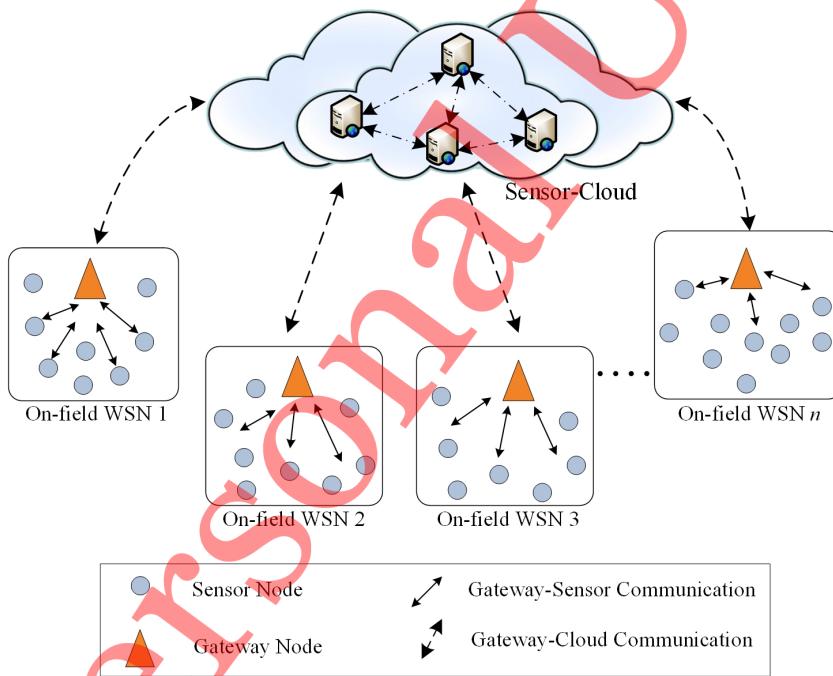


Fig. 2: The proposed system architecture

A. Challenges Specific to Agriculture

In this section, we list the challenges devising a sensor-cloud framework specific to agricultural applications. We also point out challenges specific to developing countries such as India.

- i. *Low maintenance*: The agricultural applications are desirable to have low maintenance effort. This will essentially keep the system's maintenance cost very low. Low maintenance is desirable in these systems due to the fact that a large number of end-users of these systems are typically non-technical persons.
- ii. *Scalability*: In agricultural applications, the monitoring area may cover a large area with multiple fields. Thus, it is desirable to have a scalable system with the change in target application area.
- iii. *Cost-effective solutions required*: The overall system cost is required to be low for larger scope and outreach of the applications. The challenge is to reduce the system cost targeting Low and Middle Income Countries (LMICs).
- iv. *Small and irregular land holding*: In developing countries such as India, the average land holding of a farmer is low, and the field shape is also irregular. Moreover, farmers may have non-contiguous fields allocated for them. Based on these, the field level heterogeneity is high for agricultural applications.

- 177 v. *Easy of operation*: The agricultural system and applications will be used by non-technical persons also. Thus, it is
 178 desirable to keep the operations and interactions with the system minimum.
- 179 vi. *Fault-tolerance*: Typically, the deployed systems in agricultural applications have to function in harsh environmental
 180 conditions, as they are deployed mostly at outdoor locations. Thus, tolerance against communication and other systemic
 181 failures are inevitable.

182 **B. Advantages of Sensor-cloud Architecture Over WSN**

- 183 In the following, we enlist the specific advantages of applying sensor-cloud architecture over the traditional WSN.
- 184 i. *Scalability*: Sensor-cloud architecture supports scalability of physical sensors with application/service demands. This
 185 architecture facilitates that the sensors can be accessed by multiple services and multiple users without any intervention.
- 186 ii. *Cost*: In sensor-cloud, the end-user is relieved from most of the cost incurring tasks such as sensor deployment,
 187 maintenance, and other overheads related to system up-gradation. However, he/she is only required to subscribe to
 188 services, and pay-as-per-use of the subscribed services. On the other hand, the service provider utilizes the deployed
 189 infrastructure by using it for multiple users and multiple services. Consequently, the services can be made cheaper for
 190 individual users while generating sustainable revenue for service providers.
- 191 iii. *Lifetime*: The advent of sensor-cloud provides optimal duty scheduling of the deployed sensor nodes. Due to this,
 192 the energy consumption of each sensor node can be reduced. Therefore, the overall network lifetime also increases
 193 significantly.
- 194 iv. *Reconfigurability*: Sensor-cloud provides multiple services to end-users. Based on the available services, the user can
 195 choose to switch applications, and virtually reconfigure the sensor nodes as per their demand.
- 196 v. *Fault-tolerance*: In WSNs, faults can occur randomly and can disrupt the network. However, in the sensor-cloud frame-
 197 work, the service provider provides fault-tolerance guarantees to end-users through service-level agreement (SLA). It is
 198 envisioned that sensor-cloud framework will bring in multiple service providers on a unique platform. Thus, the users
 199 will have option to choose and switch to different service providers with time.
- 200 vi. *Information Security*: Virtualization techniques enable the sensor-cloud to provide access control to users. It caters to the
 201 various layers of abstraction on the stored information and the physical sensors, thereby providing security to various
 202 levels of end-users.
- 203 vii. *Farmland Security*: Ensuring security of farmland and crop is an essential requirement for the agricultural applications.
 204 The sensor-cloud framework provides flexibility to add additional sensors or up-gradation of deployed system. Bapat *et*
 205 *al.* [46] presents a WSN-based system for detecting animal intruders and subsequently diverting them using deterring
 206 gadgets. Any existing sensor-cloud based deployment can be upgraded with installation such sensor nodes. Compared
 207 to the traditional WSNs, in the sensor-cloud architecture, the up-gradation procedure is simple and scalable. The service
 208 provider, thus, is able to provide additional services on security and intrusion detection after deployment of required
 209 sensors. Also, in case a field's data is contaminated, the abnormality in the recorded data can be detected by various
 210 existing anomaly detection techniques.
- 211 viii. *Quality of service (QoS)*: In a sensor-cloud, QoS guarantee is also defined through the use of SLAs. Thus, the end-users
 212 can choose and switch among different service providers.
- 213 ix. *Dynamic management*: The sensor-cloud framework facilitates dynamic resource sharing by applying the theory of
 214 resource abstraction [29], [36], [37]. Consequently, end-users are allowed to upgrade the service levels. Resources are
 215 dynamically allocated to services in synchronization with the change in the requirements.

