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Fair Fault-Tolerant Approach for Access Point Failures in Networked Control System Greenhouses

A Thesis Submitted by

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To THE

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Master of Science Engineering

Declaration of Authorship

I, Mohammed Ali Ba Humaish, declare that this thesis titled, Fair Fault-Tolerant Approach for Access Point Failures in Networked Control System Greenhouses, and the work presented in it are my own. I confirm that:

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- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
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Abstract

Greenhouse Networked Control Systems (NCS) are popular applications in modern agriculture due to their ability to monitor and control various environmental factors that can affect crop growth and quality. However, designing and operating a greenhouse in the context of NCS could be challenging due to the need for highly available and cost-efficient systems. This thesis presents a design methodology for greenhouse NCS that addresses these challenges, offering a framework to optimize crop productivity, minimize costs, and improve system availability and reliability. It contributes several innovations to the field of greenhouse NCS design. For example, it recommends using the 2.4GHz frequency band instead of 5GHz to minimize Access Point (AP) costs while maintaining an acceptable Packet Loss Rate (PLR) of $\leq$ 2%, and prolonging sensor battery life by reducing transmission power. Additionally, it proposes a metric, Ψ, to help management select an architecture that minimizes crop profit loss, considering factors like AP failure and repair rates, and overall greenhouse efficiency. Markov models are used to calculate steady-state availability (AVss) and determine system downtime. System availability is assessed by modeling various architectures using SHARPE. Moreover, the Quality of Experience (QoE) metric is used to enhance the selection process of optimal distributions in the event of single, double, and triple AP failures. QoE serves as a valuable tool for system designers to evaluate and compare different distribution strategies, taking into account factors such as packet loss rates, latency, and user perception. This metric enables informed decision-making in selecting the most suitable distribution strategy, ensuring robust and efficient operations of greenhouse NCS, even under challenging conditions. The simulation tool, Riverbed Modeler, is used to evaluate greenhouse NCS operation in terms of PLRs. The methodology and contributions of this thesis were validated through a case study on a greenhouse NCS found in the literature. The results show that the methodology can significantly reduce costs while maintaining an acceptable level of system reliability and performance. These contributions provide a comprehensive design methodology for greenhouse NCS, applicable to farmers and greenhouse operators, aimed at improving the quality and profitability of their yield.

ACKNOWLEDGMENTS

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List of Abbreviations

APs :	Access Points
AV_{SS} :	Steady State Availability
EEPROM :	Electrically Erasable Programmable Read-Only Memory
GSM :	Global System for Mobile communication
ICTs :	Information and Communication Technologies
IoT :	Internet of Things
IT :	Information Technology
LCD :	Liquid Crystal Display
MQTT :	Message Queuing Telemetry Transport
MTTF :	Mean Time To Failure
MTTR :	Mean Time To Repair
NCSs :	Networked Control Systems
PA :	Precision Agriculture
PLR :	Packet Loss Rate
QoE :	Quality of Experience
RTC :	Real Time Clock
SSID :	Service Set Identifier
UART :	Universal Asynchronous Receiver-Transmitter
USB :	Universal Serial Bus
WSNs :	Wireless Sensor Networks

CHAPTER 1

INTRODUCTION

This thesis proposes a methodology to minimize both cost and downtime for Networked Control Systems (NCSs) greenhouses in addition to a fair fault tolerant distribution of sensors traffic to tolerate the failures of single, double, and triple access points. The aim is to ensure that the communication between different components inside the greenhouse works correctly, so all the environmental conditions of the greenhouse are monitored, controlled, and maintained within the optimum range, which in turns ensure crops quality and productivity.

1.1 Background

In today's rapidly changing world, agriculture stands at the intersection of different challenges, including climate change, population growth, and resource depletion. To tackle these challenges and ensure sustainable food production for a growing global population, using the advantage of the latest advances in Information Technologies (IT) has become imperative. Therefore, using modern technological solutions and tools, for instance, smart greenhouses, could add remote access and control of the growth conditions of large agricultural areas without any manual intervention and enhance crop quality and production throughout the year.

Greenhouses are closed environments that are used for cultivating any kind of plants or crops and protecting them from environmental abnormalities that could affect the quality of the plants, flowers or crops. From the 17th to the 19th-century, greenhouses were just shacks of wood or brick shacks that contain some window spaces, and some tools for heating. As the materials from which greenhouses are built became cheaper and available in plenty, and as more developed ways of heating were invented, greenhouses evolved to rely more on glass and fiber-reinforced plastic materials rather than wood or brick. Then greenhouses have transformed and advanced into a structure equipped with heating, ventilation, water, and cooling systems to provide an appropriate environment for crop cultivation and care. The structure of greenhouses consists of walls and roofs that are basically made of light materials like aluminum, polycarbonate, galvanized steel, wood, plastic, or fiber-reinforced plastic (FRP) [DALAI 2020].

Greenhouse performance can be evaluated by how efficiently the different environmental conditions inside the greenhouse are monitored and adjusted, and here comes the concept of Precision Agriculture (PA) [MEHTA 2018]. It is an information technology (IT) based farm management approach to monitor, analyze, and control the conditions of farms or fields to ensure that crops and soil get what they need for ideal productivity. In precision agriculture applications, for example smart greenhouses, sensor nodes are deployed in the fields and used to sense the conditions of the surrounding environment and replace the manual observation that had been used in conventional systems. Then sensed data by sensors is sent to a central controller for processing and extracting control signals and sending them to the actuators. In addition, Internet of Things (IoT) capabilities could be integrated into farming to add remote access and control of the conditions of large-scale agricultural farms or greenhouses without any manual intervention [IBRAHIM 2019, QUY 2022]. Once the actuators receive the control commands from the controller, different actions are taken to modify or adjust the environmental conditions of the field. In general, smart or automated greenhouses are used to increase crop productivity by providing a suitable environment for planting. Hence, it is profitable for plants and crops to be cultivated in smart greenhouses where there is comprehensive monitoring of the various environmental conditions like temperature, humidity, ventilation, soil moisture, solar radiation, light intensity, precipitation, air CO2 concentration and salinity [BOTH 2015]. Moreover, they could be used in advantageous ways to ensure profitability by minimizing the use of land resources and reducing production profit loss [ELNADI 2022, BALAFOUTIS 2017].

Exploring fault tolerance within precision agriculture, especially in NCS-operated greenhouses, presents an innovative research direction. This approach can greatly enhance both reliability and availability in intelligent greenhouse systems. Fault tolerance refers to the ability of a system to keep operating without interruption despite the failure of one or more of its components. The main aim of fault-tolerant agriculture systems is to mitigate the disruptions that could arise from the failure of the hardware of software and to increase the availability and reliability of smart greenhouses [IBRAHIM 2018], which in turn leads to improving the quality of crops and ensuring farmers' safety. Therefore, it is better to keep the system working with low performance than to have the system entire fail. NCS greenhouses are one of fault-tolerant applications, where greenhouses have sensor nodes, controller, and actuators to provide a reliable decision support system that remotely monitors the environmental conditions inside the greenhouse. A fault-tolerant architecture for NCS greenhouses was introduced in [IBRAHIM 2018], focusing on controller-level failures. The study evaluated two 200m x 40m greenhouses, each divided into five 40m x 40m cells. Simulations demonstrated that if one controller fails, the other greenhouse's controller compensates, ensuring both greenhouses remain operational. In subsequent research [IBRAHIM 2019], the integration of IoT for cloud connectivity allowed remote control and advanced data analysis in NCS greenhouses. A notable advancement in fault-tolerant systems for agricultural greenhouses came with the focus on Access Points (APs) in [ELNADI 2021]. This study explored various AP failure scenarios within a greenhouse NCS, measuring nine environmental parameters. The strategy involved sensors in any cell with a failed AP transmitting data at 5mW to a neighboring functional AP. The effectiveness of this approach was confirmed by Riverbed Modeler simulations, achieving a packet loss rate (PLR) under 2% [AWAD 2017], while maintaining at least two operational APs.

The rest of the thesis is organized as follows: a literature review and related works to this research is presented in Chapter 2; chapter 3 presents a methodology to minimize cost and downtime for NCS greenhouses. Chapter 4 is about fair distributions for sensors' data to achieve high QoE and acceptable PLR. Finally, the thesis is concluded in the last chapter.

CHAPTER 2

LITERATURE REVIEW

With the global population on the rise, the demand for quality and safe agricultural products is escalating daily. Concurrently, the quantity and size of farms making substantial contributions to food supply are diminishing. This trend underscores the critical need for efficient crop production management, prominently through precision agriculture systems. This involves using cutting-edge technologies like Networked Control Systems (NCSs), Wireless Sensor Networks (WSNs), and the Internet of Things (IoT). By integrating these technologies, precision agriculture aims to boost crop yields while decreasing reliance on conventional methods and resources, including pesticides and herbicides.

Smart greenhouses could be used for fast and effective farming in small, medium, or even large agriculture areas. In greenhouses, the environmental conditions can be automatically and intelligently adjusted using advanced technologies to ensure highly healthy efficient agriculture while, at the same time, decreasing the traditional approaches that were used in the past. With the vast advances that NCSs and WSNs have witnessed in recent years, the importance of using these networks in different applications has significantly increased. While the majority of networked system applications and advancements are primarily aimed at urban settings, there's a growing body of research dedicated to adapting these systems for agricultural use. Additionally, the incorporation of Internet of Things (IoT) technology in agriculture has opened up possibilities for storing and remotely accessing sensor data. Furthermore, the data collected by these sensors can be transmitted to the cloud or a data center, facilitating data analysis and other related activities. With IoT capabilities, environmental parameters can also be remotely monitored and adjusted. IoT-based environmental monitoring systems can identify irregularities in the greenhouse's environmental conditions, which can subsequently result in alerts sent by email or text message, as well as actions like turning on various actuators to modify and regulate the environment around the greenhouse.

This chapter will cover the literature review of all the fields related to the research. First, greenhouse monitoring systems in the context of smart farming will be presented, and different related works done in this field will be discussed. Then, an overview glimpse will be given about controlling agriculture systems that are built on WSN, NCS or IoT. Finally, fault-tolerance agriculture systems will be discussed either on the level of sensor nodes, controllers, access points, or actuators.

1.2 Smart Greenhouse (Monitoring and Controlling Systems)

Smart greenhouses are a type of advanced agriculture technology that has gained increasing attention in recent years. They are designed to provide an optimal environment for plant growth while minimizing energy consumption and controlling the impact on the environment. Smart greenhouses integrate various sensors, actuators, control systems, and communication systems that work together to create a highly efficient and sustainable plant growing environment. They come in a wide range of sizes, from a small shelter with a few plants to large structures that can cover hectares of land, sometimes referred to as hot houses.

Generally, greenhouses come with two popular styles, either freestanding styles or attached styles. Freestanding greenhouses, which can be quite large and offer more flexibility in terms of space than attached greenhouses, are those that stand alone in the landscape or field. The attached type can accommodate various growing conditions but has height constraints due to its attachment to the side wall. Greenhouses have popular styles; for instance, freestanding greenhouses include Tri-Penta, Dome, Gothic arch, and gable roof [KESSLER 2012], while the attached greenhouses have designed to be attached to the home, and many of them have an entrance to the home, and they include straight-side lean-to, curved-side lean-to, and slant-side lean-to [SHAMSHIRI 2007]. Figure 2.1.1 shows the freestanding and attached styles for greenhouses.

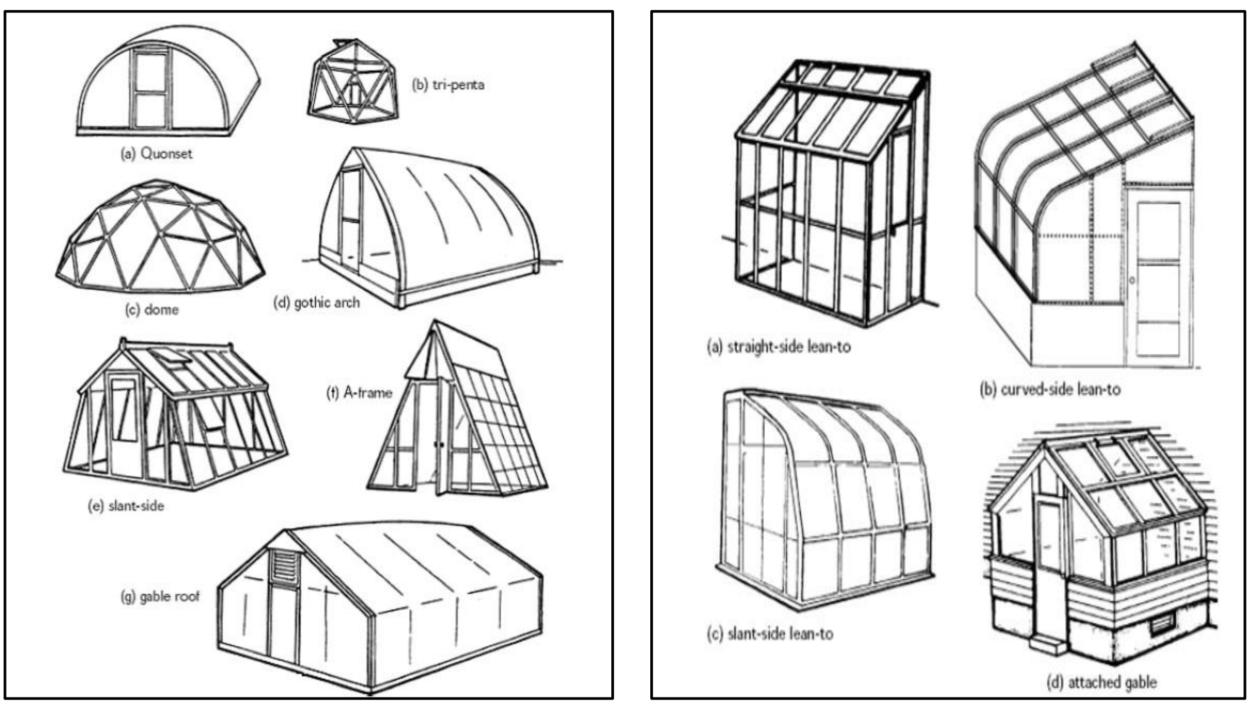

Figure 0.1.1 Freestanding and Attached Greenhouses Styles [SHAMSHIRI 2007]

A greenhouse monitoring system represents a technological solution designed to observe and regulate various environmental conditions within a greenhouse. It commonly comprises an array of sensors distributed across the greenhouse. These sensors are responsible for gathering data on key environmental factors, including humidity, temperature, light intensity, and soil moisture levels. The data collected by these sensors is then analyzed and used to make adjustments to the greenhouse's environmental controllers, such as heating and cooling systems, ventilation, and irrigation. The main purpose of a greenhouse monitoring system is to create and maintain optimal growing conditions for plants, which can help to increase crop yields and improve plant health. Access to real-time environmental data equips farmers with the necessary information to determine the best times for irrigation, fertilization, and crop harvesting. It also enables them to detect and resolve emerging issues promptly, preventing them from escalating into major concerns.

In the study by [DANITA 2018], the focus was on the development and deployment of an automated greenhouse monitoring system based on Internet of Things (IoT) technology. This system was engineered to track and manage different environmental factors within a greenhouse, including temperature, humidity, and light intensity. The aim was to optimize conditions for plant growth and enhance overall crop yield. The importance of greenhouse monitoring systems and the challenges associated with traditional manual monitoring methods are also discussed in the paper. The paper also presents a case study of the implementation of the IoT-based greenhouse monitoring system in a real-world greenhouse. The author discusses the results of the study, including the improvements in plant growth and yield, as well as the reduction in labor costs, quality improvement, providing real-time monitoring and control, and the potential for scalability. Figure 2.1.2 shows the block diagram of IoT-based greenhouse monitoring system. Overall, the paper provides valuable insights into the potential applications of IoT-based monitoring systems in farming and the benefits they can provide to farmers.

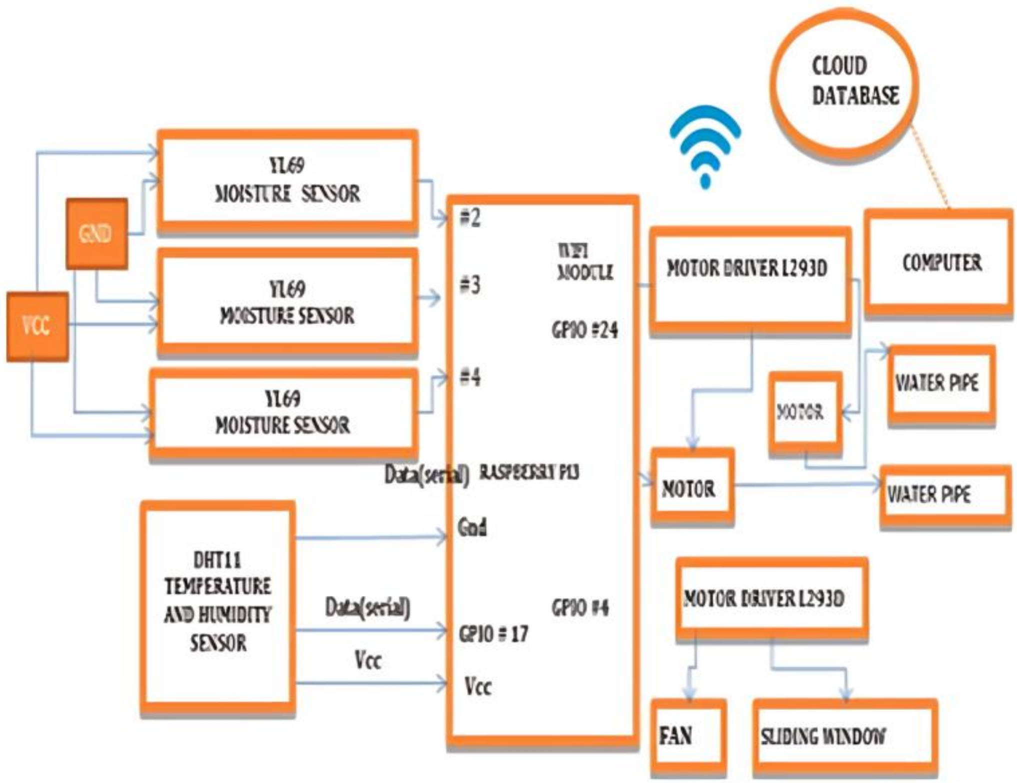

Figure 0.1.2: IoT-Based Greenhouse Monitoring System Block Diagram [DANITA 2018]

In the research presented by [CAO PHAM 2021], the authors proposed the design and implementation of a smart greenhouse monitoring system. This system utilizes Wireless Sensor Networks (WSNs) to observe and manage the environmental conditions within a greenhouse. The challenges of using traditional management strategies inside a greenhouse are discussed in the paper along with the idea of smart greenhouse monitoring systems. The proposed architecture consists of a WSN of sensors and actuators that monitor and regulate the greenhouse's temperature, humidity, light intensity, and soil moisture levels. The sensors send their data to a central gateway node, which gathers data and transmits it to a server in the cloud for data analysis. The performance of the proposed system in terms of the rate of the data received by the gateway, power consumption, availability, and reliability is also covered in the paper. The results show that the system had a 95% success rate when collecting data from the sensors at a rate of 1 sample per second. The sensors only use a few milliwatts of power, making the system energy efficient. According to the study, the system successfully kept the greenhouse's environmental conditions within suitable limits, leading to a higher productivity and less water use than with conventional production methods. Figure 2.1.3 shows an overview of the systems architecture.

