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Fault Tolerance for Access Point Failures in Smart Greenhouse Networked Control Systems

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Fault Tolerance for Access Point Failures in Smart Greenhouse Networked Control Systems

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Thesis Publications

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List of Abbreviations

PA – Precision Agriculture
IoT – Internet of things
NCS – Network Control Systems
WSN – Wireless Sensor Network
GSM – Global System for Mobile Communications
RF – Radio Frequency
USB – Universal Serial Bus
PC – Personal Computer
WMSN – Wireless Moisture Sensor Network
GPRS – General Packet Radio Services
IGMS – Intelligent Greenhouse management System
VPD – Vapor Pressure Deficit
OLED – Organic Light Emitted Diode
HHC – Hand-Held Controller
MCU – Microcontroller Unit
GUI – Graphical User Interface
EE – Energy Efficient
MQTT – MQ Telemetry Transport
PLR – Packet Loss Rate
P(t) – Probability of Survival
MTTF – Mean Time to Failure
MTTR – Mean Time to Repair
MTBF – Mean Time Between Failure
TR – Transition Rate
AVss – Steady State Availability

Abstract

The need for improving and increasing crop production, especially in harsh environmental conditions, has promoted the use of technological solutions, tools and automated methodologies inside a greenhouse to provide the best growing conditions for crops. This thesis presents an innovative fault-tolerant model on the access point level for a Networked Control Systems (NCS) greenhouse. NCS provides the ability to monitor and control the internal environmental conditions of a greenhouse such as temperature, relative humidity, and soil moisture. However, there is a risk of failures occurring at the access point level, that must be taken into consideration. Therefore, this thesis provides a comprehensive study on all access point failure cases including single, double, triple and quadruple access point failures. Riverbed Modeler is used to evaluate system performance in terms of Packet Loss Rate (PLR). For single and double access point failure scenarios, the proposed model succeeded in meeting system requirements with lower PLR values below the threshold value with 95% confidence. For triple and quadruple access point failure scenarios, Riverbed simulations showed that the system can tolerate up to three and four access point failures if the remaining active access points are placed in their ideal position within the greenhouse to provide an optimal coverage and lower PLR values. Additionally, a technique was proposed to help system designers balance between system cost (regarding access points) and the cost of system downtime. Finally, a use case is presented to find the point of diminishing returns, in which investing in access points does not only depend on their cost but also on system availability. Markov models are used to measure system downtime by calculating steady state availability (AVss). System availability was calculated by modeling several scenarios using SHARPE. As expected, it was shown that system availability increases with the increase of the number access points inside the greenhouse. While some cases showed that having three or two access points can achieve the same system availability with lower system cost but with a slight increase in system downtime.

Chapter 1
INTRODUCTION

Climate change, water shortage, and lack of environmental awareness promoted the need for new tools and automated methodologies that help in making suitable decisions and reducing the negative impacts of these factors in agriculture production. Further, the combination of information systems and information management techniques are gaining popular attention in the global setting. Several studies have shown that having an adequate control over environmental parameters such as temperature, humidity, and ventilation; can prevent the rise of plant plagues and also help in treatment in case of infections. So, in order to have a control over environmental conditions, crops are farmed in greenhouses.

Greenhouse is a structure designed for protecting tender or out-of-season plants from harsh environmental conditions. In the past, it was just a structure made of ordinary brick or timber shelters with window spaces and some means of heating. However, as glass became cheaper which is a more sophisticated form of preserving heat, greenhouses evolved to rely on glass more and less on brick or wood structures. Then it was developed into a structure that equipped with suitable infrastructure including heaters, ventilators, and watering systems so that it can provide a controlled environment to ease and facilitate crop cultivation and provide care and prevention methods to improve both quality and production. There are many variables that require continuous monitoring and regulation inside the greenhouse in order to maximize environment suitability for different plant species. These variables include temperature, humidity, light intensity, and ventilation. The sizes of the greenhouse can vary significantly ranging from small backyard-sized to one that spans multiple hectares.

Monitoring and regulating various environmental factors as the ones mentioned earlier, can evaluate the performance and efficiency of a greenhouse. Smart greenhouses are a hot topic today for precision agriculture (PA) [DANITA 2018]. Manual monitoring of the environment conditions such as temperature, humidity, and light conditions can be easily replaced by sensor nodes [IBRAHIM 2018, SAMPAIO 2017]. Additionally, integrating Internet-of-Things (IoT) capabilities can offer the ability to remotely access, store, and analyze sensor data [DAN 2015, GOMES 2015]. Adding a layer of IoT can definitely contribute in providing the ability to adjust the environment conditions inside the greenhouse remotely [SAMPAIO 2017, PALLAVI 2017]. Based on the data received from the sensor nodes, changes to greenhouse environmental condition can be adjusted, for example adjusting actuator nodes remotely to fine-tune irrigation valves and fans [BAI 2017, KODALI 2016].

Fault tolerance is an interesting research topic that can extremely improve smart greenhouse efficiency. Generally, fault tolerance is a feature that enable the system to be operational during the failure of one of its parts. It is better to have a system operated in a reduced level than to have a totally failed one. It has a wide range of day-to-day applications that are supposed to be operational all the time. In case of a smart greenhouse architecture, a fault tolerant NCS can absolutely increase the crop production, the reliability and availability of the system [IBRAHIM 2018]. The application of Wireless Sensor Networks (WSN) and Networked Control Systems (NCS) for precision agriculture systems have been investigated through various studies. These applications are considered to be a predictive solution that can help in building a reliable and adequate decision support system that are continuously needed in the field of agriculture and accordingly enhance the crop production. Hence, a hierarchical model for two greenhouses has been presented in [IBRAHIM 2018]. This model is a Networked Control System (NCS) that is composed of sensor nodes, actuators and controller. A fault-tolerant model at the controller level has been investigated and studied proving that the system is reliable and available during the failure of any of the controllers. In [IBRAHIM 2019], an in-depth analysis was conducted on the fault-model and a layer of IoT has been added to the system so that the NCS system can be connected to the cloud over the internet for data analysis and remote controlling.

This research focus on studying a Networked Control System (NCS) inside smart greenhouse through the deployment of a fault-tolerant model at the Wi-Fi Access Point level [IEEE 802.3 Standard, IEEE 802.11 Standard]. The smart NCS greenhouse is composed of several numbers of small low-cost, low-energy, easy deployable sensor nodes with different types that sample the greenhouse environment; a main controller to process and analyze the sensor data and take proper control commands; actuators to perform these control commands sent by the controller and adjust the internal environment according to the needs of the yield. It is important to study the fault tolerance of Wi-Fi access point since it plays a major role in the smart greenhouse. All sensor nodes inside the greenhouse forward their sensed data to the access point found in every cell, then the access point sends these data to the controller (via Switched Ethernet) for processing and analysis so that proper control commands are taken. Moreover, a reliability model and steady state availability model were studied for several scenarios including a technique to help system designers balance between system cost (regarding access points) and downtime cost. It will be shown that the system can withstand the failure of more than one access point while maintaining system reliability and performance as desired. Results are very satisfactory and will be presented in details in the following chapters.

The rest of the thesis is divided into the following chapters: Chapter 2 is the literature review and related works; chapter 3 presents the Riverbed simulation results of the proposed fault-tolerant model on the access point level; Chapter 4 presents Riverbed simulation results for the fault-tolerant model with triple and quadruple access point failures as well as the results of Markov models which are used to compare system downtime to system cost. Finally, the thesis is concluded in the last chapter.

Chapter 2
LITERATURE REVIEW

Due to the increasing demands for high quality and safe agriculture products, it is important to effectively manage crop production through precision agriculture. Precision agriculture is a method of using new technologies to increase crop yields and profitability while, at the same time, reducing the level of traditional inputs such as water, fertilizers and insecticides that are needed to grow crops. With the development of WSN, it has become possible to efficiently monitor and control greenhouse parameters in precision agriculture. Additionally, integrating WSN with IoT applications has helped in monitoring the environment to be able to determine system behavioral and to predict the environmental changes that will influence the growth of crops. Hence, a lot of studies have been investigated such systems that will be presented in details throughout this chapter.

2.1 Monitoring Systems

In [XIAOYAN 2013], a solution was proposed to monitor a small to medium sized greenhouse based on GSM and RF technology. Monitoring nodes and sink nodes were designed using low power chip (PTR4000), Huawei wireless module (GTM900), and Atmega16A. The monitoring system integrates the RF technology and GSM technology and apply them on the wireless monitoring nodes and sink nodes. Figure 2.1.1 shows system architecture which consists of three main parts; wireless monitoring nodes, sink nodes, and remote communication terminal based on GSM network. The monitoring nodes collect environmental data from within the greenhouse, then it sends them to the sink nodes for processing. The monitoring nodes are equipped with RF module to transmit greenhouse measured parameters to the sink nodes. The data sent from the monitored nodes to the sink nodes are processed and analyzed to take proper control decisions, then transmitted to a remote server via GSM network. The results showed that the system is reliable, stable, and able to achieve real-time monitoring of the greenhouse environment.

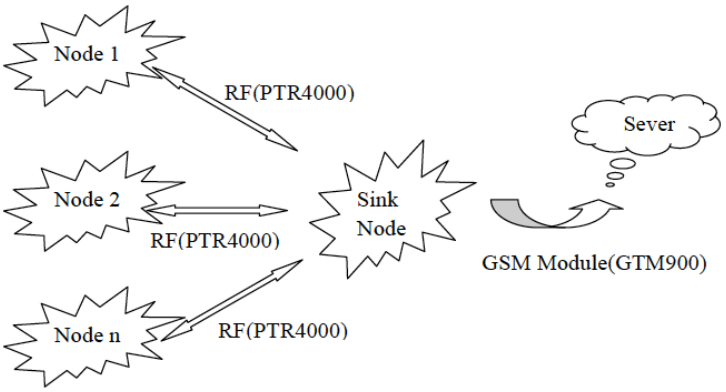

Figure 2.1.1 System Architecture [XIAOYAN 2013]

Another study was implemented in [ERAZO 2015] to investigate the impact of environmental changes on flowers through proposing a low-cost monitoring greenhouse system for watering, climate control, and lighting using Zigbee communication standard [ZigBee/IEEE 802.15.4 standard]. Figure 2.1.2 shows the block diagram for the wireless communication. The system architecture deploys Zigbee technology to transmit sensor data to the controller for processing and then transferring the information over USB to be displayed on a graphical interface. The system results showed that climate adjustment inside the greenhouse has a huge impact on the rose quality and leads to reducing the rose diseases.

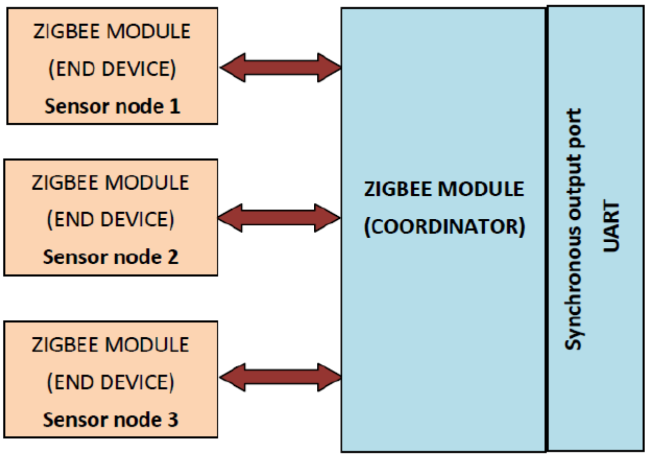

Figure 2.1.2 A Block Diagram of Wireless Communication [ERAZO 2015]

In this study [SRBINOVSKA 2015], a low-cost greenhouse monitoring system was designed based on a wireless sensor network technology to monitor key environmental parameters such as temperature, humidity, and illumination. Additionally, another study [LIU 2007] focused on the deployment of wireless sensor network prototype with two-part framework within the greenhouse; see figure 2.1.3. The first part consists of sensor nodes used to measure the internal environment condition such as temperature, light, and soil moisture. A sink node based of ARM processor is used for collecting and transferring these data wirelessly to a remote PC via short message services. The second part consists of GSM module and management software with a database running on the remote PC.

