Smart Farming For Developing Countries Economies

A LoRaWAN Based Approach

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1 Introduction

The rapid growth of the world population and climate change poses a great threat to food security. Population growth affects the capacity of the environment on food production due to changes in land use and the availability of arable land. Changes in land use and agriculture, on the other hand, contribute to a quarter of the total greenhouse gas emissions which lead to climate change which affects the livelihoods of people, especially the poor who live in rural areas [1]. Fluctuations of weather patterns have an impact on food production. In spite of this, food production globally has to increase by 70 % by 2050 to feed the growing population [2]. The problem of food security, population growth, and climate change are intertwined and there is a need to promote farming practices that are cognizant of these challenges. Technology can transform agriculture and help smallholder farmers adopt new farming approaches making them resilient to climate change.

Smallholder farmers in rural areas in developing countries are in danger of hunger in the face of climate change and they need the information to practice sustainable agriculture while at the same time produce sufficient food to feed the growing population. Furthermore, they need to understand how different plants perform in changing weather patterns and varying availability of water. Fortunately, there is technological advancement that is driving the fourth industrial revolution which is impacting all sectors by connecting physical and digital worlds. Agriculture is also experiencing this development with the adoption of Information and Communication Technology (ICT). For smallholder farmers in developing countries, this development is particularly suitable as they can leverage this technology to adjust to climate change and produce food efficiently. Adoption of technologies like the Internet of Things (IoT), edge and cloud computing coupled with sensor technology and low cost and energy-efficient wireless communication could help them in the realization of information-driven farming. Moreover, farmers get full control of their farm operations, monitor soil, crop growth at different stages and animal health. Based on the farm data farmers can optimize their farm inputs. Also, such technologies can help them diversify farming and to not only rely on rain-fed agriculture but also adopt other techniques like irrigation and hydroponic systems to complement traditional agriculture.

1.1 Motivation

The use of ICT in agriculture in developing countries is focused on the use of mobile technology to dispatch information to farmers i.e. market information, early weather alert and interaction with agricultural officers for advisory purposes [3]. To fully realize the potential of ICT and foster efficient food production, there is a need to leverage advanced technologies. However, the use of technology, especially the implementation of IoT, edge and cloud computing in agriculture has not found significant space in developing countries. This has mostly been hindered by high cost, limited internet connectivity and lack of efficient communication that offer long-range and power efficiency. The rapid development of IoT, low power wide area networks (LPWAN) together with the increased availability of low-cost hardware and open-source software offers new opportunities to design new solutions that can help farmers in rural areas.

1.2 Problem statement

There is a consensus that smallholder farmers in developing countries have to adopt technology to facilitate efficient food production and enable them to be more resilient to climate change. In addition, the use of technology has to go beyond the current mobile phone-based solutions that facilitate sharing of information regarding weather, financial services and market prices into putting technologies in the farms to get data that derive knowledge-based farming. This thesis, therefore, seeks to investigate technologies that fulfill the requirement of smart farming in developing countries and develop a solution based on the recent technological advancements.

1.3 Thesis outline

This thesis is organized as follows. Section 2.1 gives a piece of background information on population, food security and adoption of technology in agriculture. In section 2.2 we present digital dimensions of agriculture. In section 2.3 a use case used in this thesis is presented. An outline of the requirements of smart

addresses smart farming as one potential way of adopting technoly for efficient food production. In addtion, the almost automous solution of hypdropnds is more resillient against climate change than areas reliyng on natural resources in the surrounding

farming in resource-constrained regions is given in section 2.4. We also give an introduction to the different technologies that enable smart farming in section 3 and in section 3.4 we give a brief overview of the related work. Section 4 builds on the technologies discussed in section 3 and presents the system architecture and implementation of smart farming in developing countries. Section 5 gives an evaluation and directions of future work. In the final section, we give our conclusion.

2 Background

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Population growth and climate change are a global challenge and United Nation's 2030 agenda, defines 17 Sustainable Development Goals [1], among them eradication of hunger and responsible production and consumption. The demographic, climatic and environmental changes call for the use of innovative technologies to address food security problems. There is a need to use technology to regulate the consumption of depleting resources, increase productivity and enhance resilience. As Tjoa and Tjoa puts it that information and communication technologies (ICTs) has had the most impact on development, particularly on innovation, efficiency and effectiveness in all sectors[4].

Figure 1: Sustainable Development Goals.

[1] https://www.un.org/sustainabledevelopment/sustainable-development-goals/

2.1 Agriculture and Technology in developing countries

2.1.1 Population, climate change and agriculture

Besides providing food, agriculture is a source of livelihood for 36 % of the world's task force with 40-50 % of Asia and the Pacific population and two-thirds of people in sub-Saharan Africa relying on it to make a living [5]. The effects of climate change affects food production and it is felt mostly by the people in the developing world since agriculture is the main source of livelihood. Farmers in these areas are resource limited and vulnerable to the effects of climate change. Since most people depend on agriculture, which is sensitive to rainfall variability and temperature change, hunger is a significant threat in the face of climate change.

Climate change will only exacerbate water scarcity and unpredictability of water supply due to changes in weather patterns. Currently, 70 % of freshwater in the world is used for agriculture and there will be growing competition for water between agriculture, industries, and consumption in the cities [5]. In addition, 40 % of the rural population lives in river basin areas that are classified as water scarce [6]. Water scarcity in the face of climate change will affect most rural communities in sub-Saharan Africa and South Asia where water problem is already a challenge and have low capacities to adapt to changes in climate. There is a need of using technology to help the farmers in this region to adapt to climate change and practise farming techniques that cognizant of the current problems caused by climate change.

The United Nations (UN) projected in 2017 that the world population will reach 9.8 billion in 2050 and over half of this population growth (1.3 billion) and 750 million will occur in Africa and Asia respectively [7]. Yet, according to the UN Food and Agriculture Organization (FAO), 821 million (one person out of every nine in the world) are currently undernourished [8] and it is estimated that food production in Africa has to increase by 260 % by 2050 to provide food for the expected population [9]. The demand to increase in food production to feed the growing population will have an effect on the ecological footprint and the current agricultural production have already created a large ecological footprint [10]. To address food security problem and at the same time reducing ecological footprint associated with food production, agriculture has to be transformed.

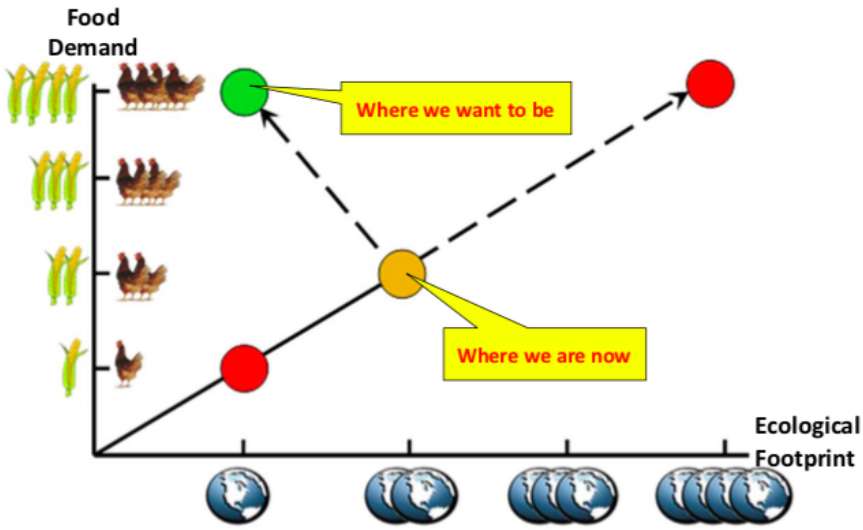

Figure 2: Food demand vs ecological footprint (Source: [10]) .

2.1.2 Uptake of agricultural technologies

In this section we will discuss the uptake of agricultural technologies in developing countries, causes of low uptake and opportunities technological developments offer.

Agricultural engineering and mechanization contributed to rise of large-scale farming and increased production and transformation of countries from agriculture to industry-based economies [11]. With the use of modern agricultural approaches like irrigation and fertilizers, the cereal production in East Asia increased by 2.8 % a year between 1961 and 2004 while there was stagnation of yields in sub-saharan African countries that didn't adopt those approaches[12].

As mentioned earlier, fourth industrial revolution has driven agriculture towards use of IoT and sensor technology that has eased farm practices. However, the implementation of these technologies has been hindered by the challenges summarised in figure 3.

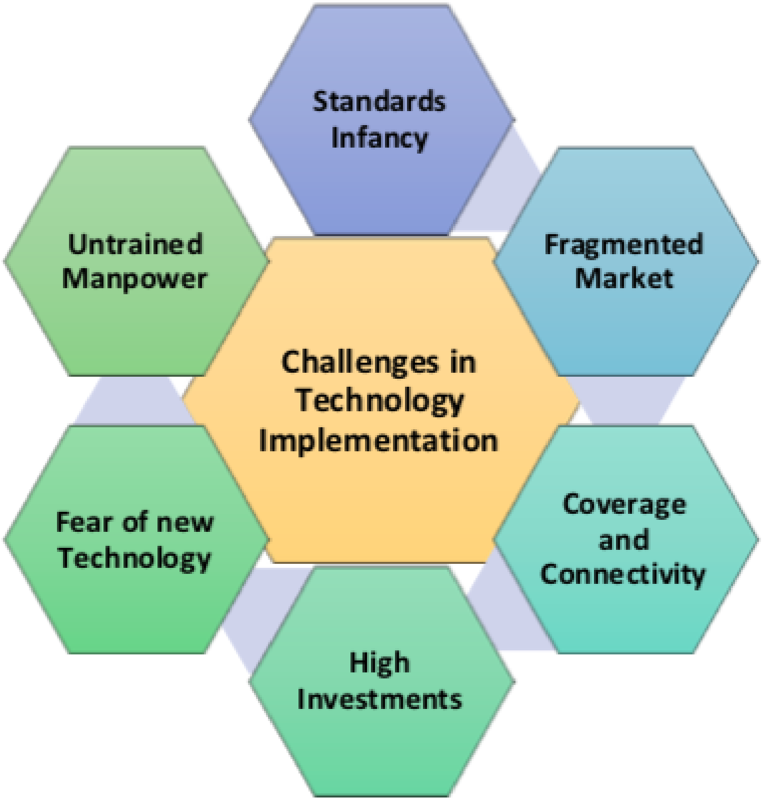

Figure 3: Major barriers that limit implementation of new technologies in agriculture (Source: [13])

Whilst the above mentioned factors applies to all, developing countries are not not keeping pace with the rest in uptake of advanced technologies due to the following additional barriers.

2.1.2.1 Socio-economic factors The social-demographic and socio-economic factors affect the adoption of new technologies [14, 15]. Farmer's education level, age and computer confidence are among the factors that hinder farmers choice of technology. The knowledge to existence of technology is also an important factor in the adoption of technology [16] and in many cases even the existing knowledge and technologies have not reached farmers in developing countries [17].

2.1.2.2 Infrastructure Adoption of smart farming in developing economies is mostly hindered by insufficient or lack of infrastructure. Access to communication infrastructure and the Internet are key enablers in the adoption of technology in agriculture. Information and communication technologies keep farms informed about the recent technologies in agriculture, weather conditions, financial services and enable connection with buyers [18]. However, according to the International Telecommunication Union (ITU), 53 % of the world's population are still unconnected to the Internet and they could not benefit from the aforementioned benefits [19]. Internet connection is not given in the most developing economies – of the 6000 gateways that are operation in the world, only 100 are in Africa inhibiting access to open and free network [20]. The UN has acknowledged the indispensability of access to information and the critical role played by communication technology. In the recently launched Sustainable development goals, one of the targets of the goal 9 seeks to 'increase access to information and communications technology and strive to provide universal and affordable access to the Internet in least developed countries by 2020 [2]. Several mobile services are already offered to farmers, but uptake and use of more advanced devices and services e.g cloud-based services are influenced by battery life of devices and access to fast internet [3].

2.1.2.3 Cost and ownership of technology Further, there is a disparity in the research, development and ownership of new technologies since public and private investment in such technologies is concentrated in high- income countries thus limiting access to emerging countries [18]. The European Union has allocated euro 95 billion to the European Rural Development Fund for modernisation of agricultural industry between 2007 and 2013

2.2 Digital Dimension of Agriculture

The use of advanced technologies has been integrated to farming and new concepts like precision farming/agriculture and smart farming concepts have emerged. While these concepts all revolve around modernization and use technology in agriculture, they have some differences.

[2] `https://www.un.org/development/desa/disabilities/envision2030-goal9.html`

2.2.1 Precision Farming

According to a report by European Parliament on Precision agriculture and the future of farming in Europe, precision agriculture is defined as: "a modern farming management concept using digital techniques to monitor and optimise agricultural production processes" [21]. The focus is optimization of farm inputs. It ranges from application of correct amount of fertilizers to the specific part of the field based on soil properties, precise water use and to giving the correct amount feed to a specific animal. Sensor, satellite navigation and positioning technology are an indispensable part of Precision Agriculture. Precision farming commenced when GPS signals were made available for the general public [22]. Precision farming has successfully been implemented in large-scale farms in Central and Northern Europe, the USA and Australia with use of Controlled Traffic Farming (CTF) and auto-guiding systems showing clear benefits [23]

According to citeauthor wolfert2014future, the development of precision agriculture is as a result of growth of farm enterprises and move from scaling of farm assets to optimization of assets[24]. With the increase of cost of the farm inputs and regulations e.g. use of fertilizers and unpredictability due to climate and market prices, different systems that collect and manage data were developed to help farmers in making right decisions. Precise monitoring and control are done to manage spatial and temporal variability of crops, animals and soil factors[10]. It differs from traditional farming by accurately identifying variations and relating spatial data to management activities [25].

2.2.2 Smart Farming

Smart farming is a recent phenomenon that came into being with the inclusion of computing technologies and the transmission of data in agriculture [26]. It overlaps with technologies like precision farming and management information systems that have been derived from farm management information systems (FMIS) [26]. It extends precision agriculture, where management is based not only on the location and on field variability but also on data that is triggered by real-time events [10]. This requires use of different technologies as depicted in figure 4.

Figure 4: A smart farming technologies (Source: [27]).

In Smart Farming, the focus is on the utilization of ICT in the cyber-physical farm management cycle [28]. This is enhanced by the advancement of nanotechnology in the last decade which enables production of small and inexpensive sensors [29]. Moreover, cloud computing and IoT promote the development of smart farming [10]. The use of sensors enables data collection and monitoring and events triggered by analysis done in the cloud. Figure 5 shows these interaction in smart farming.

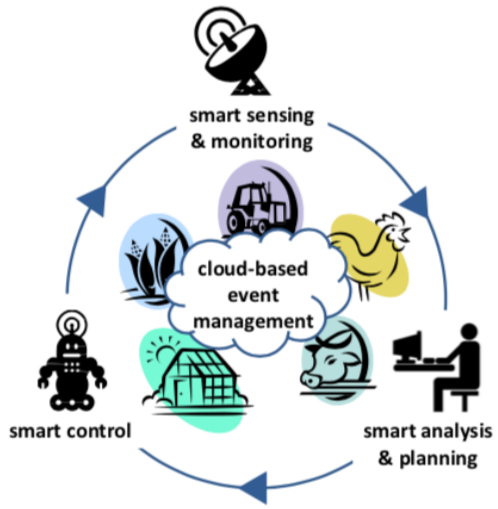

Figure 5: Smart farming management cycle (Source: [24]).

Figure 5 shows a smart farming as cycle of sensing, monitoring, analyses and cloud based control of farm events. The harvesting of data from sensors deployed in the fields aid decision making process on animal health, remote monitoring and accurate diagnosis of the soil and crop conditions and timely interventions. Farmers will also have access to historical data of weather and other inputs and they can make informed decisions. This will result in less waste, efficient use of resources and effective food production thus reduction of the ecological footprint [30].

ICT is viewed as an enabler of climate-smart farming which is "agriculture that sustainably increases productivity, resilience (adaptation), reduces/removes GreenHouse Gases(GHGs) (mitigation), and enhances achievement of national food security and development goals."[17]. But the adoption of technology by smallholder farmers in developing countries, especially in Africa, mostly revolves around the use of mobile phones and services provided through it. This includes sharing of agriculture-related information, provision of financial services, weather and market price information[3]. To further improve the practice of climate-smart farming, we can leverage technological advancement and help farmers diversify farming practices. However, this requires a holistic approach and involvement of different agents to achieve it. Indeed, as Walter et al. points out that "only if aspects of technology, diversity of crop and livestock systems, and networking and institutions (i.e. markets and policies), are considered jointly in the dialogue, should farming in the digital era be termed 'smart farming'"[30]. Figure 6 shows depicts these four factors.

We endorse their (Walter et al.) opinion as this approach is necessary for developing countries where planning and implementations of policies are mostly disjointed due to lack of resources and poor governance. Inspired by this view of smart farming and taking into consideration the complexity around the adoption of technology in developing countries as discussed in section, this thesis, we focus on following technological aspects of smart farming:

- The integration of information and communication technology into farming management systems and leverage (advancement in technology) low-cost sensors to monitor farm systems for efficient use of resources and sustainable food production.

- Making sensor data and information on smart farming accessible to farmers and sharing of data among different stakeholders. This entails the storage of data in local servers and periodic transmission to cloud for remote access for extension officers and other agents. In developing countries, farmers rely on agricultural extension officers on issues related to farming, which is usually done through field visits. Using online platforms that store data from farms will give new interaction between farms and extension officers. This will enable a timely response from agricultural officers and save on costs related to fieldwork for data collection. Early warning and timely information about farm conditions and advice from extension officers can foster effective response and measures by farmers. Augment data collected from the farms with information like the weather forecast to help farmers and extension officers in decision making and generation of actionable information.

- Use technology to diversify farming systems and introduce practices that aren't possible or required skills to do e.g. hydroponic farming (monitoring nutrient solutions) or precise irrigation to reduce water consumption (time for water and site-specific needs) thus, reconciling the need for increased food production and sustainability. This thesis used hydroponic farming as an example of diversifying farming with the help of technology.

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This will create an ecosystem that will enable data collection, analysis and intelligence sharing between farmers and other stakeholders.I

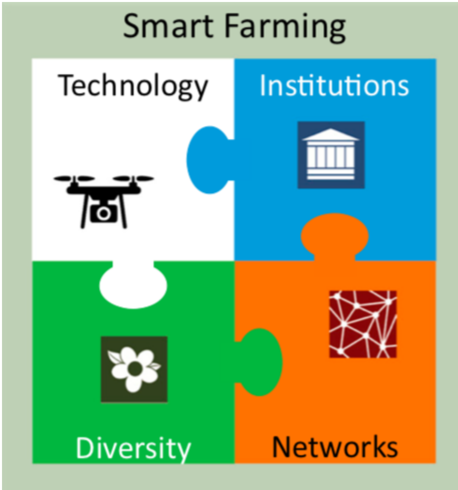


Figure 6: Smart farming in digital era. source: [30]

2.3 Use Case Scenario: Hydroponic farming

The objectives of using hydroponic farming as use case scenarios are two fold. 1) extract the functional requirements of smart farming in resource constrained setting (technologies) and 2) the need of using technology for efficient food production in the face of climate change and population growth (shortage of water and arable land).

Growing plants without soil has been practiced for a long time. This method of food production has been practiced earlier e.g hanging gardens of Babylon, the floating gardens of the Aztecs of Mexico[31]. The term Hydroponics, however, is recent and was first used by W.F. Gericke of the University of California in early 1930s [31]. Hydroponics can be defined "as the science of growing plants without the use of soil, but by the use of an inert medium, such as gravel, sand, peat, vermiculite, pumice, perlite, coco coir, sawdust, rice hulls, or other substrates, to which is added a nutrient solution containing all the essential elements needed by a plant for its normal growth and development" [31]. In hydroponic systems plants can either grow in an aqueous media or substrate[32]. In substrate approach plants grow in pots filled with growing medium e.g. sawdust while in aqueous approach they are three designs used: nutrient film technique(nutrient solutions flow through the plastic pipes with holes on which plants are placed), deep water culture(plants roots are in the nutrient solution which is aerated) and aeroponics(roots of the plants are suspended in air and are sprayed with nutrient solution continuously)[32]. Figure 7 shows nutrient film technique and deep water culture.