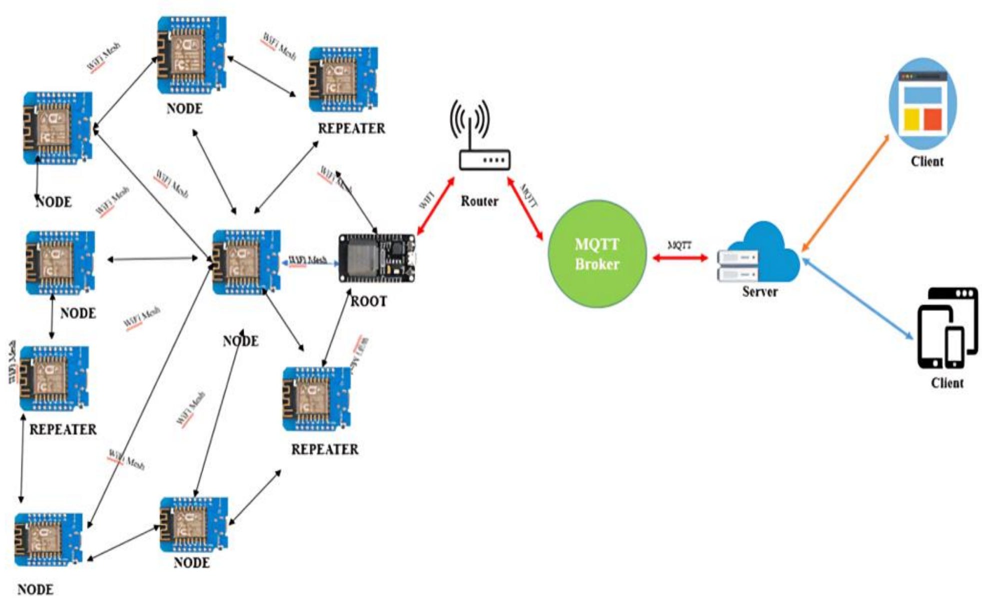

Figure 0.1.3: System Architecture Overview [CAO PHAM 2021]

AgriSys, which is a smart system designed specifically for agriculture, was presented in [ABDULLAH 2016]. Sensors were used in AgriSys to measure air temperature, humidity, soil moisture, soil PH, and light. In this study, curtains were utilized to block out the light, but there was no lighting unit to reduce the light. For the needs of water and nutrients, irrigation was used. In order to protect the plant from heat and humidity, a low-cold unit was used to handle the low temperatures. The authors claimed that the designed AgriSys system saves water and uses fewer farmers in agriculture when it is implemented. Figure 2.1.4 shows the diagram of the AgriSys.

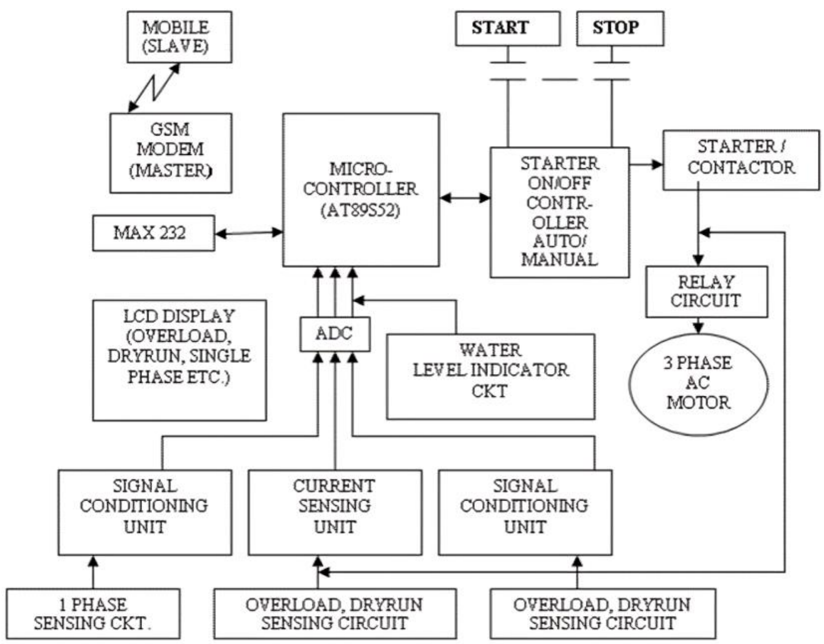

Figure 0.1.4: AgriSys Diagram [ABDULLAH 2016]

A monitoring system that includes sensors for air temperature, humidity, and soil moisture was introduced [PATEL 2014]. This system uses a microcontroller that receives the data wirelessly from sensors and sends control signals to appropriate actuators (irrigation, ventilation, etc.). However, only the irrigation system has been tested among all the actuators due to the complexity of putting all the parts together. Figure 2.1.5 presents the block diagram presented in [PATEL 2014].

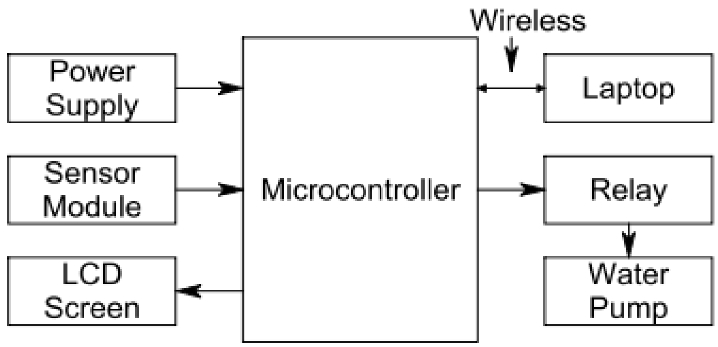

Figure 0.1.5: Block Diagram of Smart Design of Microcontroller-Based Monitoring System for Agriculture [PATEL 2014]

In [REMYA 2016], a prototype focused on monitoring and managing the climate in greenhouses was developed, employing Wireless Sensor Networks (WSN) and the Internet of Things (IoT). This prototype featured several key components: a collection of various sensors (referred to as a sensor boutique), a controller, a monitoring unit, and a system for sending and receiving messages. The sensing component included specialized sensors like the LM35 for temperature, the MQ-5 for toxic gas detection, and a fire sensor. The sensors gathered up a number of parameters, and the LCD presented them. The controlling component, the P89V51RD2 microcontroller, was connected to the sensors. The microcontroller was then linked through MAX 232 to a pump, buzzer, and GSM module. The microprocessor would activate the pump to sprinkle water when the moisture level fell below the predetermined values. Block diagram of the systems is illustrated in figure 2.1.6 The buzzer would activate to alert the user if the fire was detected. A GSM module acts as a message-sending unit that transmits greenhouse parameter values to a predetermined number. The receiver was an Android-powered smartphone playing a pre-programmed audio sound.

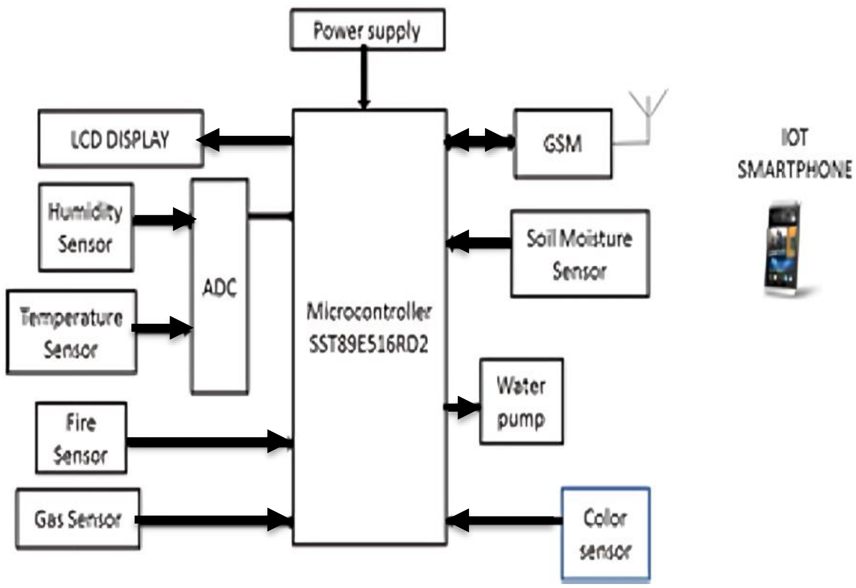

Figure 0.1.6: Systems Block Diagram [REMYA 2016]

In [TESLYUK 2015], the authors describe a mini greenhouse control system design based on Arduino. A sensor module with temperature, humidity, and light values is used to measure the greenhouse environment. Changes in the greenhouse's atmosphere are made using heaters, air conditioners, irrigation pumps, and lumps. In addition, a real-time module with its own battery provides the real-time needed for the system to function. Both the system described in [TESLYUK 2015] and our NCS greenhouse system implementation use the same ventilation mechanism and air temperature and humidity sensor. Nevertheless, no comprehensive information is provided for the other units used in [TESLYUK 2015]. On LED screen, the system's operation is shown. However, the system is not implemented in the greenhouse. Figure 2.1.7 shows the general structure of the mini greenhouse control system.

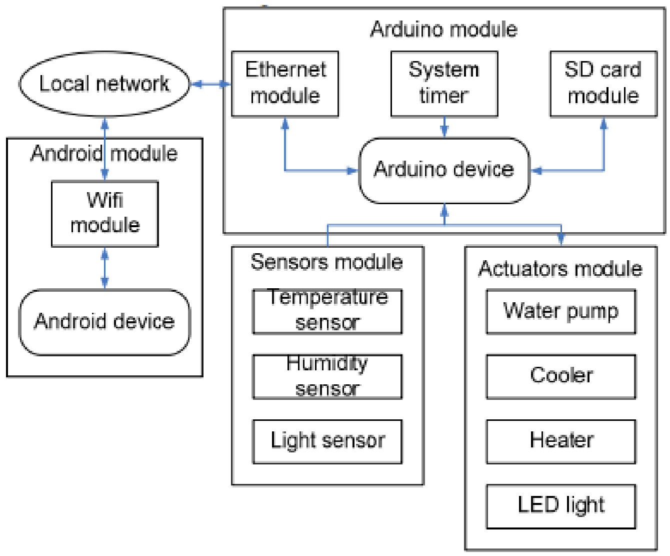

Figure 0.1.7: The Architecture of Mini Greenhouse Control System [TESLYUK 2015]

The design of a greenhouse system that monitors soil moisture and controls irrigation systems accordingly was proposed in [NANDURKAR 2014]. A smart valve and drip irrigation system were used to construct the irrigation system. The valve was designed to open when the soil moisture fell below a predetermined threshold value and remained open until the required level of moisture was reached, then the valve closed. By removing the need for human labor during irrigation, inappropriate irrigation was avoided, and electricity was saved. The proposed smart greenhouse system improved the product's quality because weather conditions and watering were both managed and controlled automatically.

Another smart irrigation system was proposed in [PATIL 2016], where the authors use an Arduino Uno to implement the system. An Ethernet protocol and a motor that is compatible with Arduino are used in this system. The system incorporates a soil moisture sensor to accurately gauge the moisture levels in the soil. The value that was measured is analyzed by Arduino: The attached servo motor to the motor shield is turned on, and irrigation is started if it falls below a predefined threshold value. Then the servo motor is turned off, and irrigation is complete when the moisture level of the soil reaches the desired value. The proposed irrigation systems efficiently decreased the number of farmers required for irrigation, but the use of additional motor has increased the setup cost. Figure 2.1.8 presents the architecture of the system.

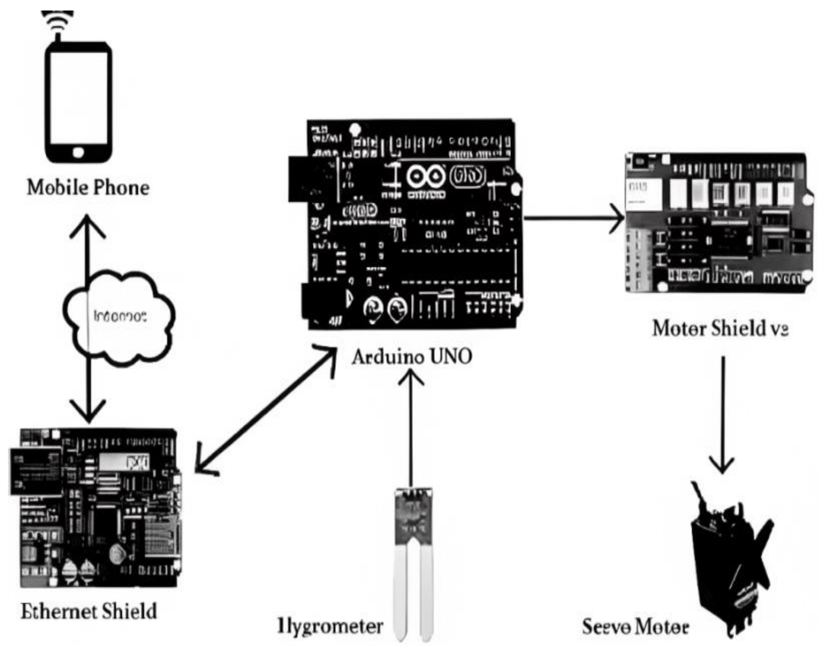

Figure 0.1.8: Smart Farming Irrigation System Architecture [PATIL 2016]

In [RANA 2013], a wireless greenhouse monitoring system was proposed, where the architecture consists of three types of sensors and a control station. The sensor nodes take reading about temperature, humidity, and light and send these readings to a central computer for processing. The system utilized ZigBee S2 links, supported by XBee modules, which were configured to collect analog readings from sensors and convert them into data packets for transmission. The central control station comprised a computer and an XBee module, interconnected via a Universal Serial Bus (USB). Sensor nodes within the greenhouse measured various environmental parameters, converted these measurements into digital format, and then wirelessly transmitted the data to the main control unit. This setup of the greenhouse system is depicted in Figure 2.1.9

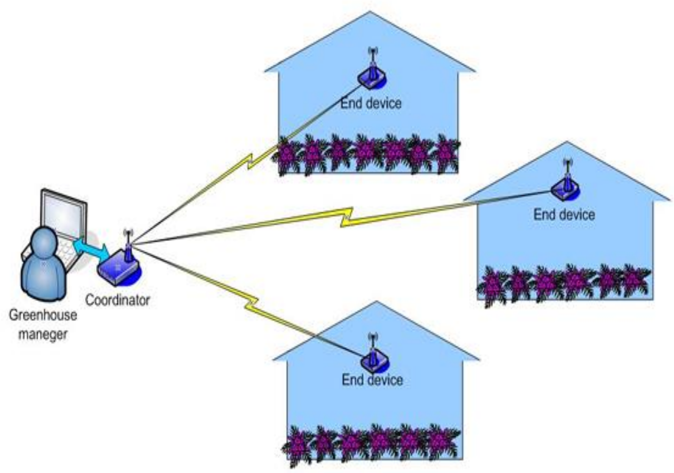

Figure 0.1.9: Greenhouse Architecture [RANA 2013]

A GSM-based greenhouse system was developed in [GURAIAH 2014] and used in agricultural fields. The controlling unit in the system comprised of ARM7LPC2148 microcontroller, and the inputs coming from many wireless sensors that measured temperature, humidity, and light intensity. The output components of the system comprised an LCD screen, a laptop, GSM technology, and various actuators. The data collected by the sensors were displayed both on the LCD and on a GPRS webpage accessible via a central computer. The structure of this GSM-based greenhouse system is depicted in Figure 2.1.10. The system's software was developed in the C programming language using Keil software. Notably, the system did not include a mobile monitoring component.

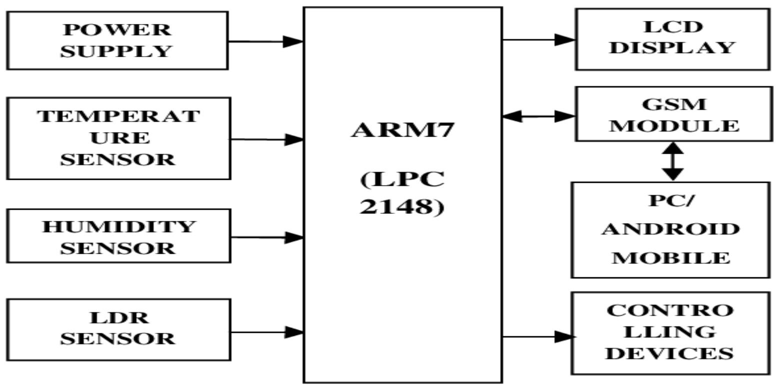

Figure 0.1.10: Greenhouse Architecture [GURAIAH 2014]

In [TAHA 2018], a remote greenhouse monitoring and control system was proposed, leveraging IoT technology. This system captures key environmental parameters within the greenhouse, like temperature, light intensity, and humidity. These parameters are sent in real-time to a Raspberry Pi server. The system comprises four main components:

- ***Sensor Nodes:*** These collect environmental data and transmit it to the server via an ESP8266 Wi-Fi module.
- ***Server:*** This central unit receives sensor data, processes it using the MQTT (Message Queuing Telemetry Transport) protocol, and uploads it to the internet. It compares the data against optimal crop growth metrics and, if necessary, signals the actuators to adjust the greenhouse environment.

- ***Monitoring Unit:*** Utilizing Red-Node software, this unit displays graphs of current temperature, humidity, and light intensity values. Users can remotely monitor these readings online.
- ***Actuators:*** These are responsible for maintaining the ideal conditions within the greenhouse based on the server's instructions.

The system's architecture is illustrated in Figure 2.1.11 This design effectively meets several key requirements, including reducing manual labor, ensuring precise control of crop conditions, enabling distributed monitoring, and providing internet access to farm data.