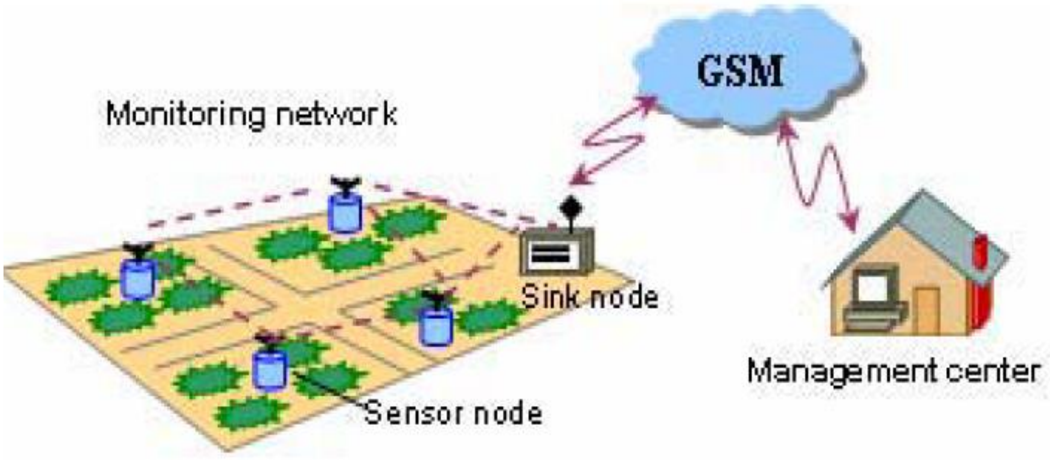

Figure 2.1.3 System Architecture [LIU 2007]

In [BAI 2017] a system design is proposed to increase the growth of vegetables. This system is composed of four modules. The first module is the data acquisition module where different sensors collect the environmental changes inside the greenhouse. The second module is using different actuators to execute the control commands. The third module is the control core module which is responsible for collecting the data collected from the sensor nodes wirelessly using Zigbee technology, forward them to the gateway and then analyze them for taking the proper control commands to be executed by the actuators. The fourth module is the power module which is used to power up the system using solar energy.

One of the most recent advancements of the greenhouse agriculture nowadays is the integration with a layer of IoT. In [GOMES 2015], the greenhouse system architecture is composed of three main components presented as follow: (1) Wireless Sensor Network, which is responsible for data acquisition and data transfer to the coordinator; (2) Network Gateway which is physically connected to the coordinator and send the collected data to the remote web server; (3) An online web server responsible for storing the received data into a database for further use. Figure 2.1.5 shows system architecture.

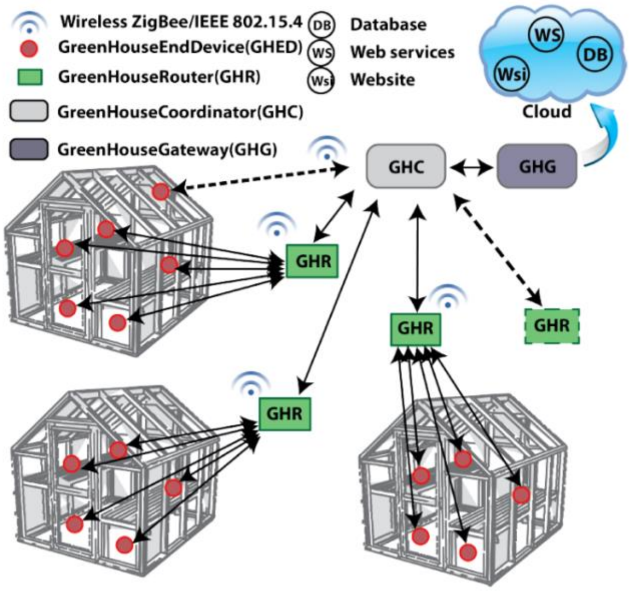

Figure 2.1.4 System Architecture [GOMES 2015]

Similarly, in [DANITA 2018] a system was developed where sensor nodes measure three different environmental parameters which are temperature, humidity, and moisture then the controller process and analyze the data collected to send its control commands to the actuators such as irrigation pipe, cooling fan, and sliding windows. Additionally, the data collected are stored in a cloud database so that it can be easily accessed remotely and also displayed on a webpage for visual access.

In [MAT 2016], proper irrigation system was achieved by using Wireless Sensor Network (WSN) technology. This study uses Wireless Moisture Sensor Network (WMSN) which is the WSN with moisture sensors. The soil moisture sensors keep monitoring the soil and accordingly send their data collected to a controller from which water valves are turned on or off. A Zigbee transceiver is used to send these readings to a gateway which is responsible for transmitting the collected data to the central unit to be displayed on Internet-enabled devices using Wi-Fi or GSM.

2.2 Monitoring and Controlling Systems

In [OMAR 2019], a WSN greenhouse automation system was proposed to provide the monitoring and control for the growing environment within the greenhouse. The proposed system proved its efficiency in increasing the economic value of the yield and saving manpower. The system is composed of a group of sensor nodes distributed to measure the internal environment changes such as temperature, humidity, soil moisture, light intensity, and carbon dioxide. The data from sensor nodes are then collected and transmitted to a coordinator node. Then, the coordinator node analyzes and process the data received from the sensor nodes and adjusts the environment accordingly by sending control commands to the actuators such as water pump, heater, cooler, and light actuator. The coordinator and sensor nodes are connected wirelessly via Zigbee technology standard and for remote monitoring and controlling a GSM cellular network is used. Figure 2.2.1 shows the schematic diagram of the proposed system structure.

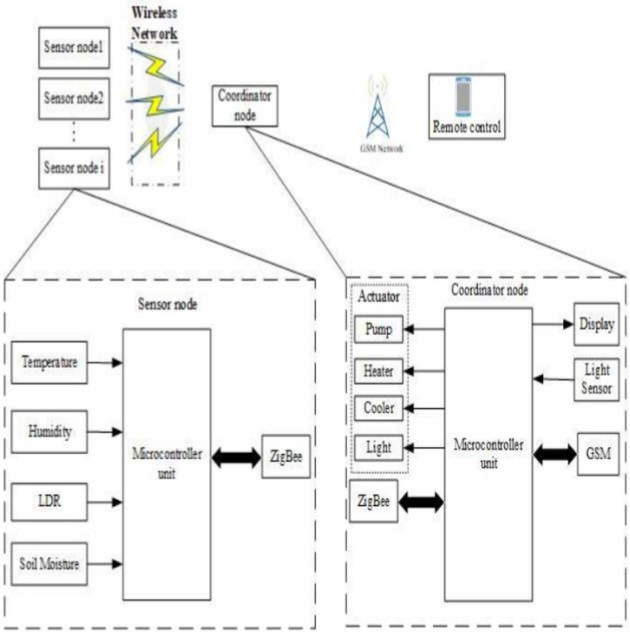

Figure 2.2.1 System Schematic Diagram [OMAR 2019]

In [RAO 2015], a proposed ubiquitous controlling and monitoring system of environmental parameters with a layer of IoT was developed inside a greenhouse in order to improve high quality of products along with proper management and data collection. The aim of this research is to be able to remotely monitor and control the greenhouse environmental parameters from anywhere and adjust the internal environment as desired. The system consists of sensor nodes to collect the environmental parameters such as temperature, light, soil moisture, and water level sensor. Atmega328 Microcontroller based on Arduino Uno to monitor and control the internal environment condition of the greenhouse. The Microcontroller receives the data sent from the sensor nodes to process and analyze them to take proper control commands and send these commands to the actuators to adjust the internal environmental condition as needed by the crops. The collected data are sent to the cloud via GSM and GPRS module so that user can access them remotely through a customized website. Figure 2.2.2 shows the system block diagram.

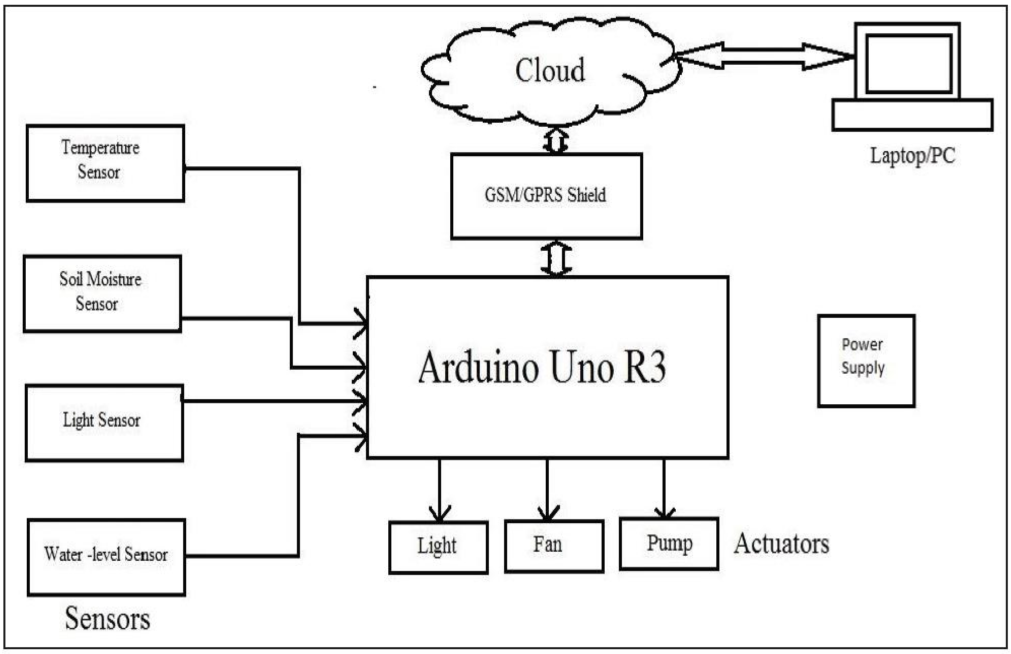

Figure 2.2.2 System Block Diagram [RAO 2015]

Greenhouse WSN was also studied in [MEKKI 2015], where sensor nodes used to measure temperature, humidity, light, moisture, and CO2. These nodes communicate with a gateway via Freakduino board using Chibi Wi-Fi and transmit the collected data remotely using GSM module. Figure 2.2.3 shows system block diagram and the system results shows an excellent improvement in the sensed parameters.