Hydroponics farming is classified as either open (nutrient solution is not reused) or closed (where solution is recovered, replenished and recycled)[33]. Hydroponics has several advantages over the traditional farming: it can be used in areas where in-ground farming is not possible e.g due to climate (cold and desert), areas with water scarcity and conditions where complete control of nutrient content is required and there is a need for increased productivity/crop yields [34]. Table 1 compares soil less culture(hydroponic) and soil(traditional).

Hydroponics, if adopted can address challenges faced by smallholder farmers in developing countries like scarcity of water, limited arable land, labour cost and reduced long growth periods [35]. In optimal growing conditions hydroponic greenhouse far out-yield varieties produced on the field e.g Tomatoes production increased in yields by 4- 10 times [31] and for the production of fodder 50 sq. m. area could produce 600 kg maize fodder in seven days compared to 1 ha of land needed to produce the same amount of fodder [35]. The major limitation of adoption of in hydroponics is the initial capital required [34] especially for smallholder farmers in developing countries. However, the cost can be reduced by low cost devices/construction material [35]. Floating hydroponic system used South East Asia is an example of low cost approach[32].

Hydroponic farming is a relatively new practice in most of the countries in developing countries with smallholder farmers barely having knowledge about it. Most smallholder farmers practice mixed farming: farmers grow crops and keep animals. Hydroponic farming is, as such, an approach that can be used to produce food crops and fodder for farm animals. Closed hydroponic could address problems faced currently due to scarcity of water and rainfall variability. The recycling of water could affect production and necessary measurements and monitoring need to be done for the farm to be economically viable. Moreover as stated in table 1 hydroponic system needs higher knowledge on technology as compared to traditional farming. IoT could solve these problem. Farmers do need to rely on experts as the information they need to make decisions is made available to them by data from sensors. Sensors can collect data of the ingredients of the solutions and this can help farmers make informed decisions at the right time. Nutrient imbalance can easily be identified and necessary action taken at the right time.

(a) deep water culture

(b) Nutrient Film Technique

Figure 7: IHydroponic Systems ([32])

	Soil	Soilless
Farming in new areas	Not always possible. Depends on the type of soil, fertility, salinity	Agriculture possible in any condition
Cultivation	Constant preparation of soil, need of machines, fuel intensive	No needed, substrates preparation or positioning on troughs/ground
Intensification of production	Limited. Monoculture brings “soil tiredness” and already decreases yields after two successive crops Soil tiredness requires crop rotation, fallow or soil sterilization, which is time consuming and interrupts crop cycles for 2–3 weeks	Monoculture is possible with no decadence of performances Substrates could be sterilized with simple means and no crop interruptions Inert media or water do not face risk of any fertility losses due to their characteristics
Plant nutrition	Variable delivery. The release depends on soil characteristics. Some deficiencies are possible. The precise delivery of nutrients according to the plant growth stage is not possible	Real time distribution of nutrients and pH according to the growth stage of the plants. Real-time control of the levels of nutrients required by plants
Nutrient use efficiency	Fertilizers broadcasted broadly, High dispersal through leaching and runoff in outdoor conditions	Minimal amount required due to microirrigation and containment of media. Water and nutrients monitoring avoid the loss of nutrients
Water use efficiency	Efficiency affected by soil texture and irrigation system	Optimal delivery trough microirrigation supported by sensors
Weed control	Need continuous control	No need of any control
Diseases and pests	Affected by soil-borne diseases and pests. Needs sterilization, crop rotation	Not affected because of no use of soil
Quality	Product characteristics depends on of the type of soil and management	Standardized production with full control of nutrients. Optimized growth
Production costs	Normal, but use of machinery necessary for soil cultivation and higher use of inputs (water). Higher costs if greenhouses/nethouses are used	Higher costs due to more expensive setting in greenhouses/nethouses and the presence of a monitoring system,
Farm management	Standard level	Expert level. Needs higher knowledge for the higher technology used

Table 1: Soil versus soilless production (Source: [32]).

2.4 Requirements of smart farming in resource constrained regions

As explained in section 2.1.2 infrastructural, economical and knowledge divide are some of the factors that contribute to low uptake of the technologies in developing economies. As such, the technical requirements suggested for the smart farming countries have to put these factors into consideration. For the sustainability and enhanced use of the technologies, the solutions should be easy for the local communities and give new meanings in their own context. In addition, they should foster local digital capacity and innovations.

2.4.1 Low cost device

The computing and sensor devices in such settings with limited resources have to be low cost and low power consuming. Computing platform like single board computer e.g. Raspberry Pi are inexpensive and could easily be installed.

2.4.2 Low power device

Power connectivity is not given in most of these regions and if it is available, power outages are frequent. Rechargeable batteries and the solar panels should thus be used power the system or act as a back-up in case of outage. Furthermore, use of solar panels is a cheap, clean and sustainable source of energy. The gateways that continuously receive power from the sensors should be power frugal especially in the receiving mode [20].

2.4.3 Cost-efficient communication

Internet connectivity is unavailable, intermittent, slow or costly in most of the developing countries. Connectivity is an essential part of the smart farming. In most IoT applications where connectivity is given, devices connect to the internet through Internet Protocol (IP) and send data directly to the edge and cloud. This is not the case in this context and connectivity is viewed as two parts: first sending of data to the edge/gateway and the second part is sending of data from edge to the cloud. Consequently, the solutions needed should include use of unlicensed bands and non-IP network that connect to the Internet through a gateway in the first layer and the second layer mobile/cellular to connect to the internet. Communication between devices and particularly wireless communication is power consuming, thus solutions that offer efficient communication, low power consumption and routing protocols with low memory requirement are required [36]. Also a cost-efficient communication is required for sending data to the cloud. Since bandwidth is limited, data mitigation techniques [25] are required in such areas to reduce the amount of bandwidth needed to send data to the cloud.

2.4.4 Software

Software acts as a bridge between things and the applications and for interoperability between devices. There are many commercial and open source software for IoT with respective strengths and weaknesses. Cost is a limiting factor when considering proprietary software. Open software enables researchers to replicate the design and customize it to meet specific needs of the context [20]. Most IoT devices are resource constrained and battery powered therefore, software used should be low memory consuming.

2.4.5 Computation and storage

The data collected by the sensors need to be stored for the decision making and to develop a knowledge base for the farmers to make necessary adjustments to the system. Cloud computing offers limitless on-demand storage and computation capacity. A key problem with the use of cloud computing is a need for connectivity to the internet which is not realistic in most of the developing countries because of cost and limited network coverage. Edge computing can substitute in areas with no coverage and complement cloud computing in areas with limited network coverage. Edge enables storage and processing of data locally and make it accessible to the users [37, 20].

2.4.6 Scalability

Scalability involves ability of system to adapt to changes e.g. increase in number of devices connected while giving optimal performance. In this case, the system should be able to accommodate the connection of new hydroponic farms, efficient transmission of data to gateways and dispense information to farmers effectively.

2.4.7 Ease of use and sustainability

Given that most smallholder farmers are not tech savvy, they need a system that is easy to operate without continuous technical support. The system should also be adaptable to different farm sizes and a short learning curve for farmers [10]. In addition, the system should equip farmers with skills and build the capacity of the communities through provision of access to information about smart farming.

3 Enabling Technologies and Related Work

Heterogeneous technologies enable smart farming by facilitating sensing, transmission, analysing and storage of data. In this section we will discuss how different technologies can be applied to meet the requirement of smart farming in emerging economies. In section 3.1 we discuss the IoT and how it promotes connection of things and data collection. In section 3.1.1 we introduce different IoT protocols and how they perform in IoT and applicability in smart farming. Section 3.2 discusses the different wireless technologies and evaluate their applicability in IoT driven farming. We discuss the trend on LPWANs and the opportunities they offer for IoT. Section 3.3 discusses the role of cloud and edge computing and how they contribute to data processing and storage and sharing of information among different stakeholders. In the last section we discuss a selection of related work on smart farming and how they make use of the technologies discussed in the previous section.

3.1 Internet of Things

The term 'Internet of Things' was coined in 1999 by Kevin Ashton and is generally viewed as interconnected devices, objects, people and software. Internet of Things is rapidly developing, and it continues to receive much attention due to many markets and applications scenarios it offers. CISCO estimates that there will be 50 billion devices connected by 2020 [38] and McKinsey Global Institute estimated in 2015 that IoT will have an economic impact of between $3.9 trillion to $11.1 trillion per year in 2025 [39]. Internet of Things is a combination of technological push, human pull for connectivity between the immediate and wider environment and it emerged from development in identification technologies e.g. RFID and barcodes and from development of networked sensors and actuators [40].

There is no agreed on definition for the Internet of things. According to European Research Cluster on the Internet of Things (IERC), Internet of Things is

"A dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual "things" have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network, often communicate data associated with users and their environments" [41].

A user centric definition is given by citeauthorgubbi2013internet. IoT is "Interconnection of sensing and actuating devices providing the ability to share information across platforms through a unified framework, developing a common operating picture for enabling innovative applications. This is achieved by seamless large scale sensing, data analytics and information representation using cutting edge ubiquitous sensing and cloud computing" [40].

IoT has many applications areas and citeauthor asghari2019internet have given a comprehensive taxonomy of different applications including health-care, environmental, smart city, commercial, industrial and general aspects[42]. Smart farming/agriculture is a subsection of environmental application scenario. IoT platforms is used different agricultural sectors and the following are some examples: a henhouse to monitor and control environmental factors (temperature, humidity, carbon dioxide, ammonia levels [43], hydroponic greenhouse [44], monitoring and control of irrigation system in rural communities [45], smart irrigation in tunnel farming [46], smart animal farm [47].

A generic three-layer IoT architecture consisting of sensing, transport and application layer is depicted in Figure 8 and it can also be extended to five layers with inclusion of network and processing layers between the second and third layer [48, 36]

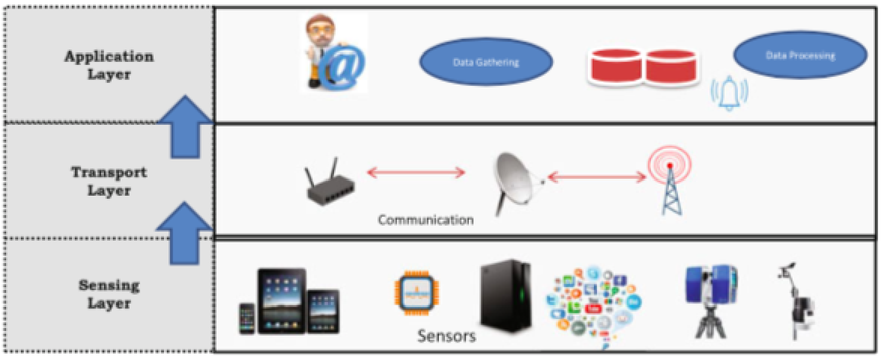


Figure 8: IoT based agricultural framework (Source: [48]).

IoT in agriculture consists of several layers interconnected things and interfaces. citeauthorray2017internet provides a six layer framework for a fully fledged agricultural solution based on IoT[29]. Figure 9 shows these six layers and interconnection between them. However, the service layer in this framework doesn't include edge plane and data is directly sent to the cloud and no analysis of data is done either at this stage.

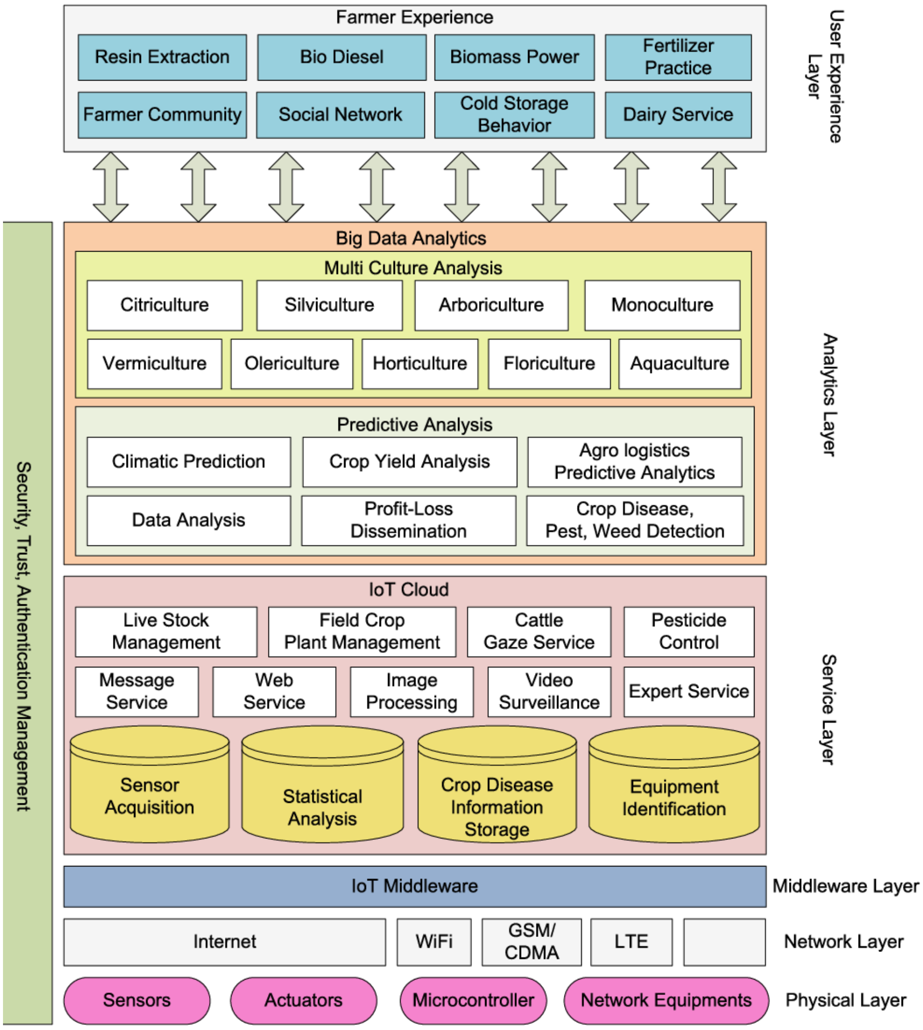


Figure 9: IoT based agricultural framework (Source: [29]).

Even though 20 years have passed since IoT was first introduced, there is no unified IoT architecture and different protocols and standards are used to connect IoT parts depending on the IoT use case. In the next section we will discuss existing IoT application layer protocols that are currently used by developers and researchers.

3.1.1 IoT application layer protocols

Application layer protocols are used to update the online servers with the current readings of the sensor nodes and also carry commands from applications to the sensor nodes [49]. Figure 10 illustrates the communication between end devices, online servers and applications. Several application layer protocols have been suggested and these include Constrained Application Protoco (CoAP), Message Queuing Telemetry Transport (MQTT), Extensible Messaging and Presence Protocol (XMPP), RESTFUL Services (Representational State Transfer), AMQP (Advanced Message Queuing Protocol - a corporate messaging protocol that emerged from financial industry [49]), Websockets and HTTP (designed for WEB and not optimal for IoT as it is heavy weight protocol [50]). In this section we will only consider MQTT and CoAP, which are the most common protocols in IoT systems.

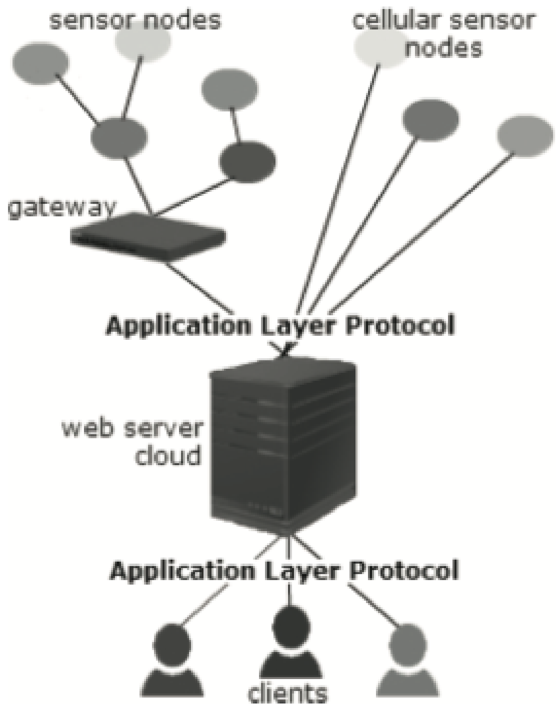


Figure 10: Application layer protocols source ([49]).

3.1.1.1 CoAP The Constrained Application Protocol (CoAP) was designed by Internet Engineering Task Force (IETF) to address the requirements of resource constrained devices[49]. It uses request/response and resource/observe (variant of publish/subscribe) architecture making it interoperable with HTTP [50]. It is uses Universal Resource Identifier (URI) rather than topics thus publishing and subscription are done to a specific URI. It is a UDP based protocol, Datagram Transport Layer Security (DTLS) is used for security and to achieve reliability and Quality of Service(QoS), it utilizes four message types: Confirmable(message needs acknowledgement by the receiver), Non-Confirmable(message doesn't need acknowledgment), Acknowledgment(reception of confirmable message confirmed) and Reset (message received but couldn't be processed) [49]. Authors in [49] argue that even though CoAP is designed for IoT, its use of DTLS for security increases network traffic as DTLS handshakes require add packets and computation resources thus affecting the battery lifespan on the end devices.

	MQTT	CoAP
Application Layer	Single Layered completely	Single Layered with 2 conceptual sub layers (Messages Layer and Request Response Layer)
Transport Layer	Runs on TCP	Runs on UDP
Reliability Mechanism	3 Quality of Service levels	Confirmable messages, Non-confirmable messages, Acknowledgements and retransmissions
Supported Architectures	Publish-Subscribe	Request-Response, Resource observe/Publish-Subscribe

Figure 11: Difference between CoAP and MQTT. source ([51]).

3.1.1.2 MQTT Message Queuing Telemetry Transport Protocol is a lightweight publish/subscribe protocol that uses topics as the addresses where the messages are published to and subscribed to by the clients [50]. Topics are contained in a broker [49] - these are servers that publishers send messages to and where clients automatically receive updates on the topic they subscribed to. They are many open source brokers e.g. mosquitto. MQTT runs on TCP and uses TLS/SSL for security [50].

3.1.1.3 Suitability in smart farming

citeauthornaik2017choice did an in-depth comparative study of four (HTTP, AMQP, MQTT and CoAP) application layer protocols have been done[50]. According to the author [50] CoAP requires lowest power and lower bandwidth than MQTT in transferring same payload under same network conditions. However, MQTT does better in terms of Quality of Services and reliability. In addition, MQTT is used by large number of organizations in the world but not yet global standard as HTTP. In [51] performance analysis between MQTT and CoAP shows that performance of the protocols depend on the network condition: MQTT packets have low delays for lower packet loss but CoAP performs better if the value of packet loss increase due to smaller UDP headers as compared to TCP headers required in retransmission of message. They also suggest that difference in performance can be exploited at the gateway by detecting network condition and using the protocol that gives best performance depending on prevailing network conditions. Whereas smart gateway has the above mentioned advantages, we have not implemented it in this thesis. However, the choice of this protocol depends on the conditions and requirements of the IoT system (consider end devices- communication between local server and user devices).

3.2 Wireless Communication Standards

Traditionally, connectivity in IoT has mainly been provided by short-range multi-hop technologies based on unlicensed spectrum or long-range cellular networks. A new promising solution for IoT wireless connectivity is the Low Power Wide Area Network (LPWAN), which offers long-range [52]. IoT can connect directly to the Internet or through a gateway. For devices to connect to the Internet directly, they must use Internet Protocol (IP) and non-IP connectivity is done through an Internet gateway. However, devices can communicate through non-IP protocols within a local network. This section will look at these three approaches and discuss their feasibility in smart agriculture in developing countries.

3.2.1 Short-range communication

The most common short-range wireless technologies include Bluetooth, ZigBee, near field communications (NFC), radio frequency Identification (RFID), ZigBee, 6LoWPAN, Thread, Wi-Fi and Z- wave which is a proprietary system [52]. These technologies are from different vendors, and one of the biggest challenges is interoperability. As shown in figure **figure needed** different some standards, one or few network layers and others define entire network layers in Open Systems Interconnection (OSI) model. This problem is addressed by different organizations that define standardization procedures and testing to guarantee interoperability between devices [53].

Short-range technologies have the advantage of low power consumption- a requirement in IoT but they have a limited coverage, which hinders its application in some IoT scenarios. These technologies are primarily used in personal area networks or local area network. In the following section we will discuss the different features of four of the common short-range protocols.