216 **IV. ENERGY OPTIMIZATION AND DUTY CYCLE COMPUTATION**

217 In this section, we show and compare the energy consumption of typical on-field WSN and the sensor-cloud framework.
 218 We adopt the optimal duty scheduling approach proposed in our previous work [35]. Using this approach, the on-field sensor
 219 nodes, in a sensor-cloud framework, are able to optimize their energy consumption.

220 **A. Energy Consumption of On-field WSN**

221 In any on-field standalone WSN $W_i \in \mathcal{W}$ (i.e. without the cloud framework), the total energy consumption ($\mathcal{E}_{W_i}(t)$) at
 222 any time t caters to the following events – communication between the sensor node $j \in W_i$ and the gateway node $G_i \in W_i$
 223 ($\mathcal{E}_{s,g}(t)$) and computation and information processing inside the node ($\mathcal{E}_p(t)$). Thus,

$$\mathcal{E}_{W_i}(t) = \mathcal{E}_{s,g}(t) + \mathcal{E}_p(t) \quad (1)$$

224 The overall energy consumption during communication between the sensor nodes ($\forall j \in W_i$) to the gateway $G_i \in W_i$ is
 225 defined as,

$$\mathcal{E}_{s,g}(t) = \sum_{j \in W_i} \aleph_j^T(t) e_{s,g}^j \quad (2)$$

226 where $\mathbb{N}_j^\tau(t)$ is the sensed information by node $j \in W_i$ at time t for the time-interval τ . The entity τ is set by the gateway
 227 node $G_i \in W_i$ and its value is determined only on local observations. Any node j 's energy consumption for communication
 228 with the gateway node is denoted as $e_{s,g}^j$.

229 Similarly, the entity $\mathcal{E}_p(t)$ is computed as follows,

$$\mathcal{E}_p(t) = \sum_{j \in W_i} \mathbb{N}_j^\tau(t) e_p^j \quad (3)$$

230 where the energy consumption in node $j \in S_i$ for its own computation and information processing is e_p^j .
 231 Therefore, we can compute the total energy consumption of an on-field WSN W_i as follows:

$$\mathcal{E}_{W_i}(t) = \sum_{j \in W_i} \mathbb{N}_j^\tau(t) (e_{s,g}^j + e_p^j) \quad (4)$$

Thus, in an on-field WSN W_i , the optimization problem for overall energy consumption is expressed as follows,

$$\text{Minimize} \quad (5)$$

$$\mathcal{E}_{W_i}(t) = \sum_{j \in W_i} \mathbb{N}_j^\tau(t) (e_{s,g}^j + e_p^j)$$

subject to

$$e_{s,g}^j |_{\min} \leq e_{s,g}^j \quad (6)$$

$$e_p^j |_{\min} \leq e_p^j \quad (7)$$

$$\tau \leq \Gamma \quad (8)$$

232 Thus, finally, the overall energy consumption for the whole on-field WSNs is,

$$\mathcal{E}(t) = \sum_{W_i \in \mathcal{W}} \mathcal{E}_{W_i}(t) \quad (9)$$

233 B. Optimization of Energy Consumption in the Sensor-cloud Framework

On the other hand, in the sensor-cloud architecture, the energy optimization problem is formulated with the help of various components of energy consumption within the network. The three major components of total energy consumption ($\mathcal{E}_{W_i}^*(t)$) are – information uploading from sensor to gateway ($e_{s,g}^j$), gateway to cloud ($e_{g,c}^u$), and in-cloud processing (e_c^p). Therefore, in summary, the optimization problem is formulated as,

$$\text{Minimize} \quad (10)$$

$$\mathcal{E}_{W_i}^*(t) = \sum_{j \in W_i} \mathbb{N}_j^{\tau^*}(t) (e_{s,g}^j + e_{g,c}^u) + \sum_{j \in W_i} \bar{\mathbb{N}}_j^{\tau^*}(t) e_c^p$$

subject to

$$e_{s,g}^j |_{\min} \leq e_{s,g}^j \quad (11)$$

$$e_{g,c}^u |_{\min} \leq e_{g,c}^u \quad (12)$$

$$e_c^p |_{\min} \leq e_c^p \quad (13)$$

$$\bar{\mathbb{N}}_j^{\tau^*}(t) \subseteq \mathbb{N}_j^{\tau^*}(t) \quad (14)$$

$$\tau^* \leq \Gamma \quad (15)$$

234 where $\mathbb{N}_j^{\tau^*}(t)$ and $\bar{\mathbb{N}}_j^{\tau^*}(t)$ represents the information sensed by node j and the subset of the information at time t for an interval
 235 of τ^* . τ^* denote the value of optimal time-interval for any W_i at time t , and it can be expended as $\tau^* = \tau_{i,t}^*$.