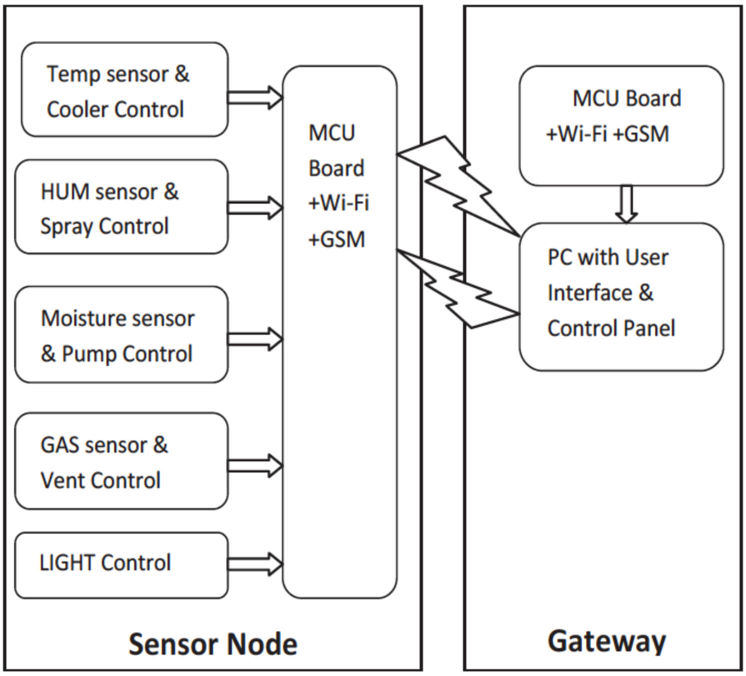

Figure 2.2.3 System Block Diagram [MEKKI 2015]

Another application for monitoring and controlling the precision irrigation system in a WSN greenhouse was implemented in [KASSIM 2014]. Where novel software system (IGMS) was developed for greenhouse management. This system provides the supervisor with information about the cultivation process, real-time data from the sensors, sensors configuration and system support. The sensors collect the data from the surrounding environment such as temperature and humidity and send them to the controller for processing. The IGMS is a web-based application in which the supervisor can access the collected data by the sensors, maintain records for user activities and send special alerts when needed. Similarly, in [PAHUJA 2013] a custom application that integrate WSN into high-level programming language was developed for greenhouse climate control. The system provides microclimate monitoring for greenhouse temperature and humidity. Additionally, it analyzes the greenhouse crops' vapor pressure deficit (VPD) which is an important parameter related to plant growth, health and crop conditions.

In [WAN 2019] a low labor cost system was developed to dynamically monitor and control a greenhouse internal environment. Using ESP8266 NodeMCU board as a central unit for the system; see figure 2.2.4 for system overview. The proposed system is monitoring and controlling the internal temperature, humidity, CO2, and soil moisture of the greenhouse through distributed sensor nodes. The data from the sensor nodes are sent to the NodeMCU module through Wi-Fi and then to the IoT platforms and OLED module so that the environmental parameters are visible to the user for controlling remotely. Additionally, the ESP8266 NodeMCU is connected to a multi-channel relay which is connected to some system actuators for control such as water pump, humidifier, light, and window. The user is able to remotely control the greenhouse environment by sending control commands to the actuators through IoT platforms via Wi-Fi module.

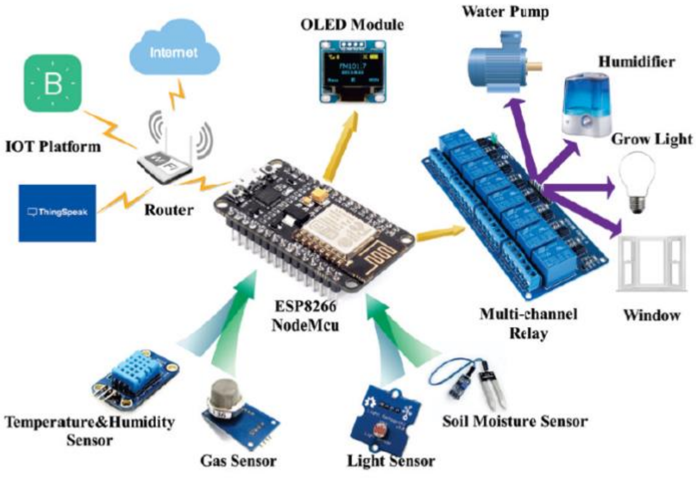

Figure 2.2.4 System Overview [WAN 2019]

In [AL-AUBIDY 2014] a design of a real-time monitoring and controlling system was proposed to for a group of greenhouses. Each greenhouse is considered as a node in a Wireless Sensor Network (WSN). The environmental parameters inside the greenhouse are being monitored and controlled through the developing of intelligent controller based on fuzzy logic. Similarly, the sensor nodes inside the greenhouse are measuring temperature, humidity, CO2, and solar radiation then send their data wirelessly to a microcontroller and accordingly the environmental parameters can be adjusted such as turning heaters ON/OFF.

In [PARK 2011], a proposed control and monitoring model was developed to monitor crop status as well as the indoor environmental changes of the greenhouse. The aim of this paper is to monitor and control any environmental changes occur inside the greenhouse and to study the factors that lead to crop diseases in order to improve productivity and protect crops from damages by blight and harmful insects. Figure 2.2.5 describes the system overall diagram.

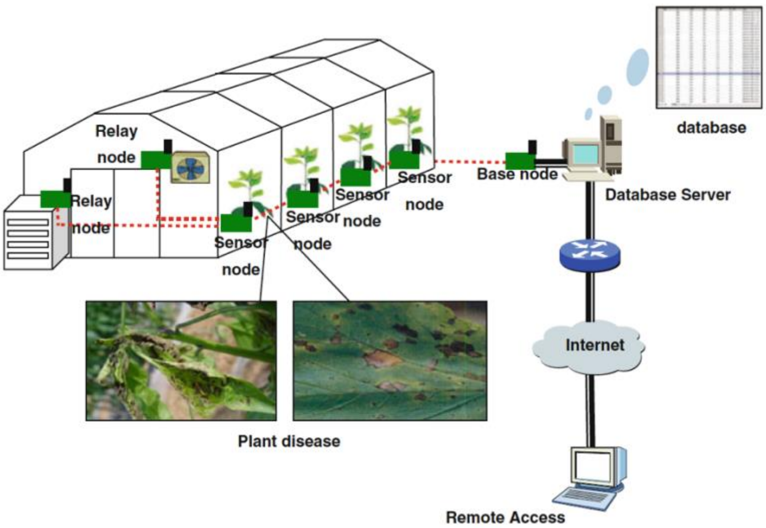

Figure 2.2.5 System Overall Diagram [PARK 2011]

The sensors inside the greenhouse are measuring the indoor temperature and humidity changes as well as leaf temperature and leaf humidity are being measured. According to the data collected from the leaf temperature and leaf humidity sensors, the environmental conditions within the greenhouse can be properly maintained. The sensors send the collected data to the base node wirelessly through Zigbee technology. The base node receives the sensor data and store them in a database, then it sends these data to a remote-control system for analysis via internet to take proper control decisions. The control commands are then sent to a relay node for controlling equipment inside the greenhouse such as window, heater, and ventilator.

In [ZHANG 2007], a study was conducted to choose the best wireless solution in building a WSN greenhouse monitoring and controlling system. The aim of the study was to compare between different wireless technology such as Wi-Fi, Bluetooth, and Zigbee to be deployed in the monitoring and controlling system. The system consists of sensor nodes to collect the environmental parameters inside the greenhouse such as temperature, humidity, and light. These collected data are sent to hand-held controller (HHC) module which is an ARM MCU integrated with Zigbee module. The HHC module store the data, process them and then it sends the control commands to the actuators inside the greenhouse to adjust the internal environment conditions of the greenhouse. Moreover, the data are also displayed on LCD to provide visual access to the user. The system preferred using Zigbee technology over other technologies because of its low-cost, high data rate, and long battery life. Figure 2.2.6 shows system overview.

In [SONG 2010], a greenhouse monitoring and controlling Wireless Sensor Network (WSN) was designed. It is composed of main controller (RF transceiver) and six wireless sensor nodes for measuring temperature, humidity, and light inside the greenhouse. The collected data from the sensor nodes are sent to the central node wirelessly vis Zigbee technology. Then these data are sent from the control node to the monitor control PC via RS232 serial port for processing and analysis and then proper control commands are sent to the actuators through the central node. Figure 2.2.7 shows schematic diagram of the control system.

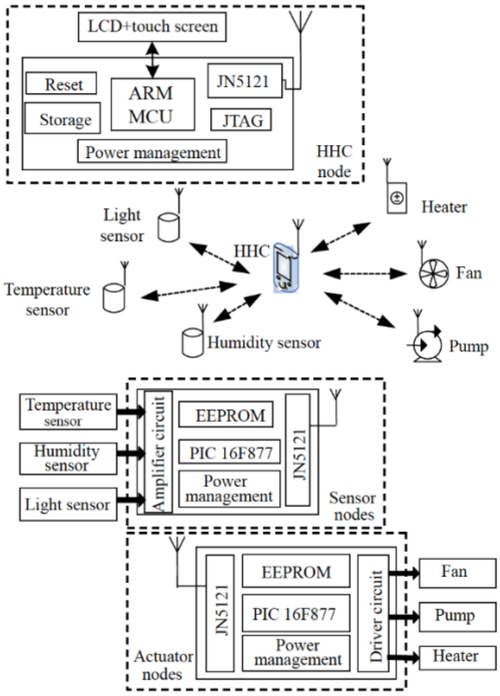

Figure 2.2.6 System Overview [ZHANG 2007]

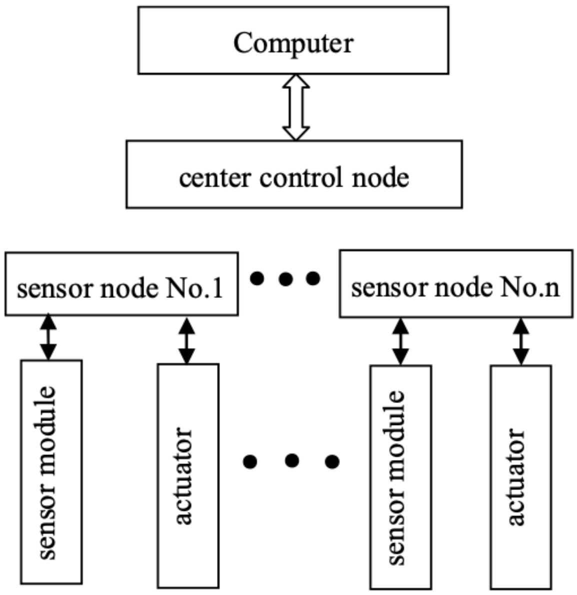

Figure 2.2.7 Control System Schematic Diagram [SONG 2010]

In [VISHWAKARMA 2020], a monitoring system is proposed using a low-cost IoT platform Node MCU module. The design aims to collect all the sensor data from sensor nodes and relay them to the Node MCU module for processing; then it sends its control commands to the actuators inside the greenhouse. Moreover, the system has a wireless Internet connection to send the collected environmental parameters to farmers smartphones for remote monitoring.