3.2.1.1 Bluetooth Bluetooth is a wireless communication technology operating on 2.4Ghz and was previously standardized as IEEE 802.15.1 but currently maintained by Bluetooth SIG [53]. It is mainly used in personal area network with range of upto 10 meters and it uses star network topology. It is a low power technology and devices are mostly battery powered. It has a throughput of upto 2MBps. Bluetooth Low Energy (BLE) is a new standard aimed at reducing power consumption and increasing the life-time of the coin cell batteries while the downside of this is low data throughput [53].

3.2.1.2 ZigBee ZigBee is based on IEEE 802.15.4 link layer standard and is managed by ZigBee Alliance. It is a low power, low cost and low throughput (up to 250KBps) with a mesh network topology making it possible to connect with thousands of nodes [53]. ZigBee network requires an application-level gateway to connect to the Internet. ZigBee has low-duty cycle and are suitable for agricultural applications where periodic information update is needed such as irrigation management, pesticide and fertilizer control and water quality management [54].

3.2.1.3 6LoWPAN 6LoWPAN 6LowPAN (IPv6 over Low power Wireless Personal Area Networks) is a standard by 6LoWPAN working group of the Internet Engineering Task Force (IETF). Compared to the other standards above, 6LoWPAN enables devices to directly communicate over the Internet [53]. It operates on 2.4-GHz and the 868MHz/915MHz ISM bands and it uses mesh network topology. It only supports IP version 6 (IPv6) thus it requires a IPv6-to-IP version 4 (IPv4) conversion protocol in the gateway [53].

3.2.1.4 Wi-Fi Wi-Fi is based on the IEEE 802.11 standard. It operates on 2.4 GHz and 5 GHz with star topology and access point (AP) as gateway. It has a range of 100m and a throughput of up to 72Mbps [55]. Most of the new devices come with Wi-Fi software and the TCP/IP software making integration easier. The downside of this standard is that it has high power consumption mainly due to high data rate and coverage. However, advanced sleep protocols and power management design mechanism to increase the lifetime of battery powered devices [53]. In agricultural applications, WiFi enables connection of multiple types of devices through heterogeneous architectures over an ad-hoc network [54].

3.2.2 Low-Power Wide Area Networks (LPWANs)

Low-Power Wide Area Networks utilize unlicensed frequency bands (2.4 GHz, 868/915 MHz, 433 MHz, and 169 MHz depending on region) and have star network topology [56]. They are known for low power consumption and wide area coverage hence they are termed as Low Power Wide Area (LPWA) technology. The new physical layer design aimed at very high receiver sensitivity enables short-range devices to have coverage of about 10-15 and 2–5 km in rural and urban areas respectively [53]. According to [52] the use this paradigm in IoT connectivity with long-range and low data rate is encouraged by the sporadic transmissions of very small packets by the IoT devices. The end devices connect to the Internet through a gateway. Some LPWAN solutions include LoRa, Sigfox, Ingenu-RPMA, DASH7, Weightless [52, 56]. DASH7 and Weightless are open source while the rest are proprietary systems. In the following sections we look at three of the most common LPWANs.

3.2.2.1 Long Range Radio (LoRa)

LoRa is a spread spectrum modulation technique developed by Semtec [3], which is based on chirp spread spectrum (CSS) technology [57]. LoRa physical layer enables long-range communication and it operates on different frequencies depending on the region: 902–928 MHz band (United States), 863– 870 MHz band (Europe), however it can also work on lower ISM bands at 433 MHz and 169 MHz [52]. LoRa is a proprietary product and one of the mostly used communication protocols built above the LoRa is LoRaWAN. LoRaWAN is an open communication protocol and network system architecture [58] by LoRa Alliance[4], a nonprofit association. LoRaWAN network architecture consist of the end nodes, gateway, and network server. The network server handles all the complexities related to packets de-duplication and decoding [57]. The end devices communicate with gateway using LoRa and from gateway packets are forwarded to network server through backhaul interfaces like 3G or Ethernet [25].

3.2.2.2 SigFox

SigFox is based on ultra-narrowband technology (UNB) and it uses 915MHz ISM band (United States) and the 868MHz (Europe) [55]. It was first released in 2009 and IoT service provider as its business model thus no documentation is publically available [52]. The communication range is upto 30 km and this is achieved by transmitting at very low data rates (up to 100bps) [55].

3.2.2.3 Ingenu-RPMA

Ingenu-RPMA is a proprietary technology by On-Ramp Wireless which developed 802.15.4k standard and owns the right to Random Phase Multiple Access technology [52]. According to [56] Ingenu-RPMA achieves higher throughput and capacity compared to other technologies that operate on sub-GHz band because of its flexibility in using spectrum across different regions. It has a typical uplink data rate of 50 kbps [59].

3.2.3 Cellular Network

Cellular network is an established world-wide system with a potential for providing ubiquitous access. These include GSM, UMTS and LTE networks. It is

[3] `https://www.semtech.com/lora/what-is-lora`
[4] `https://lora-alliance.org`

considered as a prominent candidate in the provision connectivity to IoT due to its capillary geographical coverage, technological maturity and cost effectiveness due to high revenue it generates from other services like video, voice and data [60]. However, due the expected growth of IoT devices and sporadic nature of traffic generated by them, the current cellular network could collapse because of signalling traffic from these devices [60, 52]. To address these shortcomings, revamping of second generation/ Global System for Mobile Communications (2G/ GSM) [52] and LPWA solutions have been introduced to cope with the requirements of IoT. The solutions introduced by Third Generation Partnership Project (3GPP) include EC-GSM-IoT, eMTC, LTE and NB-IoT [56]. Fifth generation (5G) standards have been released in 2018 and the earliest deployment are expected in the second quarter of 2019 whereas sixth generation (6G) is just on its start in terms of research and artificial intelligence (AI) is seen as the driver for 6G [61].

3.2.4 Connectivity with alternative low cost networks

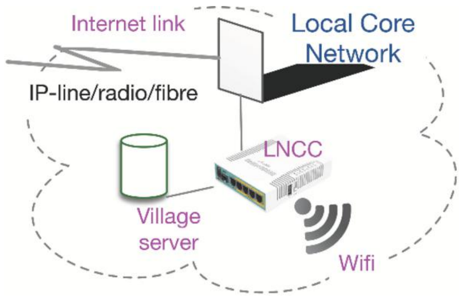
Bringing Internet connectivity to remote regions does not make a good business case for mainstream network providers. Alternative Networks have emerged and deployed in areas where that traditional network could not cover because of high initial and operational costs. privacy concerns and limited connection to the power grid [62]. Alternative networks are mostly small scale, individuals and other interested stakeholders share the cost of setting up and maintenance expenses. Most smallholder farmers in developing countries are not connected to the Internet. This hinders access to information related to smart farming and emerging technologies in general. Provision of internet connectivity is important in solving this information asymmetry.

Internet Lite is a solution by Basic Internet Foundation aimed at addressing the digital divide challenge [63]. It aims at providing affordable internet access to the residents of the developing countries and there by bridging the digital divide and working towards achievement of the UN sustainable development goals(SDG) where internet is seen as an enabler in attaining these goals. The broadband service provided by traditional mobile service providers continues to be expensive and limited thus limiting the opportunities offered by the internet to attain SDG.

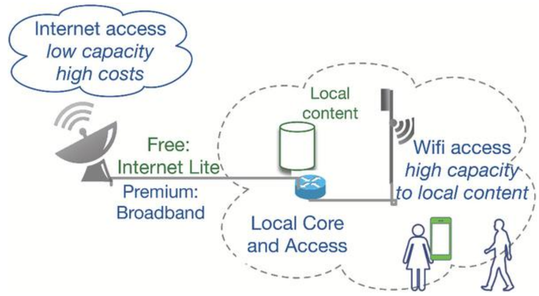
To achieve this, the Basic Internet Foundation used low-cost network infrastructure that includes local core network, a local network, a centralized core, and backhaul network [64, 65]. Figure 12a illustrates these components. citeauthorBasicInternet have defined InfoInternet standard that is aimed at making access to information free (text, pictures) [65]. This is implemented in the Local Network Control Centre (LNCC)[5]. Internet Lite solution complies with the net neutrality requirement by restricting the content type, not the content. Contents are filtered depending on the number of bits consumed. This approach accommodates both the users of basic Internet and users with paid subscriptions. For the users of Internet Lite, the dynamic content e.g. video is filtered out while the text and pictures are allowed while if a user has a voucher, then all content is allowed.

The solution offered by Basic Internet is relevant to smart farming in developing countries for these two reasons. 1) Basic Internet solution has WiFi access point (Information spots) where farmers can access information as shown in figure 12b. 2) Internet Lite offers free connectivity to Internet for text and pictures. This can be used to share data from farms to other stakeholders i.e. for transmitting data store at the local servers to the cloud where other stakeholders can access it. How this solution is integrated into the solution proposed in this thesis will be discussed in section 4.

[5] `https://its-wiki.no/wiki/BasicInternet:Home/NOsolutions`



(a) Local core network



(b) WiFi access point

Figure 12: Internet Lite source ([63])

3.2.5 Applicability in Smart farming

Figure 13 depicts a comparison of the main wireless communication technologies and parameters such as transmission range, data rate, energy consumption and cost. All these technologies have their own strengths and weaknesses and therefore a choice depends on the application scenario. In this thesis, we are considering a smart hydroponic farm in resource-constrained region (poor network coverage, lack of power connectivity). Hydroponic farm require monitoring of nutrient solutions and other factors within the greenhouse for efficient food production. In addition, farmers do not afford to install a complete monitoring system due to cost. We therefore consider a scenario where farmers have shared infrastructure such that the sensors deployed in individual farms transmit data to community owned gateway and local server that hosts the network server. In such scenario range of the wireless technology becomes a vital factor to consider as hydroponic farms owned by smallholder farmers are located in different parts of a village. Moreover, high energy efficiency and low cost is a requirement is such a scenario.

	Spectrum cost	Deployment cost	End-device cost
Sigfox	Free	>4000€/base station	<2 €
LoRa	Free	>100€/gateway >1000€/base station	3-5€
NB-IoT	>500 M€/MHz	>15000€/base station	>20 €

Table 2: A cost comparison of LoRa, SigFox and NB-IoT (Source: [66]).

Considerations	Traditional Cellular			Cellular LPWA		Proprietary LPWA			Short Range		
	2G	3G	4G	LTE-M	NB-IoT	SigFox	LoRa	Ingenu	Wi-Fi low power	ZigBee 3.0	Bluetooth LE
Outdoor coverage	>10km	>10km	>10km	>10km	>15km	>15km	>10km	>15km	<1km	<300m	<100m
Indoor coverage	High	Medium	Medium	Medium	High	High	High	Very low	Very high	Medium	Low
Energy efficiency	2-5 years	<10 days	<10 days	>10 years	>10 years	10-20 years	10-20 years	10-20 years	6-12 months	6-12 months	6-12 months
Typical uplink data rate	50 kbps	1 Mbps	10 Mbps	1 Mbps	20 kbps	100 bps	25 kbps	50 kbps	1 Mbps	250 kbps	1 Mbps
Bidirectional communication	Yes	Yes	Yes	Yes	Yes	Limited downlink	Yes in Class A	Yes	Yes	Yes	Yes
Mobility	Very high	Very high	Very high	Very high	High	Very low	Low	Medium	Medium	Low	Very low
Localization	Yes	Yes	Yes	Yes	n/a	No	Limited accuracy	n/a	Yes	Yes	yes
QoS & security	Very high	Very high	Very high	Very high	High	Very low	Low	Low	Medium	Medium	Medium
Connectivity cost	Medium	High	Very high	High	Medium	Very Low	Low	Low	Medium	Medium	Medium
Scalability	High	High	High	High	Very high	High	High	High	Low	Low	Very low
Future proofness	Medium	Medium	Very high	High	Very high	Low	High	Low	Medium	High	High
Global reach & interoperability	Very high	Very high	Very high	High	High	Medium	Low	Very low	Low	Medium	High

Figure 13: A comparison of different wireless technologies (Source: [59]).

With this in mind, we first consider the feasible wireless technology to connect the devices to edge layer and then backhaul connectivity between the edge layer and cloud. Bluetooth, ZigBee, 6LoWPAN and WiFi all have a short communication range. This will require high node density to cover a small area which also adds complexity and reduce battery lifetime. As such, they are not suitable to farming that require a shared infrastructure to reduce cost and long range is required.

A comparative study of LWPAN technologies is given [66, 67]. citeauthormekki2019comparative compare large-scale deployment of LoRa, SigFox and NB-IoT [66]. From this comparison Lora and SigFox are considered as cost-effective as spectrum and deployment cost for NB-IoT is high. SigFox end devices are cheaper but the deployment cost is high and on the other hand LoRa end devices are slightly expensive but its deployment cost is lower. Table 2 shows this comparison.

Even though LoRa is a proprietary product, its upper layer, LoRaWAN is open, operator and subscription free making it simple to deploy and manage infrastructure whereas in SigFox, users purchase end devices and subscription for the devices from the network operators [67]. In terms of cost, openness and availability SigFox is currently not feasible in most developing countries. Ingenu-RPMA has several private deployments that require a yearly subscription and upfront payment per application and device [68]. This makes it unsuitable for deployment in rural areas in developing countries.

LWPANs generally offer longer range and a limited throughput. LoRa offers long range and low bandwidth and it compliments and fill the gap cellular and short-range technologies to meet the requirements of IoT use case scenarios. Figure 14 shows this comparison. This makes it suitable for scenarios like smart farming in rural areas where farms are spread in a large area and the data from sensors in farms are short and sporadic. Transmission of data can also be limited to when a certain threshold is met.

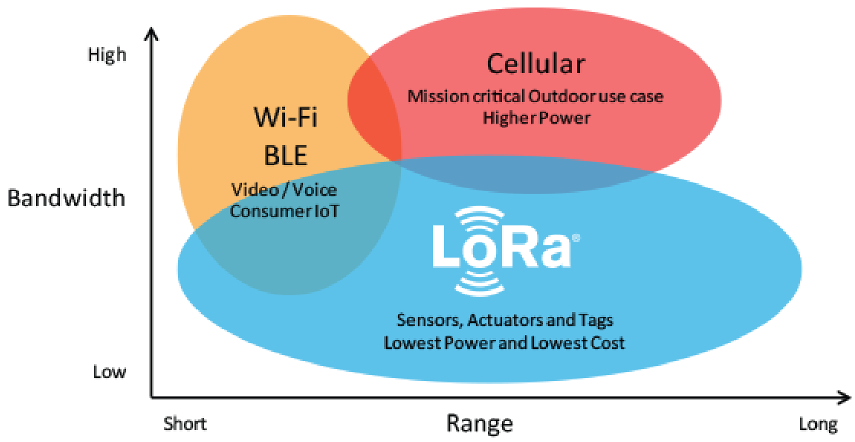


Figure 14: A range comparison of short range technologies, cellular and LoRa.

The flexibility offered by LoRa ecosystem makes it suitable for local deployment [66] and is ideal for deployment in rural areas. Low cost single board computers and micro-controllers like Raspberry Pi and Arduino can be used to construct gateways and end devices to reduce cost [69]. The proliferation of low-cost hardware, availability of open-source software and initiatives like Sparkfun[6]

[6]https://www.sparkfun.com/categories/23

and Adafruit [7] has led to the third wave of Do-It-Yourself(DIY) which is seen as revolutionary, enabling anybody anywhere to create innovative solutions and this suits well regions where industrial manufacturing infrastructure is lacking [70].

Cellular is widely available in most developing countries. The technology is mature, secure and it offers high quality of service. The disadvantage is that devices need sim cards to connect to the network and data plans offered in developing countries are very expensive. Cellular LWPANs are not yet deployed in most of these countries are thus not feasible for smart farming in the near future. In addition, they are not cost effective e.g NB-IoT as shown table 2. Cellular, however, is suitable for backhaul connectivity. From the edge server the data can be consolidated and sent to the cloud regularly depending on the needs of the smart farm ecosystem. Despite wide coverage and its presence in almost every part of the world, it continues to be expensive, especially in developing countries. Thus low cost connectivity provided by Basic Internet can complement it.

Table 3 shows a comparison of different wireless technologies that are applicable for smart farming. We considered four main factors based on the application scenario: cost, power efficiency, range, availability and openness

- very good: ++, good:+,
- reasonable: 0,
- not good: −, not so good − −,
- not applicable: X

[7] `https://www.adafruit.com`

Table 3: Cost, Energy efficiency and range

Wireless technology	Cost	Energy efficiency	Range	Availability and openness
Bluetooth	++	++	−	++
ZigBee	++	++	−	++
6LoWPAN	++	++	−	++
Wi-Fi	++	−	−	++
LoRa	++	++	++	++
SigFox	+	++	++	−
Ingenu-RPMA	++	++	-	−
Cellular-LWPN	−	++	++	−

As shown in table 3 features of LoRa are favourable for the implementation in rural areas. It offers longer range, cost and power efficiency. It also has LoRaWAN protocol which is open and enables deployment of network anywhere. From this analysis, we consider LoRa as the suitable solution for the connectivity between the devices and the gateway. Solutions offered by Basic Internet architecture can then complement cellular for connectivity between the edge layer and the cloud. Basic Internet solution also offers WiFi access points that is suitable for access of farm data that is stored locally.

3.2.6 Fundamentals of LoRa

As described in section 3.2.2.1, LoRa, a technology by Semtech, uses chirp spread spectrum(CSS) modulation to achieve long range while maintaining low power usage. The carrier signals in LoRa have chirps that enable signals to travel long range and still be demodulated even if the signal power is 20dB below the noise floor[71]. LoRa offers configuration parameters that can be modified to achieve different power consumptions, transmission distance and data rate. According to citeauthorbor2017lora, LoRa device configuration involves a combination of different bandwidth, spreading factors, coding rate and transmission power resulting to over 6720 setting combinations[72]. In the following section, we look at these four parameters, what they mean in LoRa and the inevitable trade-off because of different combinations of these factors. Table 4 gives a summary of this parameters.

Spreading Factor (SF): SF refers to how spread a chirp is and the *spread-*

ness is depedent on the numbers of bits in a chirp[73]. LoRa offers spread factor of between SF6 and SF12. An increase in SF reduces the transmission rate by half and doubles the airtime of the packet, thus increase in power consumption [72]. However, increase of transmission time gives receiver enough chances to sample the signal which results in higher signal-to-noise ratio(SNR) increasing probability of decoding correctly[73]. SF6 is used when the receiver is close to the transmitter and spreading factor of 12 is used when the distance is higher or obstacles in the path making it possible to decode/demodulate signals down to -136 dBm [74].

Coding Rate(CR): CR is a forward error correction code aimed at increasing resilience against interference [73]. These are 4/5, 4/6, 4/7 or 4/8. In LoRa 4/5 CR means that for four bits of data 1 bit is added. Higher CR leads to higher transmission time due to increased number of bits but offers improved protection from interference[72].

Bandwidth (BW): BW is a range of frequencies between the upper and lower frequencies of the transmission band. High bandwidth gives higher rate thus shorter air time but with a lower sensitity[72]. 125kHz, 250kHz and 500kHz are mostly used in LoRa.

Transmission Power (TX): LoRa permits adjustment of transmission power like other wireless radios. Transmission power directly affects the amount of power required to transmit a packet. Therefore higher TX increases the SNR thus improving chances of packet being received and survival against attenuation caused by environment at the cost of increased energy usage at the transmitting end.

LoRaWAN: While LoRa defines the physical layer which is responsible for long range communication, LoRaWAN defines the system architecture for the network and the communication protocol. Figure 16 shows the LoRa and LoRaWAN protocol stack. According to LoRaWAN specifications, the network architecture consists of the end nodes, gateways, network server and the application as show in figure 15. To avoid the complexity and battery effect of mesh network architecture, LoRaWAN employs a star topology[58]. The end nodes are agnostic of the gateways thus they are not associated with any gateway. Because of this, multiple gateways can receive data from end nodes. The network

Settings	Values	Effect
Bandwidth	125 . . . 500 kHz	Higher bandwidths allow for transmitting packets at higher data rates (1 kHz = 1 kcps), but reduce receiver sensitivity and communication range.
Spreading Factor	$2^6 \ldots 2^{12} \frac{chips}{symbol}$	Bigger spreading factors increase the signal-to-noise ratio and hence radio sensitivity, augmenting the communication range at the cost of longer packets and hence a higher energy expenditure.
Coding Rate	4/5 . . . 4/8	Larger coding rates increase the resilience to interference bursts and decoding errors at the cost of longer packets and a higher energy expenditure.
Transmission Power	4, . . . , 20 dBm	Higher transmission powers reduce the signal-to-noise ratio at the cost of an increase in the energy consumption of the transmitter.