236 We show the computation of overall energy consumption $\mathcal{E}^*(t)$ for all the on-field WSNs as follows,

$$\mathcal{E}^*(t) = \sum_{W_i \in \mathcal{W}} \mathcal{E}_{W_i}^*(t) \quad (16)$$

237 *C. Optimal Duty Scheduling*

238 The sensor-cloud framework collects the on-field information from the deployed sensor nodes at different intervals of time.
 239 It is noteworthy to mention that the time-interval of information collection is controlled by the sensor-cloud. The sensor-cloud
 240 framework can optimally decide on this parameter, and consequently, the energy consumption of the on-field WSNs can be
 241 minimized. In this regard, the following assumption is taken.

242 **Assumption 1.** For any deployed WSN W_i , the sensor-cloud framework calculates the required information update time-interval
 243 ($\tau_{i,t}$) from the received information [42].

244 The cloud-based framework computes the required time-interval $\tau_{i,t}$ for any on-field WSN W_i , as follows:

$$\tau_{i,t} = f(\mathbb{N}_t^*) \quad (17)$$

245 where \mathbb{N}_t^* represents the set of information collected by the cloud from the deployed sensor nodes at time t . \mathbb{N}_t^* is calculated
 246 using the following equation.

$$\mathbb{N}_t^* = \bigcup_{W_i \in \mathcal{W}} \mathbb{N}_i(t) \quad (18)$$

247 The optimal value of the time-interval in each step is computed with the help of time-interval determined at the t^{th} and
 248 $(t-1)^{th}$ instance. Mathematically,

$$\tau_{i,t}^* = \alpha_t \tau_{i,t} + \alpha_{t-1} \times \tau_{i,t-1}^* \quad \forall \alpha_t, \alpha_{t-1} \in [0, 1] \quad (19)$$

249 where $\tau_{i,t-1}^*$ is the value of optimal time-interval determined at the $(t-1)^{th}$ instance.

V. VIRTUALIZATION MODEL

250 In this section, we present the underlying virtualization model for the sensor-cloud framework targeting agricultural applications.
 251 We mathematically define the participating units of sensor virtualization. We define the units in two different types –
 252 *actors* and *entities*. The *actors* associated with the virtualization process are – the service providers, sensor owners, and the
 253 end-users. On the other hand, *entities* are the distinct components of virtualization related to sensors and services/applications.
 254 Thus, we define the different functions which represent the actual mapping between the different entities and actors.

255 *A. Actors*

256 We, in the following, mathematically define the components of different types of actors associated with the sensor-cloud framework.

257 **Definition 1.** In sensor-cloud, multiple service providers can coexist in the same framework. We name this actor as *Cloud Service Provider (CSP)*, defined as $CSP = \{CSP_1, CSP_2, \dots, CSP_\kappa\}$, where κ is the number of service providers.

258 In the following, we use the work ‘service provider’ and ‘cloud service provider’ interchangeably. CSPs are differentiated by their SLAs, which defines the critical service level parameters such as QoSs and fault-tolerance. Based on the region of deployment, which may be different sub-CSPs offering similar services.

259 **Definition 2.** Any CSP (CSP_i) is defined as a tuple with the following parameters:

$$CSP_i = < CSP_{id}, CSP_{type}, CSP_{zone}, CSP_\Phi, SLA_{type} > \quad (20)$$

260 where CSP_{id} is a unique identifier of the CSP and CSP_{type} indicates the type of the CSP – *national* or *regional*. CSP_{zone} holds the specific zone(s) the CSP is operating in. CSP_Φ denotes the set of services which are offered by this CSP and SLA_{type} is specific to the Service-level agreement between the CSP and the end-user.

261 **Definition 3.** A sensor owner is defined as $\theta_i \in \Theta = \{\theta_1, \theta_2, \dots, \theta_m\}$, where m is the number of owners registered at the
 262 sensor-cloud framework at any point of time. The associated parameters for a sensor owner are:

$$\theta_i = < \theta_{id}, \theta_{type}, \theta_{CSP}, \theta_\Phi > \quad (21)$$

263 where θ_{id} and θ_{type} are the sensor owner’s unique identifier and type, respectively. Similarly, θ_{CSP} and θ_Φ denote the CSPs and services associated with the sensor owner θ_i . Sometimes, a CSP organization may also deploy the sensor nodes, and thus, is recognized as a sensor owner.

264 **Definition 4.** The end-user is denoted as $U_i \in U = \{U_1, U_2, \dots, U_n\}$, where n is the number of users. End-user is a four-tuple actor defined as:

$$U_i = < U_{id}, U_{type}, U_{CSP}, U_\Phi > \quad (22)$$

265 where U_{id} and U_{type} are the user’s unique identifier and type, respectively. Similarly, the CSPs and services associated with the user U_i are denoted by U_{CSP} and U_Φ .

277 **B. Entities**

278 The different entities, which forms the essential components of the sensor-cloud framework are mathematically defined in
279 the following. In addition to the details about these components, we also discuss the inter-relation between them.