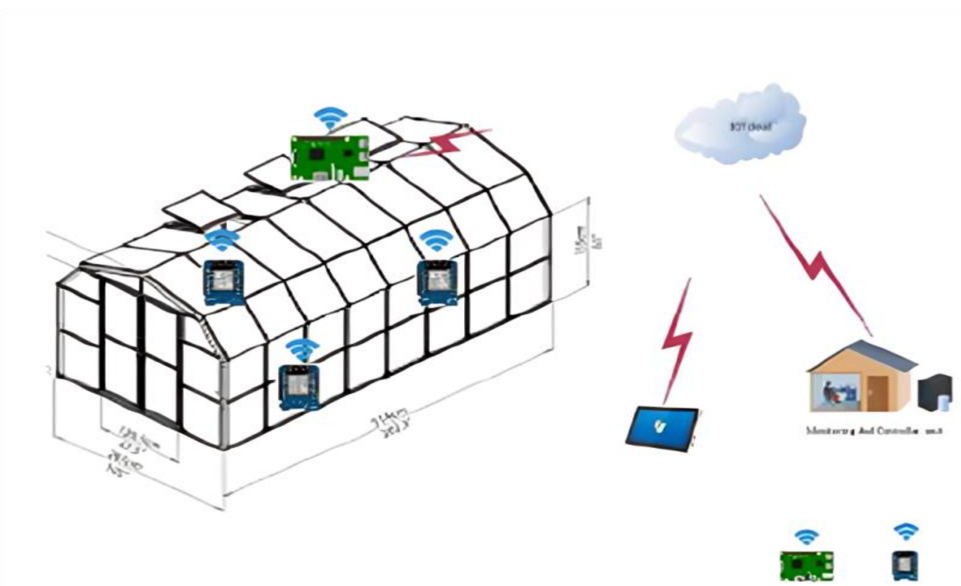

Figure 0.1.11: System Block Diagram Architecture [TAHA 2018]

In the study [MADRAP 2016], the researchers developed an embedded system specifically for greenhouse monitoring. The hardware components of this system included a PIC18F452 controller, various sensors, a graphic LCD, an EEPROM for data storage, a real-time clock (RTC) for timekeeping, and relays for controlling external actuators. For the sensor nodes 5 different sensors used to sample 5 different environmental parameters such as FC-28-D for soil moisture measurement, SY-HS-220 for humidity measurement, LM35D for temperature measurement, NORP-12-RS for light measurement, and pH sensor. The controller receive time from the RTC, and the collected data was saved in the EEPROM, and to take an action the relays were used to turn ON or OFF the actuators. Real-time parameters and analytical graphs were shown on the graphic LCD. Data from EEPROM was sent to a computer through a UART USB module for data displaying. Colling fan and heater were the actuators used to control the temperature, light bulb to increase the light, and a small heater to regulate the humidity. However, remote monitoring was not included in this study. Figure 2.1.12 shows the block diagram of greenhouse monitoring system.

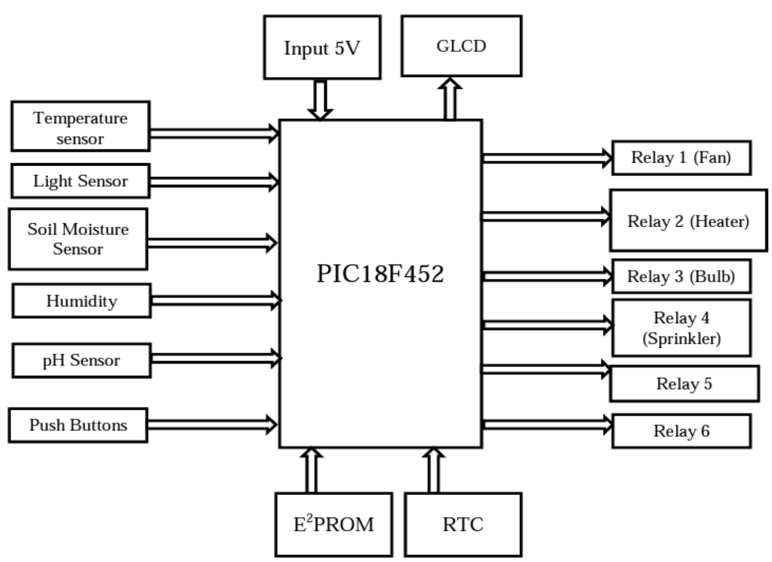

Figure 0.1.12: Block diagram of Greenhouse Monitoring and Control system [MADRAP 2016]

In the study by Sahu in 2012, the researchers developed a basic circuit controlled by a microcontroller for recording and adjusting environmental conditions like temperature, humidity, soil moisture, and light within a greenhouse. This system aims to enhance plant growth and yield. It employs a microcontroller that gathers real-time data from sensors about greenhouse conditions and operates cooling, fogging, dripping, and lighting systems accordingly. The system also includes an LCD to display sensor data and device status. Similarly, the 2022 study by Kolawole introduced a microcontroller-driven device for the automated management and observation of greenhouse conditions, including temperature control and soil moisture. This system demonstrates the elimination of manual monitoring by efficiently controlling the greenhouse environment, offering energy efficiency, reduced maintenance, and cost-effectiveness. It automates the process, providing problem-solving suggestions and ensuring precise environmental control.

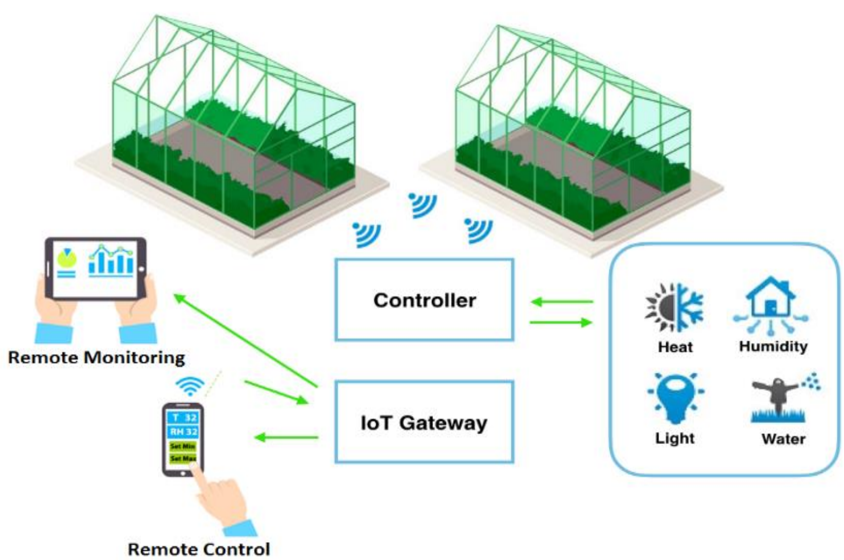

Figure 0.1.13: Smart Greenhouse Architecture

In [Shinde 2018], a monitoring system for greenhouses was developed using a wireless sensor network (WSN). This system employed a Raspberry Pi 3 circuit to continually track and read changes in soil moisture, light, temperature, and humidity. The data collected by Arduino Uno from the sensors was processed and analyzed by the Raspberry Pi. This setup enabled the Raspberry Pi to send control signals to the actuators, thereby modifying the greenhouse's internal environment to better suit crop growth. For instance, switching the water pump, heater, and light ON/OFF. Additionally, the user can monitor and control the data using an LCD display.

In the study [KUMAR 2022], researchers focused on developing a cost-effective, reliable, and user-friendly greenhouse monitoring and control system. This system leverages various sensors to detect changes in environmental conditions like temperature, humidity, and soil moisture within the greenhouse. The central component of this system is an Arduino Uno controller, which receives data from the sensors, processes and analyzes it, and accordingly controls actuators such as heaters, fans, and water pumps to adjust the interior environment as needed. A key feature of the system is its ability to communicate with the user; for instance, if the temperature falls below a certain threshold, the controller activates the fans and sends a notification to the user's phone, keeping them informed about the greenhouse's current conditions. This integration of sensor data, automated control, and user notifications ensures an efficient and responsive greenhouse management system. Additionally, the system is environmentally friendly because it powers the entire greenhouse with solar energy, which is used to charge the batteries. System block layout and diagram of the IoT-enabled greenhouse system are shown in figures 2.1.14 and 2.1.15, respectively.

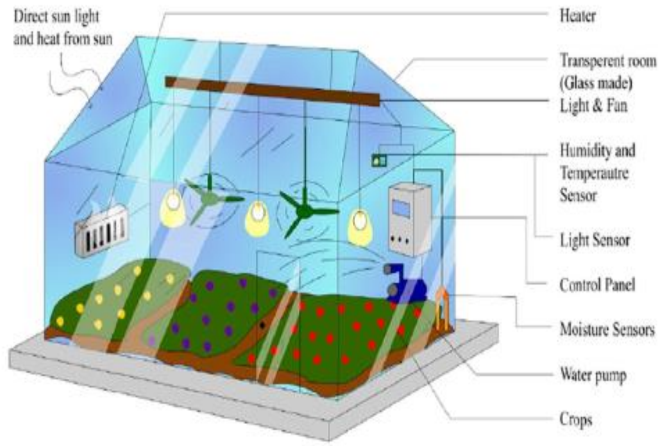

Figure 0.1.14: The Layout of Greenhouse System [KUMAR 2022]

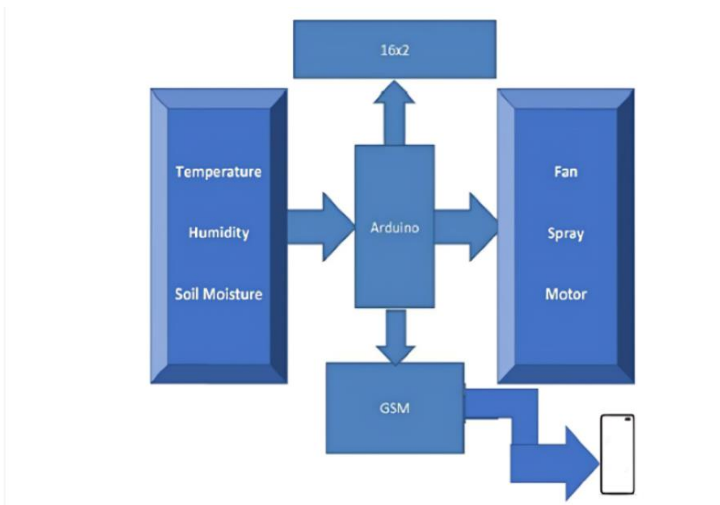

Figure 0.1.15: System Block Diagram [KUMAR 2022]

In [SUBAHI 2020], a smart IoT-based Energy Efficient (EE) system was proposed for monitoring and regulating temperature within greenhouses. This study aimed to enhance productivity by reducing production costs and conserving energy. A critical aspect of the system was tracking the external temperature to establish an accurate reference temperature for the greenhouse, ensuring it could be maintained consistently.

Moreover, the system was capable of determining the sun's angle, facilitating the management of awning openings to mitigate the effects of high temperatures. A Petri Nets model was developed for monitoring purposes and to generate the appropriate reference temperature. The design of this system's architecture is detailed in Figure 2.1.16, illustrating its structure and functionality in optimizing greenhouse conditions.

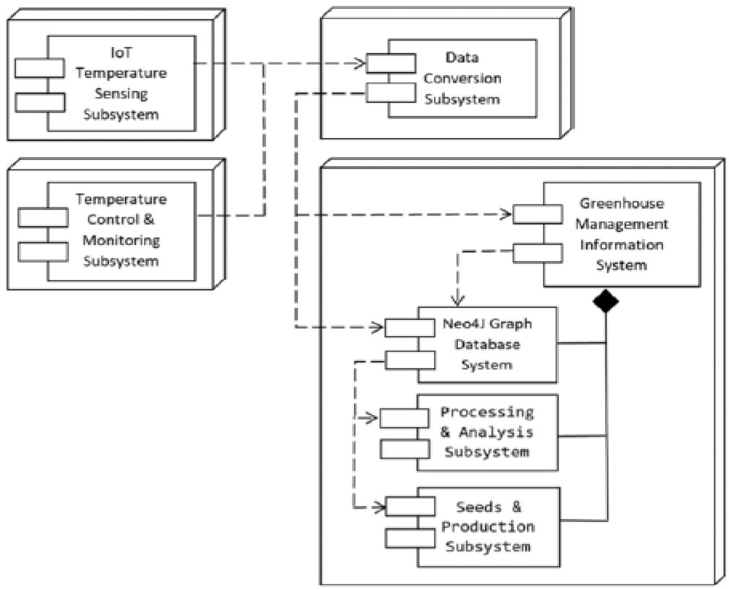

Figure 0.1.16: System Architecture [SUBAHI 2020]

Precision agriculture (PA) is increasingly incorporating machine learning to enhance crop quality and optimize resource use. PA systems rely on developing models and algorithms that learn from data to predict optimal plant growth conditions. Machine learning finds applications in crop management, soil monitoring, and climate prediction within precision agriculture. In [LIN 2021], an innovative greenhouse system was proposed, utilizing machine learning combined with remote sensing imagery to bolster agricultural economic efficiency. This system was designed to monitor, analyze, and adjust various environmental factors within the greenhouse, such as temperature, humidity, and light intensity, to optimize crop growth.

The authors recommended a hybrid approach for training a machine learning model, which involves integrating satellite remote sensing images with data collected from ground-based sensors. This model aims to accurately predict crop growth and quality. Additionally, the paper details the implementation of the proposed system and presents results from a case study conducted in an actual greenhouse. The structure and workings of this system are depicted in the system datagram shown in Figure 2.1.17, illustrating how advanced technology can significantly contribute to the efficiency of greenhouse operations.

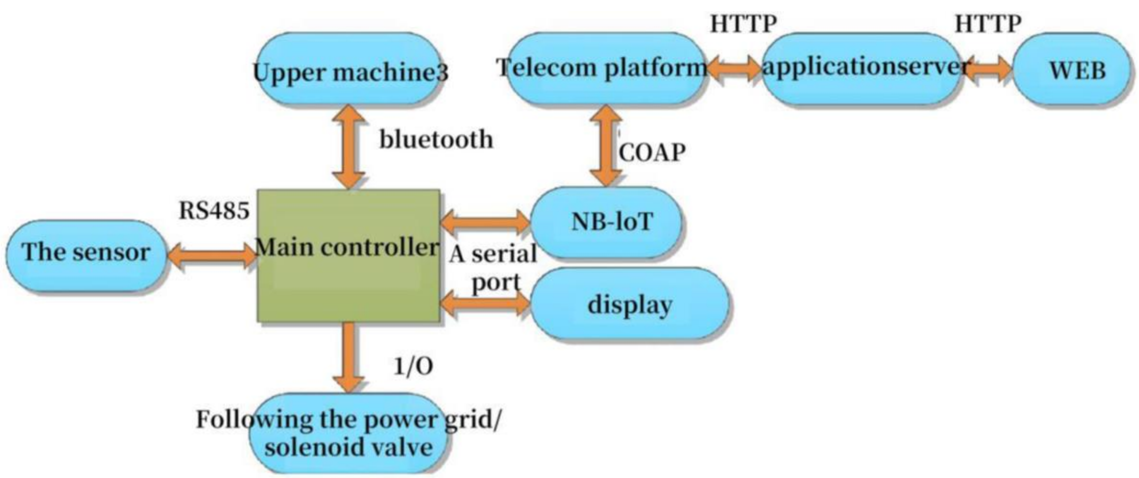

Figure 0.1.17: System Data Flow Diagram [LIN 2021]

Designing and developing an energy-efficient smart greenhouse is another research aspect of precision agriculture. It is important to pay attention to and consider peak energy use in IoT-based agriculture applications; hence, different energy prediction algorithms have been developed for IoT-based greenhouses. In [SINGH 2020] the authors proposed technique to reduce energy consumption in wireless communication systems for Internet of Things (IoT) enabled greenhouses. The proposed system consists of low-power wireless sensor nodes that are powered by energy harvesting sources and a gateway that sends data to a cloud server over long distances and at low power. The authors also suggest a new communication protocol employing adaptive transmission power and duty cycle control to reduce energy consumption. This protocol extends the lifetime of the sensor nodes and achieves a trade-off between network coverage and energy consumption. Compared to current communication protocols, the proposed system and protocol can develop sustainable and energy-efficient smart greenhouse applications and it reduces energy consumption by up to 30%, compared to traditional greenhouses. Figure 2.1.18 presents the roadmap for achieving energy efficient solution for precision agriculture applications.

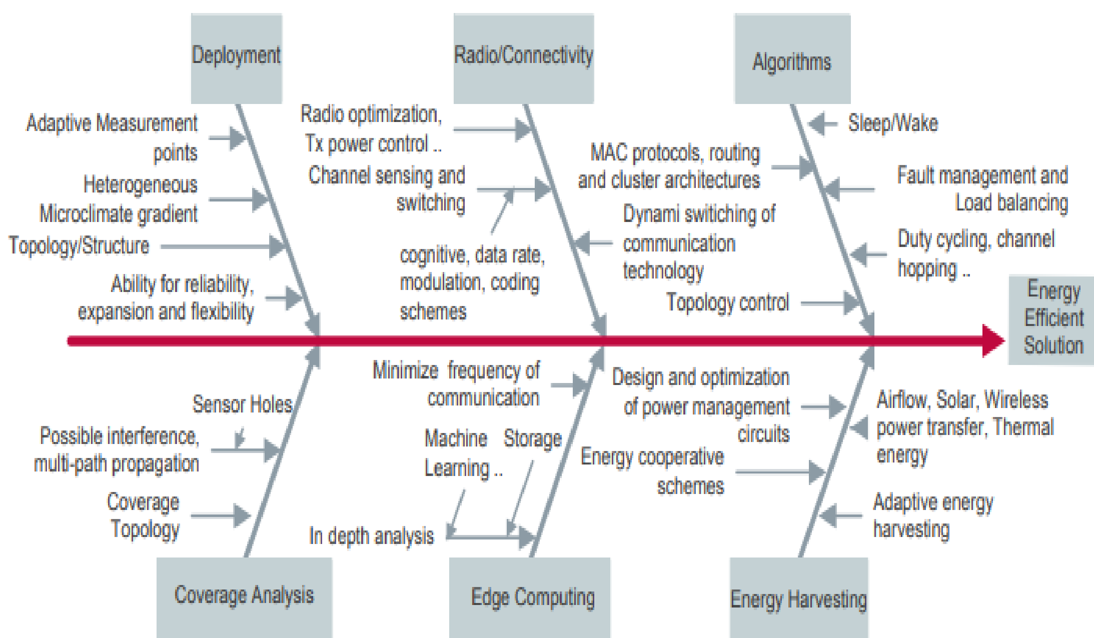

Figure 0.1.18: The roadmap for achieving energy efficient solution for precision agriculture applications [SINGH 2020].

The same in [LEE 2023], the researchers describe an intelligent (IoT)-based greenhouse farming technology that enables farmers to monitor and control crop growth remotely. The suggested system gathers data on various environmental parameters using inexpensive sensors and an energy-efficient wireless communication protocol, which is MQTT (Message Queuing Telemetry Transport). The sensors' data is transmitted to a cloud-based server for processing and analysis. The system also includes a decision support system that enables farmers to modify the greenhouse environment based on real-time information about the ideal conditions for crop growth. The proposed system is highlighted in the paper as being inexpensive and energy-efficient, making small-scale greenhouse farming operations an ideal application for it.