Table 4: LoRa configurations and effects on communication perfomance (Source: [71]).

server has the purpose of de-duplicating the packets sent by end devices, data authentication, and sending acknowledgement.

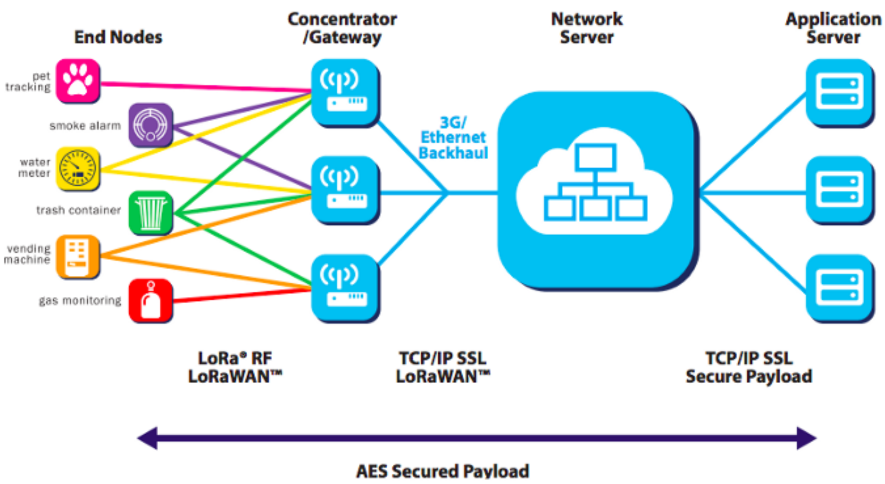


Figure 15: LoRaWAN network architecture (Source: [58]).

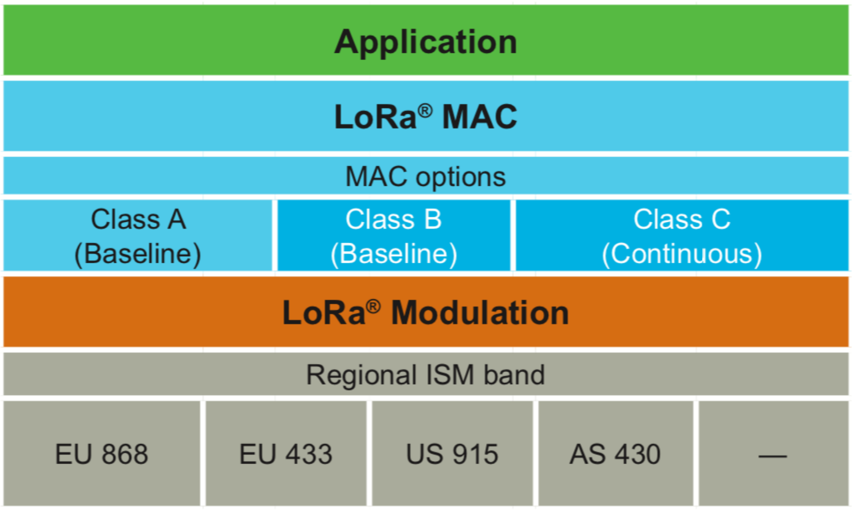


Figure 16: LoRaWAN protocol stack (Source: [58]).

The LoRaWAN network server optimizes data rates and battery lifetime using adaptive data rates (ADR)[58]. The ADR is determined by maximum SNR of the last 20 received uplink messages and from this the network server optimizes the airtime to ensure as lowest TX power is used [75]. ADR also enhances the overall capacity of the network and scalability. With ADR the network is scalable i.e. increased number of nodes supported as compared to default LoRaWAN settings[67]. The scalability is also affected by the regulatory constraints on the use of physical medium since LoRa is using ISM bands. The imposed duty cycle for LoRa is 1%. Figure 17 shows how combination of different parameters, payload size and the resulting time on air.

LoRa mode	BW	CR	SF	time on air in second for payload size of 5 bytes	55 bytes	105 bytes	155 Bytes	205 Bytes	255 Bytes
1	125	4/5	12	0.95846	2.59686	4.23526	5.87366	7.51206	9.15046
2	250	4/5	12	0.47923	1.21651	1.87187	2.52723	3.26451	3.91987
3	125	4/5	10	0.28058	0.69018	1.09978	1.50938	1.91898	2.32858
4	500	4/5	12	0.23962	0.60826	0.93594	1.26362	1.63226	1.95994
5	250	4/5	10	0.14029	0.34509	0.54989	0.75469	0.95949	1.16429
6	500	4/5	11	0.11981	0.30413	0.50893	0.69325	0.87757	1.06189
7	250	4/5	9	0.07014	0.18278	0.29542	0.40806	0.5207	0.63334
8	500	4/5	9	0.03507	0.09139	0.14771	0.20403	0.26035	0.31667
9	500	4/5	8	0.01754	0.05082	0.08154	0.11482	0.14554	0.17882
10	500	4/5	7	0.00877	0.02797	0.04589	0.06381	0.08301	0.10093

Figure 17: Time on air for different payload sizes (Source: [69]).

device type LoRa also offer better energy efficiency and are suitable for this areas as connection to power grid is not guaranteed. LoRaWAN has three end device classifications (Fig 18): class A(end device transmission followed by two short download windows), B(scheduled receive slots through synchronization by gateway beacon), and C (continuously listening: open windows to receive data) [58]. According to a predictive model by citeauthorliando2019known on the lifetime of end nodes, battery efficiency and longevity can be increased by choosing carefully the micro controllers unit used in end nodes and using the right combination of spreading factor, transmission power and duty cycle[73]. Choosing the right combination of hardware and settings is particularly important in rural areas where connection to power is not guaranteed and also reduce the cost of replacing batteries often.

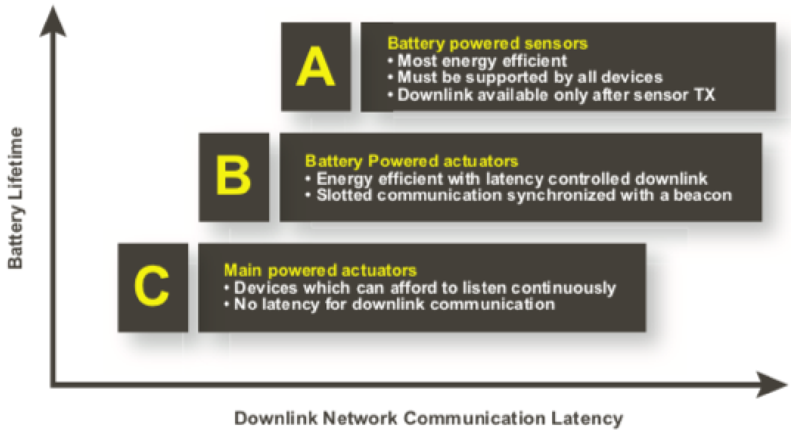


Figure 18: LoRa device classes and power consumption [58].

In this section, we have introduced different wireless technologies. We have discussed the short range technologies and cellular. The new incomers in the LPWANs the opportunities and challenges they offer. We have also introduced alternative low cost communications for remote unconnected areas. From the general requirement of the use case, LoRa was identified to fulfil the requirement and alternative networks for backhaul where cellular is unavailable. In the last section we have introduced the basics of LoRa and LoRaWAN.

3.3 Cloud vs Edge Computing

Cloud computing was seen as one of the computing paradigms that could deliver utility computing vision, namely, computing to be commoditized and offered like other utilities such as water, electricity, gas, and telephony [76]. citeauthor-vaquero2008break have analysed over 20 definitions of cloud computing and they have proposed the following definition:

"Clouds are a large pool of easily usable and accessible virtualized resources (such as hardware, development platforms and/or services). These resources can be dynamically reconfigured to adjust to a variable load (scale), allowing also for an optimum resource utilization. This pool of resources is typically exploited by a pay- per-use model in which guarantees are offered by the Infrastructure Provider by means of customized (Service-Level Agreements) SLAs" [77].

The National Institute of Standards and Technology (NIST) of the U.S. Department of Commerce has defined cloud computing as "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction " [78].

This ubiquitous and on-demand access to storage and computational resources has made cloud computing gain copious usage in different sectors. In addition, cloud centralized architecture offers effective economies of scale [79]. In the agricultural sector, the usage of cloud computing has grown due to usage of ICT and sensor technologies. This has enabled data to be collected and pushed to the cloud for storage and analysis. Production of big data from farms and storage in cloud give insights to farm operations and facilitate real-time decision making [28]. This also enables the sharing of data between different stakeholders and remote control of farming operations.

Cloud computing has enabled users to obtain computing and storage resources provided by data centres at anytime and from anywhere [80]. Cisco Internet Business Solutions Group predicted that there would be 50 billion devices connected to the Internet by 2020 [38]. The data produced by these devices at the edge of the network pose a challenge to networks and central cloud computing. The increase in number of devices and rapid advancement of Internet technologies comes with its own unique set of challenges such as latency issues for time critical applications, storage of sensitive data at external service providers raises privacy issues and limited bandwidth to transmit large amounts of data produced by the devices [81].

Edge computing has been emerging approach in distributed computing in the last few years. It extends traditional cloud computing to the edge of the network. It is worth noting that fog computing and edge computing are used interchangeably in literature. However, they are some that make distinction between these two paradigms. OpenFog consortium defines fog computing as a "system-level horizontal architecture that distributes resources and services of computing, storage, control and networking anywhere along the continuum from the cloud to things. Fog computing is different from edge computing and provides tools for distributing, orchestrating, managing, and securing resources and services across networks and between devices that reside at the edge. Edge architecture places servers, applications, and small clouds at the edge. Fog jointly works with the cloud, while edge is defined by the exclusion of cloud " [82]. citeauthoryousefpour2019all made in-depth comparison of edge and fog computing and other related paradigms. From this, edge viewed as one of the immediate first hop from IoT devices like WiFi access points or gateways[83].

Edge computing sits at the peak of Gartners Hype Cycle for Cloud Computing, 2018 [84] and disillusionment and false starts are to be expected before standardization and wide adoption. However, it has the potential to complement and decentralize the current centralized cloud architecture and legacy data centres [85].

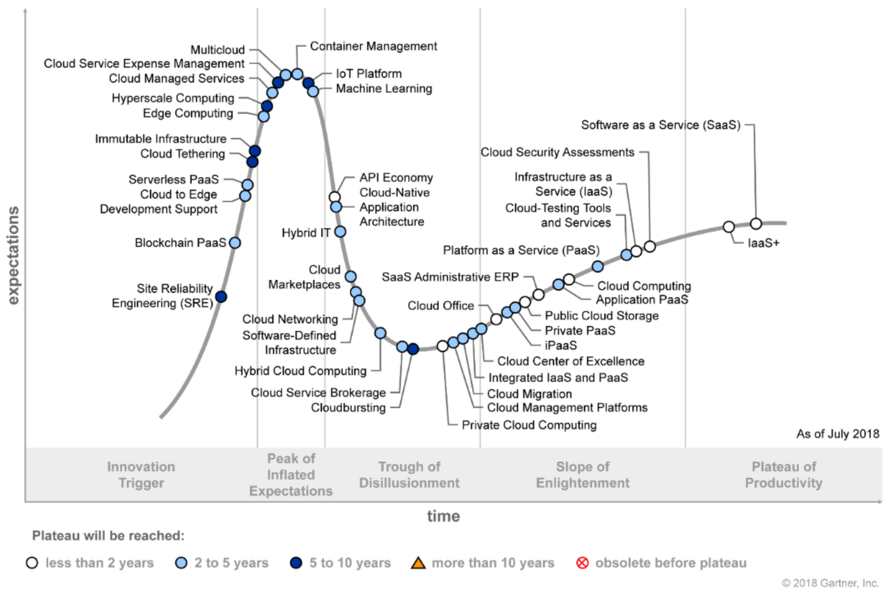


Figure 19: Gartner's Hype Cycle (Source: [84]).

Edge computing architecture is built on edge servers that offer storage, computing and networking services and enable communication and cooperation between decentralized devices without supervision by a third party [86]. This new paradigm extends the cloud services and has the potential to address the aforementioned challenges related to latency and privacy.

Traditionally IoT applications have stringent requirement of low latency, but this is not the case in smart and precision farming as network performance requirements are less stringent [44]. Furthermore, in most areas in developed countries where small-scale farmers reside is associated with insufficient infrastructure and limited bandwidth. The benefit edge computing offers in this context is filtering, pre-processing, analysing and aggregation of raw data before forwarding to cloud thus reducing bandwidth used and local caching for retrieval robustness and reducing the need for communication with cloud [87]. This also saves the user bandwidth if they depend on carriers data plan and also it gives the possibility of users to evaluate which connection and speed they can use at the edge [81]. Analysis can also be done at the edge. Edge analysis is "any data analysis task performed within an edge device (or leaf node) can be identified as edge analytics [37] e.g. smart plug instead of sending data to cloud every second can analyse data and only send when there is fluctuation in the energy consumed. In addition parameters like sampling frequency and communication frequency can be optimized to reduce bandwidth and storage cost and elongate the lifetime of the device. Knowledge inferring can also be done at the edge by comparing data collected from faulty sensor to the nearby sensor [88]. With storage and analysis at the edge improves privacy as no personal information data is stored in the centralized servers [85]. In agriculture, this is also important as regulations regarding data protection and privacy has not yet been adopted in most developing countries. Data storage at edge will enable farmers to have control over the data from their farms.

So far we have discussed how edge computing can reduce the cost of communication by reducing the amount of data transmitted to the cloud and reduce power consumption. But one of the fundamental elements that edge offers is putting humans in the control loop giving them control over their system and network links [79]. Such user centric design are important in smart farm as they put humans in loop making them part of the decision making process relating to the farm [89]. Since smart farming is data driven and decisions are based on analysis made on this, socially aware system with humans in control loop and local access to data will encourage adoption of such technologies. Adoption of technological innovations is influenced by farmers perceptions on the effectiveness and accrued benefits [90]. From this, the perception that farmers get from being in control due to benefits offered by computation done at the edge and being in the control loop and decision making could help adoption- same couldn't be said if computation is done at cloud and especially if farmers technological understanding is limited. However, the benefits offered by cloud computing in the general smart farming ecosystem shouldn't be overlooked- as it offers storage and remote access to important data to other stakeholders i.e agricultural extension officers and other experts for analysis and contribute decision making process.

Whereas the advantages of edge computing are many, in this thesis we intend to use edge analysis and storage so as to reduce the cost of transmitting data to cloud and local storage to ease access of data. Also governance policies related to transmission of data to cloud and frequency of transmission can be set depending on the needs of farmers and other stakeholders that consume the data produced at the farms. In addition simple analysis will be performed on the edge on the data received before notifications are sent to the farms. In this thesis, we therefore harness the benefits offered by edge and cloud solutions to meet the requirements of smart farming in developing countries. In deed, in most IoT applications scenario one size rarely fits all.

3.4 Related Work

The earlier applications of technology in precision and smart farming focused mostly on automating farm systems based on the data collected by sensors. citeauthorzamora2019smart argue that control area in agriculture have developed gradually and significant improvement has been achieved after integration of information and communication system into farm management system[44]. As such, there is a vast amount of literature on greenhouse and hydroponic smart farming and different approaches to monitoring of plants using sensors have been proposed. In [91], the authors have presented a current smart system that monitors the state of water that provides nutrient solution to the plants in hydroponic farming. It also presents auto calibrated pH sensors and use of wireless networks to monitor their functioning. citeauthorcrisnapati2017hommons presents a hydroponic monitoring and automation system with a responsive web framework[92]. Different wireless technologies are used in depending on the requirements of the agricultural applications scenario. In [93] a wireless control system for Tomato hydroponic farm using the 400 MHz band and IEEE 802.15.6 standard is described. The authors used 400MHz band as it less affected by plants than 2.4GHz band.

The inclusion of intermediary processing layers (edge or fog) has been recently introduced to smart farming implementations. citeauthorcaria2017smart have proposed a smart farming for animal welfare monitoring with fog layer that enables farmers to locally access the system, manually control parameters and actuators[94]. Authors in [95] present edge computing and IoT paradigms in agriculture and they implemented the system in a real hydroponic farm. A more advanced approach with edge computing and virtualization is presented by citeauthorzamora2019smart [44]. In their approach edge computing layer is enabled by Network Function Virtualization(NFV) technology so as to increases flexibility in deployment of control modules. citeauthortruong2018enabling have propose a software component to enable edge analytics on LoRaWAN[96]. The author argues that this is suitable for monitoring of environment and farmers in developing countries where network connectivity and cost are the key constraints and that data is consumed locally reducing the need for pushing data to cloud. citeauthorpham2016low have presented a low cost IoT solution based on LoRa gateway with local storage and access for rural African villages [69]. The solution suggested is part of European Union-Africa project[8] and is applied in monitoring of storage and farming facilities and it targets small and medium scale deployment scenarios in sub-Saharan Africa.

Above solutions show different implementation of different smart farming components such as IoT, edge and cloud computing and low cost approach to farming in resource constrained regions. A wide range of factors ranging from lack of infrastructure, high cost, limited access to technology to lack of technical know-how hinders the adoption of technologies in agriculture in developing countries. As such, smart farming solutions for such environments should consider the above factors for effective use of technology in food production and for sustainability of the said system. In this thesis we propose a low cost smart farming solution. Since smallholder farms are usually located in villages, it is

[8] https://www.waziup.eu

cost effective for them to share infrastructure. Consequently, LoRa communication link is used between individual farms hosting the hydroponic farms and the gateway and cellular network for backhaul. In addition, InfoInternet architecture can be integrated and used for access and local storage of sensor data. To encourage further DIY innovations and build the capacity of the local communities, a knowledge bank that includes instructions on related to system and information related farming can be stored and accessed locally. Intermediary processing layer at the edge offers pre-processing and consolidation of data, optimize communication to cloud resulting in reduced cost of pushing data to the cloud. Extensions officer can also access data remotely and give timely response to farmers.

In section two and three we have given a holistic view of the application of technology in agriculture, challenges related to the adoption of new technologies in the context of developing countries. We have suggested a smart hydroponic farming that aims at leveraging technological advancement to enable efficient food production for smallholder farmers. We have described requirements for smart hydroponic farming and suggested different technologies that can facilitate this.

4 Implementation

As already mentioned, agriculture is not exempted from the transformation caused by the fourth industrial revolution. The use of IoT and LPWANs in agriculture has already gained momentum in developed countries. In developing countries, however, mobile-based services are the main services that farmers have adopted. Due to a change in climate change and the need to produce food to feed the growing population, advanced technologies have to be adopted to food production efficient.

Considering the requirements of smart farming described in section refrequirements and the need of efficient food production, we propose a smart farming solution that draws upon IoT, edge computing and LPWANs. Recall section, LoRa was considered to conform with the requirements of cost, power consumption and long range. In addition, it offers flexibility of deploying networks as it not operator based and it allows the use of low cost hardware and open source software. This is particularly important as it can enable local individuals to design solution that meets their needs. Indeed as Fox described the availability of open source software and hardware drive the third generation of DIY, where individuals anywhere can invent solutions to meet their needs , especially in regions with minimum infrastructure [70].

In the proposed solution, the farms have a shared infrastructure. This will mainly entail the gateway and local server. The purpose is to reduce cost as it will be expensive and technically complicated for individual farmers to deploy the whole network. As such the farmers within the range of the network coverage will share the installation cost.

The rest of this section is as follows. Section 4.1 describes the architecture of the system used in this thesis. We will also discuss the various components of the system and their implementation in section 4.2 This section will also explain the experimental set-up used. In section 4.3 we discuss the results and the importance of building capacity of the farmers and their communities.