In [PALLAVI 2017], regarding a remotely controlled greenhouse, a remote sensing of agriculture parameters and control systems was developed so that any environmental changes occur inside the greenhouse are remotely monitored and controlled. The aim of this research paper is to control CO2, soil moisture, temperature, and light. Based on the data collected from the sensor nodes, proper control actions are taken for greenhouse windows and doors. similarly, in [DAN 2015], a layer of IoT was developed within the greenhouse through its connection to the controller and internet gateway over ZigBee. This system consists of four parts which are front-end data acquisition, data processing, data transmission and data reception There are several sensor and actuator nodes distributed within the greenhouse. The ZigBee coordinator receives the wireless sensor nodes information then it sends the information to the user presenting them on a GUI and it receives the control commands from the user to be executed inside the greenhouse. Figure 2.2.8 shows the system architecture.

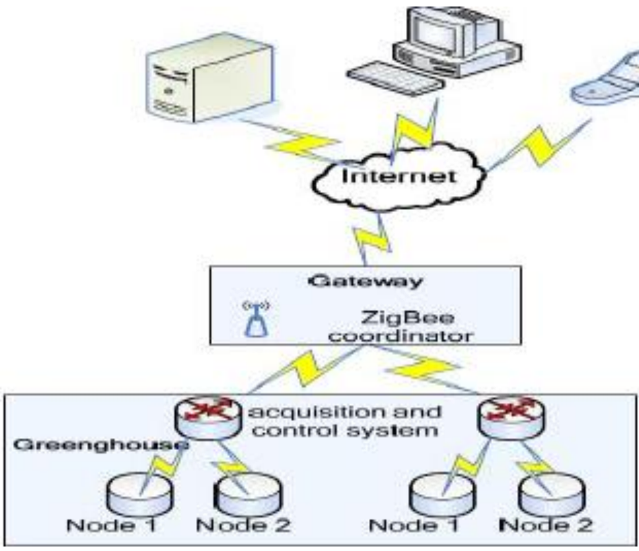

Figure 2.2.8 System Structure [DAN 2015]

In [JENNIFER 2019] an automated monitoring and controlling system using Netduino 3 Wi-Fi was proposed to improve production rate and decrease human intervention. All sensor nodes inside the greenhouse collect their data and send then to Netduino 3 Wi-Fi to take better control actions such as turning on/off the light. Then these data sent to the cloud to be stored in the cloud database where the user can get an access through mobile for monitoring and controlling. Figure 2.2.9 shows proposed system structure.

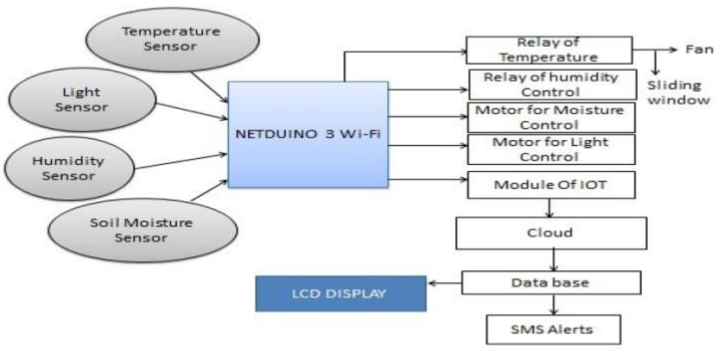

Figure 2.2.9 Proposed System Structure [JENNIFER 2019]

In [SUBAHI 2020] an intelligent Energy Efficient (EE) system based on IoT was proposed to monitor and control internal greenhouse temperature. The aim of this research is to increase productivity through decreasing production cost and saving energy consumption. The outside temperature is being monitored in order to generate an accurate reference temperature and to make sure that the greenhouse can maintain this reference temperature. Moreover, the system can determine the angle of the sun rays so that the openings and controlling of the awnings can be controlled which helps in reducing the effect of high temperature. A Petri Nets model was designed for monitoring and generating the suitable reference temperature. Figure 2.2.10 shows system architecture design.

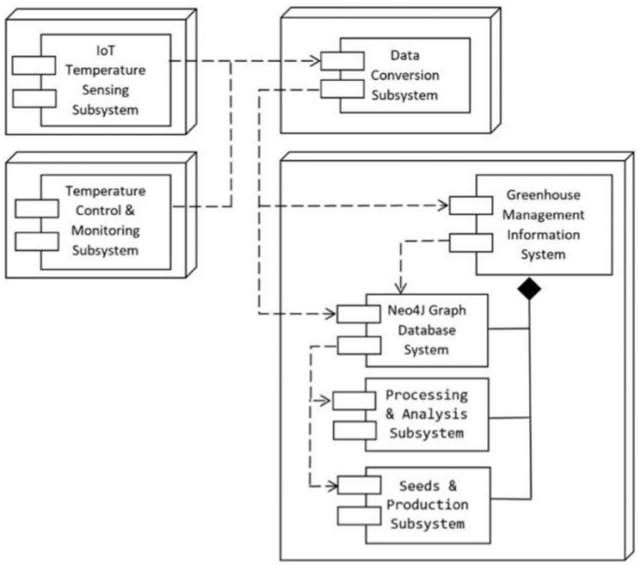

Figure 2.2.10 System Architecture [SUBAHI 2020]

The Energy Efficient (EE) system is a scalable system that is designed for handling massive amount of IoT big data captured from the sensors using dynamic graph data model for future analysis, data processing, crop growth rate, and energy consumption.

In [TAHA 2018], a remote greenhouse monitoring and controlling system was proposed. The system collects environmental changes inside the greenhouse such as temperature, light intensity, and humidity and then send them to a raspberry pi which acts as a server in real time-based internet of thing technology. The proposed system consists of sensor nodes, controlling unit, monitoring unit, and actuators. Figure 2.2.11 shows system block diagram. The system is divided into four parts: the first part, sensor nodes collect environmental parameters and transfer it to the server through ESP8266 Wi-Fi module. The second part, the server collects these sensor data and send them to the internet through MQTT protocol, and compares it to the appropriate parameters for the crop growth if any changes occur the server sends a frame to the actuators to adjust the environmental parameters within the greenhouse as required by the crop. The third part, is the monitoring unit that shows graph for current temperature, humidity, and light intensity values by using Red-Node software, the user can monitor their greenhouse online by accessing it though the website. Finally, the actuators inside the greenhouse provide an optimal condition inside the greenhouse. The system design succeeded in meeting the proposed system requirements such as reducing the human efforts, accurate control of crop conditions, distributed monitoring and data accessibility through the internet from anywhere.

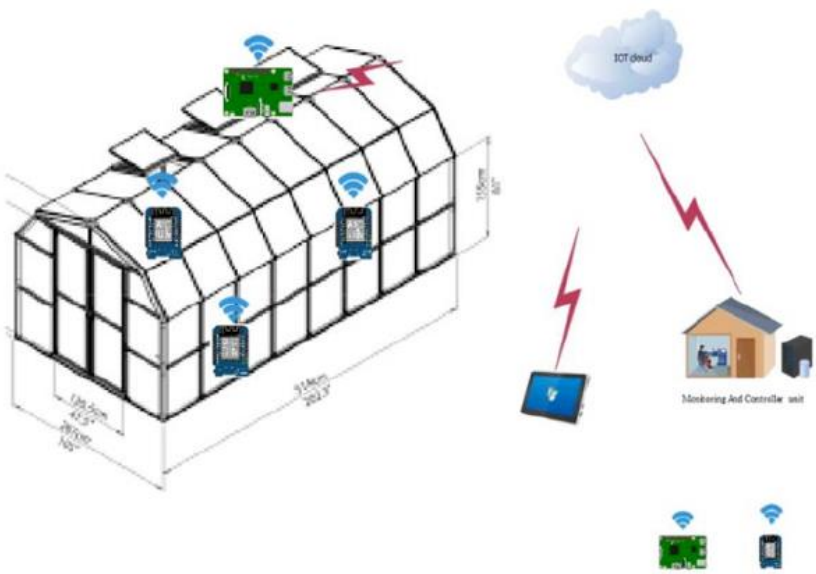

Figure 2.2.11 System Block Diagram [TAHA 2018]

In [SHINDE 2018], a wireless sensor network (WSN) was used to design a monitoring system inside a greenhouse. A simple Raspberry Pi 3 based circuit was designed to watch and read the values of the soil moisture, light, temperature, and humidity that are continuously changed inside the greenhouse. The Arduino Uno is used to get the collected data from the sensor nodes and then relay them to Raspberry Pi for process and analysis. Then the Raspberry Pi take proper control commands and send them to the actuators to adjust the internal temperature according to the needs of the crops. For example, turning the light ON/OFF, water pump and heater. Moreover, the data displayed on LCD for the user to monitor and control. Similarly, in [KUMAR 2022], a research paper aims to build a reliable, cost effective, and user-friendly monitoring and controlling system inside a greenhouse. The system consists of sensor data to sense the surroundings environmental changes occur inside the greenhouse such as temperature, humidity, and soil moisture. The collected data from the sensors are then transmitted to the main controller for processing and analysis and for taking the right control decisions to adjust the interior environment conditions as desired through sending control commands to the actuators such as heater, fans and water pump. Arduino Uno is used as a controller for the system. the action taken by the controller is sent as a notification message to the user’s phone informing him about the states of the greenhouse at this time; for instance, if the temperature inside the greenhouse is below the threshold value, the controller will take an action and open the fans and send a message to the user’s phone for updates. Moreover, the system is an environmentally friendly since it uses solar energy for battery charging and powering the whole system. Figure 2.2.12 and figure 2.2.13 show system block diagram and layout of IoT enable greenhouse system, respectively.

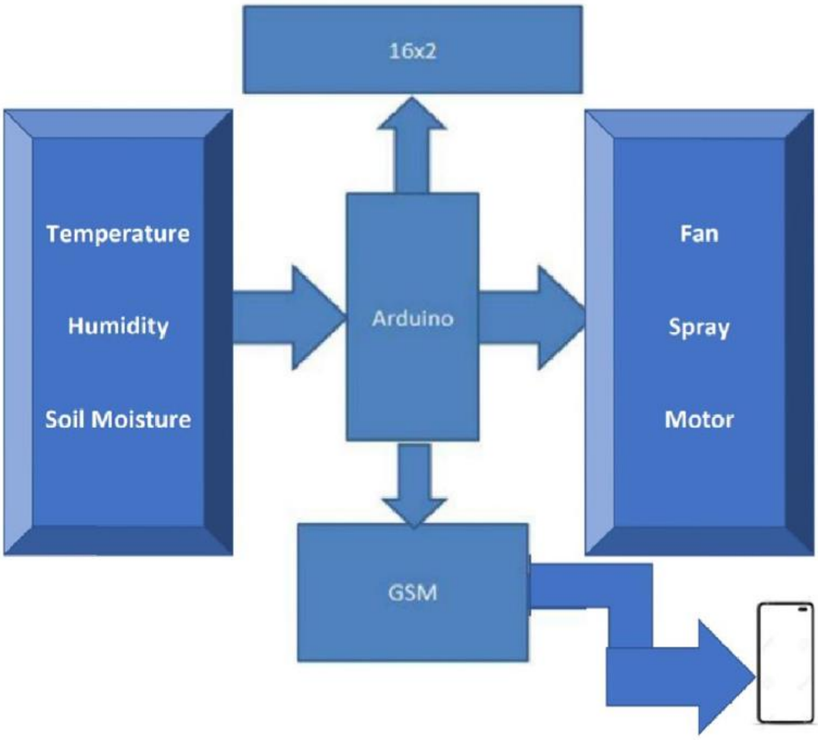

Figure 2.2.12 System Block Diagram [KUMAR 2022]