Generally speaking, the use of the modern technological techniques such as IoT, NCS, WSN and AI in PA applications enhances the productivity and quality of plants and crops, and all this is done by controlling the conditions surrounding agricultural plants to provide optimal plant environmental conditions. For this reason, this section has focused on reviewing some recent literature focused on the design and development of monitoring and control systems in smart greenhouses.

1.3 Fault-tolerant Greenhouses Systems

In the realm of precision agriculture (PA), minor fluctuations on the environmental parameters could impact crop or plants health. Hence, the PA systems should be designed to be resilient for soft and hard failures which ensure uninterrupted operation even in harsh conditions. In fact, the design of the greenhouse in this thesis was constructed based on an existing model from literature, where Wireless Sensor Network (WSN) - Networked Control Systems (NCS) architecture was utilized inside the greenhouse [IBRAHIM 2019]. WSNs consist of a cluster of nodes distributed inside the greenhouse to monitor the environmental conditions. These sensors can be arranged in diverse topographical patterns, including star, hybrid star, mesh, peer-to-peer mesh, and ring configurations. These different topologies could offer a network with several advantages, including cost reduction, simplified system diagnosis, and enhanced flexibility and reliability.

In this thesis, the architecture was developed by integrating Switched Ethernet and Wi-Fi technologies along with an IoT layer. In general, the greenhouse architecture consists of three distinct layers: layer 1, known as the Sensor/Actuator Front-end Layer, and this layer consists of some sensor nodes and cameras that transmit data to the controller. Sensor nodes were equally distributed over 5 cells to collect data about different environmental parameters such as humidity, temperature, and CO2. The sensors send these data wirelessly to the controller for processing and extracting control commands that activate the actuators. APs were used to relay sensors readings to the controller wirelessly, while actuators were connected to the APs using Ethernet protocol. In Layer 2 of the architecture, the controller acts as the central processing unit for data of sensors and cameras. Finally, in layer 3 a gateway is used to transmit the system data to the cloud for more data processing and analysis. Figure 2.2.1 shows the general architecture with the three main layers. In [IBRAHIM 2019], simulation results have shown that, even if one of the two controllers fails, the controller of the other greenhouse takes over its tasks so that both greenhouses operate successfully. Multiple simulations were performed to prove that the system has zero packet loss and an absence of delayed packets. Moreover, Markov Chains were utilized to analyze the system's reliability and steady-state availability (AV_{ss}). Consequently, the system design effectively met all specified requirements, significantly reducing downtime during failures.

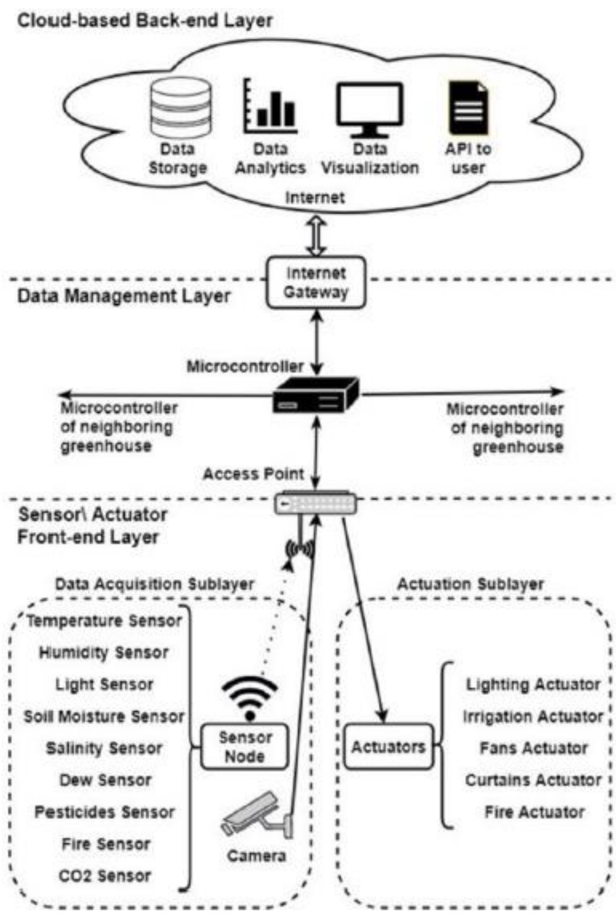

Figure 2.2.1: The System Architecture [IBRAHIM 2019]

CHAPTER 3

GREENHOUSE NETWORKED CONTROL SYSTEM DESIGN METHODOLOGY TO MINIMIZE COST AND DOWNTIME

Greenhouse networked control systems design methodology, cost minimization, and downtime reduction refer to the application of NCS principles and techniques to the design and operation of greenhouse systems. Greenhouse NCS involves the use of distributed sensors, controllers and actuators to monitor and control environmental factors such as temperature, humidity, light, and carbon dioxide levels. The access points, controller, and actuators are connected through an Ethernet switch which enables the controllers to receive sensors readings from the APs and send control signals to actuators. Cost minimization in greenhouse NCS involves optimizing the design and operation of the control system to minimize the cost of implementation, maintenance, and operation. This can be achieved through the selection of appropriate cost-effective APs, and the use of energy-efficient control strategies. Downtime reduction in greenhouse NCS involves ensuring that the control system is reliable, robust, and resilient to faults and failures.

Overall, greenhouse NCS design methodology, cost minimization, and downtime reduction are essential considerations for farmers and greenhouse operators who want to optimize crop yields, costs profit losses, and improve the reliability and performance of their greenhouse systems. This chapter introduces the first major contribution of the thesis, with a particular emphasis on the wireless NCS in greenhouses. The chapter will explore how utilizing the 2.4GHz frequency band effectively reduces costs associated with Access Points (APs) while maintaining an acceptable Packet Loss Rate (PLR). Additionally, it delves into fault-tolerant AP architectures and introduces a novel metric, Ψ. This metric is designed to account for AP failure and repair rates, along with the overall efficiency of NCS information. This is intended to assist management in selecting the most suitable architecture to minimize profit loss. The chapter also discusses findings from Riverbed simulations, particularly regarding the minimum sensor transmission power required in the 2.4GHz band. This is aimed at achieving the lowest feasible PLR while also extending the battery life of the sensors.

1.4 Greenhouse Networked Control System Descerbition

Networked control systems are distributed control systems that are connected over a communication network. In an NCS, the control signals and feedback are transmitted over a network, and the control actions are extracted by the controller and executed by the actuators. Networked control systems are becoming increasingly popular in many industrial applications, including manufacturing, transportation, energy systems, and farming. This research focuses on analyzing and enhancing the Networked Control System (NCS) structure of a greenhouse as documented in [IBRAHIM 2018]. The primary objective is to develop a robust architectural framework for the greenhouse and to introduce a comprehensive metric that integrates the Access Point (AP) Mean Time To Failure (MTTF), AP Mean Time To Repair (MTTR), and the overall efficiency of the greenhouse NCS. This metric is intended to guide management in balancing the costs of the greenhouse against anticipated profits.

In the studies [IBRAHIM 2018, IBRAHIM 2019], the greenhouse is described as measuring 200m x 40m and is subdivided into five equal cells. Each cell is equipped with 40 evenly distributed sensor nodes, summing up to a total of 200 nodes for the entire greenhouse. These sensor nodes, integral to the Internet of Things (IoT) and modern technological systems, are characterized by their low cost, low power consumption, small size, multifunctional capabilities, and their ability to communicate across varying distances. Each of these 200 sensor nodes contains nine different sensors, responsible for monitoring and controlling the environmental conditions within the greenhouse. The sensors cover a range of parameters, including temperature, humidity, dew point, salinity, light intensity, soil moisture, pesticide levels, CO2 concentration, and fire detection. The sampling rate of each sensor, detailed in Table 3.1.1, is determined by the specific environmental parameter it measures and the criticality of that parameter. This comprehensive setup allows for a detailed and responsive management of the greenhouse's internal environment, aligning with the goals of precision agriculture and efficient resource use.

Table 0.1.1: Sensors Sampling Rates [IBRAHIM 2018]

Sensors	***Sampling rates***
Temperature, humidity, salinity, dew, light, and soil moisture.	6 bytes every 30 seconds
Pesticide sensors	1 Byte every 5 seconds
CO2 and Fire	2 Bytes every 1 seconds

Each sensor node in the system consists of environmental sensors, a microcontroller, and a battery as its power source. The sensors are designed to detect environmental changes, like temperature fluctuations or variations in soil moisture. The microcontroller in these nodes is equipped with Wi-Fi capabilities, enabling the wireless transmission of collected data to the local access point within each greenhouse cell. The system employs the IEEE 802.11n Wi-Fi protocol for data transmission. For operations in the 5GHz frequency band, each cell is allocated a unique, non-overlapping channel (such as 36, 40, 44, 48, 50) to avoid interference, taking advantage of the numerous channels available in this frequency range. In contrast, for the 2.4GHz band, commonly used channels 1, 6, and 11 are utilized. Additionally, each greenhouse cell is equipped with four cameras situated at its corners. These cameras operate at a frame rate of 12 FPS and offer a resolution of 5 megapixels. To reduce potential interference between sensor data traffic and camera data traffic, the cameras are hardwired to the main controller of the greenhouse via Ethernet cables.

An illustrative diagram, shown in figure 3.1.1, depicts a single greenhouse cell. This diagram includes the placement of APs, sensor nodes, and cameras, demonstrating how they are centrally positioned within the cell to ensure efficient monitoring and data collection. This setup highlights the integration of advanced sensor technology and high-resolution imaging within the greenhouse to maintain optimal growing conditions.

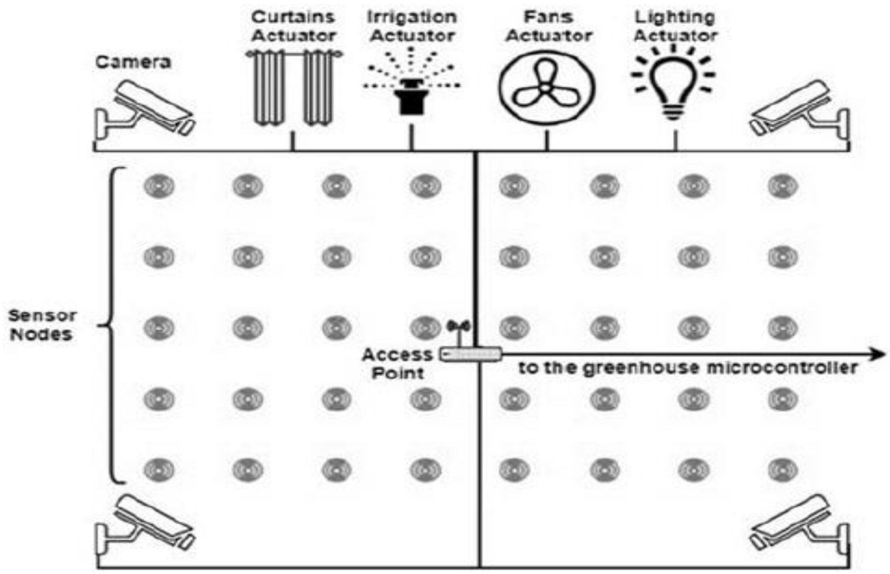

Figure 0.1.1: Single Greenhouse Cell with Sensor Nodes, Cameras, and APs [ELNADI 2021]

In the context of NCS, any device that produces an output is known as an actuator. This research involves equipping each cell of the greenhouse with four actuators that aid in regulating and modifying the internal environment, such as controlling light, fans, curtains, and irrigation valves. In addition to the sensor nodes and cameras, the greenhouse setup includes a singular fire extinguisher actuator that serves the entire structure. All actuators within this system are connected to the main controller through Ethernet cables, ensuring reliable communication and response. These actuators are programmed to operate at varying frequencies, depending on their specific roles within the greenhouse environment. For most actuators in the greenhouse, actions are triggered every 30 seconds. However, the fire extinguisher actuator, which is of paramount importance in this study, operates on a more frequent schedule, activating every second to ensure rapid response in case of fire emergencies. This prioritization underscores the critical nature of the fire actuator in maintaining safety within the greenhouse.

Figure 3.1.2 provides a visual representation of the greenhouse's actuators. This illustration likely details their placement and operational framework within the greenhouse, offering a clear understanding of how these components integrate into the overall system for efficient and safe greenhouse management.

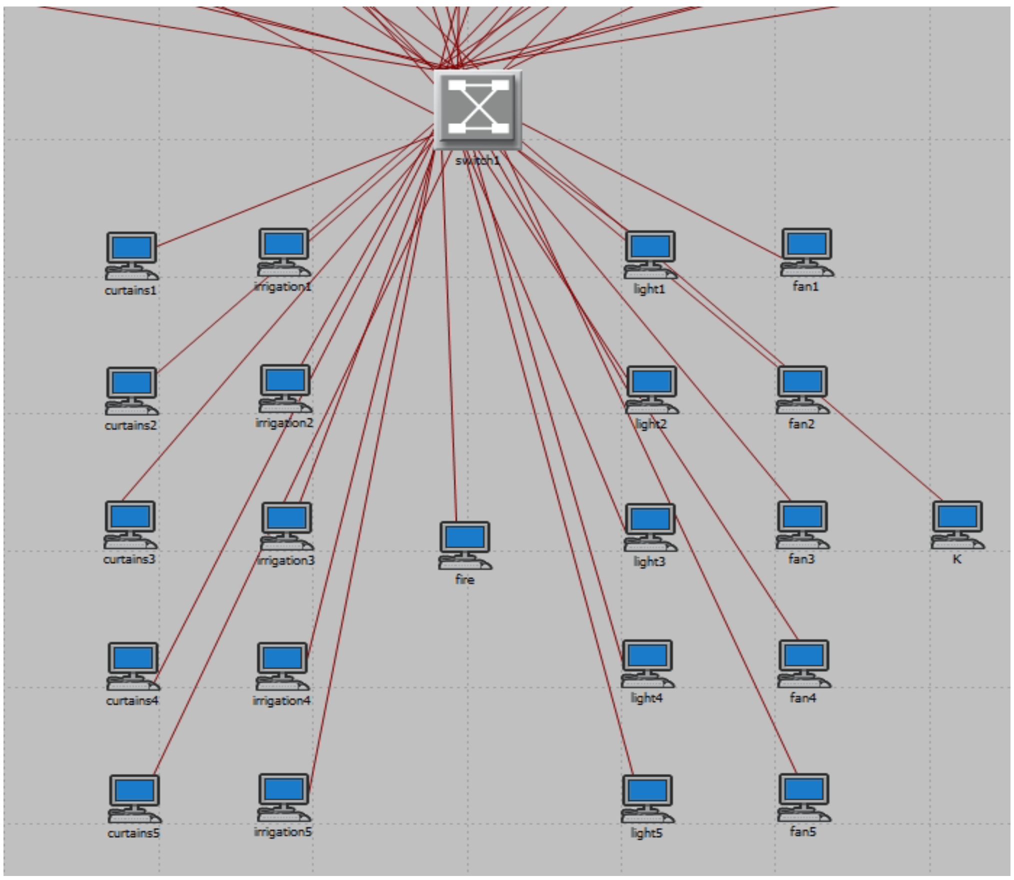

Figure 0.1.2: Greenhouse's Actuators [ELNADI 2021]

Within the greenhouse, the communication protocols employed are Wi-Fi for wireless data transmission and Ethernet cables for wired connections. Each cell in the greenhouse is outfitted with an access point (AP) that plays a crucial role in data communication. These APs are tasked with gathering data wirelessly from the sensor nodes located throughout the cell. Upon receiving data from the sensor nodes, each AP then forwards this data to the main controller of the greenhouse using the Ethernet protocol. This wired connection ensures a stable and reliable transfer of data. The main controller, upon receiving the data from the APs, processes and analyzes this information. Based on this analysis, the controller generates and dispatches control signals to the various actuators distributed within the greenhouse. These actuators then make the necessary adjustments to the greenhouse's internal environment, ensuring optimal conditions for plant growth.

For a clearer understanding of this setup, Figure 3.1.3 provides a schematic diagram. This diagram illustrates the greenhouse cells and their key components, specifically highlighting how the APs and the controller are interconnected using Switched Ethernet. This visual representation aids in comprehending the flow of data and control signals within the greenhouse, showcasing the integration of wireless and wired communication protocols in the functioning of the greenhouse NCS.

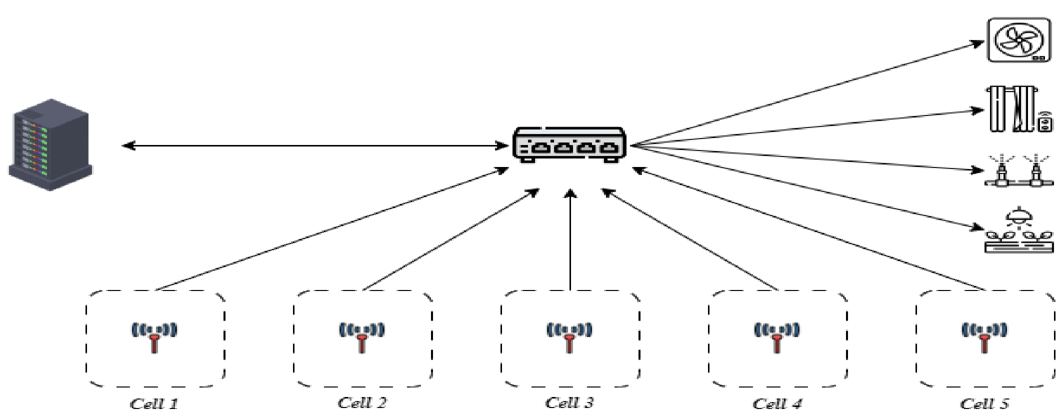

Figure 0.1.3: Greenhouse fault free architecture

Reflecting on the previous discussion, it's evident that access points (APs) are vital within the greenhouse, acting as the crucial link between the sensors and the controller. Consequently, should an AP malfunction, it results in the loss of data from the sensors in the affected cell, leading to the controller receiving partial and incomplete data. This can cause system reliability issues, potentially resulting in incorrect control actions or delayed responses. In the studies [ELNADI 2021, ELNADI 2022], the greenhouse demonstrated fault tolerance from the perspective of Access Points (APs). It was shown to function effectively with two to five APs and to a lesser extent with only one AP. This capability is particularly crucial in scenarios where reducing greenhouse costs is essential without compromising crop quality, as might be the case in developing countries. Here, utilizing just one AP, despite its marginal operation, could be a viable cost-saving measure. However, to address the risk of a single AP being a potential point of failure, a dual AP setup might offer a more robust solution, seemingly enhancing the greenhouse's reliability and profitability. This chapter will challenge that assumption, presenting the following key contributions:

- ***Optimization of AP Number:*** Redesigning the system to use fewer APs, specifically switching to the 2.4GHz instead of the 5GHz band (as discussed in [ELNADI 2022]). While the 5GHz band yields acceptable Packet Loss Rates (PLRs), it will be demonstrated that a single 2.4GHz AP can operate the entire greenhouse with even lower PLRs.
- ***Introduction of a New Metric:*** A major contribution of this research is the development of a metric that combines AP Mean Time To Failure (MTTF), AP Mean

Time To Repair (MTTR), and the efficiency of the greenhouse NCS. This metric is designed to assist management in balancing greenhouse costs against expected profits, potentially preventing intuitive yet flawed decision-making.