4.1 System architecture

The smart farming solution proposed here is aimed at helping smallholder farmers in rural areas to better monitor their hydroponics system. LoRaWAN network architecture is generally distributed with centralized cloud-based data aggregation centers which does not promote edge analytics making it unsuitable for developing countries due to the high cost of internet connectivity limiting pushing of data to cloud[96]. The solution proposed here incorporates edge layer and the system essentially comprises of three layers:

- IoT end devices layer,
- LoRa gateway and local server which hosts the edge layer and
- Cloud layer

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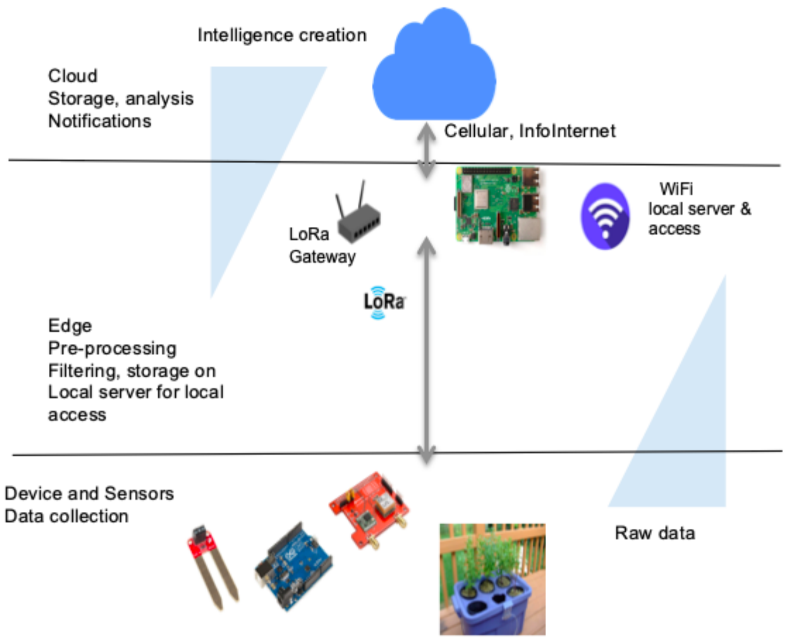


Figure 20: A three layer architecture

Figure 20 shows the three layers (Three-layer IoT architecture). The IoT end devices are located in the Hydroponic farm in the proposed solution. The edge layer consists of the LoRa gateway and local server. The local server hosts LoRaWAN network server for processing of LoRa packets and links end devices to the applications consumsing the data. This layer is responsible for processing of data so as to reduce the amount of raw data transmitted to the cloud. Typically the amount of raw data collected is big at the end device level while the intelligence created increases in the upper layers as data is processed to get meaningful information [82]. The therefore data processing is done in the local server to give meaningful information to the farmers and send notifications when necessary. The data is also stored at the local server as it consumed locally and pushing of data to cloud is not done in real time so as to overcome challenges related to the bandwidth usage and cost.

Due to minimal infrastructure and limited information on smart farming, solutions designed for developing countries do not only include collection of data and integration of communication and information to farm management system, but it also requires the provision of and access to information on smart farming. To this end we have included WiFi access points or 'information spots' from Basic Internet Foundation as access to information empowers and builds the capacity of local communities. In addition, their backhaul connectivity solution is suitable in rural area scenarios as discussed in section 3.2.4. Notification is an important part of smart systems. To this end, we have used EnvayaSMS gateway application that runs on Android phone. Figure 21 shows an overview of the whole system.

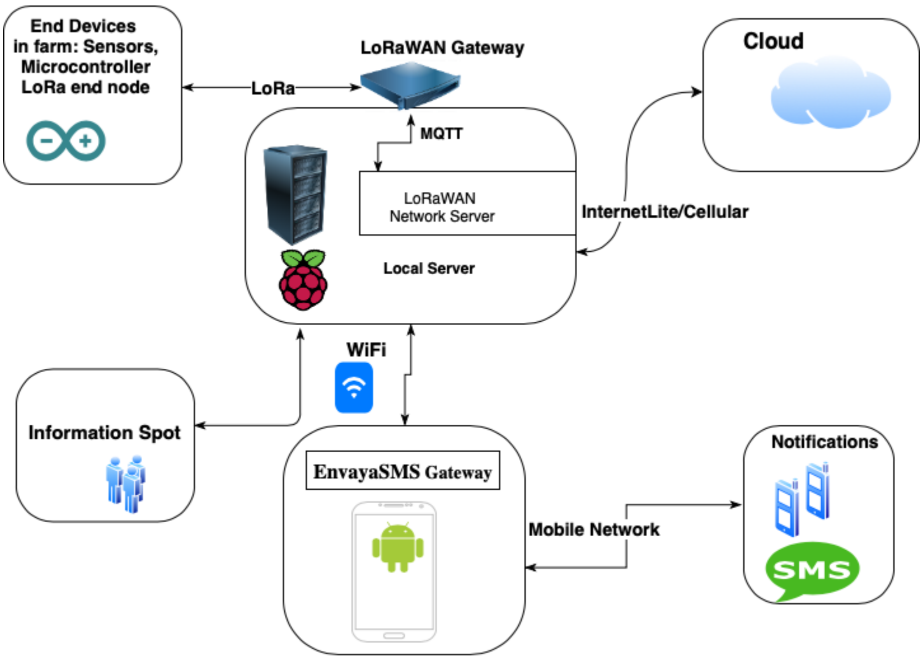
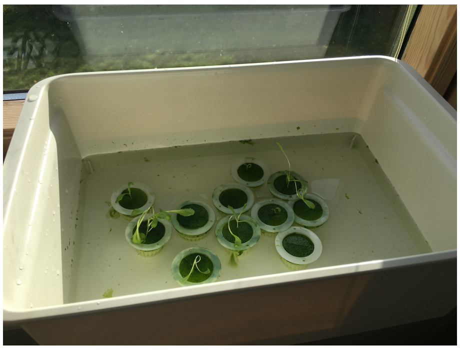


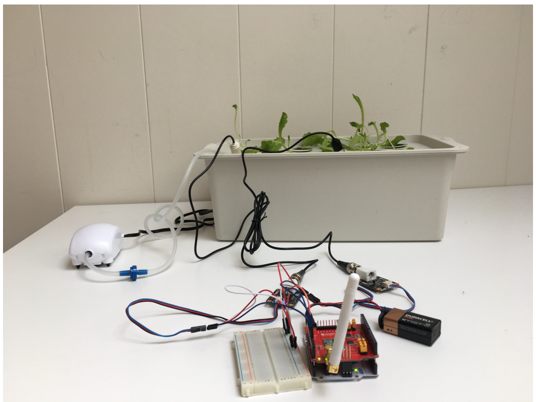
Figure 21: An overview of the system.

4.2 System implementation

Experiment set-up: We have used a simple hydroponic system and planted lettuce. This is deep water culture system, and the nutrient does not flow in our set-up. We have included an air pump to provide aeration and prevent the roots from suffocating in the water.



(a) nursery



(b) After four weeks

Figure 22: Hydroponic experiment set-up

4.2.1 End devices

The end devices comprise of:

- Sensors: pH and electrical conductivity (EC)
- Microcontroller unit(MCU)
- LoRa end nodes for transmission of data to gateway

4.2.1.1 Sensors In hydroponic farming monitoring the nutrient solution is crucial for plant health and necessary for efficient use of resources. pH and EC sensors are used to monitor the nutrients in this thesis. Electrical Conductivity (EC) is measured in siemens and it indicates the amount of dissolved material in a solution. Alternative to EC sensor is Total dissolved solids (TDS) sensor, which indicates the total dissolved parts which is measured in parts per million (ppm). TDS value is derived from EC readings and this can give different results

Table 5: Sensors used in the experiment set-up

Sensor	Manufacturer	Model	Data Interface	Voltage Input
pH sensor	DFRobot	Version 2	Analog	3.0 - 5.0V
EC sensor	DFRobot	Version 2	Analog	3.0 - 5.0V

depending on the conversion factors used [31]. In addition, different TDS sensor manufactures different conversion factors thus different readings. As such we have decided to use EC sensor. Table 5 shows the details of the sensors.

Sensor calibration

The pH, EC sensors and two standard calibration solutions are from DFRobot[9]. The EC sensor was calibrated using Arduino, two standard buffer solutions and manufactures software library [10] that uses two point calibration method. Two point calibration is used when readings from sensor are known to be fairly linear. The buffer solutions have different concentration levels: 12.88ms/cm is used to set the high end and 1413us/cm is used to set the low end of the measurement range. The software library automatically identifies the buffer solutions once the calibration procedure is initiated.

Figure 23: EC, pH probes and standard buffer calibration solutions

[9] https://www.dfrobot.com/product-1123.html
[10] https://github.com/DFRobot/DFRobot_EC

Table 6: Arduino UNO specifications

Arduino Specifications[12]	Information
Microcontroller	ATmega328P
Flash Memory	32 KB
SRAM	2KB
EEPROM	1KB
Digital I/O Pins	14
Analog Input Pins	6
Operating Voltage	5V

4.2.1.2 Microcontroller Unit The current trend of IoT end devices development is open source software and low-cost hardware providing a baseline architecture enabling users to develop their own custom end devices [97]. However, this raises compatibility problem as different sensors are developed by different vendors and might not be compatible with some boards. Arduino microcontroller development boards have inbuilt analog to digital converter making it suitable for sensing analog signals. In addition, it is widely used in education and has a huge on-line community. They are a variety of sensors that are compatible with it and many well documented open source programs. As such, we chose Arduino Uno MCU board [11]. The MCU will facilitate data acquisition and implement the LoRaWAN protocol stack as LoRa chip provides modulation only. Table 6 gives specifications of Arduino Uno

4.2.1.3 LoRa Module Since smart farming solution is noy automated and not time critical, data can be sent from the end node hourly or can be configured according to the needs of the farm. From device categories offered by LoRa, device A fits the needs of this system and is thus used in the end nodes. This also suits the power consumption requirements as transmission is initiated by the end device and done asynchronously. For communication with the gateway, a Dragino shield that is compatible with Arduino is used [13]. It is based on Semtech SX1276/SX1278 chip. More details on this lora module is shown in table 7.

[11] `https://store.arduino.cc/arduino-uno-rev3`
[13] `https://www.dragino.com/products/module/item/102-lora-shield.html`

Table 7: Dragino LoRa shield specifications

Dragino LoRa Shield for Arduino	
Specifications	Information
Chip	Semtech SX1276
Frequency	ISM 868(Pre-configured)
Bit rate	Programmable up to 300 kbps
Sensitivity	-148dBm
Compatibility	3.3V or 5.5v Arduino board

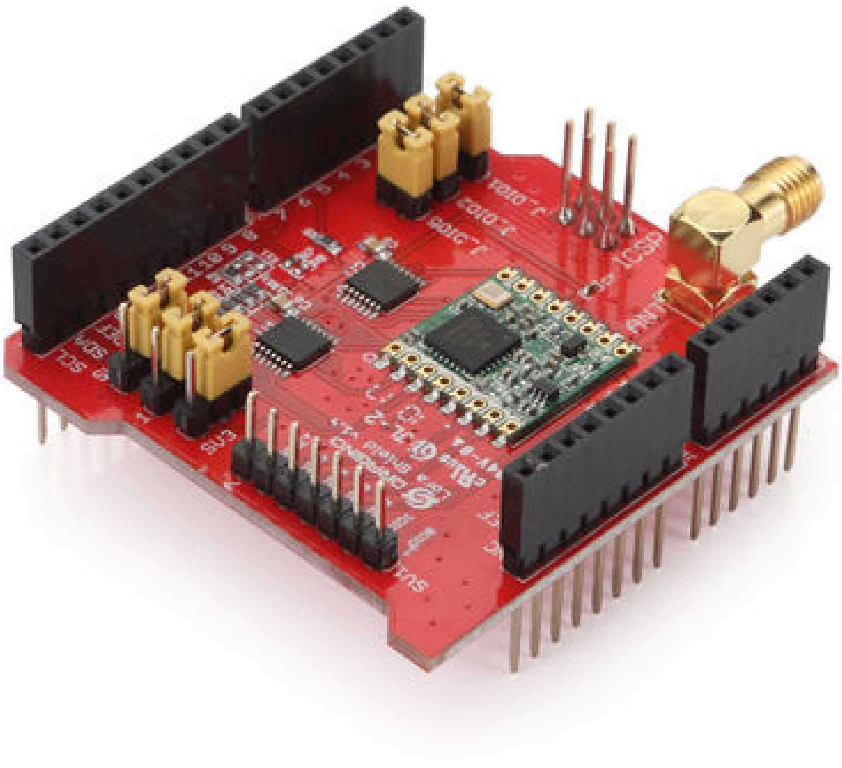


Figure 24: Dragino LoRa shield

Table 8: RAK7249 specifications

RAK7249	
Specifications[15]	Information
RAM	128MB DDR2
Flash	16MB
LoRa chip	SX1301 Mini PCIe card
Channels	8
TX Power:	27dBm (Max)
RX Sensitivity:	-142dBm (Min)
Cellular:	EG95: LTE CAT 4
GPS	L70 GPS Module
Wireless	2.4GHz 802.11b/g/n
Power consumption	12W
Power supply	Power over Ethernet(PoE)

4.2.2 LoRa gateway and Local Server

4.2.2.1 LoRa Gateway The gateway forms the link between the end devices and the LoRaWAN network server. It receives packets and runs packet forwarder that sends packets to the network server through IP/UDP. The requirements of proposed system is a gateway that can give a wide coverage and supports connection from many end devices. We used RAK7249 DIY outdoor gateway [14]. RAK7249 is based SX1301 LoRa chip. This is an enterprise grade outdoor gate that comes with LoRa, two LTE and GPS antennas(see figure 25). The cellular connectivity option it offers is suitable where InternetLite connectivity is not available. RAK7249 offers three configuration options. It can be configured as integrated system which uses the inbuilt network server, act as LoRa gateway MQTT bridge and communicate with network server through MQTT or use Semtech UDP packet forwarder. This implementation uses an external network server which offers gateway MQTT bridge functionality as such we used Semtech Packet Forwarder. Semtech developed Gateway Message Protocol(GWMS) which is the first gateway protocol for LoRaWAN. This protocol uses User Datagram Protocol (UDP) and JSON format for the frames transported. In the gateway web interface figure 26, we configured the packet forwarder to communicate with the server as shown in figure 27. Table reftable:Rak7249 shows the specifications of the gateway.

[14] https://store.rakwireless.com/products/rak7249-diy-outdoor-gateway

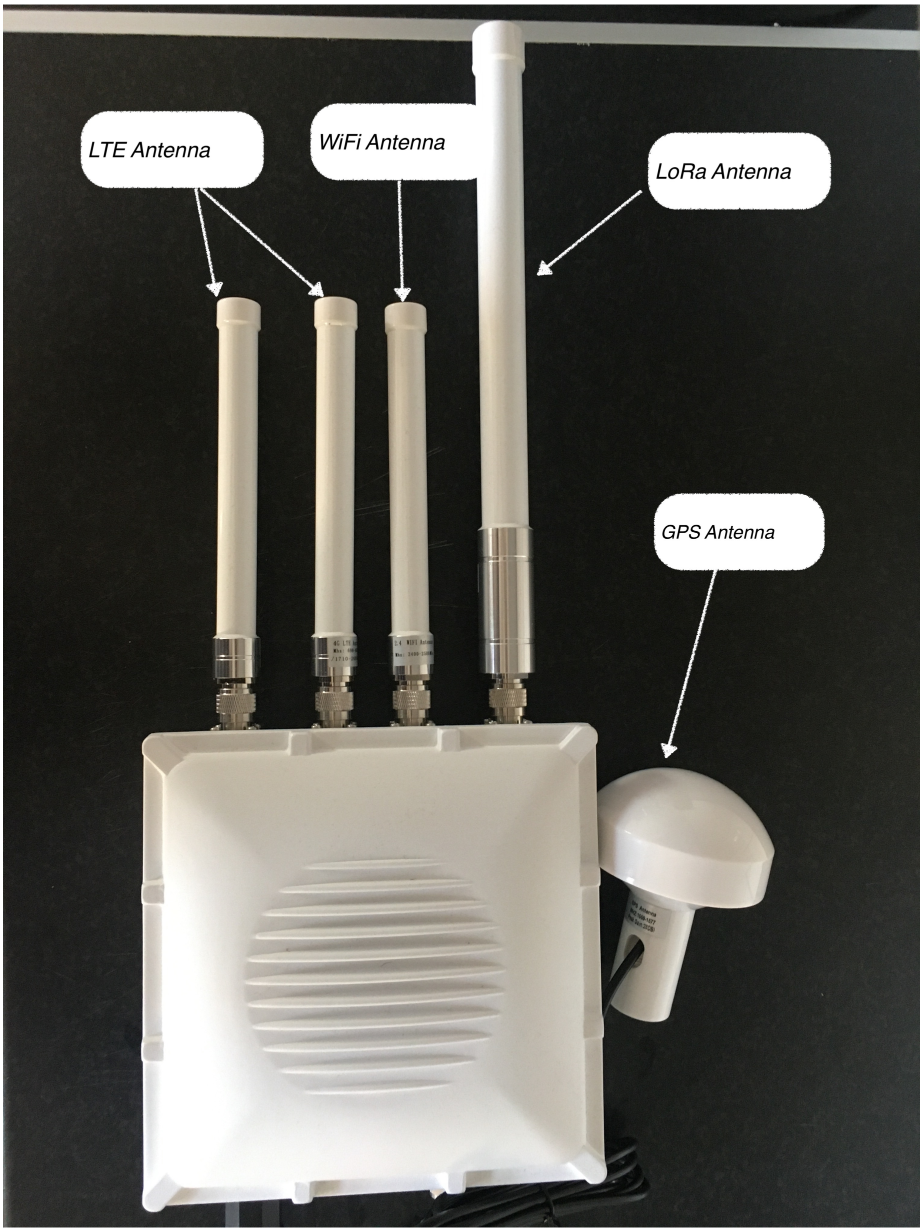


Figure 25: RAK7249 outdoor gateway

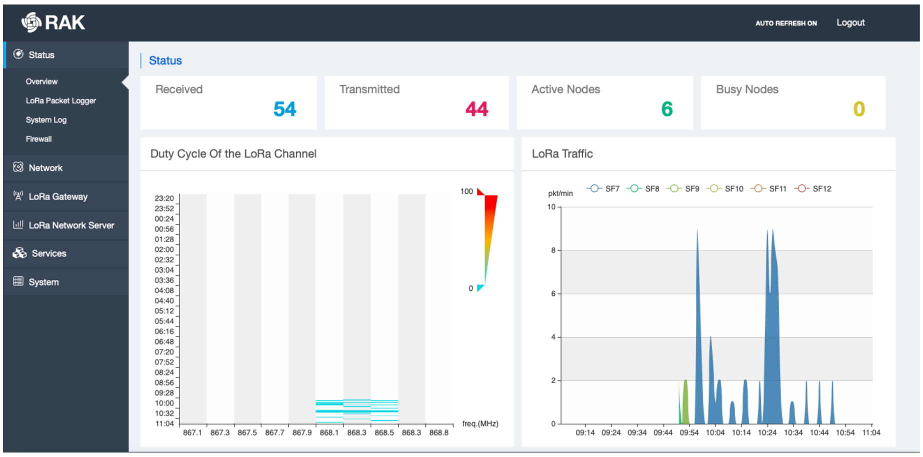


Figure 26: RAK7249 web interface

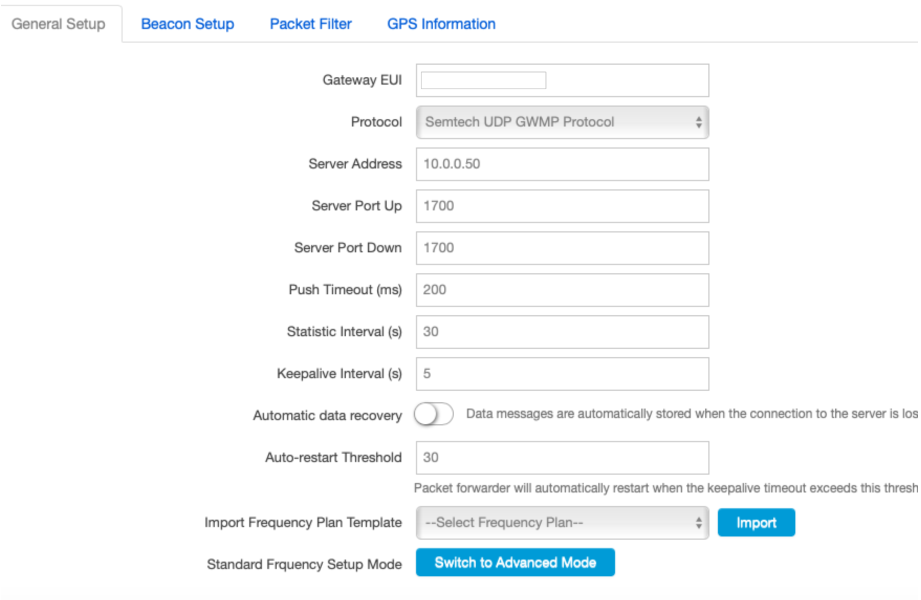


Figure 27: Semtech UDP configuration on the gateway

4.2.2.2 Local server Raspberry Pi 3+ [16] was used as the local server hosting the LoRaWAN network server. Raspberry Pi is a low cost and powerful single board computer. It has been used in several smart farming approaches e.g [94] in a low cost smart farming for monitoring animal health. In our implementation the local server hosts the LoRaWAN network server and application

[16] https://www.raspberrypi.org/products/raspberry-pi-3-model-b-plus/

Table 9: Raspberry Pi 3B+ specifications

Specifications[17]	Raspberry Pi Model 3B+ Information
RAM	1GB
CPU	Broadcom BCM2837B0 quad-core, 64-bit @1.4GHz
GPU	GPU: Broadcom Videocore-IV
Ethernet	Gigabit Ethernet
WiFi	2.4GHz and 5GHz 802.11b/g/n/ac Wi-Fi,
Bluetooth	Bluetooth 4.2, Bluetooth Low Energy (BLE)
Storage	MicroSD
Power consumption	5V

server. It also hosts the gateway bridge. These two entities can physically be separated since they perform different functions, but in this case they are both hosted in a Raspberry Pi. The local server also acts as an edge layer, an intermediary processing layer that performs the storage of sensor data, send notifications to farmer based on data analysis and also pushes data periodically to the cloud where further analysis is done. Since the suggested solution is integrated into the Basic Internet infrastructure, agriculture related information and other local content can be stored in the local server and accessed by farmers at the Wi-Fi access points. Table 9 shows the specifications of Raspberry Pi Model 3b+.

