Smart Irrigation Scheduling Algorithms and Deployment Scenarios: Challenges and Recommendations for Farming in the Sub-Saharan Africa

Supreme Ayewoh Okoh, Bala Alhaji Salihu, Suleiman Zubairu and Elizabeth N. Onwuka
Department of Telecommunication Engineering
Federal University of Technology
Minna, Nigeria
okoh.pg2012413@st.futminna.edu.ng, salbala@futminna.edu.ng, zubairman@futminna.edu.ng,
onwukaliz@futminna.edu.ng

Abstract

This paper buttresses the need for IoT-enabled agriculture, in order to tackle food insecurity globally, especially in the Sub-Saharan African (SSA) region where the global population rise is predicted to concentrate. It details the nitty-gritty involved in setting up a smart irrigation system and presents a systematic review of seven (7) scheduling algorithms used to drive smart irrigation systems. Analysis of the algorithms shows that they differ in terms of sensor inputs and level of precision. Recommendations were made in choosing a suitable algorithm and how the chosen algorithm can be deployed to withstand network connectivity problems. This paper also proposes a community Internet of Things (IoT) network to deploy smart irrigation systems and other applications of IoT-enabled agriculture, in rural areas among smallholder farmers. This is to mitigate the challenges that are likely to discourage farmers especially those in the SSA from embracing the technology.

Keywords

Smart irrigation system, scheduling algorithm, internet of things, Sub-Sahara Africa, agriculture

1. Introduction

The Internet of things (IoT) has provided us with a brilliant way of interacting with physical systems remotely via wireless sensor networks and internet technology. With IoT, the behavior of physical systems can be monitored and controlled seamlessly, and the data harnessed from sensors can be used to model physical systems, make predictions and automate processes. IoT is rapidly revolutionizing the fields of precision agriculture, control, data science, artificial intelligence, etc. Precision agriculture, for example, is leveraging on the technology to supply just the required input needed for healthy plant growth and productivity. IoT for agriculture is presently being used to measure several agricultural variables such as plant growth, rainfall, soil moisture, temperature, PH, humidity, airflow, motion in a farm, soil dielectric constant, mechanical resistance, electrochemical properties of soil, solar radiation, etc. Data gathered from sensors are mined and used for soil erosion control, disease diagnosis of plants and animals, fertilizer application, field monitoring, crop yield analysis, smart irrigation application, etc.

Irrigation is an age-long practice that is adopted to ensure continuous cropping irrespective of seasonal changes, so that food production can always meet demand. The global population rise predicted by the United Nations (UN) Department of Economic and Social Affairs(UN, 2019) is yet an omen that is drawing serious attention to methods and practices that can be used to boost agricultural throughput and ascertain food security in the nations. Presently, research on the use of IoT-enabled irrigation systems is gaining attention. Smart irrigation system powered by IoT promises better crop yield, water conservation and reduces labor while also making irrigation practice germane and attractive to farmers.

What makes an irrigation system smart is the algorithm that drives it. Designing computationally efficient, cost-efficient, and high precision algorithm for optimum crop yield is a research concern in precision agriculture. In the SSA, the major concern is how to drive the technology among smallholder farmers who produce over 80% of the food(Sirimanne, 2017; Swiss Agency for Development and Cooperation (SDC): Strategy 2017 – 2020, Global

Programme Food Security, edited by Federal Department of Foreign Affairs FDFA, n.d.). In order to truly ensure food security, and promote inclusive IoT-enabled agriculture, measures must be taken both in the design and deployment of IoT systems to apprehend the possible issues of resistance to the technology among farmers. This paper presents recommendations in this regard.

The rest of the paper is arranged thus: sub-section 1.1 presents the objectives of this study, section 2 examines the various components needed in setting up a smart irrigation system, section 3 analyzes seven (7) irrigation algorithms which are: Water balance technique with Penman-Montieth equations (WB-PM), water balance with Hargreaves equation (WB-H), only Soil Moisture control (SM), Water Balance plus Soil Moisture feedback control (WB+SM), Time-Temperature Thresholding (TTL), Crop Water Stress Index (CWSI) and fuzzy logic techniques. It also presents real-life applications of these algorithms and their strengths and weaknesses. Section 4 discusses the various ways algorithms can be deployed for smart farming. Section 5 discusses the challenges that are likely to oppose the adoption of the technology among SSA farmers and proposes a community IoT network as a way forward while section 6 concludes the paper.