- ***Sensor Power Management:*** Given that the 2.4GHz band results in lower PLRs than the 5GHz band, the study identifies the lowest sensor transmission power needed to keep the PLR below 2%. This approach aims to extend the battery life of the sensors.

The greenhouse model in [ELNADI 2021] will be used as a case study to illustrate these contributions. Importantly, while a specific greenhouse setup is examined, the broader significance of this research lies in the general applicability of its proposed methodology to any greenhouse. Additionally, the introduced metric provides a valuable tool for evaluating cost and profit implications in greenhouse operations.

1.5 NCS Greenhouse With 2.4 GHz

Greenhouse farming is an increasingly popular method for growing crops in a controlled environment, enabling farmers to optimize plant growth and increase yields. Networked Control System (NCS) technology provides an innovative approach to optimize greenhouse conditions by leveraging wireless sensors and actuators for real-time monitoring and control. The 2.4GHz band is a popular frequency band used in wireless communication systems, offering several advantages in smart greenhouse applications. This band provides reliable connectivity, can transmit data over long distances without interference, and is widely available and compatible with a range of devices. This section we will explore the advantages of using the 2.4GHz band in smart greenhouses, and how it can enhance the efficiency, sustainability, and productivity of modern agriculture by achieving lower PLR compared to the 5 GHz band.

In the context of developing countries, where cost considerations are paramount in designing greenhouse NCS, the research in [ELNADI 2022] revealed that a 200m×40m greenhouse can function effectively with five APs, but can also manage with just one AP, albeit less optimally. As a result, it might be advantageous to operate with only one or, at most, two APs.

Opting for the 2.4GHz frequency band becomes a practical choice under such constraints due to its superior coverage area. Additionally, the 2.4GHz band offers three non-interfering channels – 1, 6, and 11, as illustrated in figure 3.2.1. These channels can potentially enable the greenhouse to function successfully with one or two APs, achieving a lower Packet Loss Rate (PLR) in comparison to using the 5GHz band. This approach suggests a strategic adaptation in frequency band selection, aligning with the cost-sensitive requirements of greenhouse operations in developing regions.

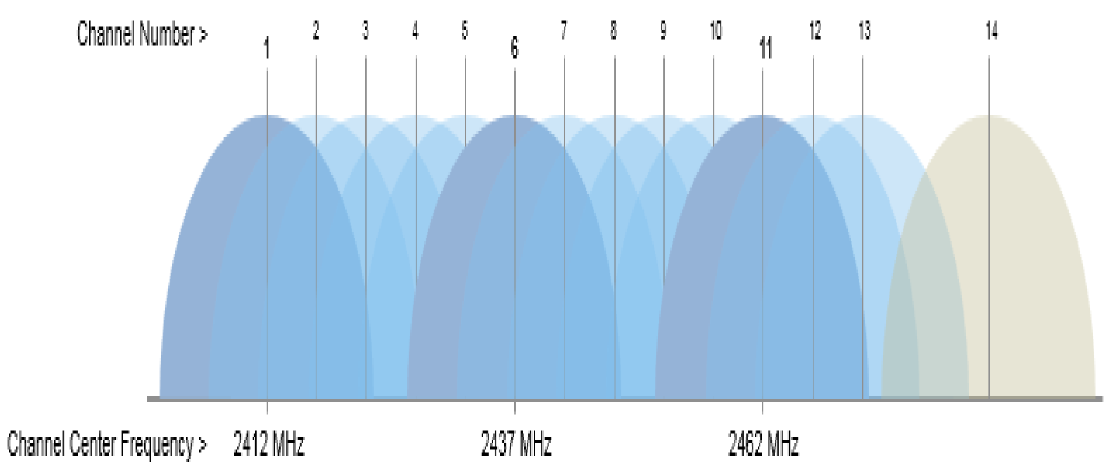

Figure 0.2.1: Non-overlapping Channel for 2.4 GHz band

In [IBRAHIM 2019], the described greenhouse spans 200m×40m and is subdivided into five equal square cells, each measuring 40m×40m. The arrangement of these cells is depicted in Figure 3.2.2. In this setup, different architectural strategies are employed for the placement of APs, depending on whether one or two APs are used. For the single AP architecture, the AP is centrally located in cell 3. This strategic placement allows for optimal coverage across the greenhouse with just one AP. In contrast, for the two AP architecture, the APs are positioned at the centers of cells 2 and 4. This distribution ensures a more balanced coverage across the greenhouse area.

The sensor nodes within this system operate with a transmit power of 5mW, and the chosen frequency band for transmission is 2.4GHz. To minimize interference in the two AP setup, non-interfering channels 1 and 11 are utilized. In scenarios where only a single AP is operational, channel 6 is employed to manage the communication needs. This approach to channel selection and AP placement is designed to ensure efficient coverage and data transmission within the greenhouse, regardless of the number of APs in use.

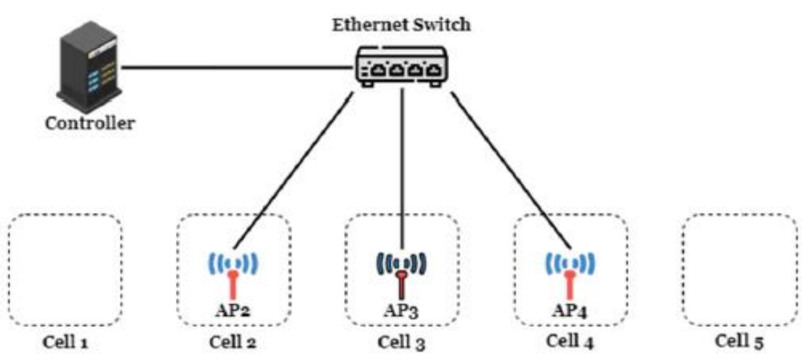

Figure 0.2.2: Greenhouse with Wi-Fi APs in cell 3 or cell (2 and 4), connected via Switched Ethernet to the controller [Ba Humaish 2023]

Riverbed simulations were employed in [ELNADI 2022] to model the performance of greenhouse architectures using one and two Access Point (AP) setups. These simulations revealed that in a configuration with two APs located in cells 2 and 4, the Packet Loss Rate (PLR) percentages were notably lower than in a similar setup utilizing the 5GHz band. Specifically, the PLR for the 2.4GHz band ranged between 0.149% and 0.208%, compared to the 5GHz scenario, which recorded a PLR between 0.174% and 0.228%.

Delving deeper into the comparative analysis of frequency bands, further Riverbed simulations were conducted to assess the performance of a single AP setup in the greenhouse. In this scenario, with one AP placed in cell 3 (as illustrated in Figure 3.2.2), and maintaining the same transmission power of 5mW, the results are quite revealing. The Packet Loss Rate (PLR) for the 2.4GHz band was observed to range between 0.537% and 0.642%. In contrast, when utilizing the 5GHz band under the same conditions, the PLR was significantly higher, ranging from 1.80% to 2.22%. This data demonstrates that by reducing the number of APs in the greenhouse while operating on the 2.4GHz band, a lower PLR can be achieved compared to the 5GHz band. It's noteworthy that while the PLR was marginal (barely acceptable) using the 5GHz band, it falls well within the acceptable range (below 2%) when utilizing the 2.4GHz band. This finding highlights the effectiveness of the 2.4GHz frequency in providing sufficient coverage and maintaining a lower PLR, even with a reduced number of APs in the greenhouse network.

These findings are systematically presented in Table 3.2.1, which compares the PLR outcomes for both one and two AP architectures across the 2.4GHz and 5GHz frequency bands. The PLR values mentioned were derived following a 95% confidence analysis, ensuring statistical reliability in the results. Additionally, Figure 3.2.3 illustrates the traffic received by the Controller (measured in Bytes/sec) when operating within the 2.4GHz frequency band. This visual representation aids in understanding the data flow and network efficiency under different AP configurations, further supporting the analysis of the system's performance in various greenhouse scenarios.

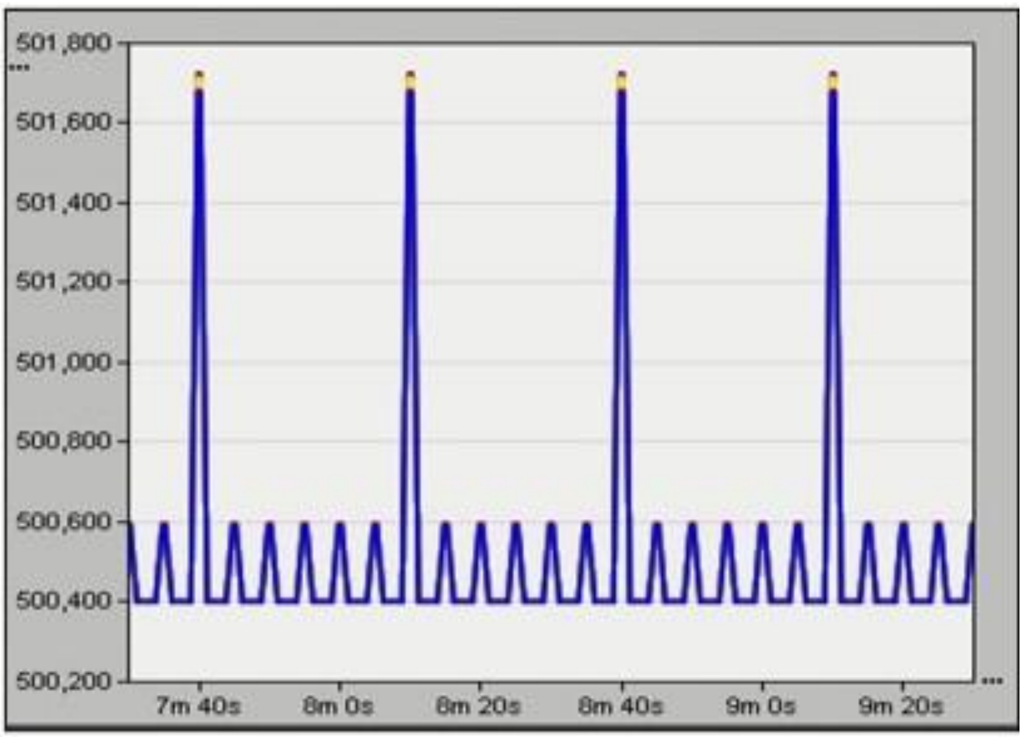

Figure 0.2.3: Traffic received by the controller (Bytes/sec) [Ba Humaish 2023]

Table 0.2.1: PLR (%) for One and Two AP Architectures using 2.4 and 5 GHz frequency bands [Ba Humaish 2023]

Frequency band	*Packet Loss Rate (PLR) %*	
	2 AP architecture APs in cell (2 and 4)	*1 AP architecture AP in cell (3)*
2.4 GHz	[0.149, 0.208]	[0.537, 0.642]
5 GHz	[0.174, 0.228]	[1.80, 2.22]

In general, using the 2.4GHz band in smart greenhouses offers several advantages. The frequency band is widely available and supported by a range of devices, making it easy to integrate into the architecture proposed in [IBRAHIM 2019]. Additionally, it provides reliable connectivity and can transmit data over long distances without interference. This is particularly important in large greenhouse facilities where there may be numerous wireless sensor nodes are used. The 2.4GHz band also allows for real-time monitoring of environmental conditions, enabling growers to adjust settings and optimize plant growth. Furthermore, the use of this band in smart greenhouses can lead to increased efficiency and reduced energy costs, as it allows for more precise control of heating, ventilation, and lighting systems. Overall, the 2.4GHz band is a valuable tool for growers looking to create efficient and reliable greenhouse environments.

1.6 Metric (Ψ)to Minimize the Crops' Profit Loss of the Greenhouse

NCS greenhouses are an advanced agricultural technology that uses sensors, automation, and data analytics to create the optimal growing environment for plants. This technology has the potential to increase crop yields, reduce resource use, and improve the quality of crops. However, NCS greenhouse systems can be expensive to install and maintain, particularly in developing countries. In addition, crop losses due to unmonitored environmental (e.g. AP failures) can cause significant profit loss for farmers. Thus, finding ways to minimize profit loss in smart greenhouses is crucial to maximize the benefits of this technology.

In the context of developing countries, where cost is a crucial factor, the choice of AP architecture in a greenhouse takes on added significance. A single AP setup is the most cost-effective option, but recent challenges in supply chains have emphasized the importance of system longevity. This consideration has led to the use of the two-AP architecture as a means to balance both lifetime and cost.

The two APs, strategically located in cells 2 and 4 as depicted in Figure 3.2.2, address the vulnerability of a single point of failure that arises when only one AP is used in cell 3. While intuitively, a two AP architecture is expected to yield higher steady-state availability, this isn't always the case. To navigate these complexities, a new metric, Ψ, is proposed. This metric aims to analyze the combined effects of AP Mean Time To Failure (MTTF), AP Mean Time To Repair (MTTR) - considering supply chain limitations — and the impact of the efficiency of the greenhouse NCS on crop quality. The goal is to assist management in making informed decisions that minimize profit loss in the greenhouse. Interestingly, the Ψ metric might reveal scenarios where a single AP solution could be more beneficial than a two AP setup, challenging conventional assumptions. This is particularly relevant in enabling farmers in developing countries to optimize their operations in smart greenhouses, thereby enhancing their livelihoods and contributing to global food security.

To effectively apply the Ψ metric, it's based on steady-state performability ($Perf_{ss}$), necessitating the use of a Markov model to determine the steady-state probabilities of the system residing in each state. This Markov model is illustrated in Figure 3.3.1, providing a foundational tool for evaluating the greenhouse's network performance under varying configurations.

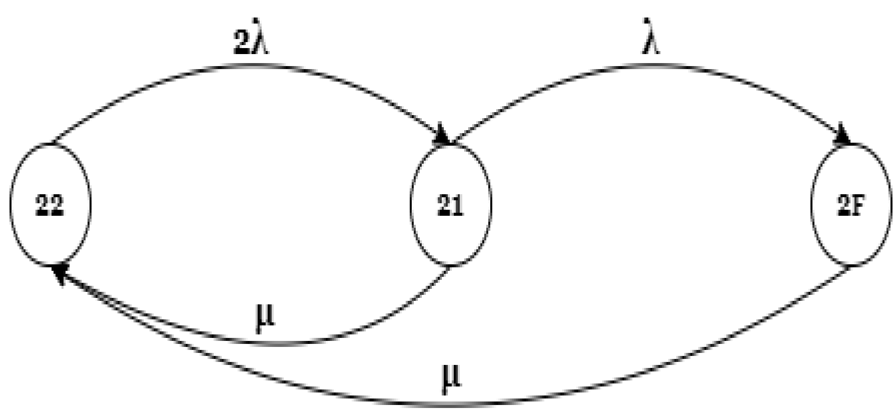

Figure 0.3.1: Markov model for 2 APs [Ba Humaish 2023]

The described system's operation, regardless of the operating frequency (5GHz or 2.4GHz) and sensor transmission power, begins in state "22", where both APs located in cells 2 and 4 are functioning. In the event of a failure of one AP (at a rate of 2λ), the system shifts to state "21", in which only one AP remains operational. During this state, the working AP is relocated to cell 3 to optimize coverage. In state “21”, the repair process is initiated, involving the procurement, delivery, and installation of a new AP. This process is time-consuming, factoring in the purchase, shipping, and setup of the AP in the greenhouse. If the other functioning AP fails during this repair period, before the new AP is installed, the system moves into a total failure state, “2F”, at a rate of λ. Subsequently, another AP is ordered. Given that the transit time is a significant component of the MTTR, the system transitions from state “2F” and “21” back to the initial operational state “22” at a rate of μ.

To analyze this system, the Chapman-Kolmogorov equations, as referenced in [SIEWIOREK 1998], can be applied. These equations are instrumental in understanding the probabilistic behavior of the system over time. Accordingly, a transition matrix for the Markov Model can be formulated, detailing the rates of moving between these states. This matrix provides a quantitative framework for assessing the reliability and availability of the APs in the greenhouse NCS, allowing for a more precise evaluation of the system's performance under various failure and repair scenarios.

$$TR = \begin{bmatrix} -2\lambda & 2\lambda & 0 \\ \mu & -(\lambda+\mu) & \lambda \\ \mu & 0 & -\mu \end{bmatrix} \qquad (1)$$

The probability of the system being either in state 22, 21 or 2F is:

$$PR = [P_{22} \quad P_{21} \quad P_{2F}] \tag{2}$$

Hence,

$$\left[\frac{dP_{22}}{dt} \quad \frac{dP_{21}}{dt} \quad \frac{dP_{2F}}{dt}\right] = TR * PR \tag{3}$$

Where:

$$\frac{dP_{22}}{dt} = (-2\lambda)P_{22} + \mu P_{21} + \mu P_{2F} \tag{4}$$

$$\frac{dP_{21}}{dt} = (2\lambda)P_{22} + (-\lambda - \mu)P_{21} \tag{5}$$

$$\frac{dP_{2F}}{dt} = (\lambda)P_{22} + (-\mu)P_{2F} \tag{6}$$

$$P_{22} + P_{21} + P_{2F} = 1 \tag{7}$$

Since the steady state probabilities are required, hence.

$$\frac{dP_{22}}{dt} = \frac{dP_{21}}{dt} = \frac{dP_{2F}}{dt} = 0 \tag{8}$$

The steady state probabilities can then be obtained. For example,

$$P_{2F} = \frac{2\lambda^2}{2\lambda^2 + 3\lambda\mu + \mu^2} \tag{9}$$

Table 3.3.1 presents the steady-state probabilities for the greenhouse system under different scenarios, varying by the failure rates (λ) and repair rates (μ). These probabilities are crucial for understanding the reliability and availability of the system over time, especially in the context of the APs within the greenhouse. Additionally, Table 3.2.1 provides insights into the performance of the greenhouse network, particularly focusing on the PLR values for both the one and two AP architectures. In this table, the upper limit of the confidence interval is used, which offers a conservative estimate of the PLR. This approach ensures that the PLR values considered are not underestimating potential data loss issues, thereby providing a more robust framework for assessing the network's reliability.

Together, these tables form a comprehensive dataset that allows for a detailed analysis of the greenhouse's networked control system, taking into account both the likelihood of system failures and repairs, as well as the operational effectiveness of the system as measured by PLR. This data is integral to decision-making processes regarding the architecture of the greenhouse NCS, especially when considering trade-offs between cost, reliability, and overall system performance.