Configuration architectures

In experimental set-up, the gateway and the Raspberry Pi are in the same local network. The LoRaWAN components used in this thesis are from an open source LoRaServer project[18] that offers applications that can be implemented flexibly. While a common alternative is the The Things Network(TTN) a crowd sourced community network, it doesn't not offer the flexibility needed in the developing world scenario. Because TTN's network server is hosted in Cloud it would be expensive to transmit data. LoRa Server components include LoRa Gateway bridge, LoRa Server and LoRa App Server. All of these three components are installed in the same server. The LoRa Server project offers two main architecture as shown in 28. The difference in these two approaches is where the LoRa Gateway bridge is installed. It can either be installed in the gateway or on a separate server that may or may not host the other components.

[18] `https://www.loraserver.io`

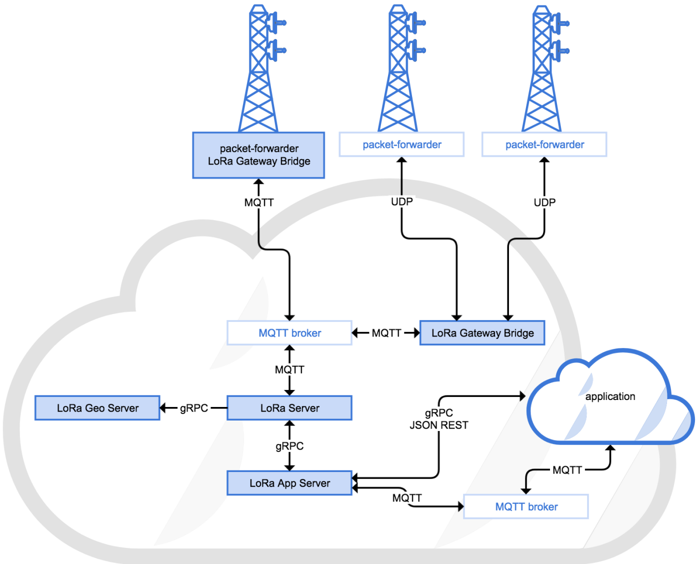


Figure 28: General LoRaWAN configuration architectures.

The configuration used in this thesis is shown in 29. The gateway bridge is installed in the same server together with other components. We chose this configuration because a single gateway bridge handles the conversion of packets from different gateways in case the system is scaled to increase coverage. As mentioned earlier RAK7249, also has inbuilt LoRa gateway bridge, but we have not used it because the message formats on gateway is not compatible with the LoRa server project message formats at the time of this writing.

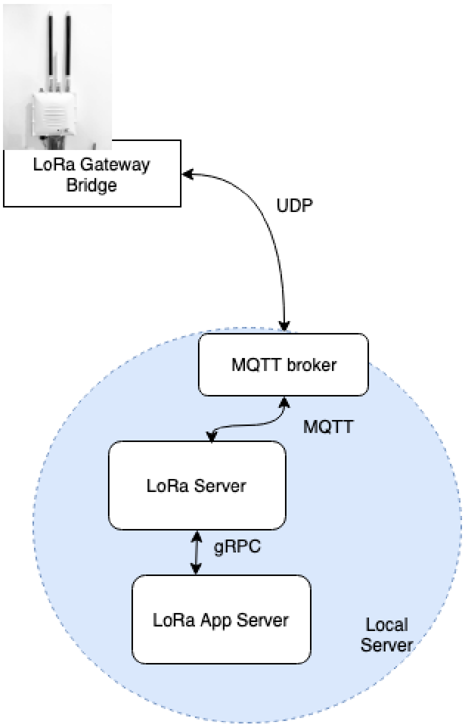


Figure 29: Gateway bridge, LoRa server and LoRa app server are installed in the same server instance.

LoRa Gateway bridge. LoRa gateway bridge abstracts LoRa packets to messages that can be sent over MQTT.

LoRa Server LoRaWAN network server handles the general state of the network, processing of uplink and scheduling of downlink communication. It is also responsible for de-duplication of packets if the packets are sent from different gateways such that messages are sent to the applications once. It also serves the function of scheduling downlink transmissions.

LoRa App Server It provides a web-interface to enable management of users and is also an inventory for applications and devices. Live LoRaWAN frames can also be inspected through this interface. It also encrypts and decrypts application payloads thus network server can not access them. It also generates application key and manages join-request of network and end device activation. It also provides integration like HTTP, integration with databases e.g. InfluxDB and it also offers MQTT, gRPC[19] and RESTful API for integration with other applications.

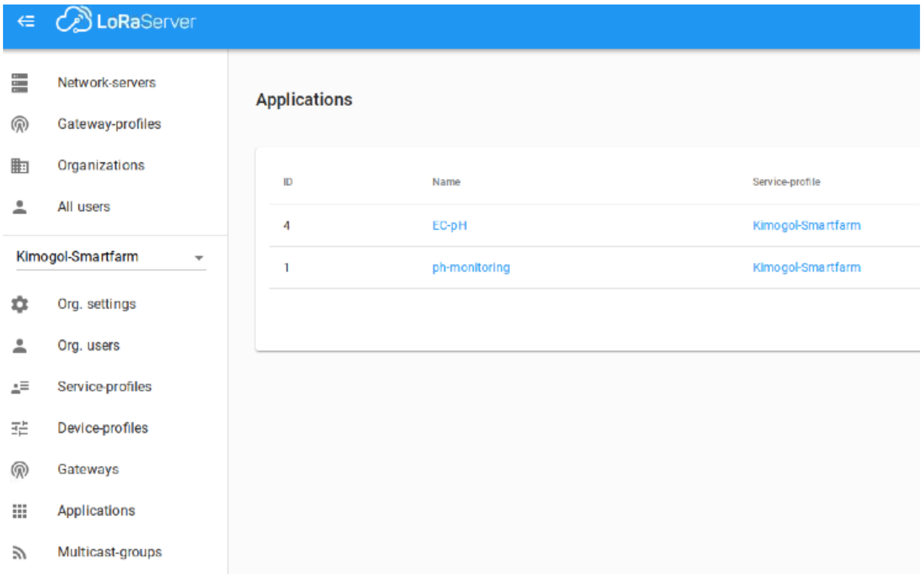


Figure 30: LoRa App Server web-interface

LoRa Server components and their dependencies were installed in Raspberry Pi. Because the LoRa gateway bridge uses publish-subscribe communication, Mosquitto, a lightweight broker that implements MQTT protocols was also installed. The Semtech UDP packet forwarder that runs on the gateway forwards the data to the LoRa Gateway Bridge which converts the LoRa packets to MQTT and publishes to topic that LoRA Server subscribes to.

4.2.3 Data collection, transmission and processing

4.2.3.1 End Device Activation LoRaWAN offers two methods for activating end nodes: Over the air activation(OTAA) and Activation By Personalization (ABP). Device activation is handle by the LoRa App Server and this can be done through the web-interface- see figure 30. When applications and devices are created they are assigned 64 bit end device identifier (**DevEUI**) and application identifier(**AppEUI**) (EUI - Extended Unique Identifier) [98]. The devices are dynamically also assigned 32-bit address(**DevAddr**) and is used to

[19] `https://grpc.io`

Software	
LoRa Server	LoRa Server
	LoRa App Server
	LoRa Gateway bridge
	PostgreSQL - to persist gateway data
Broker	Mosquitto[20]
Node-red	Node-red[21] server
Database	InfluxDb[22]
Visualization	Grafana[23]
Notification	EnvayaSMS[24] server

Table 10: Software

identify the device after it joins the network[98]. LoRaWAN also has further three more security keys network session key (**NwkSKey**),Application session key (**AppSKey**) and Application key (**AppKey**). End devices and the network use (**NwkSKey**) to calculate message integrity code(MIC) for the purpose of data integrity while AppSKey is used to encrypt and decrypt payload[98]. In ABP (**DevAddr**), (**NwkSKey**) and (**AppSKey**) are preprogrammed in the end device and also stored in the network thus device is only attached to a specific network. Activation process therefore does not go through the join request and accept procedure. On the other hand OTAA uses (**DevEUI**), (**AppEUI**) and (**AppKey**) which must be stored both in the network and the end device for the join procedure. (**AppKey**) is used to generate the (**NwkSKey**) and (**AppSKey**). The (**DevAddr**) is also dynamically assigned in the process. In our case OTAA was used to connect the end device to the network. To facilitate this we used Arduino LoRaWAN-MAC-in-C(LMIC) library [25] that was developed by International Business Machines(IBM). Dragino LoRa shield was connected to the Arduino and since shield is based on Arduino form factor no jumper cables were required for connection. Then (**DevEUI**), (**AppEUI**) and (**AppKey**) generated in the LoRa App Server were added to sketch. Once the sketch is uploaded to the Arduino, the end device activation process starts automatically.

4.2.3.2 Reading sensor values and transmitting Figure 31 shows the state of the end device. After the activation the end device starts to transmit

[25] `https://github.com/matthijskooijman/arduino-lmic`

data. The EC and pH codes were adapted from the DFRobot product libraries [26] and LMIC library. This code can be found in appendix A. The data mitigation techniques used here is data compression which involves encoding data at end nodes and decoding them at the application server. This technique reduces size of information transmitted and reduce power consumption thus improving battery life[25]. Because the EC and pH do not change significantly within an hour, values are transmitted to the gateway once every hour. Before the transmission the sensor readings are encoded as shown in the following code.

```
void do_send(osjob_t* j) {
  struct sensorValues ss = ecread();
  float structec = ss.ec;
  float structph = ss.ph;
  byte payload1[4];
  uint32_t ecValue = structec*100;
  uint32_t phValue = structph*100;
  payload1[0] =highByte(ecValue);
  payload1[1] =lowByte(ecValue);
  payload1[2] =highByte(phValue);
  payload1[3] =lowByte(phValue);

  if (LMIC.opmode & OP_TXRXPEND) {
    Serial.println(F("OP_TXRXPEND, not sending"));
  } else {
     LMIC_setTxData2(1, payload1, sizeof(payload1), 0);
    Serial.println(F("Packet queued"));
    Serial.println(LMIC.freq);
  }}
```

[26] https://wiki.dfrobot.com/Gravity__Analog_Electrical_Conductivity_Sensor___Meter_V2__K=1__SKU_DFR0300

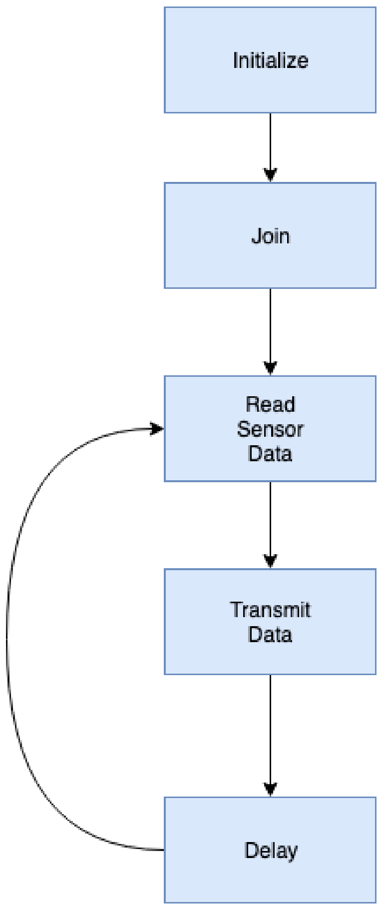


Figure 31: State machine end device

4.2.3.3 Data processing The flow of the data from the end devices to the applications is depicted in figure 32. The UDP Semtec software running in gateway forwards the data to LoRa-Gateway- bridge. LoRa Gateway bridge publishes messages to a topic which LoRa server subscribes to. LoRa server sends the data to the LoRa App Server through gRPC api. Here the data is decoded and is published to mosquitto broker for application using MQTT can access them. In the LoRa App server we used the following custom JavaScript code to decode the payload.

```
function Decode(fPort, bytes) {
    var ec = (bytes[0] << 8) | bytes[1];
```

```
    var ph = (bytes[2] << 8) | bytes[3];

    var dataout = {
        "sensorvalues": {
            'ec': ec / 100,
            'ph': ph / 100
        },
    };
    return dataout;
}
```

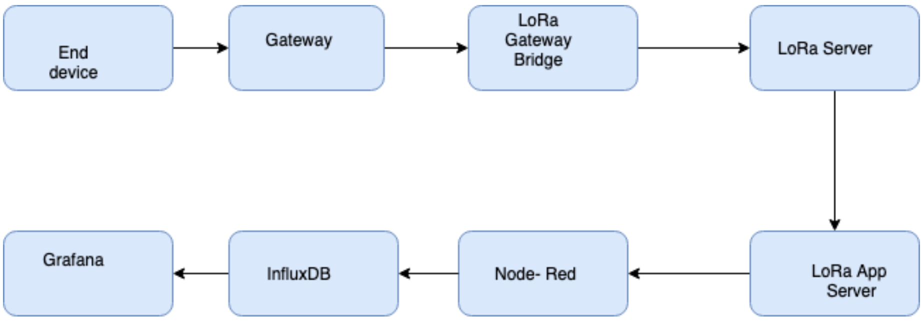


Figure 32: Data flow.

To integrate other functions to our system, we have used Node-Red, an open source web based programming tool. It is a flow-based program and can easily be used to connect things, applications and process the data they produce. It offers a broad collection of nodes in the palette that can be dragged and dropped into the flow canvas. In Node-red we use MQTT client which subscribes to topics published by the LoRa App server. The event in MQTT topics are in this format: **application/[applicationID]/device/[devEUI]/rx**. applicationID is automatically generated and can be found in the LoRa App Server web interface. In this case the node named EC-PH in figure 33 is the MQTT client and it subscribes to this topic:

application/4/device/8a90dc387df11f42/rx

Following is an example of the data received after subscribing to the above topic in Node-Red. It shows the end device details, gateway details, Received

Signal Strength Indicator(RSSI), SNR and it also indicates that ADR has been activated. It also contains the values of the sensor data.

"{"applicationID":"4","applicationName":"EC–pH",
"deviceName":"EC–pH_Hydroponic",
"devEUI":"8a90dc387df11f42","rxInfo":
[{"gatewayID":"XXXXXXXXXX","name":"RAK7249",
"time":"2019−10−12T11:49:03.960173Z","rssi":−55,
"loRaSNR":10,"location":{"latitude":60.44765,
"longitude":12.05757,"altitude":349}}],
"txInfo":{"frequency":868300000,"dr":5},"adr":true
,"fCnt":34,"fPort":1,"data":"AE4CmA=="
,"object":{"sensorvalues":{"ec":0.78,"ph":6.64}}}"

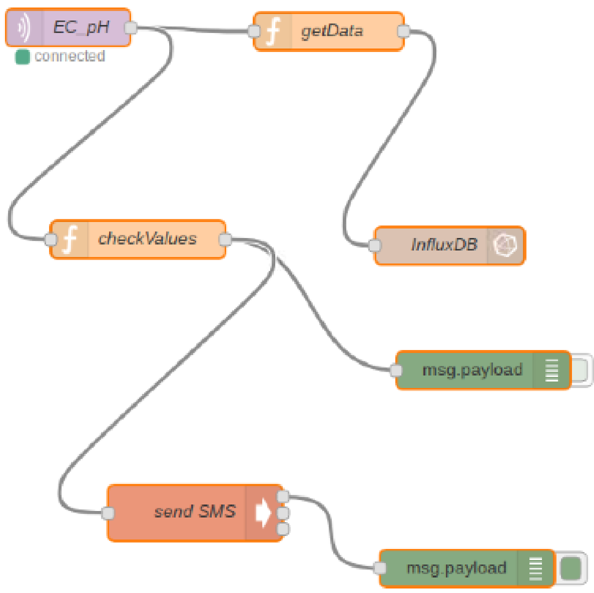


Figure 33: Node-red flow

The data received is in a string format and we used JSON.parse() function to get a JSON object so as to extract the payloads. We used InfluxDB to store the sensor data. InfluxDB is an open source time series database that enables storage of sensor data in an equally spaced time intervals. This makes it suitable for IoT application. It suits the need of smart farming as data is stored with a specific time-stamp making data analysis easy. Furthermore, this enables analysis with a high level of granularity. Farmers or the experts helping farmers can get information on how plants absorb nutrients and they can make informed decisions on when and what amount of nutrient solution to use.

In Node-Red we used a function node, named getData - see figure 33 for data extraction and posting them to the InfluxDB. Since sensors will be deployed in different sections of the hydroponic farm, knowledge inference can be done using such functions to compare data and identify faulty sensors. We have, however, not implemented this since we only have single EC and pH sensors in the experimental set-up. For data visualization we used Grafana - an open source tool for visualization which comes with data source plug-in for InfluxDB. We created dashboard on Grafana and visualized data with graphs to show the pH and EC levels. This can help system administrators to get insights from the data and valuable information which can help farmers make informed decisions. Interactive graphics help better understand underlying data and with time series representation of database, farm conditions can be compared to crop performance.

Edge Analysis With edge computation bandwidth usage can be optimized and simple data analytic can be performed. Edge layer defines the rules related to storage of data and sending of notifications. Alerts are sent to the farmers depending on the sensor readings. If the sensor readings fall below a set value then farmers are notified through SMS. For growth of lettuce a pH of 5.5 to 6.5 and EC of 0.8 to 1.2 ms is considered suitable for the growth of the plant. We have implemented a function in Node-Red that checks whether sensor data is within the above defined values. Node-red's exec node executes a command that sends notifications. We will discuss SMS gateway in 4.2.3.4. As such edge also manages the connection between the server and gateway application app running on an Android phone.

4.2.3.4 SMS gateway Notifications are important part of the IoT system as this informs users of the conditions of the things they are monitoring. The choice of notification system depends on the type of devices used by the clients. In most developing countries basic and feature phones remain the most commonly used devices and uptake of smart devices are influenced by battery life and access to fast internet [3]. Most farmers in rural areas use low-tech phones whose primary communication channels is SMS and voice. Even farmers with smartphones are restricted from using apps due to expensive data plans thus use of data connectivity orientated services are not suitable. In addition phones have limited processing capabilities and might not support apps. The most suitable way to send notifications in this case is SMS. However, setting up a gateway with telecommunication operators and getting short codes that is accessible from local numbers is costly. Lightweight SMS gateway application that reside on Android phones like RapidSMS [27] and frontlineSMS [28] have already been used in health sector to send reminders to enhance postnatal care appointments [99] and SMS based alert system to monitor pregnancy, maternal and child deaths [100]. In [101], EnvayaSMS [29], an open-source SMS gateway was used to support immunization programs. We can leverage this technology by integrating into smart farming solutions suggested here. Since the phone will be using local phone number, the cost is reduced as compared to using cloud based SMS aggregator like Twilio[30]. In this thesis we are using EnvayaSMS as it does not require subscription as frontlineSMS. It also offers expansion packs to increase messages sent per hour to 500 from the 100 per hour limit on Android phones. An example of EnvayaSMS configuration with web server hosted in cloud is shown in figure 34. However, in our implementation the server that sends notifications is hosted locally.