1.1 Objectives

The objectives of this paper are to: 1. present the components of a smart irrigation setup, 2. carry out a systematic review on seven (7) smart irrigation algorithms, 3. recommend a viable and cost-efficient one for smallholder farmers, 4. presents a suitable technique for deploying smart irrigation algorithms to weather network connectivity problems and, 5. recommend a community IoT network to deploy smart farming systems in rural areas among smallholder farmers.

2. Setting up a Smart Irrigation System

Smart or IoT-enabled irrigation systems are composed of sensors that collect data about soil water content, soil water stress, and climate conditions. The data are processed and stored on the cloud via an internet-enabled gateway. Further processing and analysis are carried out on the collected data either on the gateway, cloud, or both to estimate the water need of plants and meet the need automatically without human intervention via control signals sent to actuators. The analyzed data is presented to users on a web or mobile application to help them monitor their farms and make informed decisions. Figure 1 gives an overview of an IoT-enabled irrigation system.

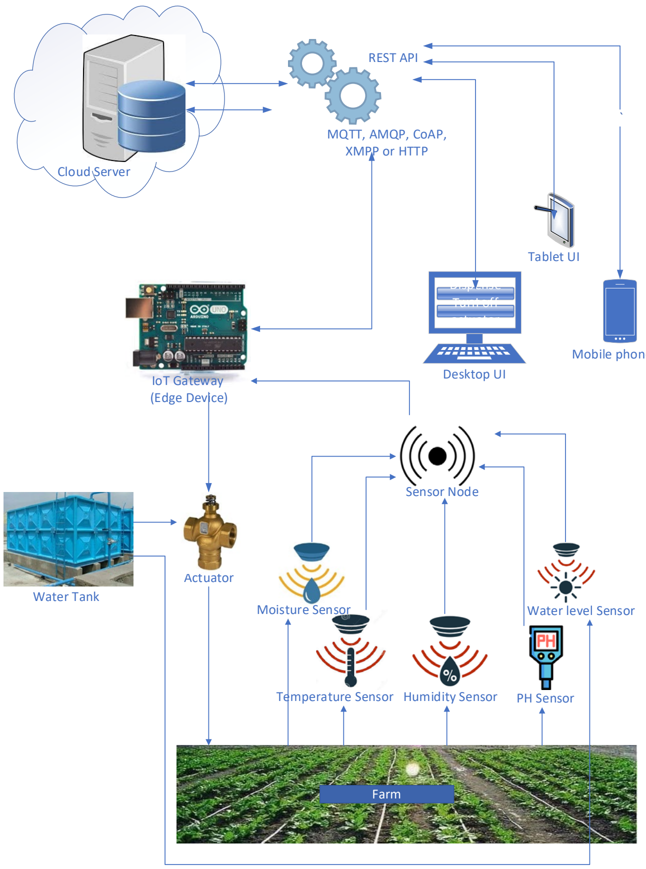

Figure 1: IoT-enabled Irrigation System Model

In setting up a smart irrigation system, several factors must be put into consideration. Factors such as: 1. crop type, 2. type of irrigation, 3. farm size, 4. soil topography, 5. size and site of the farm office, 6. volume, number and site of the water tanks, 7. type of soil, soil homogeneity and water holding capacity, 8. type and number of sensors required, 9. sensor placement, 10. sensor node and gateway design or purchase of already-made nodes, 11. choice of actuator and actuator placement, 12. choice of communication technology e.g. Bluetooth, Zigbee, Z-wave, WiFi, LoRa (Muthukrishnan et al., 2021), etc. between the sensor nodes and the gateway, 13. choice of communication protocol e.g. Message Queuing Telemetry Transport (MQTT), Advance Message Queuing Protocol (AMQP), Constrain Application Protocol (CoAP), HyperText Transfer Protocol (HTTP)(Gupta & Tiwari, 2020), etc. between the gateway and the cloud, 15. cloud platform design or subscription to existing platforms and 16. scheduling algorithm and deployment technique. Figure 2 captures the points for consideration in setting up a smart irrigation system while Figure 3 shows the Federal University of Technology (FUT) Minna ongoing smart irrigation setup.