Table 0.3.1: Steady State Probabilities for 1 And 2 APs [Ba Humaish 2023]

λ	μ	*Steady State Probabilities*				
		1 AP		*2 AP*		
		P_{11}	P_{1F}	P_{22}	P_{21}	P_{2F}
3	121.667	0.976	0.024	0.953	0.046	0.001
	24.333	0.890	0.109	0.802	0.176	0.022
	12.167	0.802	0.198	0.669	0.265	0.065
1	121.667	0.992	0.008	0.984	0.016	0.0001
	24.333	0.961	0.039	0.924	0.073	0.003
	12.167	0.924	0.076	0.858	0.131	0.011
0.333	121.667	0.997	0.003	0.995	0.0049	0.00002
	24.333	0.987	0.013	0.973	0.026	0.0004
	12.167	0.973	0.027	0.948	0.0501	0.0014

Based on the tables above, for the two AP architecture, the proposed metric is as follows:

$$\Psi_2 = P_{22} * PLR_2 + P_{21} * PLR_1 + P_{2F} * \alpha \tag{10}$$

Where PLR_2 represents the PLR obtained from Riverbed simulations with APs located in cells 2 and 4, while PLR_1 is the PLR for the scenario with only one AP in cell 3. In the context of calculating performability, each state of the system is associated with a specific cost or penalty, with the PLR being the penalty factor representing the loss of information in each state.

In state 2F, where the system is in total failure due to both APs being non-operational, the PLR is considered to be 100%. This total loss of information transmission is why the PLR does not contribute to the third term in the equation (as multiplying by 1 doesn't change the value). In such a scenario, manual operation of the greenhouse becomes necessary, though its feasibility depends on the availability of qualified personnel, which might not always be the case. The factor α in the equation accounts for the possibility of manual operation. If manual operation is not possible, and there's a risk of crop loss, α is set to 1. Conversely, if qualified personnel are available to manually manage the greenhouse, α is set to a value less than 1. The more skilled the personnel, the lower the value of α, indicating less information loss and reduced impact on the greenhouse's operation.

The metric Ψ_2, therefore, reflects the "information loss" due to AP failure/repair and the PLR, which varies depending on the architecture. When this metric is multiplied by the expected annual profit of the greenhouse, it provides an estimated value of the expected loss in profit. This calculation can then be used to weigh against the cost of the APs, aiding management in making an informed decision about which AP architecture to choose for optimal operation and profitability.

In a NCS greenhouse with a single AP architecture, the corresponding Markov model is composed of merely two states, as noted in [SIEWIOREK 1998, DUBROVA 2013]. These include: State “11”, indicating the system is fully operational, and State “1F”, representing the condition where the system is non-functional or down.

$$P_{11} = \frac{\mu}{\lambda + \mu} \quad (11)$$

$$P_{1F} = \frac{\lambda}{\lambda + \mu} \quad (12)$$

Hence the metric Ψ_1 can be calcul-ated for the greenhouse with only one AP in cell 3 as follow:

$$\Psi_1 = P_{11} * PLR_1 + P_{1F} * \alpha \quad (13)$$

Table 3.3.2 shows the Ψ1 and Ψ2 values normalized to the lowest Ψ obtained, namely Ψ2 for λ=0.333/year and μ=121.667/year – 2.4GHz, and some counterintuitive situations will be discussed below it to illustrate the importance of Ψ1 and Ψ2.

Table 0.3.2: Metric for Different Scenarios for one and two APs architecture [Ba Humaish 2023]

λ	***μ***	***Ψ***			
		5 GHz		***2.4 GHz***	
		1AP, Ψ_1	2AP, Ψ_2	1AP, Ψ_1	2AP, Ψ2
3	121.667	21.50	2.04	14.31	1.61
	24.333	61.07	12.94	54.51	11.57
	12.167	101.72	34.32	95.81	32.30
1	121.667	14.15	1.29	6.85	1.08
	24.333	28.61	3.17	21.54	2.54
	12.167	45.46	7.34	38.65	6.30
0.333	121.667	11.65	1.13	4.30	1.00
	24.333	16.62	1.49	9.36	1.21
	12.167	22.69	2.20	15.52	1.74

1.6.1 One AP Better Than Two Architecture

By examining two different scenarios from table 3.3.2, particularly focusing on the 5GHz frequency band, it becomes evident that certain situations may favor a one AP architecture over the two AP setup in terms of the metric outcome.

In the first scenario, the system operates with a single AP, characterized by a failure rate (λ) of 0.333 per year (MTTF = 3 years), and a repair rate (μ) of 121.667 per year (MTTR = 3 days). This results in a metric $\Psi 1$ of 11.65. Conversely, the second scenario involves two APs with a higher failure rate of 3 per year (MTTF = 4 months) and a repair rate of 12.167 per year (MTTR = 1 month), leading to a $\Psi 2$ of 34.32. The fact that $\Psi 2$ is greater than $\Psi 1$ suggests that operating with one AP results in a smaller loss compared to using two APs. Additionally, when the first scenario is compared to a situation where two APs have a failure rate of 3 per year (MTTF = 4 months) but a faster repair rate of 24.333 per year (MTTR = 15 days), it still shows that a single AP architecture leads to less profit loss than a two AP architecture.

This observation might be counterintuitive, especially in scenarios where, at the time of design, a more expensive and reliable AP (with an MTTF of 3 years) is available in the market, as opposed to a less costly AP with a shorter MTTF of 4 months. Management might initially assume that using two cheaper, less reliable APs would increase system availability due to fault tolerance. However, the Ψ metric challenges this assumption, demonstrating that this might not be the case.

This result highlights the importance of the proposed technique; without it, predicting the most efficient design model a priori, especially when considering varying failure and repair rates, would be challenging. It underscores the necessity of a systematic approach to decision-making in system design, especially in terms of balancing cost, reliability, and overall system performance.

1.6.2 2.4GHz vs 5GHz

The comparison between the 2.4GHz and 5GHz frequency bands for a greenhouse system with two APs reveals some interesting insights, especially when referring to Table 3.3.2. For each pair of failure rate (λ) and repair rate (μ), the Ψ2 metric does not show much variation between the two bands. This observation is particularly relevant in scenarios where multiple greenhouses are situated in close proximity. In such cases, it's recommended to use the 5GHz band due to its 24 non-overlapping channels, which significantly reduce the risk of channel interference between adjacent greenhouses. In contrast, the 2.4GHz band, with only three non-overlapping channels, is less suitable for areas with numerous closely located greenhouses.

One might assume that for a single greenhouse, switching to the 2.4GHz band would be preferable. However, the Ψ metric suggests that this shift is not necessarily required. When analyzing the one AP architecture, the Ψ1 metric is considerably higher for the 5GHz band, indicating greater potential losses. Thus, if interference is not a concern, the 2.4GHz band emerges as the more advantageous choice according to the Ψ1 metric. This preference is based on its lower likelihood of incurring significant losses in a single AP setup, making it a more suitable option in situations where interference from neighboring greenhouses is not a factor.

1.6.3 AP Choice

When considering a two AP architecture in both 2.4GHz and 5GHz frequency bands, the decision between different AP options available in the local market becomes crucial. Let's assume two AP choices: a more expensive one with a failure rate (λ) of 0.333 per year (MTTF = 3 years) and a less expensive AP with higher failure rates, one at λ = 1/year (MTTF = 1 year) and the other at λ = 3/year (MTTF = 4 months), all having a repair rate (μ) of 121.667 per year (MTTR = 3 days). The Ψ2 values for both frequency bands are quite similar. For example, in the 5GHz band with failure rates of 3, 1, and 0.333 per year, the corresponding Ψ2 values are 2.04, 1.29, and 1.13, respectively. This suggests that opting for the less expensive AP (λ = 3/year) could be more cost-effective, as the savings on the AP cost outweigh the minor differences in Ψ2 values. Conversely, for a one AP architecture, using the 2.4GHz band in conjunction with the more expensive AP seems to be a better option to minimize potential profit loss from crop failure.

These scenarios underscore the importance of employing the Ψ metric, which can reveal counter-intuitive outcomes. However, it's important to recognize that these numerical results are specific to the case studies in [IBRAHIM 2019, ELNADI 2021], and the real value lies in the methodology itself.

For any greenhouse architecture, the Riverbed simulator is utilized to ascertain the PLR for different architectures with one or two APs, factoring in the physical dimensions and transmitting powers of APs and sensors. The MTTF and MTTR of available APs are then incorporated into the Markov models (as shown in Figure 3.3.1) to determine the steady state probabilities of the system states. These probabilities, along with the PLR values, are plugged into the Ψ metric. Based on Ψ values, along with the cost of APs and expected annual profits, management can make informed decisions about the most suitable architecture for their greenhouse.

1.7 Prolonging Sensors Battery Lifetime

Sensors play a crucial role in precision agriculture, where they are used to monitor the environment that surrounds the plants inside the greenhouses. However, NCS, WSN, or IoT networks consume a lot of energy, particularly if the sensors constantly send data, which could deplete the sensors' battery lifetime and cause more expensive maintenance. Hence, finding a technique to reduce energy consumed by sensor nodes is an important task in smart greenhouses applications.

In [ELNADI 2022], it was proved that two APs are sufficient to effectively manage all five cells of the greenhouse. Consequently, shifting to the 2.4GHz frequency band becomes an appealing choice due to its superior coverage capabilities. This band provides three non-interfering channels (1, 6, and 11), which can proficiently support greenhouse operations with two APs.

Riverbed simulations underpin this strategy, indicating that with two APs positioned in cells 2 and 4 and operating on the 2.4GHz band, the PLR falls between 1.232% and 1.564% for a sensor transmission power of just 0.4mW. This PLR is comfortably below the 2% threshold, thereby significantly enhancing the system's energy efficiency to 92%. As a result, the sensors' battery life is prolonged. However, it's important to note that reducing the transmission power below 0.4mW in the 2.4GHz band results in an unacceptable PLR, exceeding the 2% limit. Further analysis, assuming the greenhouse operates with a single AP in cell 3, also supports the use of the 2.4GHz band. Simulations show that with one AP in cell 3 and sensor transmission power at 1.2mW, the PLR ranges from 0.594% to 0.739%, again staying below the 2% upper limit. When comparing the 5GHz and 2.4GHz bands, given the maximum PLR allowance of 2%, the 2.4GHz band emerges as the more efficient option, requiring much lower sensor transmission power, which in turn extends the battery life of the sensors. These findings are detailed in Table 3.4.1, which outlines the transmission power requirements for sensor nodes using the 2.4 GHz frequency band. This data is crucial for designing a greenhouse NCS that is not only effective in terms of connectivity and data transmission but also efficient in energy consumption and operational longevity.

Table 0.4.1: Sensor Transmission Power vs PLR (%) - 2.4 GHz [Ba Humaish 2023]

Number of APs	*Sensor's transmission power*	*PLR [μ – λ, μ + λ] %*
1	0.5 mW	[31.675, 32.083]
	1 mW	[2.998, 3.682]
	1.2 mW	[0.594, 0.739]
2	0.2 mW	[41.592, 42.847]
	0.3 mW	[8.415, 8.826]
	0.4 mW	[0.594, 0.739]

CHAPTER 4

Resilient Architecture and Rerouting Strategies in Greenhouse Networked Control Systems: A Comprehensive Analysis of Access Point Failures and Network Adaptations

In the realm of precision agriculture, where advanced technologies are used in horticulture, the design of resilient networked systems within greenhouses stands as a pivotal undertaking. A key challenge in this domain is ensuring the uninterrupted flow of data from sensors to controllers which enhances the cultivation environments where the surrounding conditions are automatically monitored and adjusted in real-time. In pursuit of this reliable data transmission, the focus should be lighted onto the architectural backbone of these wireless networks (Access Points APs) which serve as connection bridges between sensors and processing units.

This chapter delves into an essential facet of the Networked Control Systems (NCS) greenhouse: the optimal distributions of sensor data redirecting in the face of AP failures. Again, the greenhouse of (200x40) m which was divided into 5 cells, each equipped with 40 sensors and one AP in the center will used. There is one central control unit that is connected to the APs through the Ethernet protocol. Sensor nodes wirelessly send their data to the APs using the 5GHz band to mitigate potential interference issues. In fact, as with any communication architecture, APs failure is inevitable. Hence, to address this challenge, different simulations were performed to come up with the optimal distributions in the presence of the APs failure. The Packet Loss Rate (PLR) is the metric used to indicate if the simulated distribution is acceptable or not, the PLR should not exceed 2%. In addition to the PLR, Quality of Experience (QoE) metric will be used in this chapter in order to choose the best distribution among several distributions that have PLR of less than 2%. The QoE refers to the overall satisfaction and perceived quality of service that the user experiences when using NCS Greenhouse. It encompasses various factors such as system performance, reliability, latency (PLR), and throughput (traffic received) [HOßFELD 2017]. So, when one AP experiences failure, the network adapts to this failure scenario with distinct distributions to reroute the sensors' data to the functioning APs. Likewise, as more access points experience failures, the scenarios multiply, culminating in one distribution for the one AP architecture where this AP should be installed in cell 3. More specifically, the contributions of this chapter are as follows:

- Firstly, focusing on using the same methodology as in [ELNADI 2021], while considering the failure of the APs, different distributions for data rerouting will be proposed for each failure scenario while keeping the PLR less than 2%.
- Second, one of the major contributions is using the QoE metric that will help designers select the best distribution among many optimal distributions in the case of AP failures. This metric considers the PLR of each cell individually and can be used as an indicator of the number of days over the year that the system will be unmonitored.

The contributions of this chapter are not merely theoretical results; they are grounded in meticulous and comprehensive simulations that were conducted using Riverbed Modeler. These simulations range from fault-free scenarios to architecture with only one active AP.

1.8 Fair Distributions for Sensors Data in the Presence of APs Failures

Wireless sensor networks (WSNs) and Networked Control Systems (NCSs) have become progressively important technologies in the agricultural sector, particularly in smart greenhouses. These networks rely on access points (APs) which provide reliable connections between sensors and controllers. However, in practical applications, APs are e not immune to failures, and this significantly impacts the performance of the greenhouses since the environmental parameters change rapidly and continuous monitoring of them is a crucial task. The failure of an AP can lead to data loss and delayed responses in environmental control, directly affecting plant health.

This section will explore the different scenarios that emerge in the presence of the failure of any one of the 5 APs in the greenhouse, then propose different distributions for data rerouting among the functioning APs so the PLR maintains within the threshold (PLR $\leq$ 2%) [AWAD 2017].

The same methodology as in [ELNADI 2021] will be used as the system starts operating with 5 active APs, and in this scenario, there is no need for data rerouting since each AP will handle the data that comes from its cell. However, with every additional failure of any APs, the scenarios will increase, as well as the distributions of redirecting the sensor data for each scenario. Taking into account that the assumption here is that the relocation of the available APs to other cells is not possible either due to the lack of technical skills of the farmers or the far location of the greenhouse from farm office administration. Firstly, all the possible scenarios for the system, ranging from fault free scenarios to one AP scenarios will are presented in table 4.1.1.

Table 4.1.1: The comprehensive scenarios of the system

Architecture	*Possible scenarios*
Fault free architecture	AP12345
4AP architecture	AP1234
	AP1235
	AP1245
	AP1345
	AP2345
3 AP architecture	AP123
	AP124
	AP125
	AP134
	AP135
	AP145
	AP234
	AP235
	AP245
	AP345
2 AP architecture	AP12
	AP13
	AP14
	AP15
	AP23

	AP24
	AP25
	AP34
	AP35
	AP45
1 AP architecture	AP1
	AP2
	AP3
	AP4
	AP5

As discussed above, in the case of the 5AP architecture (fault-free scenario), there is no need for data rerouting, as the sensors of each cell will send their data to the corresponding AP. Similarly, in the case of the one AP architecture (quadrable AP failures), all the cells should send their data to the functioning AP. Therefore, these two architectures have not been included in the simulations. Furthermore, there are some symmetric scenarios that emerge from each architecture. These scenarios, while distinct in configuration, yield identical outcomes in terms of data flow and network performance. Therefore, to optimize simulation efficiency and avoid redundancy, only one scenario from each symmetric pair is subjected to simulation. Hence, only one of them will be simulated since the other one will produce the same results. Table 4.1.2 shows the scenarios that are simulated and the symmetric cases for each scenario.

Table 4.1.2: The symmetric scenarios of the system

System architecture	*Possible scenarios*
4 AP architecture	AP1234 symmetric to AP2345
	AP1235 symmetric to AP1345
	AP1245
3 AP architecture	AP123 symmetric to AP345
	AP124 symmetric to AP245
	AP125 symmetric to AP145
	AP134 symmetric to AP235
	AP135
	AP234
2 AP architecture	AP12 symmetric to AP45
	AP13 symmetric to AP35
	AP14 symmetric to AP25
	AP15
	AP23 symmetric to AP34
	AP24

Table 4.1.3 shows the different scenarios of the failure cases and the distributions for each scenario. AP123 will be used to indicate that access points (1, 2, and 3) are alive while access points (4 and 5) have failure. Riverbed Modeler is used to simulate all the scenarios and the PLRs were obtained, with a 95% confidence analysis.