[27] `https://www.rapidsms.org`
[28] `https://www.frontlinesms.com`
[29] `http://sms.envaya.org`
[30] `https://www.twilio.com`

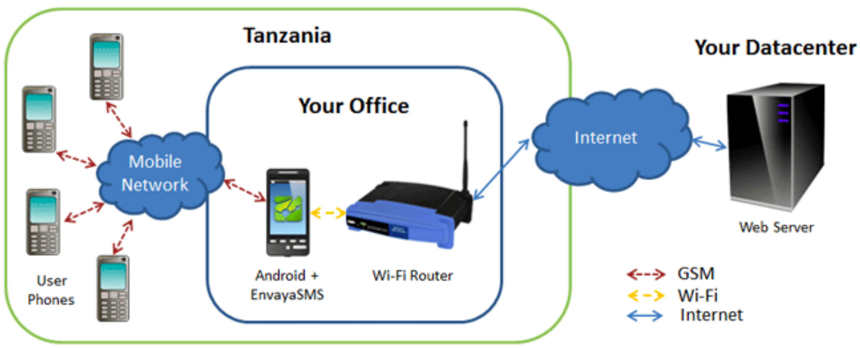


Figure 34: EnvayaSMS configuration

From EnvayaSMS webpage, it is stated that the app can run any Android phone with Android version 1.6 or higher. In this case we used MoTo G Plus [31] phone running on Android 8.1.0. The phone is connected to the same local WiFi as the Raspberry Pi. Scripts from the EnvayaSMS github repository [32] was used to handle the server functions. In these repository they are three main scripts that we used in this implementation. These are server.php, gateway.php and send_smsphp. The first scripts is a standalone HTTP server, the second script implements the EnvayaSMS API while the last one enables sending of messages from the command line. The server script was enabled to run at the Raspberry Pi on start-up. In the App settings the server Uniform Resource Locator (URL) was set to the path of the script implementing the EnvayaSMS API that is also on the Raspberry Pi as shown in Figure 35. The app was configured to poll for new messages every 5 minutes. Figure 35 shows the app configuration and the app polling for messages.

As mentioned earlier SMS alerts are triggered after the sensor values fall or go beyond a certain range. To trigger sending of messages, we analysed the sensor data in Node-red, checkValues function as shown in 33. This function analyses the data and the payload it returns contains the message and phone number of the recipient. The messages can be customized to the local language in this function. Node-red offers execute node (exec) that can be used to run scripts and programs. The payload of checkValue function are passed to the exec node. This node runs php(send_sms.php) script that queues the message

[31] https://www.motorola.com/us/products/moto-g-plus
[32] http://github.com/youngj/EnvayaSMS

to the local file system. This message is sent to the EnvayaSMS gateway app once it sends a request to the server for outgoing sms. EnvayaSMS gateway uses an HTTP POST request to poll for outgoing messages and send status of the sent messages to the server.

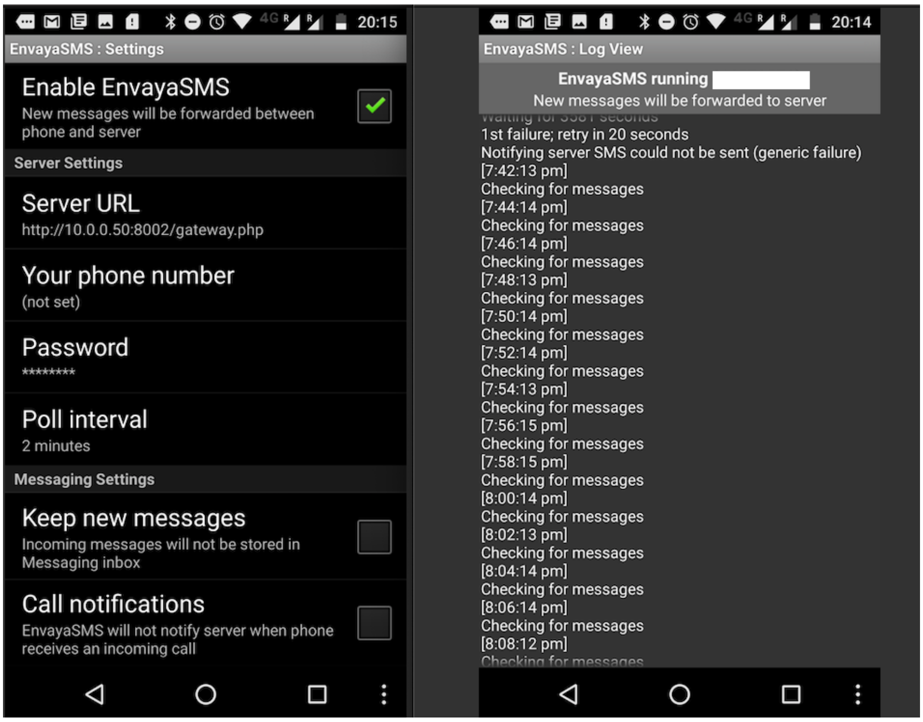


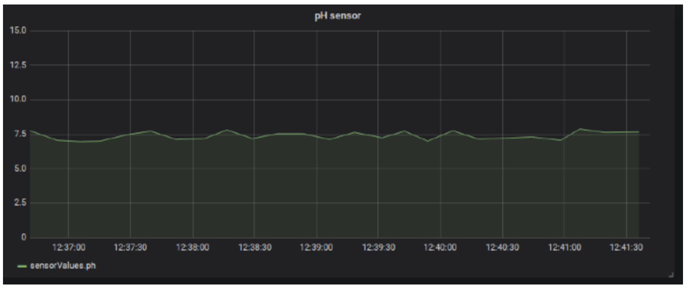
Figure 35: EnvayaSMS configuration and log view.

4.2.4 Cloud

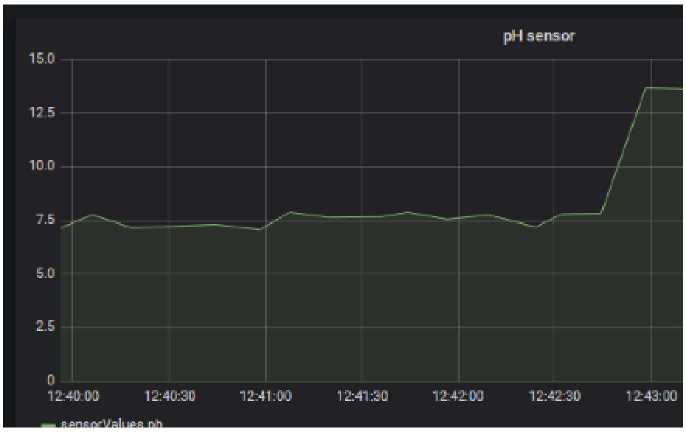
As discussed in section 3.3, Cloud offers ubiquitous and on-demand access to computing resources making it suitable for storage and processing of huge data produced by IoT. It allows data consolidation, long term data analysis and effective way to share data with stakeholders and agricultural extension officers. However, lack of or limited internet connectivity and cost is hindering the uptake of this computing paradigm in developing countries. In the proposed solution we have incorporated Basic Internet's connectivity solution as a backhaul option to cellular network as depicted in figure 21. Because the InfoInternet standard allows text and pictures, sensor data can be categorised as text and be transmitted for free. With this solution sensor data can be shared with other stakeholders. Since data is consumed locally and data analysis that trigger alerts is also done locally, transmission of data to cloud needs not to be done in real-time. Moreover, IoT based smart farming in this scenario is latency tolerant as no process are automated in this implementation. Consequently data can be pushed to the cloud at pre-defined time. Batch transfers to the cloud can also be enabled in the local server subject to data ownership framework guidelines. As much as data sharing is important for smart farming, there is a need for a regulated transparency and a framework for sharing of farmers data with government(agricultural extension officers) and other stakeholders[30]. In this thesis the focus is mainly on local data processing and access but data ownership is an area that needs to be considered when this system and other smart farms are deployed in the real world.

4.3 Results and Discussion

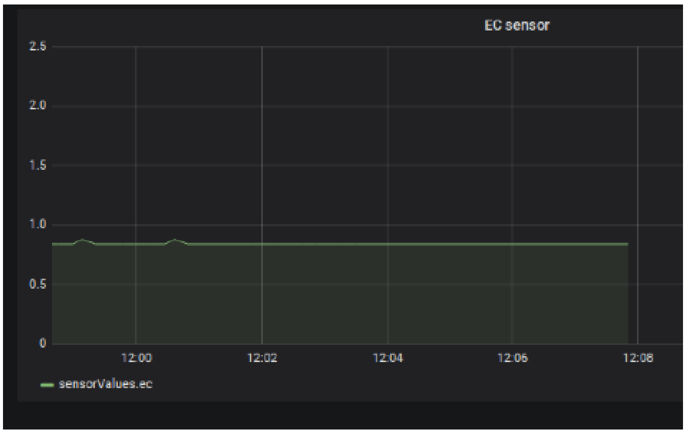
In this thesis we suggest a smart farming based on IoT and LoRaWAN approach to monitor the conditions of hydroponic system. The sensor data are collected and transmitted periodically to the network server, analysed and stored in InfluxDB. We use an open source visualization tool to visualize data simplifying the understanding of the underlying data. Figure reffig:resultgraph shows the EC and pH levels. From the Grafana dashboard, data can be checked as frequently as seconds to a year, making it simple to identify crop performance and the amount of nutrients used. Overtime farmers will identify which plants to grow in the hydroponic system depending on the season to complement traditional farming. Agricultural extension officers can help smallholder farmers with the analysis of data and give advice based on the results.



(a) pH



(b) pH hike



(c) EC

Figure 36: pH, EC visualization on Grafana

We have also observed that the EC probe affects the pH values. Once the EC is inserted into the nutrient solution, the pH values almost doubles, as shown in figure 36b. We have not investigated this further and is left as part of future work. However, from a design perspective, pH and EC sensor can be placed at different stages in hydroponic system.

Using Node-Red we have analysed data and sent notifications to an SMS-gateway that is running on Android phone. The SMSgateway can manage to send 500 messages per hour if the expansion packets are used. Since this system is not time critical, delayed notifications are tolerated.

As mentioned in section reffundementalslora, the network server handles the data rate using adaptive data rates. In this implementation LoRa Server is responsible for the data rate. ADR was activated and from the analysis of the meta-data in LoRa app server live LoRaWAN packets shows that a spreading factor of 7 is used because the gateway and the end device are just a few meters from each other. The graph from RAK7249 web interface also confirms this as depicted in figure 37.

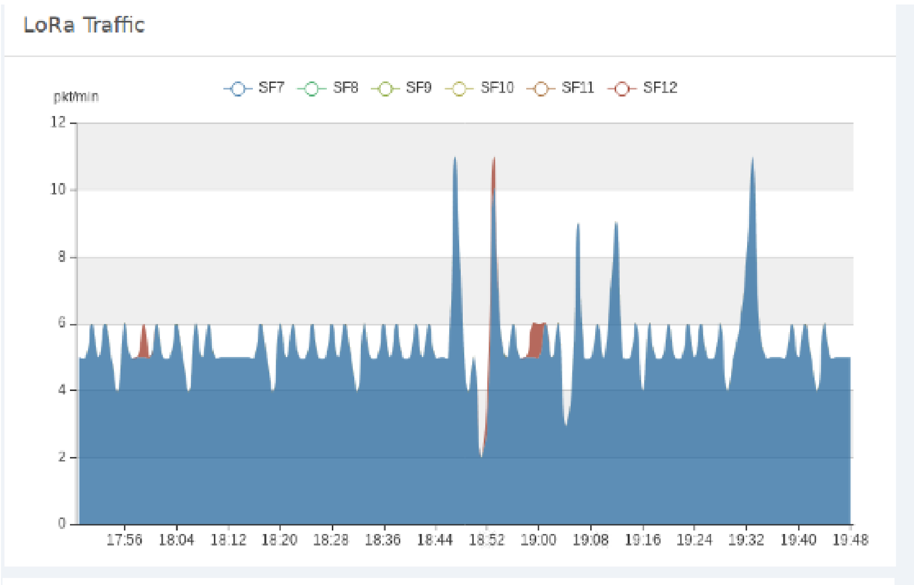


Figure 37: LoRa Traffic per minute and the spreading factor.

4.3.1 From data collection to empowerment

The term empowerment has many definitions and meanings in different contexts. In this section, we focus on how smart farming and access to information empowers local communities. According to Mukherjee, empowerment, in the context of ICT and development, revolves around building capacities of individuals and communities, giving choices and enhancing participation. More important to this thesis is improving the individual's ability to do instrumental roles (a person's everyday task)[102]. In the smart farming solution proposed, the goal is to enable smallholder farmers do their farming(instrumental role) efficiently and diversify their crop farming (having a choice) by using smart hydroponic system. Hydroponic system can complement the 'normal' farming(arable) when the weather conditions are unfavourable. By connecting farm to digital world through IoT, smallholder farmers get another dimension on interacting with their farms. With this technology information driven agriculture is encouraged, increase efficient food production and reducing over-dependence on rain-fed agriculture and thus empowering farmers to transition to sustainable farming.

To fully realize the potential of smart farming and make it sustainable, capacity building must be done. To this end, we have included Informations spots from the Basic Internet solution in the proposed approach. Information spots will be a reference point where farmers can access data from their farms and other local content that is relevant to them. In addition, information related to building LoRaWAN network, sensor calibration and maintenance can be stored in local servers and access through WiFi.

Basic Internet's Internet Lite is aimed at bringing connectivity to the rural areas and bridging the digital divide by providing access to information. The intention of inclusion of this approach into the solution proposed in this thesis, is to provide information about the smart farming and empower local communities by reducing information asymmetry. Since text and pictures are free in the Internet Lite, farmers can access the internet without incurring additional cost and they can also access local content through the WiFi in the information spots. Similarly, farmers can access information related to sustainable farming practices and technologies that facilitate smart farming.

Information spots will also be a point to access value-added services: Here local meteorological departments can share weather information and agricultural departments can provide advisory services and information related to smart farming, disease outbreaks, information on fertilizers and nutrients for hydroponic farming.

5 Evaluation and future work

5.1 Evaluation

In this section, we will analyze the proposed solution against the requirements of smart farming discussed in section 2.4. Evaluation metrics and relation to overall IoT Key Performance Indicators

What is the value of this system?

5.1.1 Cost

We will consider the capital expenditure (CAPEX) and operational expenditure (OPEX). In this cost evaluation, we will only consider the cost related to *technology* part of the solution. As such the cost related to setting up a hydroponic farm has not been analyzed. However, they are a wide range of literature that covers this topic e.g Naik and Singh suggested cheap materials that can be used to set up a greenhouse for hydroponic farm for the cultivation of fodder [35].

To meet the cost requirement, we have proposed a shared infrastructure where the community shares the initial and maintenance cost. The gateway and local server are core components of the shared infrastructure. This is the reason for choosing a gateway that can give wide coverage. The proposed solution uses RAK7249 outdoor gateway with a range of at least 15KM line-of-sight according to the documentation[33]. Thus the farmers within the range of this can share the cost. RAK7249 goes for $599 at the time of this writing. For the local server, we have used Raspberry Pi 3+ which costs $35. The total CAPEX for the shared infrastructure is $634. For each specific hydroponic farm, LoRa node and MCU are needed and these cost $21 and $16 respectively. LoRa is operating on ISM bands that are free, no initial and operational charges are incurred in the use of those frequencies (868MHz in Europe).

The cost of pH and EC sensor was $110. Currently, the common pH and EC probes in the market are mostly hand-held and are not suitable for IoT applications for monitoring smart farms. The cost for this varies but these are

[33] `https://downloads.rakwireless.com/en/LoRa/DIY-Gateway-RAK7249/Hardware-Specification/DIY_Outdoor_Gateway_RAK7249_Product_Brief_V1.2.pdf`

some of them: Bluelab handy EC-pen[34], cost $109 and ADWA pH-pen[35] which cost $70. The cost of the sensors used in the proposed solution is relatively lower as compared to other alternatives and they are also suitable and convenient for IoT applications in smart farming. However, they are laboratory grade and can not be immersed in the nutrient solution for long. Atlas Scientific has industry grade EC [36] and pH[37] sensors that cost $162 and $40 respectively. These are suitable for smart farming and as they can be submerged to nutrient solutions indefinitely. LoRa technology and IoT are still in their nascent form and with the continuous decrease in the cost of electronics, cheaper sensors and MCU designed for these kinds of applications will be available soon.

Even though farmers can share the cost of the shared infrastructure, the cost of this system i.e. sensors in the farms is still beyond the reach of smallholder farmers and alternative approaches are needed. Recall section 2.2.2, a holistic approach for smart farming in developing countries is needed to realize the potential of technology to make food production efficient. It is, therefore, necessary to include other actors e.g local governments, non-governmental organizations(NGOs), academia and industry to help rural farmers set-up these systems. With significant amounts of aid going into food support especially in sub-Saharan Africa, there is a need to invest such fundings into farming systems that leverage recently technological advancement (IoT and LPWAN). Such cooperation with development agents can make smart farming affordable to smallholder farmers. Besides development agents can cooperate with local and international institutions to develop customized solutions that meet the requirement of the smart farms for resource-constrained settings. This has already been done before and District Health Information System (DHIS)[38] - a health management information system that was developed at the University of Oslo, is an example of academia and other development agents helping in addressing the issues related to health. Similarly, smart farms solutions suggested here can be implemented in the same way. This reduces the financial burden of setting up from the smallholder farmers and at the same time address the problems

[34] https://www.gartnerbutikken.no/products/bluelab-handy-ec-penn2
[35] https://www.gartnerbutikken.no/products/adwa-ph-penn2
[36] https://www.atlas-scientific.com/product_pages/probes/ec_k1-0-mini.html
[37] https://www.atlas-scientific.com/product_pages/probes/c-ph-probe.html
[38] https://www.dhis2.org

related to the food crisis in the face of climate change.

5.1.2 Power consumption

Most of the rural areas in developing countries are not connected to the power grid. All components used in this thesis can be powered by a battery. The gateway can operate on 12V/10AH batteries according to the documentation[39]. The MCU, LoRa node and sensors can be powered by rechargeable batteries. Also, solar power which offers a cheap and renewable source of energy can be used to power the system. However, solar panels will increase initial cost, but a worthy investment in the long term thus recurring costs will be reduced as batteries won't be changed often. The end devices, Dragino shield, is class A devices that are the most energy-efficient as they initiate transmission. ADR has been initiated which streamlines transmission power, payload length, and SF. To further reduce energy consumption, transmissions have been set to once every hour as conditions of the farm does not change rapidly.

5.1.3 Cost-efficient communication

As mentioned earlier, the communication between sensors and gateway is through LoRa technology that uses ISM bands and no cost is incurred in using those frequencies. Realtime transfer of sensor data to the cloud is costly due to bandwidth usage or might not be possible due to a lack of connectivity. The proposed solution has a local server that offers local storage and computation to facilitate edge computation. Further, compression and batch transfers can be done at the edge layer to reduce bandwidth consumption. The Wi-Fi available in the information spots will help farmers access the information related to their farms e.g Grafana dashboards to get an insight into their farms. Since content is hosted locally, farmers will not incur additional costs compared to the cloud-based system.

Notifications are sent from an Android-based SMS gateway application that uses a local number. EnvayaSMS is compatible with old versions of Android OS (Version 1.6) and can be installed on cheap and widely available Android

[39] `https://downloads.rakwireless.com/en/LoRa/DIY-Gateway-RAK7249/Hardware-Specification/DIY_Outdoor_Gateway_RAK7249_Product_Brief_V1.2.pdf`

phones. This reduces the cost of sending SMS notifications as local sim cards are used thus local SMS rates applied. This is cheaper compared to other solutions like Twilio that require a monthly subscription and limitation on the number of messages sent per data. They are other SMSgateway apps in the market e.g FrontlineSMS and Telerivet [40] - but they also require a subscription. Using EnvayaSMS is cheaper and satisfies the requirements of the proposed solution.

5.1.4 Software

One limiting factor to the adoption of technology in developing countries is the lack of access to new technology and ownership rights of technology. Fortunately, there has been an increasing focus on the need to democratize technology and knowledge and open source software has revolutionized this. In the implementation of the proposed solution, we have used open-source software, open and widely used standards. This software has a large community and free of licenses that restrict its usage. Considering the computing capacities of the end node and local server (Raspberry Pi 3+), we have used lightweight protocols e.g MQTT that are efficient in bandwidth and power consumption. For network server, which is an important part of the LoRaWAN, we used components of the LoRaServer Project. For storage and visualization, InfluxDB and Grafana were used. These are also open-source software tools. Node-red which is also open source gives the platform that is suitable for IoT implementations and easy to program system functionalities. As mentioned in the previous sections, EnvayaSMS gateway was used to send notifications to farmers.