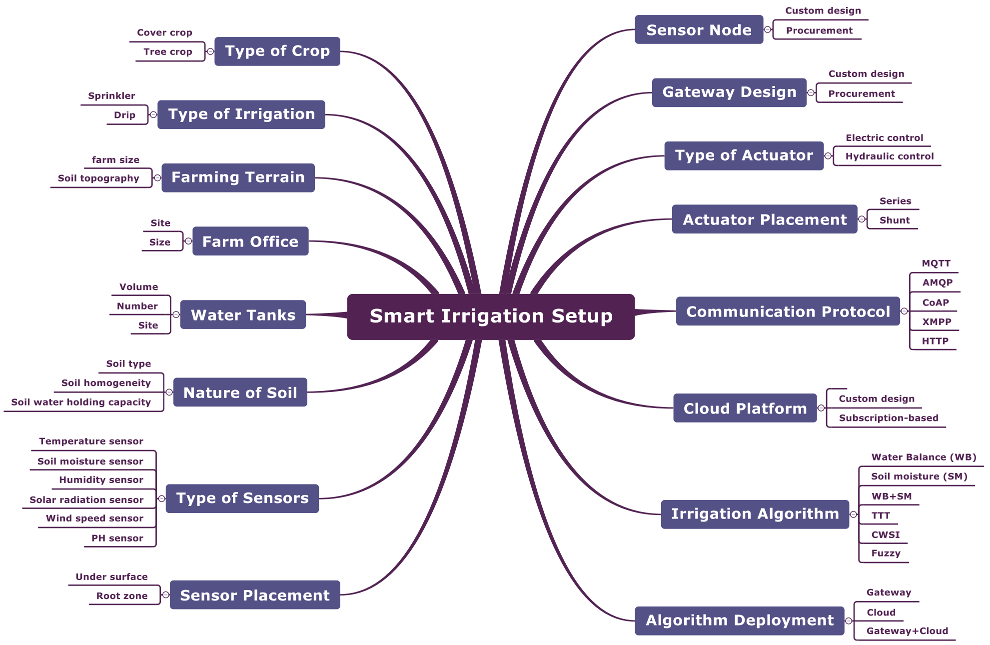

Figure 2: Points of Consideration in Setting up a Smart Irrigation System

Figure 3: FUT Minna ongoing smart irrigation setup

From Figure 3, picture A shows the experimental farm office where the IoT gateway is powered by solar energy. The gateway communicates with the cloud via MQTT protocol, while the nodes communicate with the gateway via LoRa. B shows the drip irrigation plot. C shows a solar-powered sensor node containing soil moisture, temperature, and humidity sensors. D reveals the water tanks. Each tank contains an ultrasonic sensor for measuring the water level and consequently the volume of water in the tank. E reveals a shield for the actuator nodes and valves powered by solar energy, while F shows the actuators and valves' position and their backup power source (Lithium battery) charged by a solar panel. All factors highlighted are very important, but the focal point of a smart irrigation system is the scheduling algorithm. A suitable algorithm must be able to autonomously determine when to trigger and stop irrigation.

2. Scheduling Algorithms

Majority of irrigation scheduling algorithms depend on the crop's evapotranspiration (ET_c). This crop property tells the amount of water loss from the soil via evaporation and the plant via transpiration. It is calculated from reference evapotranspiration (ET_o) which is commonly evaluated using Penman-Monteith (PM) equation or Hargreaves (H) equation. PM equation depends on many climatic input parameters from sensors such as temperature, humidity, solar radiation, and wind speed, while H-equation on the other hand uses only temperature as sensor input. Though PM equation gives a more accurate result, it has a higher computational complexity when compared to H-equation as shown in Figure 4 and Figure 5. All equations are defined in (Testa et al., 2011) except equation 52 defined in (Allen et al., 1998).