280

281 **Definition 5.** A physical sensor node $w_i \in W$ is defined as a tuple using the following parameters,

$$w_i = \langle w_{id}, w_{type}, w_{state}, w_{loc}, w_{\theta}, w_{CSP} \rangle \quad (23)$$

282 where w_{id} , w_{type} , w_{state} and w_{loc} denote the physical sensor's identifier, type, state, and deployment location respectively.
283 w_{θ} denotes the owner of the sensor. The set of CSP which has access to this sensor are denoted by w_{CSP} .

284 **Definition 6.** A virtual sensor $s_i \in S$ is defined as a tuple comprising of the following parameters:

$$s_i = \langle s_{id}, s_{type}, s_{state}, s_{loc}, s_{CSP}, s_{\phi}, s_{crop}, s_{\mathcal{A}}, s_{\chi} \rangle \quad (24)$$

285 where s_{id} , s_{type} and s_{state} denote the virtual sensor's identifier, type, and state, respectively. The location of the deployed
286 sensor is indicated by s_{loc} . The set of CSPs which has access to s_i is denoted by s_{CSP} , s_{ϕ} defines the services associated with
287 s_i , and s_{crop} refers to the set of the crops associated with the sensor s_i . The influence area of a deployed sensor is denoted
288 by $s_{\mathcal{A}}$. A sensor may also be used for deriving values for different types of sensors. In this case, s_{χ} denotes the set of the
289 possible derived sensors.

290 The virtual sensor id s_{id} for any particular sensor s_i is defined by the CSP. Therefore, for a specific CSP, s_{id} is unique.
291 Mathematically,

$$s_i.s_{id} \neq s_j.s_{id} \quad \forall s_i, s_j \in S; CSP_k \in CSP \quad (25)$$

292 **Definition 7.** A service $\phi \in \Phi$ is defined as:

$$\phi = \langle \phi_{id}, \phi_{type}, \phi_{\mathcal{S}}, \phi_{cov}, SLA_{\phi} \rangle \quad (26)$$

293 where ϕ_{id} and ϕ_{type} denote the service identifier and its type, respectively, and $\phi_{\mathcal{S}}$ represents the set of sensors for any
294 particular CSP attached with this service. For example, the virtual sensor s_i for CSP_k is defined as,

$$s_i \in \{CSP_k.CSP_{\Phi}.\phi_{\mathcal{S}}\}; \quad CSP_k \in CSP \quad (27)$$

295 **Definition 8.** The coverage of a service is defined as the total influence area ($s_{\mathcal{A}}$) covered by the sensors associated with the
296 service. Mathematically,

$$\phi_{cov} = \bigcup_{s_i} s_i.s_{\mathcal{A}} \quad \forall s_i \in \{CSP_k.CSP_{\Phi}.\phi_{\mathcal{S}}\}; CSP_k \in CSP \quad (28)$$

297 **Definition 9.** Service-level agreement (SLA) for any service $\phi \in \Phi$ is denoted by a tuple comprising of the following parameters:

$$SLA_{\phi} = \langle SLA_{id}, QoS_{th}, fault_{th}, \mathcal{R}(\cdot) \rangle \quad (29)$$

298 where \mathcal{R} denotes the access levels granted to the end-user. Thus, using this metric, we can clearly define the actors which
299 are given access to the service information at various levels.

300 **C. Functions**

301 In this process, the allowed sensor types are also checked while granting access to a certain service, and consequently, access
302 to the attached sensors. Any service has a specific set of sensors which are compatible with the service type, and thus, may
303 be attached with it. Furthermore, the access between the actors and the field sensors depends on the security levels i.e. access
304 levels defined in the SLA.

305

306 **Definition 10.** We define the relation between the set of sensor types (\mathbb{T}) and the service type (τ) using the Sensor-Service
307 Compatibility (S2C) function $\Gamma(\cdot)$. This compatibility check ensures proper filtering of the information for rightful access to
308 the actors.

$$\Gamma(\tau_i) = \{\mathbb{T}_i | \mathbb{T}_i \in \mathbb{T}; \tau_i = \phi_i.\phi_{type}\} \quad (30)$$

309 Here τ_i the service type of i^{th} service.

310

311 **Definition 11.** The ingress rules $\mathcal{R}(\cdot)$ which define the actors and the manner in which they gain access to the service related
312 information. Therefore,

$$\mathcal{R}(x_i) = \{s_i | s_i \in S; s_i.s_{\phi}.SLA_{\phi} \in SLA\} \quad x_i = \{CSP_i, \theta_i, U_i\} \quad (31)$$

313 where x_i denotes an actor, which may be CSP, sensor owner, or an end-user.

314

315 **Definition 12.** The mapping between a physical sensor and a virtual sensor is defined by the function $f_{p2v}(\cdot)$.

$$s_i = f_{p2v}(w_j) \quad s_i \in \mathcal{S}, w_i \in W \quad (32)$$

316 A physical sensor can be attached to multiple virtual sensors of different CSPs. On the other hand, a virtual sensor can also
317 be attached with multiple physical sensors.