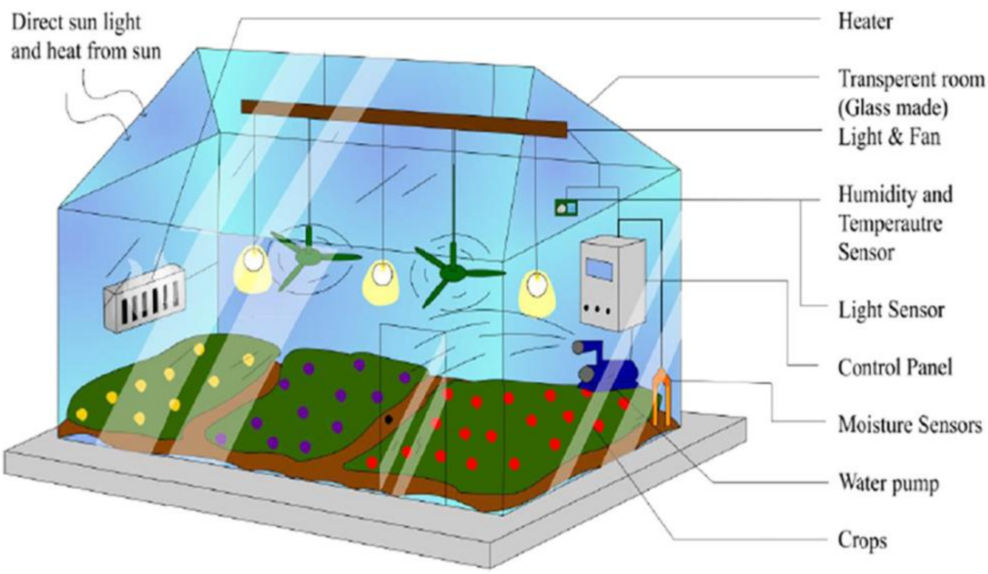

Figure 2.2.13 IoT Layout of Greenhouse System [KUMAR 2022]

2.3 Fault-Tolerant Systems

In this thesis, the proposed greenhouse architecture was built on an existing model found in literature in which a WSN NCS architecture was proposed on two greenhouses [IBRAHIM 2019]. A WSN is a network which consists of a of small low-cost and low-power sensor nodes. These sensor nodes are easily deployed and such network is able to provide scalability, flexibility and most importantly cost reduction. In the context of this research, the used architecture was built using the combination of two different technologies which are Switched Ethernet and Wi-Fi with the addition of a layer of IoT. The architecture is composed of three layers which are Layer 1 Sensor/Actuator Front-end Layer, Layer 2 Data Management Layer and Layer 3 Cloud-based Back-end Layer. In layer 1, the sensor nodes and cameras are sending their data collected to the controller for processing and analysis and take the right control commands in a timely manner. The greenhouse is divided into 5 identical cells. Sensor nodes are distributed evenly inside the greenhouse. These nodes are used for collecting great data flow regarding any environmental changes that occur inside the greenhouse such as temperature, humidity, CO2, soil moisture, light intensity, salinity, dew, pesticide, and fire. These data from the sensor nodes sent wirelessly to the main controller of the greenhouse to take proper control commands, then these commands are sent to the actuators such as fans, light, irrigation valves, curtains, and fire to adjust the environment as needed. The sensor nodes have a Wi-Fi interface to enable them to send the data wirelessly to the local access points which relay these data to the main controller of the greenhouse. The actuators are connected to the access point via Ethernet cable in order to receive the control action commands from the controller. The cameras transmit their live video traffic to the access point via Ethernet cable. In layer 2, the controller of the greenhouse is a very powerful microcontroller and it is considered the brain of the greenhouse. And finally in layer 3, an Internet gateway is used to relay the collected data after processing and analysis to a cloud server for storage and data analysis. Figure 2.13 shows the proposed system architecture. This paper main contribution was the design of channel allocation scheme in order to prevent interference in such a very large greenhouse system. Moreover, a fault-tolerant model was developed on the controller level. In which, if one of the controllers fail, the other controller takes over the whole entire operation of the two-greenhouse system. With the aid of a powerful simulation tool like Riverbed Modeler, it has been proven through several simulations that the system has zero packet loss and does not suffer from any over delayed packets. Additionally, Markov Chains were developed to calculate system reliability and steady state availability. Hence, the design succeeded in meeting system requirements and decreasing downtime during failures.

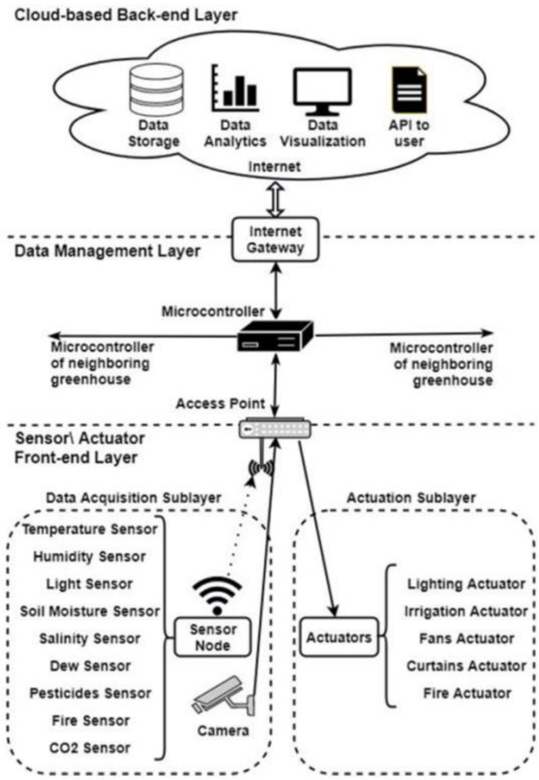

Figure 2.3.1 The Proposed System Architecture [IBRAHIM 2019]

Chapter 3
PERFORMANCE OF PROPOSED FAULT-TOLERANT MODEL FOR SINGLE AND DOUBLE ACCESS POINT FAILURES WITHIN A GREENHOUSE NCS ARCHITECTURE

It is of a great importance to add a layer of protection to a mission-critical applications or systems to ensure its high availability and business continuity; this can be achieved through the deployment of a fault-tolerant model. Generally speaking, fault tolerance is the ability of the system to be operated continually without any interruption when one or more of its components fail. In this thesis, the objective of creating a fault-tolerant model is to prevent any disruption that might occur from a single point of failure; in this case access point failures. This chapter will present the first contribution of this thesis. A fault-tolerant model is proposed to manage the failures of access points inside a greenhouse architecture achieving actual data management while sustaining minimum packet loss. First, the system architecture will be described. Next, the fault model along with failure handling will be explained showing how the system is performing during the failure of one or more of its access points and how the collected data from the sensor nodes in the failed cells are being handled.

3.1 Proposed Model

3.1.1 System Description

Networked Control System (NCS) is a type of distributed control systems where sensors, actuators, control systems, and other devices are interconnected by communication networks. It is an interdisciplinary research area that combines both the study of control and network theory. In this paper, an existing greenhouse architecture is studied in order to build a reliable

NCS. Additionally, a fault-tolerant model is proposed to protect the system from access point failures. In this system, the dimension of the greenhouse is 200m x 40m and it is divided into 5 equal cells. Each cell has 40 sensor nodes that are evenly distributed. The recent advances in wireless communications and electronics have led to improving sensor nodes by being produced in low-cost, low-power, small size, multi-functional, and with the ability to communicate over short distances. The sensors have become a vital component in the IoT and the modern world. In this study, the greenhouse has a total of 200 sensor nodes, one sensor node consists of 9 different sensors that are used to sense and control the surrounding environment. Each sensor has its own sampling rate presented below in table 3.1.1.1. the difference in the sampling rate depends on what environmental parameter is being measured and how critical is that parameter. Such measured parameters are temperature, humidity, dew, salinity, light, soil moisture, pesticide, CO2, and fire.

Table 3.1.1.1 Sensors Sampling Rates [IBRAHIM 2019]

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 second

A sensor node is composed of sensors, a microcontroller, and a power source. A sensor detects the changes occurring in the surrounding environment such as changes in temperature or soil moisture. The microcontroller has a Wi-Fi interface so that the sensed data collected by the sensor nodes are sent wirelessly to the local access point within the greenhouse cell. The used Wi-Fi protocol is IEEE 802.11n with 5GHz frequency band. Each cell has its own non-interfering channel due to the abundance of frequency channels. Additionally, each cell has 4 cameras placed at its corners. The camera’s transmission rate is 12 FPS and 5MP resolution and are connected to the greenhouse main controller through Ethernet cables so that the interference between the sensors’ traffic and cameras’ traffic would be reduced. Figure 3.1.1.1 shows a single greenhouse cell with sensor nodes, cameras, and APs placed in the middle of the cell.

Figure 3.1.1.1 Single Greenhouse Cell with Sensor Nodes, Cameras, and APs [Elnadi 2021]

In the context of WSN NCS, any output device is an actuator. In this study, each cell inside the greenhouse is equipped with 4 actuators that help in controlling the internal environment and adjusting it as needed such as controlling light, irrigation valves, fans, and curtains. Moreover, there is only one fire extinguisher actuator for the whole greenhouse. All the actuators are connecting to the controller via Ethernet cable and performing their actions with different rates, depending on the function of the actuator. For example, all the actuators inside the greenhouse take action every 30 seconds except the fire actuator, which is the most critical actuator in this study, takes action every 1 second. Figure 3.1.1.2 shows the actuators inside the greenhouse.

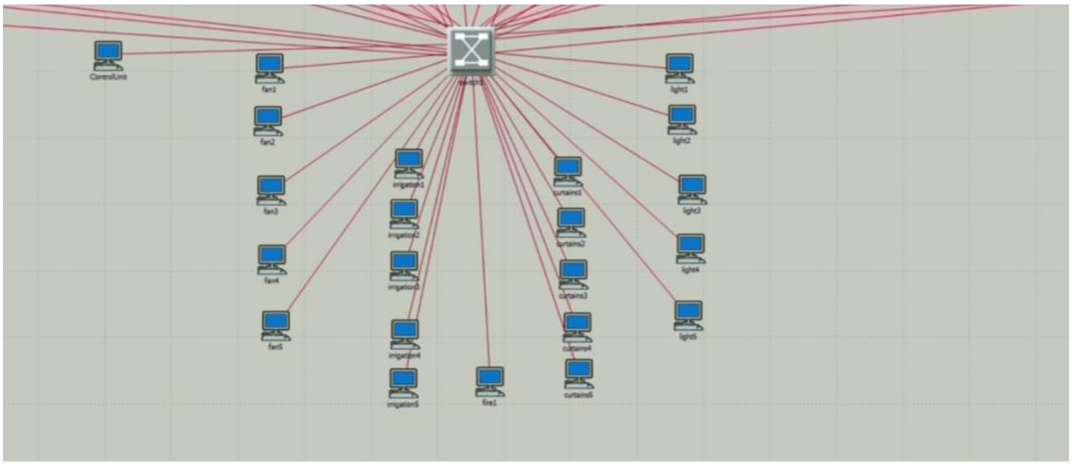

Figure 3.1.1.2 The Actuators Inside the Greenhouse [Elnadi 2021]

The network inside the greenhouse is a hybrid network since it combines between two technologies which are Wi-Fi and Ethernet cables. Each cell inside the greenhouse has its own access point that is responsible for transmitting the data collected from the sensor nodes to the main controller of the greenhouse. The access point receives the data from the sensor nodes wirelessly and send these data to the controller via Ethernet. When the controller receives the sensors' data from the access points it performs some processing and analyzes and afterwards it sends control commands to the actuators in the greenhouse for adjusting the internal environment. Figure 3.1.1.3 shows a schematic diagram of greenhouse cells along with its main components which are the APs and controller that are both connected via Switched Ethernet.