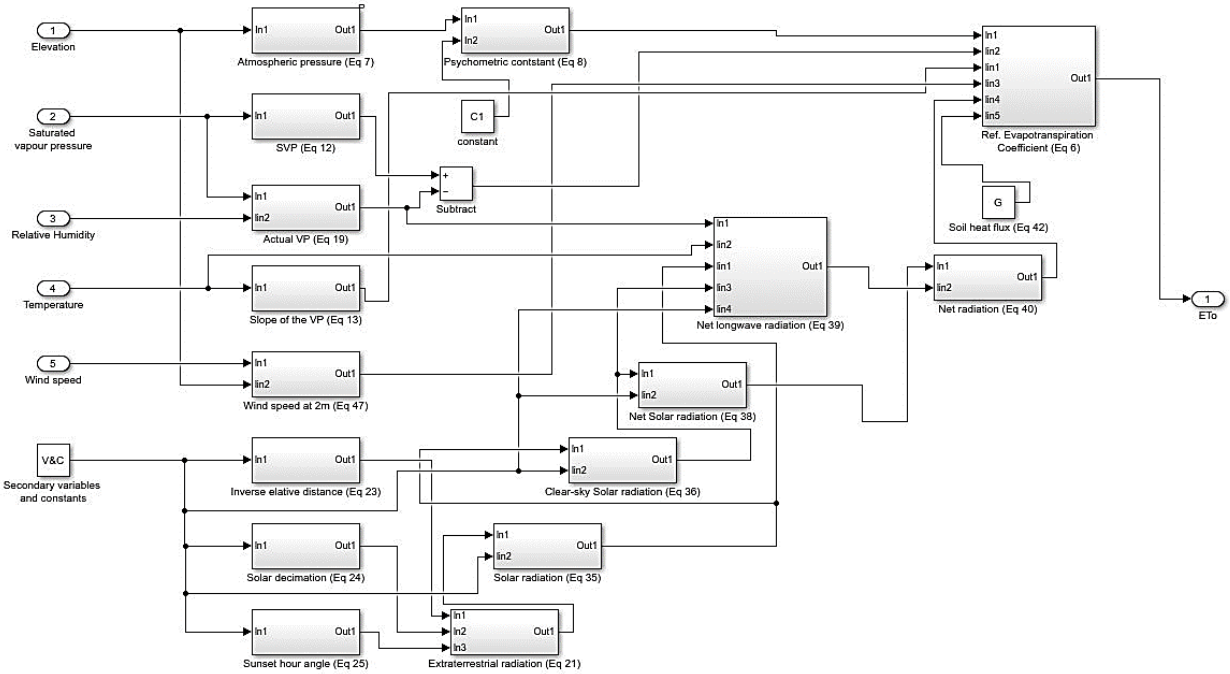

Figure 4. Computational Model of PM Equation

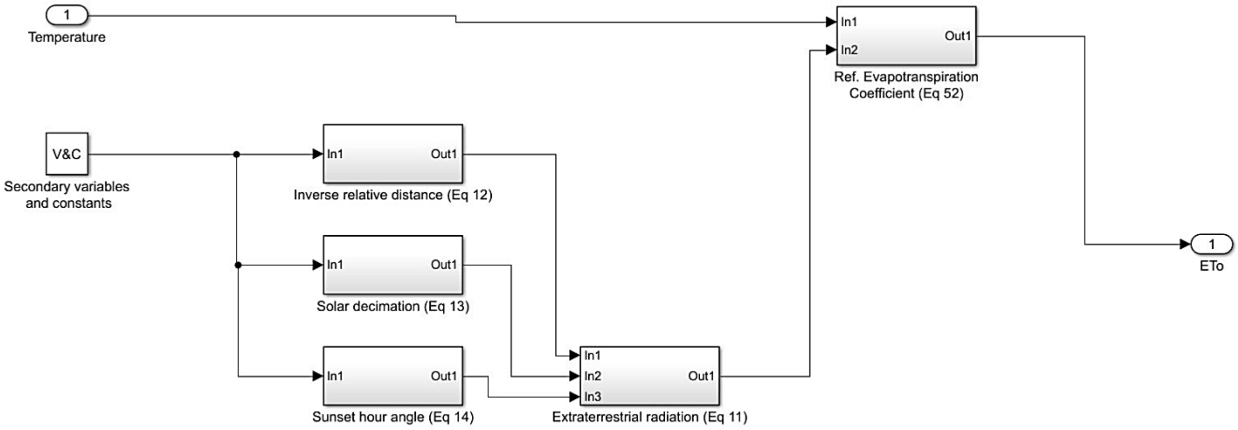

Figure 5. Computational Model of H-Equation

This section discusses seven (7) irrigation scheduling algorithms and the results of their application in crop cultivation. Water Balance technique using PM equation (WB-PM) uses PM to compute the water need of plants, this is called a feed-forward algorithm. The ET_o computed by PM equation is used to compute the daily irrigation dose (DID) of plants. The DID is the amount of water lost by the soil and plant due to evaporation and transpiration respectively plus any extra volume based on the plant's growth stage (see equations 1 and 2)(Millán et al., 2019).

$$DIDs = ET_c \times fKcb + pending + addtional\_vol \quad 1$$

$$ET_c = ET_o(Kcb \times fKcb + Ke) \quad 2$$

Where ET_c is the crop evapotranspiration coefficient, $fKcb$ is the adjustment factor for the basal crop coefficient (Kcb) according to seasonal plan and water balance, Ke is the soil water evaporation coefficient, $pending$ is the volume of water pending from previous irrigation while $addtional\_vol$ is the extra-amount of water applied based on the crop's growth stage. Water balance technique using H-equation (WB-H) works the same way as WB-PM technique but uses H-equation in the computation of the ET_o. This approach is cheaper than using PM equation because it requires less computation and fewer sensor inputs, it traded off accuracy for computational convenience. However, using water balance technique alone conserves water but reduces crop yield due to under-irrigation during the crop's growing season. The success of WB approach is based on the accuracy of the estimated ET_o and building a precise Kcb curve over the crop's growing season based on site-specific calibration, measurement of soil water-holding capacity, and rainfall (Hunsaker et al., 2015; Jones, 2004). Getting all of these accurately could be challenging.

Using Soil Moisture Sensor (SMS) alone for irrigation scheduling is also a common practice (Bousbih et al., 2018; Gagandeep et al., 2018; Gutierrez et al., 2014; Sui, 2017; Yadav et al., n.d.). This technique depends only on soil moisture sensor (SMS) value and requires less computation to make irrigation decisions. Sui (2017) applied this technique to automate irrigation in a cotton farm in Mid-South US while Yadav et al (2020) also applied it in the cultivation of lettuce, tomatoes, sorghum, and corn on the university farm at California State University. From their