Table 4.1.3: Optimal Distributions of Sensor Data for Each Failure Scenario with the Overall PLR

Failure case	*Scenario name*	*Data redirection (traffic distribution)*	*PLR [μ – λ, μ + λ]%*
AP12345	AP12345	1 → 1, 2 → 2, 3 → 3, 4 → 4, 5 → 5	[0.333, 0.3411]
AP1234 symmetric to AP2345	AP1234	1 → 1, 2 → 2, 3 → 3, 4 → 4, 5 → 4	[0.0162, 0.0394]
AP1235 symmetric to AP1345	AP1235_A	1 → 1, 2 → 2, 3 → 3, 4 → 3, 5 → 5	[0.0166, 0.0365]
	AP1235_B	1 → 1, 2 → 2, 3 → 3, 4 → 3+5, 5 → 5	[0.0122, 0.0358]
AP1245	AP1245_A	1 → 1, 2 → 2, 3 → 2, 4 → 4, 5 → 5	[0.0239, 0.0518]
	AP1245_B	1 → 1, 2 → 2, 3 → 2+4, 4 → 4, 5 → 5	[0.0095, 0.0309]
AP123 symmetric to AP345	AP123_A	1 → 1, 2 → 2, 3 → 3, 4 → 2, 5 → 3	[0.2562, 0.3928]
	AP123_B	1 → 1, 2 → 2, 3 → 3, 4 → 3, 5 → 3	[0.3052, 0.4978]
	AP123_C	1 → 1, 2 → 2, 3 → 3, 4 → 2+3, 5 → 3	[0.2022, 0.314]
	AP123_D	1 → 1, 2 → 1, 3 → 1+2, 4 → 2, 5 → 3	[0.2318, 0.3375]
	AP123_F	1 → 1, 2 → 1+2, 3 → 2+3, 4 → 3, 5 → 3	[0.2315, 0.367]
AP124 symmetric to AP245	AP124_A	1 → 1, 2 → 2, 3 → 2, 4 → 4, 5 → 4	[0.0504, 0.0885]
	AP124_B	1 → 1, 2 → 2, 3 → 2+4, 4 → 4, 5 → 4	[0.0784, 0.1261]
	AP124_C	1 → 1, 2 → 1+2, 3 → 2+4, 4 → 4, 5 → 4	[0.0281, 0.0578]
	AP124_D	1 → 1, 2 → 2, 3 → 2+4, 4 → 2+4, 5 → 4	[0.0623, 0.1044]
	AP124_E	1 → 1, 2 → 1, 3 → 2, 4 → 2+4, 5 → 4	[1.7464, 5.0188]
AP125 symmetric to	AP125_A	1 → 1, 2 → 2, 3 → 2, 4 → 5, 5 → 5	[0.0501, 0.0862]
	AP125_B	1 → 1, 2 → 1+2, 3 → 2, 4 → 5, 5 → 5	[0.0329, 0.0631]
	AP125_C	1 → 1, 2 → 2, 3 → 1+2, 4 → 5, 5 → 5	[0.0333, 0.0627]

AP145	AP125_D	1 → 1, 2 → 1, 3 → 2, 4 → 2+5, 5 → 5	[0.0316, 0.0643]
AP234	AP234_A	1 → 2, 2 → 2+3, 3 → 3, 4 → 3+4, 5 → 4	[0.0684, 0.1084]
	AP234_B	1 → 2, 2 → 2, 3 → 3, 4 → 4, 5 → 4	[0.0596, 0.0994]
AP134 symmetric to AP235	AP134_A	1 → 1, 2 → 1+3, 3 → 3, 4 → 4, 5 → 4	[0.0479, 0.091]
	AP134_B	1 → 1, 2 → 1, 3 → 3, 4 → 3+4, 5 → 4	[5.1636, 14.9803]
	AP134_C	1 → 1, 2 → 1, 3 → 3, 4 → 4, 5 → 3+4	[0.0374, 0.0686]
	AP134_D	1 → 1, 2 → 3, 3 → 3, 4 → 4, 5 → 4	[0.0405, 0.0782]
AP135	AP135_A	1 → 1, 2 → 1, 3 → 3, 4 → 5, 5 → 5	[0.0533, 0.0856
	AP135_B	1 → 1, 2 → 1+3, 3 → 3, 4 → 3+5, 5 → 5	[0.0402, 0.0734]
AP12 symmetric to AP45	AP12_A	1 → 1, 2 → 2, 3 → 1, 4 → 2, 5 → 2	[19.383, 19.520]
	AP12_B	1 → 1, 2 → 2, 3 → 1, 4 → 1+2, 5 → 2	[16.0265, 17.0023]
AP13 symmetric to AP35	AP13_A	1 → 1, 2 → 1, 3 → 3, 4 → 3, 5 → 3	[0.3703, 0.5792]
	AP13_B	1 → 1, 2 → 1, 3 → 1, 4 → 3, 5 → 3	[0.5474, 0.7127]
	AP13_C	1 → 1, 2 → 1, 3 → 1+3, 4 → 3, 5 → 3	[0.3146, 0.4328]
AP14 symmetric to AP25	AP14_A	1 → 1, 2 → 1, 3 → 1, 4 → 4, 5 → 4	[0.3695, 0.5324]
	AP14_B	1 → 1, 2 → 1, 3 → 1+4, 4 → 4, 5 → 4	[0.1617, 0.2322]
	AP14_C	1 → 1, 2 → 1, 3 → 4, 4 → 4, 5 → 4	[0.162, 0.2143]
AP15	AP15_A	1 → 1, 2 → 1, 3 → 1+5, 4 → 5, 5 → 5	[0.1452, 0.2108]
	AP15_B	1 → 1, 2 → 1, 3 → 1, 4 → 5, 5 → 5	[0.326, 0.5127]
AP23 symmetric to AP34	AP23_A	1 → 2, 2 → 2, 3 → 3, 4 → 3, 5 → 3	[0.3664, 0.5149]
	AP23_B	1 → 2, 2 → 2, 3 → 2+3, 4 → 3, 5 → 3	[0.3137, 0.4492]
	AP23_C	1 → 2, 2 → 2, 3 → 3, 4 → 2+3, 5 → 3	[0.327, 0.5038]
	AP23_D	1 → 2, 2 → 2, 3 → 2, 4 → 3, 5 → 3	[0.3179, 0.4526]
	AP23_E	1 → 2, 2 → 2, 3 → 3, 4 → 3, 5 → 2+3	[9.1558, 9.4552]

	AP23_F	1 → 2+3, 2 → 2, 3 → 2+3, 4 → 2+3, 5 → 3	[0.3116, 0.4774]
AP24	AP24_A	1 → 2, 2 → 2, 3 → 2+4, 4 → 4, 5 → 4	[0.1559, 0.228]
	AP24_B	1 → 2, 2 → 2, 3 → 2, 4 → 4, 5 → 4	[0.1972, 0.2624]

It is clear that, for each failure scenario, the proposed distributions meet the system requirements since the redirections of data were selected based on the minimum distance between the cell sensors and the functioning AP, taking into account the load that the AP handles. For example, in scenario AP123, one might think that the reasonable distribution is to redirect the data of cells 4 and 5 to APs 2 and 3, respectively, while data of cells 1, 2, and 3 are sent to their APs. However, this thinking is incorrect since the data of cell 5 is transmitted over 2 hubs to AP3, hence traffic of cell 3 should be split between AP1 and AP2 so AP3 will be idle to receive cell 5 traffic and immediately switch it to the controller without additional delay.

In fact, PLR is a wide metric that shows the overall PLR for the entire system and indicates if the threshold (2%) is violated or not. However, the granularity of this metric is insufficient to determine whether this loss is more concentrated in one cell than in others or not. Hence, the next section will propose the fairness of the Quality of the Experience (QoE) metric that uses the PLR at per cell level and in conjunction with the overall PLR to give us a more informative evaluation of the different distributions for each failure scenario.

1.9 Determining the Optimal Distribution for Traffic Rerouting Based on QoE Fairness

Quality of Experience (QoE) holds significant importance in the realm of smart greenhouses as it serves as a crucial metric for assessing the satisfaction and perception of end-users regarding the system's overall performance. These end-users encompass a diverse range of individuals, including farmers, researchers, agricultural experts, and technologists. QoE refers to the evaluation of the farmers' satisfaction and perception of the performance of NCS greenhouse and its technologies. The concept of QoE extends beyond traditional performance metrics such as efficiency and output, encompassing user-centric aspects like ease of use, reliability, and the intuitiveness of the technology. In a smart greenhouse environment, this means assessing how effectively the NCS integrates into daily agricultural practices, its impact on crop yield and quality, and its contribution to simplifying farming tasks.

In fact, QoE will be used as a scale to rate or score the quality of service (QoS). Therefore, the QoS of the NCS greenhouse should be mapped to the QoE score. The Packet Loss Rate (PLR) is a critical measurement of this system and should be between 0 - 2%. Hence, we can safely map QoE to the PLR, where 0% means the best QoE, and 2% represents the worst. Firstly, the PLR has been averaged over 8 traffic cycles, each lasting 30 seconds. Therefore, the Riverbed Modeler simulations will cover a time window of 240 seconds. Hence, the PLR can be extrapolated to determine the number of days throughout the year that the crops or plants are unmonitored. Table 4.2.1 shows the mapping between the unmonitored days per year and the QoE.

Table 4.2.1: The Mapping between the QoE and Unmonitored System (days/year)

Unmonitored days/year	*% of year*	*QoE score*
0.25	0.0685	10 (Best)
0.5	0.1369	9
1	0.2739	8
2	0.5479	7
3	0.8219	6
4	1.0959	5
5	1.3699	4
6	1.6438	3
7	1.9178	2
8	2.1918	1 (worst)

Hence, the final mapping between the QoS (PLR) and the QoE is presented in table 4.2.2

Table 4.2.2: The Mapping between the PLR for each Cell and the QoE

QoE	*PLR*
10 (High)	0 ≤ PLR < 0.1369
9	0.1369 ≤ PLR < 0.2739
8	0.2739 ≤ PLR < 0.5479
7	0.5479 ≤ PLR < 0.8219
6	0.8219 ≤ PLR < 1.0959
5	1.0959 ≤ PLR < 1.3699
4	1.3699 ≤ PLR < 1.6438
3	1.6438≤ PLR < 1.9178
2	1.9178 ≤ PLR < 2.1918
1 (Low)	2.1918 ≤ PLR

From [Hoßfeld 2017], we can get the formula that relate the PLR for each cell to the QoE fairness as in eq (14)

$$Fairness\ QoE = 1 - \frac{2\,\sigma}{H - L} \qquad (14)$$

Where σ is the standard deviation of QoE values across cells for given scenario.

Hence, extensive simulations have been conducted using Riverbed Modeler to determine the PLR at the level of each cell. Equation (14) is then utilized to calculate the fairness of the QoE, providing valuable decisions about the optimal distribution for each failure scenario. The QoE values for all simulated scenarios are presented in table 4.2.3.

Table 4.2.3: The QoE Fairness and the PLRs for each Cell in the NCS Greenhouse

Scenario name	*QoE fairness*	*Overall PLR*	*PLR of cell 1*	*PLR of cell 2*	*PLR of cell 3*	*PLR of cell 4*	*PLR of cell 5*
AP12345	1	[0.333, 0.341]	[0.328, 0.351]	[0.333, 0.333]	[0.328, 0.351]	[0.327, 0.352]	[0.333, 0.333]
AP1234	1	[0.016, 0.039]	[0.0, 0.0]	[0.0, 0.019]	[0.0, 0.037]	[0.009, 0.079]	[0.033, 0.119]
AP1235_A	1	[0.017, 0.037]	[0.0, 0.029]	[0.0, 0.0]	[0.01, 0.066]	[0.035, 0.129]	[0.0, 0.0]
AP1235_B	1	[0.012, 0.036]	[0.0, 0.029]	[0.0, 0.019]	[0.01, 0.066]	[0.005, 0.083]	[0.0, 0.046]
AP1245_A	1	[0.024, 0.052]	[0.0, 0.019]	[0.025, 0.089]	[0.061, 0.179]	[0.0, 0.0]	[0.0, 0.019]
AP1245_B	1	[0.009, 0.031]	[0.0, 0.019]	[0.015, 0.086]	[0.002, 0.049]	[0.0, 0.039]	[0.0, 0.0]
AP123_A	0.6125	[0.256, 0.393]	[0.0, 0.029]	[0.038, 0.139]	[0.006, 0.057]	[0.498, 0.816]	[0.559, 1.108]
AP123_B	0.5051	[0.305, 0.498]	[0.0, 0.0189]	[0.0, 0.0]	[0.192, 0.325]	[0.219, 0.361]	[1.013, 1.891]
AP123_C	0.6557	[0.202, 0.314]	[0.0, 0.0]	[0.0, 0.029]	[0.11, 0.256]	[0.061, 0.141]	[0.721, 1.276]
AP123_D	0.8337	[0.232, 0.338]	[0.137, 0.279]	[0.133, 0.284]	[0.060, 0.167]	[0.361, 0.576]	[0.264, 0.595]

AP123_E	0.7333	[0.157, 0.25]	[0.0, 0.0]	[0.031, 0.108]	[0.060, 0.167]	[0.019, 0.081]	[0.564, 1.002]
AP123_F	0.5691	[0.232, 0.367]	[0.002, 0.049]	[0.0, 0.039]	[0.054, 0.148]	[0.179, 0.314]	[0.769, 1.439]
AP124_A	1	[0.050, 0.089]	[0.0, 0.019]	[0.023, 0.129]	[0.020, 0.094]	[0.057, 0.16]	[0.050, 0.152]
AP124_B	0.8911	[0.078, 0.126]	[0.0, 0.019]	[0.0, 0.029]	[0.066, 0.173]	[0.143, 0.287]	[0.094, 0.222]
AP124_C	1	[0.028, 0.058]	[0.002, 0.049]	[0.0, 0.039]	[0.002, 0.049]	[0.051, 0.139]	[0.011, 0.090]
AP124_D	1	[0.062, 0.104]	[0.033, 0.119]	[0.067, 0.199]	[0.0, 0.0]	[0.059, 0.155]	[0.050, 0.152]
AP124_E	0.2	[1.746, 5.019]	[0.029, 0.122]	[0.054, 0.148]	[0.0, 0.029]	[8.541, 24.88]	[0.0, 0.029]
AP125_A	1	[0.050, 0.086]	[0.0, 0.039]	[0.031, 0.108]	[0.044, 0.145]	[0.015, 0.086]	[0.063, 0.151]
AP125_B	1	[0.0329, 0.063]	[0.002, 0.049]	[0.0, 0.039]	[0.002, 0.049]	[0.041, 0.111]	[0.044, 0.145]
AP125_C	1	[0.033, 0.0627]	[0.015, 0.074]	[0.006, 0.057]	[0.0, 0.0]	[0.063, 0.164]	[0.019, 0.081]
AP125_D	1	[0.032, 0.064]	[0.035, 0.142]	[0.061, 0.141]	[0.002, 0.049]	[0.0, 0.019]	[0.0, 0.039]
AP234_A	0.9111	[0.068, 0.108]	[0.088, 0.203]	[0.047, 0.142]	[0.0, 0.0]	[0.045, 0.132]	[0.074, 0.154]
AP234_B	1	[0.059, 0.099]	[0.045, 0.132]	[0.044, 0.145]	[0.049, 0.128]	[0.041, 0.136]	[0.005, 0.071]
AP134_A	1	[0.048, 0.091]	[0.024, 0.153]	[0.005, 0.083]	[0.0, 0.029]	[0.033, 0.119]	[0.070, 0.182]
AP134_B	0.0202	[5.164, 14.980]	[0.015, 0.074]	[0.069, 0.158]	[0.054, 0.148]	[8.569, 24.93]	[17.02, 49.68]
AP134_C	1	[0.037, 0.069]	[0.054, 0.148]	[0.057, 0.145]	[0.006, 0.057]	[0.0, 0.039]	[0.0, 0.029]
AP134_D	1	[0.041, 0.078]	[0.0, 0.0]	[0.022, 0.105]	[0.026, 0.101]	[0.054, 0.148]	[0.024, 0.115]
AP135_A	1	[0.053, 0.086]	[0.031, 0.108]	[0.066, 0.161]	[0.0, 0.0]	[0.049, 0.128]	[0.039, 0.115]
AP135_B	1	[0.040, 0.073]	[0.01, 0.066]	[0.047, 0.142]	[0.045, 0.132]	[0.016, 0.098]	[0.0, 0.019]
AP13_A	0.5131	[0.370, 0.579]	[0.027, 0.112]	[0.018, 0.081]	[0.221, 0.385]	[0.265, 0.454]	[1.122, 2.060]
AP13_B	0.5468	[0.547, 0.713]	[0.211, 0.369]	[0.195, 0.386]	[1.282, 2.001	[0.0, 0.039]	[0.621, 1.198]

AP13_C	0.7408	[0.315, 0.433]	[0.123, 0.230]	[0.230, 0.401]	[0.186, 0.332]	[0.084, 0.194]	[0.698, 1.259]
AP13_D	0.5424	[0.688, 0.873]	[1.046, 1.783]	[0.105, 0.248]	[0.634, 1.147]	[0.162, 0.318]	[0.882, 1.479]
AP14_A	0.5051	[0.369, 0.532]	[0.230, 0.363]	[0.170, 0.297]	[1.135, 1.984]	[0.049, 0.128]	[0.037, 0.115]
AP14_B	1	[0.162, 0.232]	[0.158, 0.259]	[0.129, 0.249]	[0.087, 0.368]	[0.138, 0.241]	[0.105, 0.236]
AP14_C	0.8911	[0.162, 0.214]	[0.038, 0.139]	[0.044, 0.145]	[0.161, 0.344]	[0.147, 0.320]	[0.195, 0.348]
AP15_A	0.9111	[0.145, 0.211]	[0.128, 0.276]	[0.119, 0.259]	[0.152, 0.265]	[0.126, 0.227]	[0.052, 0.175]
AP15_B	0.5051	[0.326, 0.513]	[0.151, 0.317]	[0.273, 0.434]	[0.921, 1.819]	[0.026, 0.101]	[0.037, 0.115]
AP23_A	0.5051	[0.366, 0.515]	[0.039, 0.125]	[0.041, 0.148]	[0.255, 0.402]	[0.196, 0.335]	[1.109, 1.757]
AP23_B	0.6444	[0.314, 0.449]	[0.094, 0.222]	[0.118, 0.236]	[0.130, 0.299]	[0.112, 0.241]	[0.848, 1.513]
AP23_C	0.6444	[0.327, 0.504]	[0.099, 0.255]	[0.143, 0.349]	[0.125, 0.267]	[0.144, 0.272]	[0.842, 1.658]
AP23_D	0.7052	[0.318, 0.453]	[0.249, 0.433]	[0.253, 0.416]	[0.186, 0.332]	[0.050, 0.152]	[0.604, 1.177]
AP23_E	0.2889	[9.156, 9.455]	[0.129, 0.301]	[0.091, 0.199]	[0.102, 0.214]	[0.095, 0.209]	[45.07, 46.53]
AP23_F	0.6125	[0.312, 0.477]	[0.082, 0.221]	[0.157, 0.272]	[0.104, 0.275]	[0.077, 0.188]	[0.896, 1.683]
AP24_A	1	[0.156, 0.228]	[0.158, 0.322]	[0.114, 0.29]	[0.091, 0.224]	[0.118, 0.273]	[0.096, 0.232]
AP24_B	0.8012	[0.197, 0.262]	[0.299, 0.471]	[0.178, 0.365]	[0.276, 0.469]	[0.015, 0.074]	[0.037, 0.115]

Here are some examples that highlight the importance of QoE fairness in determining the optimal distribution for each scenario. This determination would not be possible without considering this metric that takes into account the PLR of each cell individually. For example, in scenario AP123, one might assume that the best distribution is AP123_E (1 → 1, 2 → 2, 3 → 2+3, 4 → 2+3, 5 → 3) due to its lower PLR compared to other scenarios. However, this choice is incorrect because the PLR of cell 5 is significantly higher than the other cells, resulting in lower QoE fairness compared to AP123_D (1 → 1, 2 → 1, 3 → 1+2, 4 → 2, 5 → 3), which is the optimal distribution for this failure scenario. On the other hand, in scenario AP125, all distributions have equal QoE fairness values of one. In this case, the overall PLR of the system is used to determine the best distribution. Furthermore, the QoE fairness metric is crucial for selecting the optimal distribution in the 2AP NCS greenhouse architecture due to the significant variation in packet loss rates among the five cells, leading to different QoE fairness values. Therefore, the best distribution is the one with a QoE fairness close to one.