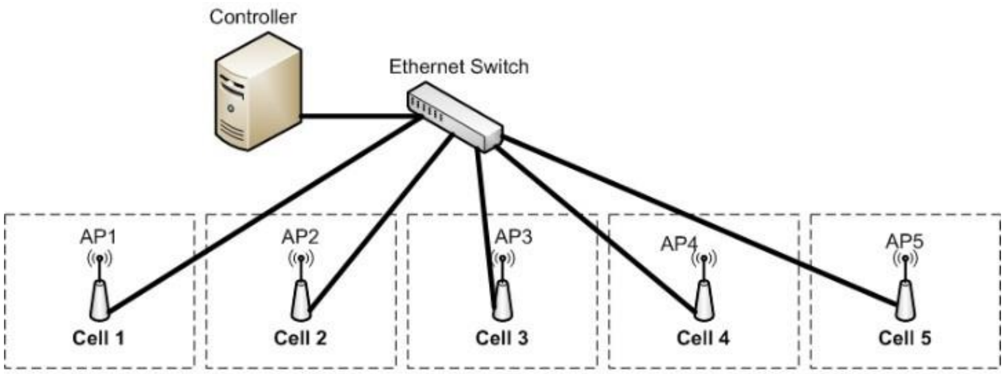

Figure 3.1.1.3 Fault Free Greenhouse Schematic [Elnadi 2021]

3.1.2 System Fault Model

In the view of what was mentioned before, access points have a significant role inside the greenhouse. It is the connection between the sensor nodes and the controller. For illustration see figure 3.1.2.1, if the access points in cell 4 and cell 5 failed, the data in cell 4 and cell 5 will be lost and part of the received data at the controller will be missing. Missing significant data at the controller will degrade system reliability by taking wrong control action or not taking the proper action in a timely manner. Hence, the aim of this research study is to ensure that all the data collected by the sensor nodes are safely received by the controller without any packet drop and within an acceptable timeframe. Accordingly, access points failure scenarios were studied which are: single access point failures, double adjacent access point failures, and double non-adjacent access point failures. In fact, failures will occur eventually, however, in order to mitigate these failures a fault-tolerant model is proposed to measure the system response and to see how it will act during the failure of one or more of its access points. This will assist in taking the necessary steps during these failures while keeping the system reliable, available, and well maintained with minimum packet drop.

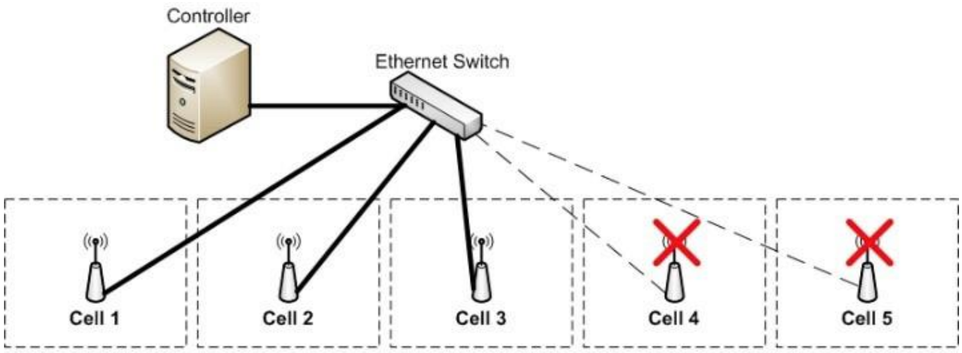

Figure 3.1.2.1 Greenhouse cells with AP Failure Occur in Cell 4 and Cell 5 [Elnadi 2021]

3.1.3 System Fault Handling

In order to achieve a robust control system that is able to recognize and respond to network errors that happen to the data during its transmission from the sensor nodes to the controller via access points, two methods were studied. The first method is during the failure of the access point, the sensor nodes will be redirected automatically to send their sensed data to the nearest operational access point. For example, assume cell 1 has an access point failure while the other cells are working properly, the sensor nodes inside cell 1 will be redirected to send their collected data to access point 2 in cell 2 which is the nearest working access point in this case. The second method is instead of sending all the collected data to only one working access point, the data will be divided equally and distributed between two working access points. For instance, if access point 3 in cell 3 failed, all the data from the sensor nodes in cell 3 will be divided equally and distributed between access point 2 in cell 2 and access point 4 in cell 4. So that the load has been divided between two access point instead of only one. In fact, there are some cases where the first method will be more suitable especially during the failure of access point at one of the edge cells such as cell 1 or cell 5. However, in other cases method two will be more fitting. In general, both cases have proven their success in meeting system requirements and will be discussed in detail later.

The internal environment of the greenhouse is free of any obstacles such as walls or barriers. Only the sensor nodes are placed on the ground and the access points are installed in the middle of the cell ceiling, thus the communication model is assumed to be a free space model and this “indoor” setting is equivalent to an outdoor setting with a line-of-sight between the sensor nodes which are the transmitters and the access points which are the receivers.

In order to test the performance of the wireless sensor network (WSN) inside the greenhouse during the failure of any of the access points, four different simulation scenarios were tested to cover all the expected situations that might occur inside the greenhouse and hinder its operation. These scenarios are: fault-free scenario, single access point failure scenarios, double access point failures scenarios, and double non-adjacent access point failures scenarios.

3.1.4 System Simulation Scenarios

This section will discuss in details all the expected simulation scenarios of access point failures that might occur inside the greenhouse.

The first scenario is the fault-free scenario**.** This scenario is simple, it tests the implemented network that consists of sensor nodes, actuators, access points and the controller, and it makes sure that all the nodes are connected and the communication between the nodes are well setup. In this scenario, all the access points are working properly without any failure. The sensor nodes send their sensed data to the access points then the access points forward these collected data to the controller for processing, and analyzing. The controller then sends the right control commands to the actuators so that the environment inside the greenhouse can be adjusted as desired. This scenario shows that when all the access points are working properly, the system does not suffer from any packet loss and all the data from the sensor nodes will be received at the controller on time as well as the controller will be able to take the right control decisions.

The second simulated scenario is the single access point simulation scenarios. This scenario tests the performance of the system when one of the access points inside the greenhouse fails. There are two types of failures that might occur, failure at one of the edge cells for example, cell 1 and cell 5 and failure that takes place in one of the middle cells such as cell 2 or cell 3 or cell 4. The reason for classifying the failures is to save time and to avoid repeating the same simulation over and over again. For instance, there are five cases in which access point can be failed. There might be an access point failure in cell 1 or cell 2 or cell 3 or cell 4 or cell 5. Only one access point fails at a time. Table 3.1.4.1 shows all the expected single access point failures.

Table 3.1.4.1 All Expected Single Access Point Failure Scenarios [Elnadi 2021]

Working Access Points	Failed Access point
2,3,4,5	1
1,3,4,5	2
1,2,4,5	3
1,2,3,5	4
1,2,3,4	5

As mentioned earlier, there are two similar cases where one access point might fail which are the failure at one of the edge cells; cell 1 and cell 5. Similarly, there are three cases where access point might be failed at one of the middle cells; cell 2, cell3, and cell 4. Therefore, some scenarios have been chosen for the simulation, these scenarios represent all the five cases of access point failures occur at the edge cell and in the middle cell. Table 3.1.4.2 shows the simulated scenarios with a single access point failure.

Table 3.1.4.2 Simulated Scenarios with Single Access Point Failure [Elnadi 2021]

Working Access Point	Failed Access Point
1,3,4,5	2
1,2,3,4	5

Double adjacent access point failure scenarios are the third type of the simulated scenarios in this research paper. In these scenarios, only two access points at two adjacent cells fail simultaneously. The expected scenarios for this case are presented in table 3.1.4.3. similarly, as in single access point failure, some scenarios have been chosen for the simulations while others have been skipped to avoid reptation. For example, the scenario with access point failures in cell 1 and cell 2 is similar to the one with access point failures in cell 4 and cell 5. Likewise, the scenario with access point failure in cell 2 and cell 3 is similar to the one with access point failure in cell 3 and cell 4. Table 3.1.4.4 shows the simulated scenarios for double adjacent access point failures.

Table 3.1.4.3 Expected Double Adjacent Access Point Failures [Elnadi 2021]

Working Access Point	Failed Access Points
3,4,5	1,2
1,2,5	3,4
1,2,3	4,5
1,4,5	2,3

Table 3.1.4.4 Simulated Scenarios for Double Adjacent Access Point Failures [Elnadi 2021]

Working Access Points	Failed Access Points
1,4,5	2,3
1,2,3	4,5

Finally, double non-adjacent access point failure scenarios are the scenarios where two access points in a non-adjacent cell failed simultaneously. There are three different cases regarding this type of access point failures scenarios which are two access point failed separated by either one cell with a working access point, two cells with two working access points or three cells with three working access points. Table 3.1.4.5 presents all the possible combination for these failures.

Table 3.1.4.5 All Possible Combination of Double Non-Adjacent Access Point Failures [Elnadi 2021]

Double non-adjacent AP failure (separated by one working AP)	
Working APs	**Failed APs**
2,4,5	1,3
1,2,4	3,5
1,3,5	2,4
Double non-adjacent AP failure (separated by two working APs)	
Working APs	**Failed APs**
2,3,5	1,4
1,3,4	2,5
Double non-adjacent AP (separated by three working APs)	
Working APs	**Failed APs**
2,3,4	1,5

In case of double non-adjacent access point failure separated by one cell with working access point, there are two mirror scenarios which are the scenario with an access points failure in cell 1 and cell 3, and the scenario with an access point failure in cell 3 and cell 5. Only the second scenario will be simulated along with the scenario with an access point failure in cell 2 and cell 4, while the other one will be skipped to avoid reptation. Table 3.1.4.6 shows the chosen simulated scenarios.

Similarly, in case of double non-adjacent access point failure separated by two cells with two working access points, the only two scenarios for this case are similar to each other; these scenarios are one with access point failure in cell 2 and cell 5, and the one with access point failure in cell 1 and cell 4. Only one of them will be simulated. Table 3.1.4.7 show the simulated scenarios for this case.

In the case of double non-adjacent access point failure separated by three cells with three working access points, only one scenario is available which is the one with access point failure in cell 1 and cell 5.

Table 3.1.4.6 Simulated Scenarios for Double Non-Adjacent Access Points Separated by One Working Access Point [Elnadi 2021]

Working Access Points	Failed Access Points
1,2,4	3,5
1,3,5	2,4

Table 3.1.4.7 Simulated Scenarios for Double Non-Adjacent Access Points Separated by Two Working Access Points [Elnadi 2021]

Working Access Points	Failed Access Points
1,3,4	2,5

The internal environment inside the greenhouse is free of obstacles therefore it is considered to be a free space environment where the indoor operation is equivalent to an outdoor operation with a line-of-sight between the transmitter and the receiver. Accordingly, the failed non-adjacent access points separated by 1, 2, or 3 access points can be represented by one scenario; the scenario with an access point failure in cell 1 and cell 3. Table 3.1.4.8 show all the scenarios that comprehensively cover all the expected situations in case of single and double access point failure.