results, the irrigation scheduling algorithm worked fairly well. This scheduling technique depends heavily on the reliability and sensitivity of the soil moisture sensors used. For optimum results, the authors recommended onsite calibration of sensors and adjustment of the weights assigned to sensor values at different depths and the threshold to schedule irrigation at different stages of growth of the crop

A number of irrigation algorithms aim at improving the precision of the DID using a feedback control. Soil moisture (SM) feedback control for example combines WB and SMS in the estimation of the DID of crops (Millán et al., 2019; Osroosh, Peters, Campbell, et al., 2016). Casadesús et al.(2012) applied this technique in the cultivation of prunus persica in Catalonia (Spain). The authors confirm that the technique eliminates the shortages or excesses involved in the estimation of DID using only the WB technique. Their work achieved 62% of water conservation when compared to WB technique without any negative impact on the plant. Time-Temperature Thresholding (TTT) is also used for tuning the DID obtained from WB technique. In this approach (O'Shaughnessy & Evett, 2010; Osroosh, Peters, Campbell, et al., 2016), the times at which the crop's temperature exceeds a given threshold are cumulated over a 24-hour period. When the cumulated time exceeds a threshold, irrigation is triggered. If the cumulated time does not exceed the threshold within a 24-hour period, it is reset to zero. Crop Water Stress Index (CWSI) is another DID tuning technique to improve its precision (Anda, 2009; Kumar et al., 2020, 2020; Susan A. O'Shaughnessy et al., 2012; Osroosh et al., 2015; Osroosh, Peters, & Campbell, 2016; Osroosh, Peters, Campbell, et al., 2016; Shellie & King, 2020; Taghvaeian et al., 2014; Tekelioğlu et al., 2017). Irrigation is triggered when the estimated CWSI exceeds a threshold. CWSI can further be improved by a temperature threshold (CWSI-TT) (O'Shaughnessy et al., 2012). O'Shaughnessy et al.(2012) applied the algorithm in the cultivation of grain sorghum, their result showed 80% yield. Osroosh et al.(2016) stated that CWSI and TTT do not require onsite calibration thus reducing labor cost. The algorithms delivered enough water to apple trees and avoided water stress. From their comparison with the WB and WB+SM techniques, CWSI and TTT gave a higher precision in water delivery with a better crop yield. Evaluation of the TTT was described by Evett et al. (1996) while Osroosh et al. (2015) described the computation of CWSI.