As discussed, sensors may be faced with scenarios where their corresponding AP has failed, and they must determine, without human intervention, to which AP they must connect, from the subset of remaining functional APs. The default behavior of most devices is to favor the AP with the highest perceived signal strength, indicating high proximity. However, various devices offer the ability to set a priority list for Wi-Fi network SSIDs.

For example, if a wireless node recognizes 3 Wi-Fi network SSIDs as available to connect to (ID_AP1, ID_AP2, and ID_AP3), it is possible to configure a priority list, such that ID_AP2 is favored, followed by ID_AP1, and finally ID_AP3. This can typically done through most device GUIs or through command lines on Windows or Android devices for example. It is assumed, in this study, that the sensors are similarly configurable. Furthermore, each of the five APs is broadcasting its SSID, and, while it may not be ideal for a sensor from cell 1 to communicate via AP5 (due to distance and resulting PLR), cell 1 is still aware of AP5 being active or failed, due to the absence or presence of the broadcast SSID. As such, it can be assumed that at any point throughout a sensor's lifetime, it will be fully aware of the system state. Hence, each sensor can be programmed prior to deployment with a mapping of "remaining active APs" to "favored AP". So, at any point in time, including the Fault-Free case, a sensor will be aware of the system's active APs. This will also allow for unconventional scenarios, where a sensor may need to disconnect from its current AP, and reroute traffic to another, for improved QoE Fairness, as determined by the results previously presented. The comprehensive subsets of the detected APs and which APs should be selected by the left and right half of each cell are shown in table 4.2.4.

Table 4.2.4: Selected SSIDs by each Half of each cell in the Greenhouse

Detected SSIDs	*Cell 1*		*Cell 2*		*Cell 3*		*Cell 4*		*Cell 5*	
	Left side sensors	*Right side sensors*	*Left side sensors*	*Right side sensors*	*Left side sensors*	*Right side sensors*	*Left side sensors*	*Right side sensors*	*Left side sensors*	*Right side sensors*
	Selected SSIDs	*Selected SSIDs*	*Selected SSIDs*	*Selected SSIDs*	*Selected SSIDs*	*Selected SSIDs*	*Selected SSIDs*	*Selected SSIDs*	*Selected SSIDs*	*Selected SSIDs*
AP12345	1	1	2	2	3	3	4	4	5	5
AP1234	1	1	2	2	3	3	4	4	4	4
AP1235	1	1	2	2	3	3	3	5	5	5
AP1245	1	1	2	2	2	4	4	4	5	5
AP1345	1	1	1	3	3	3	4	4	5	5
AP2345	2	2	2	2	3	3	4	4	5	5
AP123	1	1	1	1	1	2	2	2	3	3
AP124	1	1	1	2	2	4	4	4	4	4
AP125	1	1	2	2	1	2	5	5	5	5
AP134	1	1	1	1	3	3	4	4	3	4
AP135	1	1	1	3	3	3	3	5	5	5
AP145	1	1	1	1	4	5	4	4	5	5
AP234	2	2	2	2	3	3	4	4	4	4

AP235	2	3	2	2	3	3	5	5	5	5
AP245	2	2	2	2	2	4	4	5	5	5
AP345	3	3	4	4	4	5	5	5	5	5
AP13	1	1	1	1	1	3	3	3	3	3
AP14	1	1	1	1	1	4	4	4	4	4
AP15	1	1	1	1	1	5	5	5	5	5
AP23	2	2	2	2	2	2	3	3	3	3
AP24	2	2	2	2	2	4	4	4	4	4
AP25	2	2	2	2	2	5	5	5	5	5
AP34	3	3	3	3	4	4	4	4	4	4
AP35	3	3	3	3	3	5	5	5	5	5
AP3	3	3	3	3	3	3	3	3	3	3

In fact, the scenarios mentioned in the table above are those with a Packet Loss Rate (PLR) of less than 2%, as indicated in Table 4.2.3. However, there are some scenarios with PLRs exceeding 2%, as shown in Table 4.2.5. In these cases, manual intervention is required, wherein the engineer or farmer must descend into the greenhouse to reposition the Access Points (APs) to locations that ensure a PLR of less than 2%. This, in turn, ensures higher reliability in monitoring crops, thereby increasing their quality and productivity.

Table 4.2.5: Optimal Architectures for Scenarios that Violated PLR Threshold

Failure scenario	*PLR [$\mu - \lambda$, $\mu + \lambda$] %*	*Alternative optimal architecture*	*PLR [$\mu - \lambda$, $\mu + \lambda$] %*
AP12	[19.383, 19.520]	AP24	[0.156, 0.228]
AP45	[18.958, 19.486]		
AP1	[40.247, 40.576]	AP3	[1.80, 2.22]

AP2	[20.503, 20.943]		
AP4	[20.453, 20.849]		
AP5	[40.387, 40.656]		

CHAPTER 5

CONCLUSION

In conclusion, the incorporation of new innovative agricultural systems, like precision agriculture, will effectively address the challenges of climate change and realize the objectives of enhancing crop production, cutting costs, and optimizing yields. The contributions put forth in this thesis play a crucial role in creating a supportive and managerial instrument for the agricultural sectors. It is anticipated that these outcomes can be extrapolated to benefit other sectors such as industry as well. Moreover, this research has played a part in offering a cost-effective alternative for acquiring and processing information, thereby generating valuable insights to enhance agricultural productivity.

This thesis delved into examining a greenhouse system within a Networked Control System (NCS), specifically by implementing a fault-tolerant model at the access point level. Additionally, it explored aspects crucial to precision agriculture, such as system availability and lifespan. It discusses the design and optimization of greenhouse NCS through the use of distributed sensors, controllers, and actuators to monitor and control environmental factors. The greenhouse structure is compartmentalized into five similar cells, each spanning 40m x 40m, resulting in a total area of 200m x 40m. Within each greenhouse cell, there are wireless sensor nodes, wired actuators, a set of wired cameras, and an access point. Furthermore, a controller oversees the entire cells, tasked with collecting data from sensor nodes via the APs, processing and analyzing it, and then sending relevant control commands to the actuators to regulate the internal climate of the greenhouse. The controller is linked to the access points via Switched Ethernet.

A fault-tolerant model was presented on the level of APs focusing on using the 2.4GHz frequency band to minimize the cost of NCS greenhouse by operating the system with one or at most two APs with maintaining a Packet Loss Rate (PLR ≤ 2%) less than the 5GHz frequency band. Furthermore, fault-tolerant AP architectures were investigated to propose a metric Ψ that incorporates AP failure and repair rates, as well as NCS information efficiency to help management select an appropriate architecture to minimize profit loss, and to make decisions regarding the tradeoff between greenhouse cost and expected profit. This metric may prevent management from making intuitive but incorrect decisions. Additionally, the 2.4GHz band was utilized to determine the minimum sensor transmission power that ensures the minimum acceptable PLR, thereby prolonging the lifetime of the sensors' batteries.

Additionally, in this thesis, various data rerouting distributions were proposed for each failure scenario to maintain a PLR below 2%. Comprehensive simulations were conducted using Riverbed Modeler to determine the optimal distribution for each failure case without the need to install the remaining functioning APs to locations near the controller unit. Also, the QoE was used as a valuable metric to help designers select the best distribution among many optimal distributions in the case of AP failures. This metric considers the PLR of each cell individually and can be used as an indicator of the number of days over the year that the system will be unmonitored.

The contributions of this thesis are not merely theoretical results; they are grounded in meticulous and comprehensive simulations that were conducted using Riverbed Modeler. These simulations range from fault-free scenarios to architecture with only one active AP. The proposed methodology and metrics can be applied to any greenhouse, and they provide a useful framework for designing and operating greenhouse NCS that is cost-effective, reliable, and resilient.

Looking ahead, this thesis lays the groundwork for several promising research and development paths. The scalability of Networked Control Systems (NCS) for larger or multiple greenhouse setups will be a focus, heralding a new era for widespread implementation in industrial agriculture. The potential of Artificial Intelligence and Machine Learning will be harnessed for predictive analytics and system optimization, allowing for a dynamic response to the changing needs of crops and environmental conditions. Testing and adaptation of the system in various agricultural settings, including open-field farms, will validate the robustness and adaptability of this model. Beyond agriculture, the transferability of NCS fault tolerance principles will be assessed for vital sectors such as healthcare, industrial automation, smart cities, and autonomous vehicles, enriching the design of NCS and contributing to the resilience and efficiency of these essential systems. The future work emanating from this thesis is poised to push the boundaries of agricultural technology and networked control systems into new and innovative frontiers.

REFERENCES

[Abdullah 2016] A. Abdullah, S. Al Enazi and I. Damaj, "AgriSys: A smart and ubiquitous controlled-environment agriculture system," 2016 3rd MEC International Conference on Big Data and Smart City (ICBDSC), Muscat, Oman, 2016, pp. 1-6, doi: 10.1109/ICBDSC.2016.7460386.

[Awad 2017] M.M. Awad, H.H. Halawa, M. Rentschler, R.M. Daoud, and H.H. Amer, "Novel system architecture for railway wireless communications," Proceedings of the 17th IEEE International Conference on Smart Technologies EUROCON, Ohrid, Macedonia, July 2017.

[Ba Humaish 2023] Mohammed Ba Humaish, Tarek Refaat, Hassanein Amer, Hassan El Menier, Ramez Daoud and Nora Ali, "Greenhouse Networked Control System Design Methodology to Minimize Cost & Downtime," Proceedings of the 15th International Conference on Computer and Automation Engineering (ICCAE), Sydney, Australia, March 2023.

[Balafoutis 2017] A. Balafoutis et al., "Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics," Sustainability, vol. 9, no. 8, July 2017, doi: 10.3390/su9081339.

[Both 2015] A.J. Both et al., "Guidelines for measuring and reporting environmental parameters for experiments in greenhouses," Plant Methods, vol. 11, no. 1, pp. 1–18, September 2015.

[Cao Pham 2021] T. Cao Pham, H. Bich Vo and N. Quang Tran, "A Design of Greenhouse Monitoring System Based on Low-Cost Mesh Wi-Fi Wireless Sensor Network," 2021 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS), Toronto, ON, Canada, 2021, pp. 1-6, doi: 10.1109/IEMTRONICS52119.2021.9422655.

[Dubrova 2013] E. Dubrova, 'Fault-Tolerant Design', Springer, 2013.

[Danita 2018] M. Danita, B. Mathew, N. Shereen, N. Sharon and J.J. Paul, "IoT based automated greenhouse monitoring system," Proceedings of the Second International Conference on Intelligent Computing and Control Systems ICICCS, Madurai, India, pp. 1933–1937, June 2019.

[Dalai 2020] S. Dalai, B. Tripathy, S. Mohnta, B. Suha and B. Palai, "Green-houses: Types and Structural Components," in Protected Cultivation and Smart Agriculture, 2nd edition, S. Maitra, D.J. Gaikwad and T. Shankar, Eds. New Delhi, India: New Delhi Publishers, 2020, pp. 09-17.

[Elnadi 2021] Yasmine Elnadi, Tarek Refaat, Ramez Daoud and Hassanein Amer, "Fault Tolerance for Access Point Failures in Smart Greenhouse Networked Control Systems," Proceedings of the International Conference on Smart Technologies EUROCON, Lviv, Ukraine, July 2021.

[Elnadi 2022] Yasmine A. Elnadi, Tarek K. Refaat, Ramez M. Daoud, Hassanein H. Amer and Nora A. Ali, "Effects of Supply Chain Volatility on Smart Greenhouses: Balancing Cost & System Availability", Proceedings of the International Conference on Electronics, Computers and Artificial Intelligence ECAI, Ploiești, Romania, June 2022.

[Farval 2019] S. Fraval et al., "Food Access Deficiencies in Sub-saharan Africa: Prevalence and Implications for Agricultural Interventions," Front. Sustain. Food System, Vol. 3, Novemer 2019, doi: 10.3389/fsufs.2019.00104.

[Guraiah 2014] B. Guraiah, and G. Nagaswetha, "GSM Based Greenhouse Monitoring System For Agricultural Field," IJPES International Journal of Professional Engineering Studies 3, September 2014.

[Hoßfeld 2017] T. Hoßfeld, L. Skorin-Kapov, P. E. Heegaard and M. Varela, "Definition of QoE Fairness in Shared Systems," in IEEE Communications Letters, vol. 21, no. 1, pp. 184-187, Jan. 2017, doi: 10.1109/LCOMM.2016.2616342.

[Ibrahim 2018] H. Ibrahim et al., “A High Availability Networked Control System Architecture for Precision Agriculture," 2018 International Conference on Computer and Applications (ICCA), August 2018, pp. 457-460, doi: 10.1109/COMAPP.2018.8460420.

[Ibrahim 2019]] H. Ibrahim, N. Mostafa, H. Halawa, M. Elsalamouny, R. Daoud, H. Amer, Y.A. Elnadi, A. Shaarawi, A. Khattab and H. ElSayed, “A layered IoT architecture for greenhouse monitoring and remote control”, SN - Applied Sciences, Springer Nature, 1(3):223, February 2019.

[Kessler2012] J.R. Kessler, “Greenhouse Construction and Applications.” domerama.org. http://www.domerama.com/types-of-domes/greenhouses/hobby-greenhouse-construction/ (accessed Mar. 25, 2022).

[Kumar 2022] Abhishek Kumar, Vikrant Singh, Saurabh Kumar, Shiva Pujan Jaiswal, Vikas Singh Bhadoria,IoT enabled system to monitor and control greenhouse,Materials Today: Proceedings,Volume 49, Part 8,2022,Pages 3137-3141,ISSN 2214-7853,https://doi.org/10.1016/j.matpr.2020.11.040.

[Kolawole 2013] K. K. Kolawole, and W.S. Alausa, “Microcontroller Based Green House Control Device,” In Proceedings of International Journal Of Engineering And Science (IJES), Volume 2, Issue 11, PP 129-135, Novmber 2013.

[Lee 2023] K. Lee, M. J. Islam, H. Lee, W. Kim, S. -K. Lee and B. Kim, "IoT Based Intelligent Greenhouse Farming Technology with Low Cost and Energy Efficiency," 2023 International Conference on Electronics, Information, and Communication (ICEIC), Singapore, 2023, pp. 1-3, doi: 10.1109/ICEIC57457.2023.10049868.

[Lin 2021] F. Lin, Y. Weng, H. Chen, and P. Zhuang, “Intelligent Greenhouse System Based on Remote Sensing Images and Machine Learning Promotes The Efficiency Of Agricultural Economic Growth,” Environmental Technology & Innovation, Volume 24, 2021, ISSN 2352-1864, https://doi.org/10.1016/j.eti.2021.101758.

[Madrap 2016] P. I. Madrap and A. Deshmukh, "PIC Microcontroller Based Greenhouse Monitoring and Control System," International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, vol. 5, no. 9, September 2016.

[Mehta 2018] A. Mehta and M. Masdekar, "Precision Agriculture – A Modern Approach To Smart Farming," International Journal of Scientific & Engineering Research, vol. 9, no. 2, pp. 23–26, Feburary 2018.

[Meza 2021] I. Meza et al., "Drought risk for agricultural systems in South Africa: Drivers, spatial patterns, and implications for drought risk management," Science of the Total Environment, vol. 799. August 2021, doi: 10.1016/j.scitotenv.2021.149505.

[Nandurkar 2014] S. R. Nandurkar, V. R. Thool, and R. C. Thool, "Design and Development of Precision Agriculture System Using Wireless Sensor Network," In 2014 First International Conference on Automation, Control, Energy and Systems (ACES), pages 1–6, Feb 2014.

[Patel 2014] N. R. Patel, P. D. Kale, G. N. Raut, P. G. Choudhari, N. R. Patel and A. Bherani, "Smart design of microcontroller based monitoring system for agriculture," 2014 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2014], Nagercoil, India, 2014, pp. 1710-1713, doi: 10.1109/ICCPCT.2014.7054949.

[Patil 2016] A. Patil, M. Beldar, A. Naik and S. Deshpande, "Smart farming using Arduino and data mining," 2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom), New Delhi, India, March 2016, pp. 1913-1917.

[Quy 2022] V.K. Quy et al., "IoT-enabled smart agriculture: Architecture,applications, and challenges," Applied Sciences, vol. 12, no. 7, March 2022.

[Remya 2016] R. Koshy, M.D. Yaseen, N. Shaji, N.J Harish, M. Ajay, "Greenhouse Monitoring and Control Based on IOT Using WSN," ITSI Transactions on Electrical and Electronics Engineering (ITSI-TEEE), 2320 – 8945, Volume -4, Issue -3, India, 2016

[Rana 2013] Rana H.H, A.F. Marhoon, and M.T. Rashid, “Wireless monitor and control system for greenhouse,” IJCSMC International Journal of Computer Science and Mobile Computing, Vol. 2, Issue. 12, December 2013, pages 69-87.

[Siewiorek 1998] D.P. Siewiorek and R.S. Swarz, "Reliable Computer Systems Design and Evaluation," A K Peters, Natick, Massachusetts, 1998.

[Shamshiri 2007] R. Shamshiri, “Principles of Greenhouse Control Engineering Institute of Advanced Technology,” 2007.

[Singh 2020] R. K. Singh, R. Berkvens and M. Weyn, “Energy Efficient Wireless Communication for IoT Enabled Greenhouses,” 2020 International Conference on COMmunication Systems & NETworkS (COMSNETS), Bengaluru, India, 2020, pp. 885-887, doi: 10.1109/COMSNETS48256.2020.9027392.

[Shinde 2018] D. Shinde and N. Siddiqui, "IOT Based Environment change Monitoring & Controlling in Greenhouse using WSN," 2018 International Conference on Information , Communication, Engineering and Technology (ICICET), 2018, pp. 1-5, doi: 10.1109/ICICET.2018.8533808.

[Sahu 2012] K. Sahu, and S. Mazumdar, “Digitally Greenhouse Monitoring and Controlling of System based on Embedded System,” In Proceedings of International Journal of Scientific & Engineering Research, Vol. 3, January- 2012.

[Subahi 2020] A. F. Subahi and K. E. Bouazza, "An Intelligent IoT-Based System Design for Controlling and Monitoring Greenhouse Temperature," in IEEE Access, vol. 8, pp. 125488-125500, 2020, doi: 10.1109/ACCESS.2020.3007955.

[Teslyuk 2015] T. Teslyuk, P. Denysyuk, A. Kernytskyy and V. Teslyuk, “Automated control system for arduino and android based intelligent greenhouse,” 2015 XI International Conference on Perspective Technologies and Methods in MEMS Design (MEMSTECH), Lviv, Ukraine, September 2015, pp. 7-10.

[Taha 2018] F. M. A. Taha, A. A. Osman, S. D. Awadalkareem, M. S. A. Omer and R. S. M. Saadaldeen, “A Design of a Remote Greenhouse Monitoring and Controlling System Based on Internet of Things,” 2018 International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCCEEE), 2018, pp. 1-6, doi: 10.1109/ICCCEEE.2018.8515866.