Table 3.1.4.8 List of All Simulated Scenarios [Elnadi 2021]

Working Access Points	Failed Access Points
1,2,3,4	5
1,3,4,5	2
1,4,5	2,3
1,2,3	4,5
2,4,5	1,3

3.1.5 Performance Evaluation Metric

In this research, the Packet Loss Rate (PLR) is the metric used for the evaluation of the system performance. The PLR is simply the ratio of lost packets to the total number of sent packets and this value should not exceed 2% according to [AWAD 2017]. PLR means that during the transmission some data will be dropped; if the PLR value exceeded 2% this means that the controller might take wrong control actions or, alternatively, not taking the appropriate actions.

3.2 Simulation Results

All the simulation scenarios were performed using Riverbed Modeler simulation tool [Official website for Riverbed Modeler]. It is a fast and powerful simulation engine for designing and analyzing communication networks. It also provides the ability to efficiently analyze the performance of the network infrastructure models to a realistic scale. The value of the PLR indicates whether the system is working properly or not. If the PLR $\leq$2%, this means that the proposed model succussed in meeting system requirements.

To calculate the PLR, the average wireless data received from all sensor nodes at the controller is first calculated. It is important to highlight that Riverbed considers packets dropped due to contention, collisions, and errors that require retransmission. If a packet is marked as received by the destination, this confirms that the payload/packet was error-free. Hence, throughout this thesis, a PLR value of X% implies that the packets that were received (100%-X%) are all valid and non-erroneous packets. As mentioned earlier in table 3.1.1.1, sensor nodes have three different sampling rates that are clearly displayed in figure 3.2.1. This figure shows that the sensor node sends 2 bytes every 1 second, an additional 1 byte every 5 seconds, and also additional 6 bytes every 30 seconds. The total number of bytes sent each second follows this pattern in table 3.2.1 and it is repeated every 30 seconds. These sensor data pattern will be visually clear in figure 3.2.1. where the shorter spike represents the traffic sent by the sensor nodes (3 Bytes) after 5 seconds that can be broken down into 2 Bytes every 1 second plus 1 Byte every 5 seconds. The longer spike represents the traffic sent by the sensor node (9 Bytes) after 30 seconds that can be broken down into 3 Bytes every 5 seconds plus 6 Bytes every 30 seconds.

Table 3.2.1 Sensors' Data Pattern

Sensors 'data pattern	2 2 2 2 3 2 2 2 2 3 2 2 2 2 3 2 2 2 2 3 2 2 2 2 3 2 2 2 2 9

Figure 3.2.2 shows the data received by one of the actuators where each actuator receives 10 bytes every 30 seconds. Moreover, the data sent by the camera which is 25 Kbps is shown in figure 3.2.3. Next, it will be shown how the average expected data received at the controller will be calculated. All the following figures show the data received in Bytes (y-axis) versus Time in minutes and seconds (x-axis).

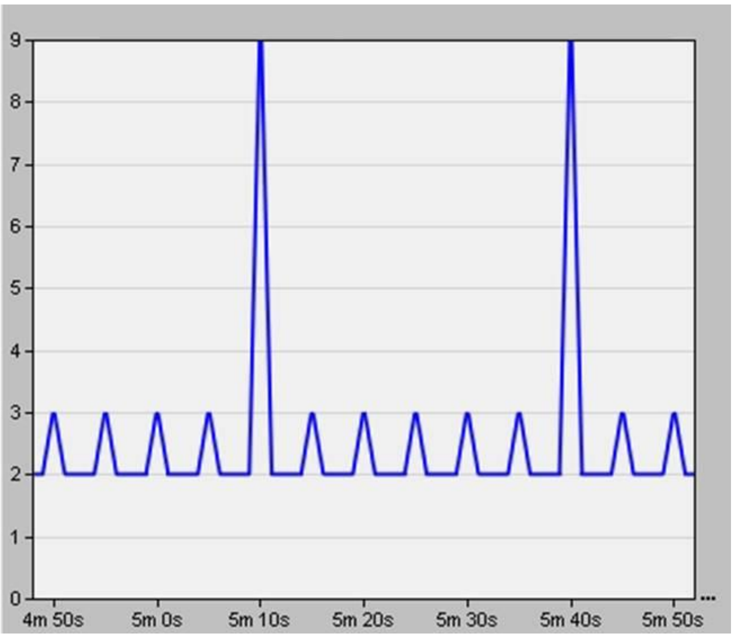

Figure 3.2.1 Traffic Received by The Controller in Bytes Verses Time in Minutes and Seconds [Elnadi 2021]

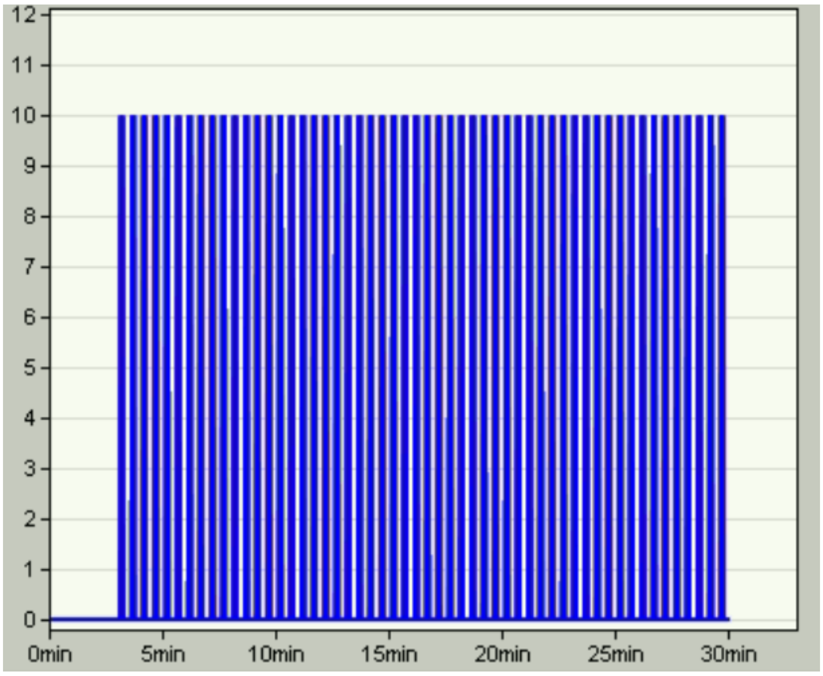

Figure 3.2.2 Traffic Received by The Light Actuator in Bytes versus Time in Minutes [Elnadi 2021]

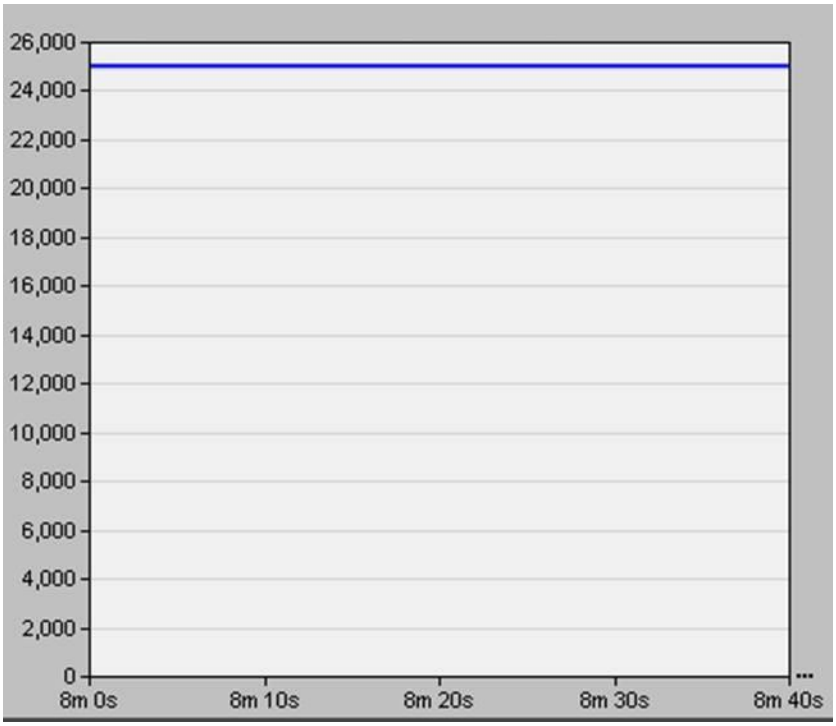

Figure 3.6.3 Traffic Sent by The Camera in Bytes verses Time in Minutes and Seconds [Elnadi 2021]

The periodic cycle of the entire system takes 30 seconds based on the different sensor nodes sampling rates. Therefore, the system packet loss and average data received are calculated within 30 seconds, given that the number of sensor nodes inside the greenhouse is 200. Therefore:

(30/5) ×1×200
+ (30/1) ×2×200
+ (30/30) ×6×200
=1200 + 12000 + 1200 = 14400 Bytes
Hence the average is:
14400/30 sec = 480 Bytes/sec

So, it is expected to receive an average of 480 Bytes/sec of sensors' collected data at the controller. Then, confidence analysis is applied on the received data to calculate the Packet Loss Rate (PLR) using the following formula:

$$PLR = \frac{N^{tx} - N^{rx}}{N^{tx}} \times 100\%$$

As mentioned earlier that the packet loss rate (PLR) represents the value of the total number of dropped packets to the total number of sent packets, so, N^{tx} and N^{rx} are the number of transmitted data and received data, respectively.

The Riverbed simulation results showed that in the case of fault-free scenario the PLR value is equal to zero which means that the system has not experienced any packet loss, and all the data collected from the sensor nodes have been transmitted and received wholly at the controller.

Furthermore, the case in which access point 2 in cell 2 failed, the data transmitted from the sensor nodes to the controller can either be distributed between access point 1 in cell 1 and access point 3 in cell 3 or it can be redirected fully to access point 1 in cell 1 or access point 3 in cell 3. Both ways yield satisfactory results and succeeded in meeting system requirements in maintaining minimum packet loss below the threshold value 2%.

One of the interesting points that has been investigated and simulated is when both access point 4 in cell 4 and access point 5 in cell 5 failed at a time, the data from the sensor nodes were redirected as follow; cell 4 forwarded its data to access point 2 in cell 2 and cell 5 forwarded its data to access point 3 in cell 3. This case proved that one cell can carry its own load and also takes over the load of another cell. Additionally, it not only takes the load of its direct failed neighbor cell but also it can take over the load of one cell further. That's why the sensors' data has been distributed in this way achieving successful results of PLR value below the threshold value 2%.

In conclusion, when applying the above formula with 95% confidence analysis on all the list of simulated scenarios presented in table 3.1.4.8, the PLR values were below the 2% threshold value. This has successfully proven that the fault-tolerant NCS greenhouse is meeting the system requirements.