Scheduling algorithms based on Fuzzy logic (Fuzzy) are also being used to automate irrigation systems. Though many of the algorithms are only hypothetical(Alomar & Alazzam, 2019; Anand et al., 2015; Chakchouk et al., 2017; Cruz et al., 2017; Elashiri & Shawky, 2018; Faye et al., 2000; Navarro-Hellín et al., 2015; Rudy Hendrawan et al., 2019; Viani et al., 2017; Yahyaoui et al., 2014; Zhu & Azar, 2015), some have been deployed in practical systems. Alfin & Sarno (2018), for example, applied fuzzy logic approach in implementing an automatic irrigation system to control soil moisture content in a sugarcane farm. The stages in the system design were divided into two; the fuzzification process and the defuzzification process. The fuzzification process uses soil moisture, PH and temperature as input parameters and as criteria for assessment. In the second stage, a total of six (6) membership functions were employed in the defuzzification process. Their model provided an efficient means of maintaining the soil moisture required by the sugarcane farm. Figure 6 gives a summary of the irrigation algorithms discussed and their input parameters.

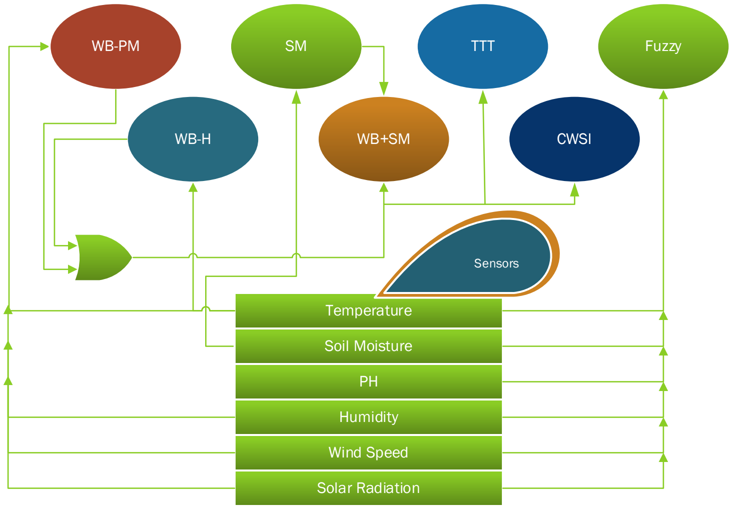

Figure 6. Irrigation Scheduling Algorithms and Input Parameters

4. Deployment Scenarios

Some of the challenges arising from running smart irrigation systems are traceable to the deployment of the scheduling algorithm. An algorithm that functions very well in a given system may function poorly in another based on how it is deployed. Scheduling algorithm can be deployed on any of the following configurations.

4.1 Edge Only Deployment

Deploying the scheduling algorithm exclusively on an Edge device ought to be the best approach since the Edge device is closer to the farm and does not depend on internet connection to communicate to actuators. The challenge to this is that some algorithms require complex computations on large volumes of datasets to arrive at a decision. This is therefore a limitation due to constrain in the memory and processing capacity of Edge devices.