318

319 **Definition 13.** The selection function $f_{sel}(\cdot)$ is defines the relation between a service and the concerned sensor nodes. For
320 any offered service, the concerned sensor nodes can be found using this function. Therefore,

$$\phi_S = f_{sel}(\phi_i) \quad \forall \phi_i \in \Phi, s_i \in S \quad (33)$$

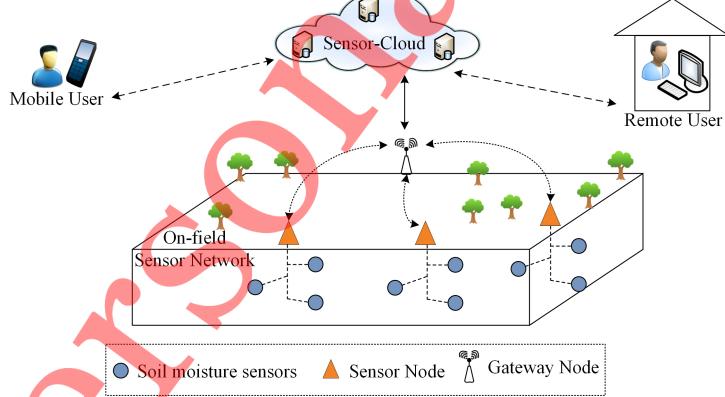
321 The function returns the set of concerned sensor nodes ϕ_S for service ϕ_i having a coverage of ϕ_{cov} . The concerned SLA
322 is defined by SLA_ϕ .

VI. CASE STUDIES – TYPICAL APPLICATIONS

324 In this section, we discuss two typical agricultural applications designed using the sensor-cloud framework.

A. Irrigation Management

325 Figure 3 shows a typical application of irrigation management using the sensor-cloud framework. In this application, the
326 on-field sensor network is deployed at the users' fields with application specific sensors. For example, water level sensors can
327 be used only for crops which require standing water, and soil moisture sensors for other cases. However, sometimes, both these
328 sensors can be present in the nodes helps the node to be reusable for different types of applications. It also empowers the
329 node to measure whether the field is water-logged or not in case of heavy rain. In such situation, actuation of water removing
330 pumps can be possible with the help of water-logging information. Optionally, the nodes can have soil temperature sensors,
331 ambient temperature and humidity sensors as well.



332 Fig. 3: Typical application scenario: irrigation management using sensor-cloud framework

333 In the sensor-cloud framework, these nodes are deployed by the service providers or sensor owners. The end-users subscribe
334 to the irrigation management service and access the on-field information. Thereby, they are able to monitor the change in field
335 conditions, and are able to control the irrigation schedule. In this framework, the micro-weather information is also taken into
336 consideration while determining the proper irrigation schedule [45].

B. Crop Disease Monitoring

337 Crop disease monitoring is a potential service that can help the farmers in taking counter measures against the crop diseases.
338 In Figure 4, we depict a example scenario of crop disease monitoring with on-field sensors and Unmanned Aerial Vehicles
339 (UAVs). The service offers dynamic monitoring of the crop disease. The UAVs (drones) are deployed for on-demand use
340 of pesticides at specific locations. Limited use of pesticides and fertilizers also enhances the crop quality, while keeping the
341 farming cost lower. In the cloud-based framework, the local climate related information [47] such as ambient temperature,
342 humidity, wind speed can also be included while taking decisions on crop disease. One recent work by Gonçalves *et al.*
343 studied the influence of mobility in precision spray based systems with WSN. In Ref. [48], UAVs are used for video sensing
344 in precision agriculture.

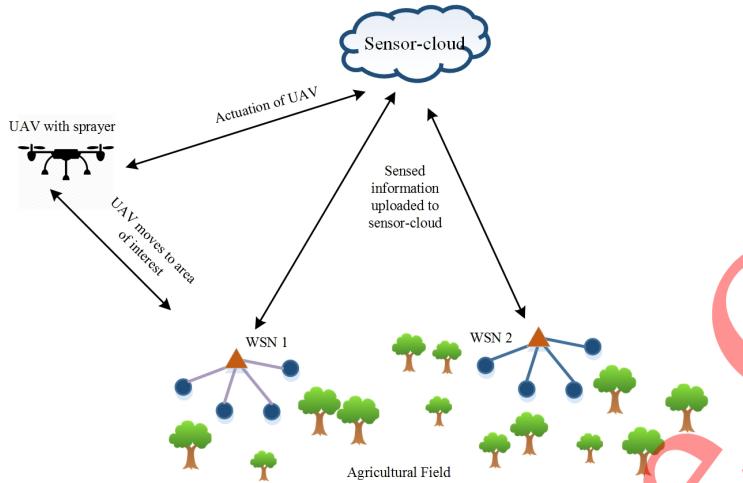


Fig. 4: Typical application scenario: crop disease monitoring using sensor-cloud framework

TABLE I: Simulation Parameters

Parameter	Value
Number of WSNs	10
Number of nodes in a WSN	50 - 100
Simulation Area	$10 \text{ Km} \times 10 \text{ Km}$
Transmission Range of a sensor node (r)	100 m
Initial energy of a node	200 J
Threshold battery level (W_{th})	25 J

346

VII. PERFORMANCE EVALUATION

347 A. Simulation Settings

348 To evaluate our proposed scheme, we perform simulations using the NS-3 (<http://www.nsnam.org/>) simulator (version: 3.14).
 349 Table I enlists the simulation parameters. We use different performance metrics and evaluate the results with respect to the
 350 metrics.

351 In the simulations, we simulated two different scenarios – traditional WSN (without the sensor-cloud framework) and the
 352 proposed sensor-cloud based framework. We considered a total of 10 different WSNs deployed in a field area spanning $10 \text{ Km} \times 10 \text{ Km}$.
 353 Each WSN consists of randomly 50–100 nodes. The nodes in any WSN send their data to cloud at ‘duty intervals’
 354 defined by the cloud. Accordingly, we calculate the energy consumption of the on-field WSNs, and compute the remaining
 355 lifetime of the WSNs. In our experiments, we considered the following unit cost values: $c_{depl} = 1$, $c_s = 2$, $c_{repr} = 0.3$, and
 356 $c_{sc} = 1$. We also considered 20% of the nodes to be faulty.