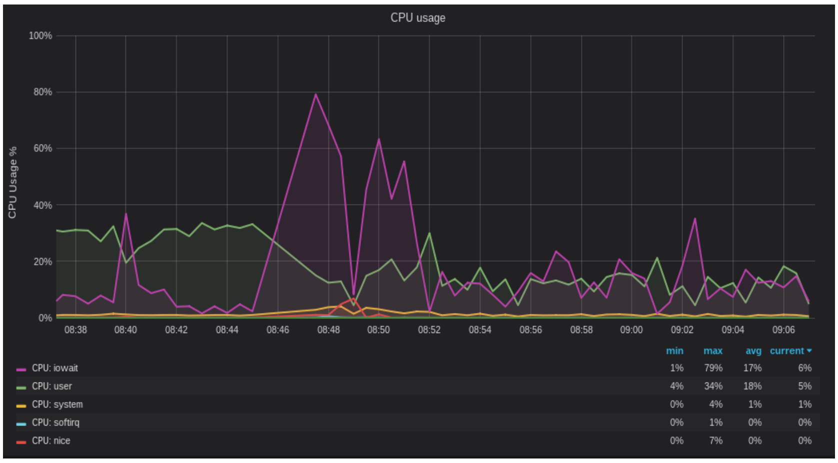
To build the capacity of the local community, platforms that contain free information on farming can be hosted in the local server and accessed from the information spots. They are platforms that provide free information for different sectors e.g in education Khan Academy, in health (yeboo.com - part of Basic Internet services) offers free teaching videos for health workers in a low resource setting. Similarly, content that is related to farming can be hosted in the local server and accessed at the information spots.

[40] `https://telerivet.com`

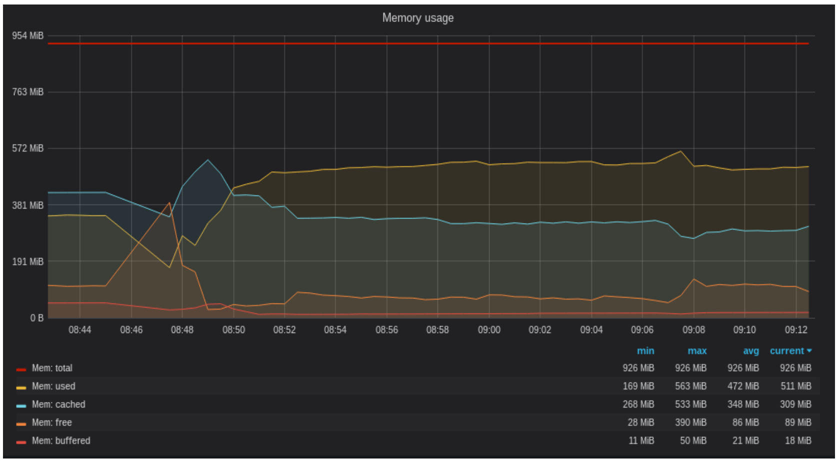
5.1.5 Computation and storage

In the proposed solution all computation is done at the edge. All components of the LoRaServer project (LoRa-Gateway Bridge, LoRaServer, LoRa-App-Server) are running locally on the Raspberry Pi 3+. Data analysis is also done locally and activation of notification is also processed in the local server. EnvayaSMS server is also hosted on the same machine. This reduces the cost of sending data to the cloud for processing. We have, however, suggested the inclusion of the cloud layer in the system for long-term storage, analysis and sharing information with other stakeholders. To minimize the cost, Basic Internet Foundation's Internet Lite is adopted into the solution to offer internet connectivity.

We used a 16 GB SD card for the experiment but the storage can be expanded if there is a need. In the current set up the sensors transmit data every hour. This is 4 bytes per hour, 96 bytes per day, 2880 bytes per month and 34 560 bytes per year. The current set-up can easily handle this amount of data.



(a) CPU usage



(b) Memory Usage

Figure 38: CPU and Memory usage visualization on Grafana

5.1.6 Scalability

The Network capacity of the LoRaWAN network is determined by the frequency of data transmission, data rate, the number of channels in the gateway and duty cycle as discussed in section [58]. The regulation on the duty cycle depends on the region. In Europe, the duty cycle for the 868 ISM band is 1 %. This equates to 36 sec/hour transmission per end device (Number of seconds in a day 86400 *1/100 = 864 seconds per day). In the experimental set-up, the data is transmitted once every hour which is below 36 sec/hour thus complying with duty cycle requirements. RAK7249 gateway has 8 channels and ADR has been enabled to optimize the performance and capacity of the network. Also, it had a 15KM line-of-sight offering sufficient coverage in rural areas.

The scale of data produced (amount of data: number of sensors, frequency of transmission per hydroponic farm) is small as compared to big data in other IoT sectors, but in countries with limited internet and high cost, even small data transmission is costly. The proposed solution mainly focuses on storing data at the local servers. However, the use of InternetLite for connectivity with cloud enables long term storage and sharing of data with other stakeholders.

5.1.7 Ease of Use and sustainability

The ease of use affects the dynamics of adoption and scaling up of the new technologies in any environment. It also affects the perceived benefits of smart farming. Farmers are generally not early adopters of technology and for farmers in developing countries where knowledge of even existing technology is limited, new technologies should be easy to use so to encourage their adoption. In the proposed solution, the farmers share the infrastructure. Farmers only need to install end devices (sensors, MCU and LoRa transceiver) in their hydroponic farms while the gateway and the network server are hosted in a single place.

The use of smartphones is increasing gradually, but basic and feature phones remain the dominant mobile devices used in developing countries. As discussed in section 4.2.3.4 the high cost of mobile and battery life affects the uptake of smart devices in emerging markets. Application-based notifications require data-based connection to the internet making it not suitable for smallholder farmers who can not afford to have daily data bundle subscriptions. Based on this, the suitable notification service is SMS and in text format. Text messages are a format that can easily be understood and is a service that is available even in feature phones. EnvayaSMS offers a cost-efficient SMS notification compared to app-based notifications or other SMS aggregators like Twilio.

It is important to involve farmers in the control loop and in the decision-making process. The suggested solution gives the farmers the necessary information for them to make changes related to their hydroponic system. For farmers, especially in rural areas where the use of technology is not common, the sense of being in control of the system gives them the confidence to use and sustain the system. Besides notifications through SMS is simple to use and read. Since the notification system is running locally messages are written in the local language for local farmers to understand. This cost-efficient approach makes this system sustainable.

The inclusion of technology can also encourage the youth into farming. With a smart hydroponic farm, youth can be motivated to go farming and create job opportunities. In most developing countries, youths migrate to cities and the practice of agriculture has been left to the older generation. With the digitalization of farming, like the system proposed here, the profile of farming is improved increasing the chances of youth adopting this as a source of employment. The ease of use evaluated here is not only on how simple this system is for farmers to use, but also this system simplifies and modernizes farming for the younger generation to practice it.

In table 11 we have given a summary of the evaluation. As mentioned in cost evaluation, the cost of sensors for this use case is expensive while the cost for gateway and local server are shared making it reasonable. Cloud offers computation, storage and is scalable thus performs better than the solution suggested here.

Legends:

- very good: ++, good:+,
- reasonable: 0,
- not good: −, not so good − −,
- not applicable: X

Table 11: Evaluation of the proposed solution

Evaluation Criteria	Specification	Smart farming		
		Device layer MCU, LoRA sensor	Edge layer Gateway, Raspberry Pi	Cloud layer
Cost	Capex: senor	– –	X	X
	Capex: MCU/Transceiver	++	++	X
	Capex: Gateway/Pi	X	"o" 0	X
	Opex	0	++	X
Power consumption	Efficiency	++	++	X
Communication	LoRa	++	++	X
Software	Open source	++	++	X
Computation and storage	Computation	+	+	++
	Storage	X	+	++
Scalability	Increase number of end devices	X	++	X
	Increased volume of sensor data	X	+	++
	Increased number of users	X	++	X
	Coverage area	X	++	++
Ease of Use	Installation	+	++	X
	Maintenance	+	++	X

Note: the legend used...
Mention the highlights ...

5.2 Future Works

Open issues - technical: EnvayaSMS is not optimized for IoT scenarios and is currently using HTTP. MQTT could be a better protocol in terms of

Other open issues: end-user involvement in the development of smart farming(living lab).

Sustainable business model for the local communities: Having few sensors only for hydroponic farming might not viable but with doing it together with other applications e.g monitoring irrigation system will improve the return on the investment. Help local communities identify crops that give high returns and can do well on hydroponic farming.

6 Conclusion

Agriculture and climate change are interlinked. Agricultural contributes to greenhouses emission and change in weather patterns affects food production. However, food production has to increase because of rapid population growth. This growth in population is projected to occur mostly in developing countries. They is, therefore, a need to facilitate smallholder farmers in these countries to produce efficiently.

The use of IoT in agriculture will increase over the coming years even in developing countries, albeit slowly compared to their developed counterparts. Currently, mobile phone-based services are the most common service available to smallholder farmers. There is a need to leverage advanced technologies and use low-cost hard and open source software to monitor and enhance a conservative use of resources to make food production efficient.

In this thesis, we have presented a smart hydroponic farming solution for smallholder farmers in developing countries. The suggested solution takes a holistic view of smart farming that involves the use of technology to monitor farms, diversify farming practices and reduce the overreliance of rain-fed agriculture. Further, the approach gives another dimension for interaction between farmers, agricultural extension officers, and other stakeholders by the use of sensor data to make informed decisions. We based the proposed solution on IoT and LoRaWAN including the edge layer that performs data processing and sends notifications. We have suggested a shared infrastructure where farmers share the cost of the gateway and local server. The proposed solution draws upon availability of open-source software and low-cost hardware for MCU and the LoRa transceivers. However, the cost of sensors for the hydroponic system is still high and we have suggested cooperation with local governments and development agents to reduce the financial burden from farmers.

One of the bottlenecks to the adoption of technology is the lack of Internet connectivity. To this end, we have adopted Basic Internet's Internet Lite for connectivity between edge and cloud layer. Further, we have integrated information spots for access farm data and other value-added services like weather information, advisory information from can be access. Access to such information will build the capacity and empower the local communities.

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A Program code

A.1 End device activation, sensor reading and transmission code

The code below is adapted from the DFRobot library and LMIC library for LoRa activation and transmission of packets.

```
/***************************************************************************

 ***************************************************************************

#include <lmic.h>
#include <hal/hal.h>
#include "DFRobot_EC.h"
#include "DFRobot_PH.h"
#include <EEPROM.h>

#define PH_PIN A1
#define EC_PIN A2
float voltageEC,voltagePH, phValue, ecValue,temperature = 25;
DFRobot_PH ph;
DFRobot_EC ec;
struct sensorValues {
 float ec;
 float ph;
};

// EUI little-endian format
static const u1_t PROGMEM APPEUI[8] = { 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x0
void os_getArtEui (u1_t* buf) {
  memcpy_P(buf, APPEUI, 8);
}

// little endian format
```

```
static const u1_t PROGMEM DEVEUI[8] = { 0x42, 0x1f, 0xf1, 0x7d, 0x38, 0xdc, 0x9
void os_getDevEui (u1_t* buf) {
  memcpy_P(buf, DEVEUI, 8);
}

static const u1_t PROGMEM APPKEY[16] = { 0x2c, 0xd3, 0x2e, 0x10, 0xf0, 0x2d, 0x

void os_getDevKey (u1_t* buf) {
  memcpy_P(buf, APPKEY, 16);
}

//static uint8_t mydata[] = { 0,0,0,0,0,0,0,0};
static osjob_t sendjob;

// Schedule TX every this many seconds (might become longer due to duty
// cycle limitations).
const unsigned TX_INTERVAL = 10;

// Pin mapping
const lmic_pinmap lmic_pins = {
   .nss = 10,
   .rxtx = LMIC_UNUSED_PIN,
   .rst = 9,
   .dio = {2, 6, 7},
};

void onEvent (ev_t ev) {
   Serial.print(os_getTime());
   Serial.print(": ");
   switch (ev) {
      case EV_SCAN_TIMEOUT:
         Serial.println(F("EV_SCAN_TIMEOUT"));
         break;
```

```
case EV_BEACON_FOUND:
  Serial.println(F("EV_BEACON_FOUND"));
  break;
case EV_BEACON_MISSED:
  Serial.println(F("EV_BEACON_MISSED"));
  break;
case EV_BEACON_TRACKED:
  Serial.println(F("EV_BEACON_TRACKED"));
  break;
case EV_JOINING:
  Serial.println(F("EV_JOINING"));
  break;
case EV_JOINED:
  Serial.println(F("EV_JOINED"));


  LMIC_setLinkCheckMode(0);
  break;
case EV_RFU1:
  Serial.println(F("EV_RFU1"));
  break;
case EV_JOIN_FAILED:
  Serial.println(F("EV_JOIN_FAILED"));
  break;
case EV_REJOIN_FAILED:
  Serial.println(F("EV_REJOIN_FAILED"));
  break;
  break;
case EV_TXCOMPLETE:
  Serial.println(F("EV_TXCOMPLETE (includes waiting for RX windows)"));
  if (LMIC.txrxFlags & TXRX_ACK)
    Serial.println(F("Received ack"));
  if (LMIC.dataLen) {
```

```
        Serial.println(F("Received "));
        Serial.println(LMIC.dataLen);
        Serial.println(F(" bytes of payload"));
      }
      // Scheduling next transmission
      os_setTimedCallback(&sendjob, os_getTime() + sec2osticks(TX_INTERVAL), do
      break;
    case EV_LOST_TSYNC:
      Serial.println(F("EV_LOST_TSYNC"));
      break;
    case EV_RESET:
      Serial.println(F("EV_RESET"));
      break;
    case EV_RXCOMPLETE:
      // data received in ping slot
      Serial.println(F("EV_RXCOMPLETE"));
      break;
    case EV_LINK_DEAD:
      Serial.println(F("EV_LINK_DEAD"));
      break;
    case EV_LINK_ALIVE:
      Serial.println(F("EV_LINK_ALIVE"));
      break;
    default:
      Serial.println(F("Unknown event"));
      break;
  }
}

void do_send(osjob_t* j) {

  struct sensorValues ss = ecread();
  float structec = ss.ec;
```

```
  float structph = ss.ph;
  byte payload1[4];
  uint32_t ecValue = structec*100;
  uint32_t phValue = structph*100;
  payload1[0] =highByte(ecValue);
  payload1[1] =lowByte(ecValue);
  payload1[2] =highByte(phValue);
  payload1[3] =lowByte(phValue);


  if (LMIC.opmode & OP_TXRXPEND) {
    Serial.println(F("OP_TXRXPEND, not sending"));
  } else {
     LMIC_setTxData2(1, payload1, sizeof(payload1), 0); //paload1

    Serial.println(F("Packet queued"));
    Serial.println(LMIC.freq);
  }
  //Next transmission after TX_COMPLETE
}

void setup() {
  Serial.begin(115200);
  Serial.println(F("Starting"));
  ph.begin();
  ec.begin();

  // LMIC init
  os_init();
  // Reset the MAC state. Session and pending data transfers will be discarded.
  LMIC_reset();
  LMIC_setClockError(MAX_CLOCK_ERROR * 1 / 100);
  LMIC_disableChannel(1);
```

```
  LMIC_disableChannel(2);
  printotaainformation();

  // Start job (sending automatically starts OTAA too)
  do_send(&sendjob);
}
//print OTAA info
void printotaainformation(void)
{
  unsigned char i;
  unsigned char chartemp;
  unsigned char messagelength;

  Serial.println(F("OTAA mode to join network"));
  Serial.print("DevEui: ");
  for (i = 0; i <= 7; i++)
  {
    chartemp = pgm_read_word_near(DEVEUI+7-i);
    covertandprint((chartemp >> 4) & 0xf);
    covertandprint(chartemp & 0xf);
  }
  Serial.println("");
  Serial.print("AppEui: ");
  for (i = 0; i <=7; i++)
  {
    chartemp = pgm_read_word_near(APPEUI+7-i);
    covertandprint((chartemp >> 4) & 0xf);
    covertandprint(chartemp & 0xf);
  }

  Serial.println("");
  Serial.print("AppKey: ");
  //memcpy_P(buftemp, APPKEY, 16);
```

```
  for (i = 0; i <= 15; i++)
  {
    chartemp = pgm_read_word_near(APPKEY+i);
    //Serial.print(buftemp[i],HEX);
    covertandprint((chartemp >> 4) & 0xf);
    covertandprint(chartemp & 0xf);
  }
  Serial.println("");

 /* Serial.println("In this SW will send following information to network(uplin
 // messagelength = strlen(mydata);
  //for (i = 0; i <= messagelength-1; i++)
  //{
   // Serial.print(char(mydata[i]));
  //}
  Serial.print((char*)mydata);
  Serial.println("");
  Serial.println("mydata thing"); // add one new line*/
}

void covertandprint(unsigned char value)
{
  switch (value)
  {
    case 0  : Serial.print("0"); break;
    case 1  : Serial.print("1"); break;
    case 2  : Serial.print("2"); break;
    case 3  : Serial.print("3"); break;
    case 4  : Serial.print("4"); break;
    case 5  : Serial.print("5"); break;
    case 6  : Serial.print("6"); break;
    case 7  : Serial.print("7"); break;
    case 8  : Serial.print("8"); break;
```

```
    case 9   :  Serial.print("9");  break;
    case 10   :  Serial.print("A");  break;
    case 11   :  Serial.print("B");  break;
    case 12   :  Serial.print("C");  break;
    case 13   :  Serial.print("D");  break;
    case 14   :  Serial.print("E");  break;
    case 15 :   Serial.print("F");  break;
    default  :
      Serial.print("?");     break;
  }
}

//Read sensor Values
struct sensorValues ecread(){

  float ecValueRead;
  struct sensorValues val;
    char cmd[10];
   static unsigned long timepoint = millis();
    if(millis()-timepoint>1000U)   //time interval: 1s
    {
      timepoint = millis();
       voltagePH = analogRead(PH_PIN)/1024.0*5000;
// read the ph voltage
       phValue      = ph.readPH(voltagePH,temperature);
// convert voltage to pH with temperature compensation
       /*Serial.print("pH:");
       Serial.print(phValue,2);*/

      voltageEC = analogRead(EC_PIN)/1024.0*5000;   // read the voltage
      ecValueRead =   ec.readEC(voltageEC,temperature);   // convert voltage to E
      /*.print("temperature:");
      Serial.print(temperature,1);
```

```
      Serial.print("^C  EC:");
      Serial.print(ecValueRead,2);
      Serial.println("ms/cm");*/
      val.ec = 0.2;
      val.ph = 3.14;

     // val.ec = ecValueRead;
     // val.ph = phValue-7;
      Serial.println("transmitting now");
      delay(300000);
      //delay(3000);
      Serial.println("transmitting after delay");
      return val;

      //return ecValueRead;
    }

    if(readSerial(cmd)){
       strupr(cmd);
       if(strstr(cmd,"PH")){
         ph.calibration(voltagePH,temperature,cmd);
//PH calibration process by Serail CMD
        }
        if(strstr(cmd,"EC")){
         ec.calibration(voltageEC,temperature,cmd);
//EC calibration process by Serail CMD
        }
    }
    //ec.calibration(voltageEC,temperature);  // calibration process by Serail
}

int i = 0;
bool readSerial(char result[]){
```

```
    while(Serial.available() > 0){
        char inChar = Serial.read();
        if(inChar == '\n'){
            result[i] = '\0';
            Serial.flush();
            i=0;
            return true;
        }
        if(inChar != '\r'){
            result[i] = inChar;
            i++;
        }
        delay(1);
    }
    return false;
}


void loop() {
  os_runloop_once();

}
```

A.2 Custom decode function in LoRa App Server

Custom JavaScript decode function was used in the LoRa App Server

```
function Decode(fPort, bytes) {
    var ec = (bytes[0] << 8) | bytes[1];
    var ph = (bytes[2] << 8) | bytes[3];

    var dataout = {
        "sensorvalues": {
            'ec': ec / 100,
```

```
            'ph': ph / 100
        },
    };
    return dataout;
}
```

B RAK811 trials

Rak811 lora node issues and action taken trying to fix it.