4.2 Cloud Only Deployment

In this scenario, the control algorithm is implemented on the cloud exclusively. The advantage of this technique is that the complexity of an algorithm does not constitute a challenge due to the high processing capacity and storage of cloud servers. However, in rural areas where internet connectivity may intermittently fail, relying solely on the cloud may result in unacceptable failure and consequent negative impact on crop yield.

4.3 Edge plus Cloud Deployment

In this deployment scenario, control activities are shared between the Edge and Cloud devices. The cloud performs the complex computations and communicates its results to the Edge. The Edge device then uses the results to make control decisions. Though the approach involves coding part of the algorithm on the Edge and the bulk of it on the Cloud device, it eliminates the challenges associated with implementing control only on the Edge or Cloud device. It is the way forward in driving IoT systems in areas where network connectivity is a challenge. Not only does it solve the local problem, but it also gives a global view of the managed farm. Multiple farms could be managed with one cloud system.

5. Challenges and Recommendation for Farming in the SSA

In the SSA, 84% of the farmers are smallholder farmers, poor, uneducated, and leaving in rural areas but produce about 80% of the food(Sirimanne, 2017; Swiss Agency for Development and Cooperation (SDC): Strategy 2017 – 2020, Global Programme Food Security, edited by Federal Department of Foreign Affairs FDFA, n.d.). The status of farmers in the region is likely to hinder them from embracing the technology except effort is made in the design and deployment stages to include this special group. Another issue of concern in deploying this technology in the region is internet connectivity challenge. Rural areas where farming activities are centered are poorly covered by mobile phone networks, which is the major source of internet connectivity(David & Grobler, 2020). In order to overcome these challenges, the following proposal and recommendations are worthy of consideration.

- **A proposed Community IoT Network for Smallholder Farmers in Rural Areas**

In an individual or single-user application, the entire IoT network is dedicated to a user. All the cost of procuring equipment and setting up the system is borne by the individual. This is good for privacy and exclusive control but expensive for smallholder farmers. In order to tackle the cost, illiteracy, and connectivity challenges, a community IoT network is proposed. In community or multiuser deployment, an IoT network is designed to serve many farms in close proximity. Each farmer is only required to purchase required sensors, actuators, and edge device. The edge device from each farm will be connected to a Fog device (a device that can handle larger traffic compared to an edge device) installed in a central farm office with internet connectivity as shown in Figure 7.

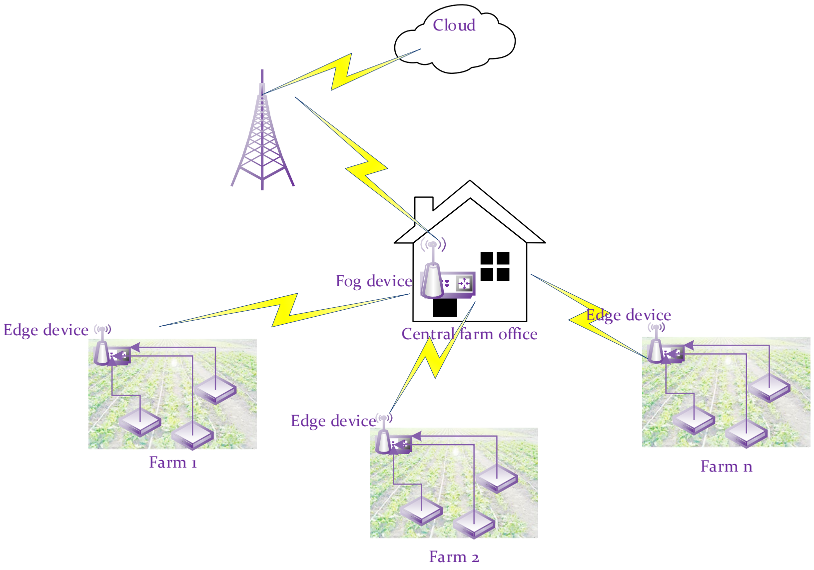

Figure 7. A Proposed Community IoT Network

Control and local monitoring of each farm can be achieved from the central fog device and edge device of each farm while the cloud can be used for complex data mining and predictive analysis. This system will leverage on economy of scale to reduce the cost implications from each farmer since the cost of running the Fog device and internet service will be shared among the farmers. A dedicated cloud platform can be built for this purpose to further reduce cost. This is a potent technique to drive IoT-enabled agriculture among smallholder farmers in rural areas. Agricultural institutions and government agencies can set up and manage community IoT networks in villages to encourage IoT-enabled farming. Apart from mitigating cost and internet connectivity issues, this will also solve the illiteracy challenge since sensor installation and all technical needs will be managed by experts from the central farm office.