357 We simulate such a network keeping in mind the irrigation management application presented in Section VI-A. In the
 358 simulation based experiment, we considered 10 different WSNs deployed over a area of $10 \text{ Km} \times 10 \text{ Km}$. Here, each
 359 WSN consists of 50–100 nodes, on an average. For simplicity, we keep the simulated nodes to be homogeneous. This type of
 360 configuration mimics an irrigation management application where the sensor nodes are deployed at different fields covering
 361 a vast area. These sensor nodes communicate with the cloud via their local gateway. Thereafter, we performed dynamic duty
 362 scheduling for these WSNs and accordingly compute their network lifetime. We show the utility of sensor-cloud over the
 363 WSNs, and calculate the cost for end-users for both sensor-cloud framework and traditional approach.

364 B. Evaluation Metrics

365 We studied the performance of the proposed system model with respect to the following metrics:

- 366 • *Energy consumption*: The energy consumption of the deployed sensor nodes is computed for both traditional WSN and
 367 the sensor-cloud based framework. We define these entities in Sections IV-A and IV-B.
- 368 • *Duty*: In this work, duty is defined as the effective *active time* of a sensor node for a given period of time. In our
 369 simulations, the duty value for sensor-cloud framework is selected optimally, as explained in Section IV.
- 370 • *Network lifetime*: We define the network lifetime as in the percentage of nodes which has not yet depleted their battery
 371 or their battery level is greater than that of a predefined threshold level. Thus, the metric is evaluated as the percentage
 372 of alive nodes over time.
- 373 • *Utility*: Utility is defined as the *benefit* or *gain* achieved in proposed framework (\mathcal{U}_{cloud}) over the traditional framework
 374 (\mathcal{U}_{WSN}). We present the individual utility gain ($\mathcal{U}_{indv}(W_i)$) as well as the average utility gain ($\mathcal{U}_{ovAvg}(W_i)$) with different

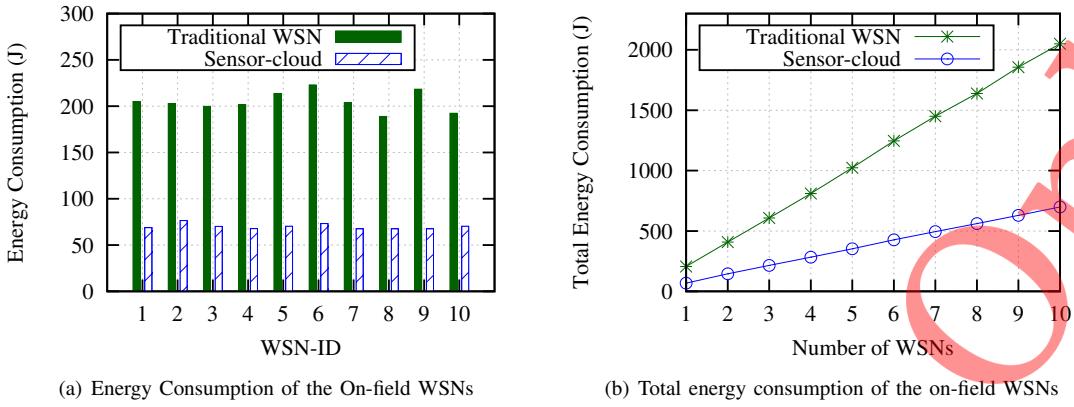


Fig. 5: Energy Consumption

number of WSNs. The individual utility reflects the utility gain of a specific WSN (e.g., W_i) in sensor-cloud framework over the traditional approach. On the other hand, average utility reflects the *overall* utility gain with multiple WSNs (e.g., W_1 to W_i) in a sensor-cloud framework over the traditional approach. Mathematically,

$$\mathcal{U}_{indv}(W_i) = \frac{\mathcal{U}_{cloud} - \mathcal{U}_{WSN}}{\mathcal{U}_{WSN}} \times 100\% \quad \forall W_i \in W$$

$$\mathcal{U}_{ovAvg}(W_i) = \frac{\sum_{W_1}^{W_i} \mathcal{U}_{cloud} - \sum_{W_1}^{W_i} \mathcal{U}_{WSN}}{\sum_{W_1}^{W_i} \mathcal{U}_{WSN}} \times 100\% \quad \forall W_i \in W$$

- *Cost:* We define the overall cost for the end-users in sensor-cloud (C_{SC}) and traditional WSN (C_{WSN}) as follows:

$$C_{SC} = n \times c_{sc} \quad \forall n \in \theta_i \cdot \theta_\Phi \cdot \phi_S; \forall \theta_i \in \Theta$$

where c_{sc} is the unit price per sensor allocated in the subscribed service.

$$C_{WSN} = n_1 \times (c_s + c_{depl} + c_{repr}) + n_2 \times c_{depl}$$

where c_s is the cost of each sensor, c_{depl} and c_{repr} are the cost of sensor deployment and repair, respectively, n_1 is the number of sensor nodes originally deployed, and n_2 is the number of faulty nodes, which are eventually replaced.

375 C. Results and Analysis

376 In the following, we present the simulation-based results for the traditional WSN and the sensor-cloud framework. We
377 compare and analyze the performance of both the framework with different performance metrics.