- To mitigate internet connectivity issues and computational complexity of certain algorithms, control algorithms should be deployed on the edge and cloud platforms. Major computations should be done on the cloud while the edge should use the cloud's results to make control decisions.

- To mitigate cost, algorithms that require a fewer number of sensor inputs should be considered and tunned for improved accuracy. Onsite calibration of sensors is also recommended for better precision. Scheduling algorithms should be deployed intelligently to avoid poor crop yield.

6. Conclusion

In conclusion, it is obvious that to tackle global food insecurity, IoT-enabled agriculture is the way forward. Regions of predicted high population-rise such as the SSA should be encouraged to embrace the technology by factoring their special needs in the design and deployment of IoT drivers for the region. The scheduling algorithm is key to the success of a smart irrigation system. An algorithm that requires less computation and a smaller number of sensor inputs without compromising healthy crop growth is the choice algorithm. Such an algorithm should be deployed on the Edge and Cloud devices to tackle issues that may arise due to poor internet connectivity and computational complexity. From the seven (7) algorithms analyzed, Hargreaves equation and soil moisture sensor feedback control algorithm is found to be both cost-efficient and effective for healthy crop growth. It is therefore recommended for smallholder farmers. The proposed community IoT network should be implemented by corporate organizations, government agencies, and agricultural institutions, as it will serve as a doorway to compel smallholder farmers to hook up with the technological trend.

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Biographies

Supreme Ayewoh Okoh holds a B.Eng. degree in Telecommunication Engineering from Federal University of Technology Minna, Nigeria with first class honors. He is currently working towards his M.Eng. degree in Communications Engineering in the same university, and a M.Ed. degree in Advance Teaching at University of the People, Pasadena California, USA. His research interests include precision agriculture, spectrum management, network security, channel coding, optimization algorithms, computational intelligence, blockchain mining, machine learning, big data, cloud computing, internet of things, adolescent development and spiritual intelligence.

Zubair Suleiman had his B.Eng degree in Electrical & Computer Engineering 2003, M.Eng. in Communication Engineering from the same university and PhD. degree in Wireless Sensor Networks from Faculty of Electrical Engineering MIMOS (Lab) Center of Excellence in Telecommunication Technology, Johor, UniversitiTeknologi Malaysia. He is a lecturer in the Department of Telecommunication Engineering, Federal University of Technology Minna, Nigeria. His research interest areas are, Wireless Sensor Networks, Embedded Systems, Data communication & Networking, Technological Development in third World Countries. Wireless communication, Optical Fiber Communications, Next Generation Networks and Biomedical Technology.

Bala Alhaji Salihu received the B.Eng. and M.S. degrees in electrical and computer engineering from the Federal University of Technology, Minna, Nigeria, in 2004 and 2011, respectively, and the Ph.D. degree in communication and information systems from Beijing University of Posts and Telecommunications, Beijing, China, in 2015. From 2006 to 2010, he worked as an Assistance Lecturer in the Department of Electrical and Computer Engineering, Federal University of Technology, and later transferred to Telecommunication Engineering Department in 2010. His research interests include wireless communication, network architecture, network management systems, and radio resource management in LTE-Advanced.

Elizabeth N. Onwuka is a Professor of Telecommunications Engineering. She holds a Ph.D. in Communications and Information Systems Engineering, from Tsinghua University, Beijing, People's Republic of China; a Master of Engineering degree, in Telecommunications; and a Bachelor of Engineering degree from Electrical and Computer Engineering Department, Federal University of Technology (FUT) Minna, Niger State, Nigeria. Her research interest includes Mobile communications network, Mobile IP networks, Handoff management, Paging, Network integration, Resource management in wireless networks, spectrum management, and Big Data Analytics.