378 *1) Energy Consumption:* In this section, the results for the energy consumption for both traditional as well as sensor-cloud
379 scenarios are presented. Energy consumption for the individual on-field WSNs is presented in Figure 5(a). On the other hand,
380 Figure 5(b) shows the results for the different number of WSNs and the corresponding cumulative energy consumption. In
381 these scenarios, the energy consumption of the field nodes is controlled by the duty value selected for them. In the sensor-cloud
382 framework, as presented in Section IV, the duty value is selected optimally. The results presented in Figures 5(a) and 5(b)
383 indicate the the energy-efficiency of the sensor-cloud framework.

384 *2) Duty:* Figure 6 shows the duty values allocated to the on-field WSNs at different instants of time. These values are
385 computed by the cloud dynamically, and are consequently allocated to the deployed networks. It is noteworthy that the duty
386 values allocated to a WSN is fully independent of the duty values allocated to the other WSNs. This dynamic duty allocation
387 is particularly useful in optimal energy scheduling for the on-field networks. Accordingly, the energy consumption in the
388 sensor-cloud framework reduced over that of the traditional WSN based framework.

389 *3) Network Lifetime:* We present the results for the network lifetime of on-field WSNs for both the traditional and sensor-
390 cloud based frameworks in Figure 7. In this figure, the results for traditional approaches are marked as 'T-WSN' (which stands
391 for the acronym of Traditional WSN), and the results for the proposed sensor-cloud based framework are denoted by 'S-C'
392 (which stands for the acronym of Sensor-cloud). The figure depicts the results for all the deployed WSNs (e.g. 1-10). For
393 example, the on-field WSN is tagged with the legend 'WSN1'. The energy consumption of the on-field WSNs in the sensor-
394 cloud based framework is less than that of the traditional WSN based framework due to optimal duty scheduling. Also, unlike
395 the traditional WSN based framework, multi-hop routing is not required in the sensor-cloud based framework. Consequently,
396 the lifetime of the nodes in the on-field WSNs in the traditional approach depletes rapidly compared to the proposed approach.

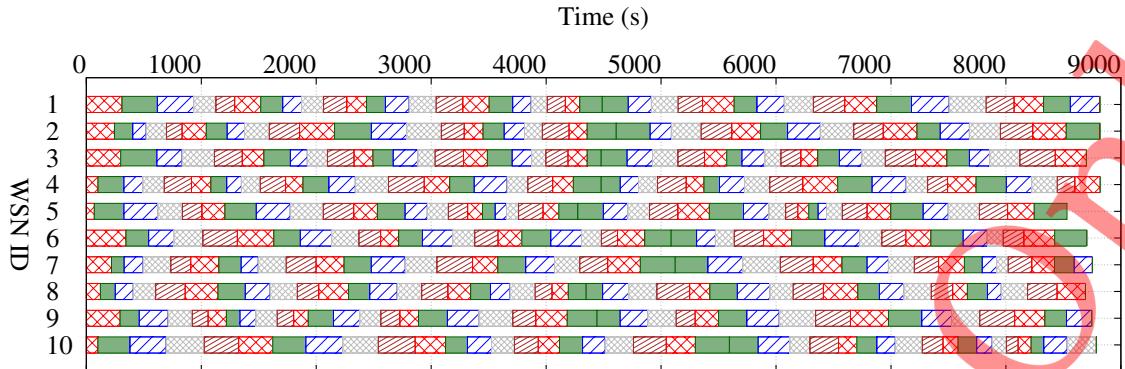


Fig. 6: Duty scheduling in the proposed scheme

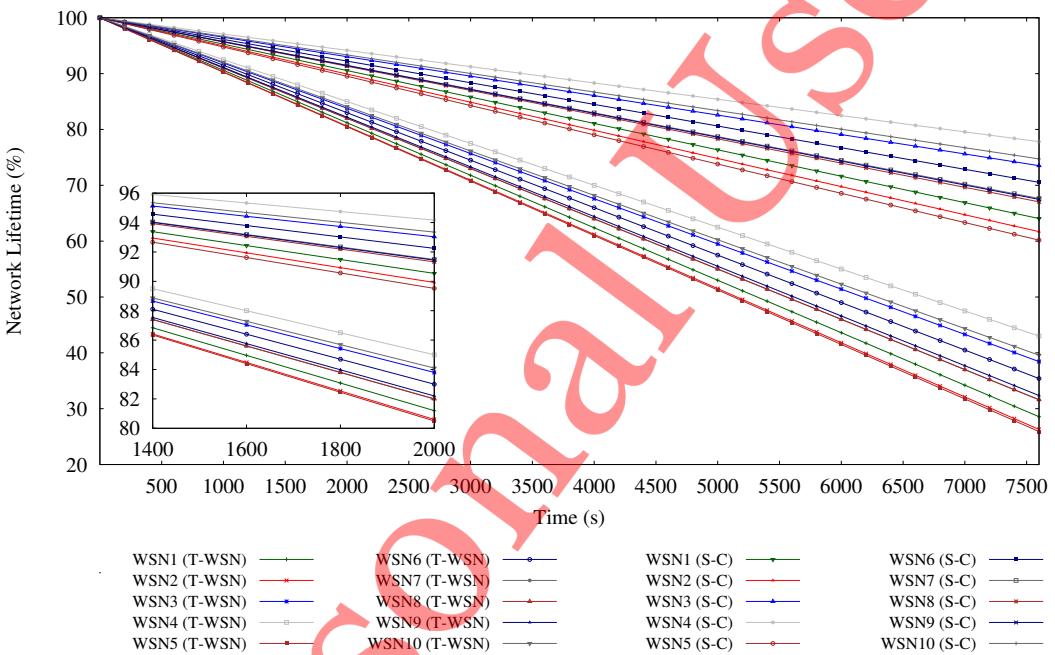


Fig. 7: Network lifetime for individual sensor networks with and without cloud

397 4) *Utility*: We present the utility of the proposed scheme over the traditional approach in Figure 8. We demonstrate the
 398 individual utility gain ($U_{indv}(W_i)$) as well as the average utility gain ($U_{ovAvg}(W_i)$) with different number of WSNs. The
 399 individual utility reflects the utility gain of that specific WSN (e.g., W_i) in the sensor-cloud framework over the traditional
 400 approach. On the other hand, the average utility reflects the *overall* utility gain with that many number of WSNs (e.g., W_1 to
 401 W_i) in sensor-cloud framework over the traditional approach. Therefore, when the number of WSN is 1, the individual and
 402 cumulative utilities are the same. However, sometimes the individual utility is greater than the cumulative utility, and the vice
 403 versa may also be possible. For example, for WSN id 7, the individual utility is greater than the cumulative utility, which
 404 refers to the situation that the other WSNs, with ids 1-6, have less utility than that of WSN id 7, and as result, the average
 405 utility is less than the individual utility gain. On the other hand, for WSN id 8, the opposite happens, and thus, the average
 406 utility gain is greater than the individual utility gain.

407 5) *Cost*: We analyze the cost incurred to any end-user in the sensor-cloud framework as well as in the traditional WSN
 408 based framework. In Figure 9(a), the cost incurred by the end-users in different WSNs is shown. The total cost with increasing
 409 number of on-field WSNs is plotted in Figure 9(b). The sensor-cloud remains cost-effective to the end-users, as they are only
 410 charged for their service access. The other expenditure incurred in the traditional framework, such as purchase, deployment
 411 and maintenance, are accounted for the service providers or the sensor owners.

412 From these figures, we also find that the total cost for each WSN remains nearly same for the sensor-cloud framework.
 413 However, for the WSN based traditional framework, various types of costs results in varying total cost for each WSNs. Also,
 414 from Figure 9(a), it is evident that for individual end-users, the incurred cost will be lower in sensor-cloud framework than

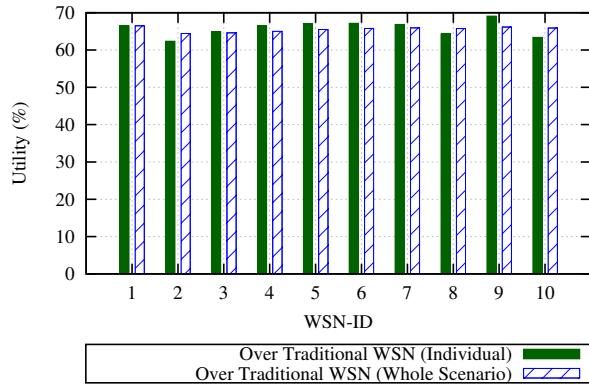


Fig. 8: Utility of the on-field WSNs

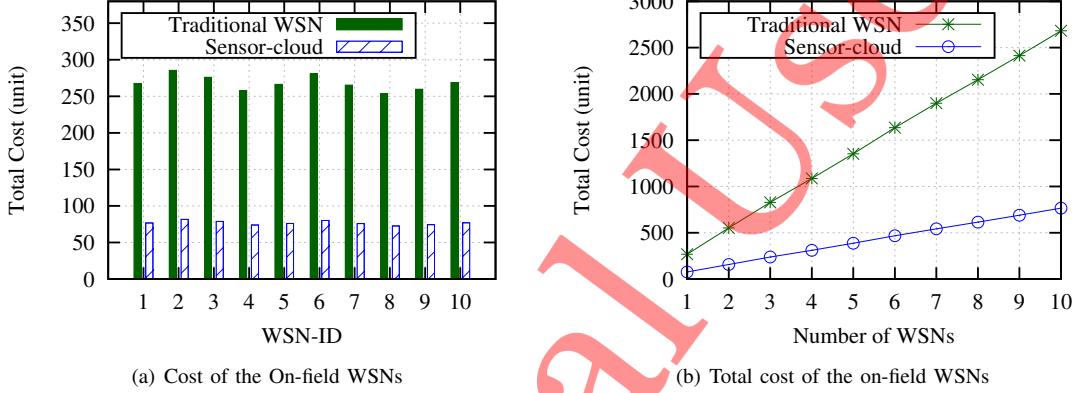


Fig. 9: Cost incurred for end-users

415 that of the traditional WSNs.

VIII. CONCLUSION

416 In this paper, we analyzed the benefits of using a sensor-cloud framework for efficient management of various agricultural
 417 applications. We discussed the specific challenges associated with designing a sensor-cloud system for agricultural applications.
 418 We mathematically devised the virtualization technique underlying the proposed sensor-cloud framework by considering specific
 419 challenges. Consequently, the energy optimization framework for sensor-cloud is presented and the duty scheduling to conserve
 420 energy in this framework is discussed. The existing works for sensor-cloud computing for agriculture does not specifically define
 421 the specific components associated with it. We present case studies of different applications as an example of the framework.
 422 Finally, with simulation-based results, we show the justification for choosing the framework for agricultural applications.
 423

424 In the future, we plan to extend the proposed framework for various other agricultural applications. Consequently, features
 425 related to mobility-aware dynamic service management are also required to be added in the framework.

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