Chapter 4
SYSTEM AVAILABILITY AND COST FOR THE PROPOSED MODEL

There are two common metrics the industry uses to express a system's ability to tolerate failures which are reliability and availability. A reliable system means that the system will remain operational (potentially despite failures) for the duration of its mission; reliability can be thought of as the quality of the uptime. Very high reliability is important in most critical applications, in which failure could mean loss of life. On the other hand, system availability is a metric used to measure the probability that a system is not failed or undergoing a repair action when it needs to be used. High availability is important in many applications and it has a direct impact on the financial health of a business, in which every minute of downtime is translated into significant profit loss. In this greenhouse system architecture, as shown in chapter 3, the proposed fault-tolerant model has successfully helped in keeping the system available and reliable, in which despite single and double access point failures, the system can operate successfully with a 95% confidence and without experiencing unexpected data loss over the specified threshold value which is 2% [ELNADI 2021]. This chapter [ELNADI 2022] will first present an extensive study on the remaining access point failure scenarios including triple and quadrable access point failures. Showing that the greenhouse architecture can safely survive three and four access point failures taking into account some changes to provide optimal coverage and to guarantee an efficient system performance. Next, another important contribution of this research will be discussed which is providing a technique to help system designers to have an insight and to be able to suitably balance between system cost (regarding access points) and downtime cost; where the cost of downtime is measured using system steady state availability [ELNADI 2022]. In addition to that, a use case will be presented showing that investing in access points not only depends on the cost point of view but also depends on how it impacts the system steady state availability.

4.1 Remaining Access Point Failure Cases and Simulations

4.1.1 Triple and Quadruple Access Point Failure Scenarios

A good fault-tolerant system design requires a careful study of design, failures, causes of failures and how system respond to these failures. Therefore, it was important to continue the work and study triple and quadruple access point failure cases and show how the system will operate during these failures while maintaining minimum packet loss rate (PLR) and achieving a desired system performance. The tables below 4.1.1.1 and 4.1.1.2 show comprehensively all the expected and possible triple and quarriable access point failure scenarios, respectively.

These tables contain four columns in which the first one represents the active/operational access points, the second column represents the failed access points, the distance the sensors would have to take to redirect their traffic is shown in the third column and finally the fourth column shows the real destinations from which the sensor data will be redirected to, per failed access point.

As mentioned earlier that in order to handle sensors' data in a failed cell, the sensors' traffic either be redirected to the nearest operational cell with an operational access point or split evenly between two active access points. For illustration, in table 4.1.1.1 the scenario with active access points 4 and 5 and failed access points 1, 2, and 3, the traffic is redirected as follows access point 1 and 2 were redirected to access point 4 (1 → 4, 2→4), while access point 3 were redirected to access point 5 (3→5). It is also shown that the maximum distance the sensors' data need to travel in cells is 3, where access point 1 and 2 need to reach access point 4.

Table 4.1.1.1 Triple APs Failure Scenario Cases [Elnadi 2022]

Active APs	Failed APs	Max. Distance(cells)	Traffic Redirection
1,2	3,4,5	3	3→1, 4→2, 5→2
2,3	1,4,5	2	1→2, 4→3, 5→3
3,4	1,2,5	2	1→3, 2→3, 5→4
4,5	1,2,3	3	1→4, 2→4, 3→5
1,3	2,4,5	2	2→1, 4→3, 5→3
2,4	1,3,5	1	1→2, 3→2+4, 5→4
3,5	1,2,4	2	1→3, 2→3, 4→5
1,4	2,3,5	1	2→1, 3→4, 5→4
2,5	1,3,4	1	1→2, 3→2, 4→5

1,5	2,3,4	2	2→1, 3→1+5, 4→5

Table 4.1.1.2 Quadruple APs Failure Scenario Cases [Elnadi 2022]

Active APs	Failed APs	Max. Distance(cells)	Traffic Redirection
1	2,3,4,5	4	2→1, 3→1, 4→1, 5→1
2	1,3,4,5	3	1→2, 3→2, 4→2, 5→2
3	1,2,4,5	2	1→3, 2→3, 4→3, 5→3
4	1,2,3,5	3	1→4, 2→4, 3→4, 5→4
5	1,2,3,4	4	1→5, 2→5, 3→5, 4→5

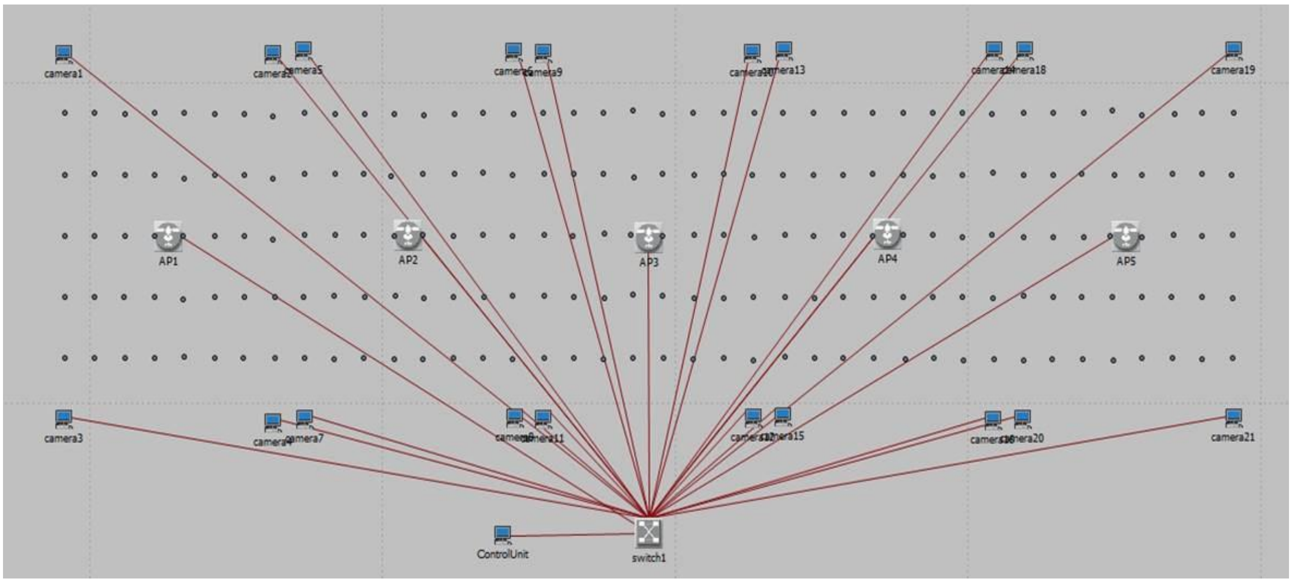

Figure 4.1.1.1 Riverbed Simulated Smart Greenhouse Topology [Elnadi 2022]

Some cases require to mix between the two data handling methods in order to minimize the communication distance between failed cells and active cells and not to overload the cell with too much data. For example, in the case where the active access points are 2 and 4 and the failed access points are 1, 3, and 5, the sensors' traffic is redirected as follows cell 1 and cell 5 will send their collected data to cell 2 and cell 4, respectively. While cell 3 will split its data traffic evenly between cell 2 and cell 4 (3→2+4).

The access point failure scenarios presented in table 4.1.1.1 and 4.1.1.2 can be reduced to only seven scenarios shown in table 4.1.1.3 based on the maximum distance traveled in cells and the traffic redirection pattern. Using the Riverbed Modeler simulation tool, the PLR value can be calculated with a 95% confidence analysis.

Table 4.1.1.3 Triple and Quadruple APs Failure Simulated Scenarios and PLR Results [Elnadi 2022]

Active APs	Failed APs	Max. Distance (cells)	PLR [$\mu-\Delta$, $\mu+\Delta$] (%)
1,2	3,4,5	3	[19.520, 19.383]
2,3	1,4,5	2	[0.316, 0.462]
3,5	1,2,4	2	[0.416, 0.652]
2,4	1,3,5	1	[0.174, 0.228]
1	2,3,4,5	4	[40.247, 40.576]
2	1,3,4,5	3	[20.503, 20.943]
3	1,2,4,5	2	[1.80, 2.22]

It can be seen in table 4.1.1.3 that the lowest PLR values obtained for triple and quadruple access point failures are in the scenario with active access points in cell 2 and 4 and the scenario with active access point in cell 3, respectively. This indicates that the location of these access points in such cases is ideal resulting in lower PLR values. The upper confidence limit in the quadruple access point failure scenario with active access point 3, shown in table

4.1.1.3, exceeds the 2% PLR threshold. It exceeds by a tiny value of 0.22%. This is the worst-case scenario, and an extreme case in which this slight increase of PLR value is considered to be acceptable. On the other hand, the failures occur in scenario with active access points in cell 1 and 2, and scenario with active access point in cell 1, and scenario with active access point in cell 2, have resulted in an unacceptable PLR value that's far beyond the specified threshold value which is greater than by 19%. In fact, it is not easy to predict the failure of the access point or even identify its precise location beforehand and the owner/supervisor wouldn't simply hope for a failure to happen in ideal locations such as cell 2 and cell 4 in case of triple access point failure and cell 3 in case of quadruple access point failure. Therefore, it is advisable that during these failures, the owner/supervisor should relocate the active access points into cells that yield lower PLR values and what helps is that most crops able to withstand changes to their environment for a short period of time. By doing so, the system will be successfully able to tolerate single, double, triple, and quadruple access point failures with a little human intervention. The following figures are representing the sensors' traffic received by the controller in the following scenarios: scenario with active access point in cell 3, scenario with active access points in cell 2 and cell 4, scenario with active access points in cell 1 and cell 2, and scenario with failed access point in cell 5 while the rest are functioning properly. All the figures show the traffic received by the controller in Bytes (y-axis) verses Time in minutes and seconds (x-axis).

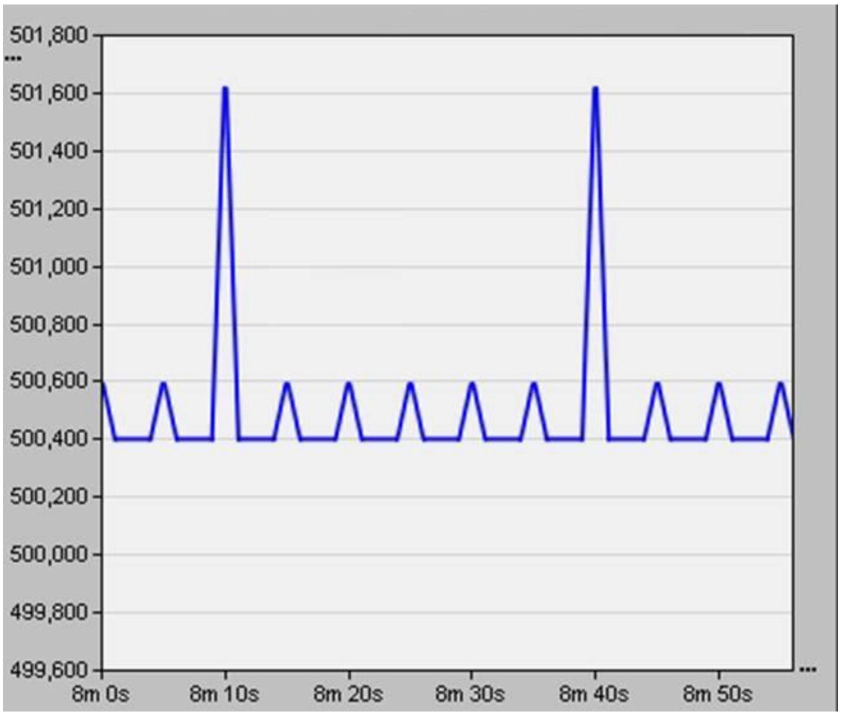

Figure 4.1.1.2 Traffic Received by the Controller in Bytes Verses Time in Minutes and Seconds When AP in Cell 3 is Active [Elnadi 2022]

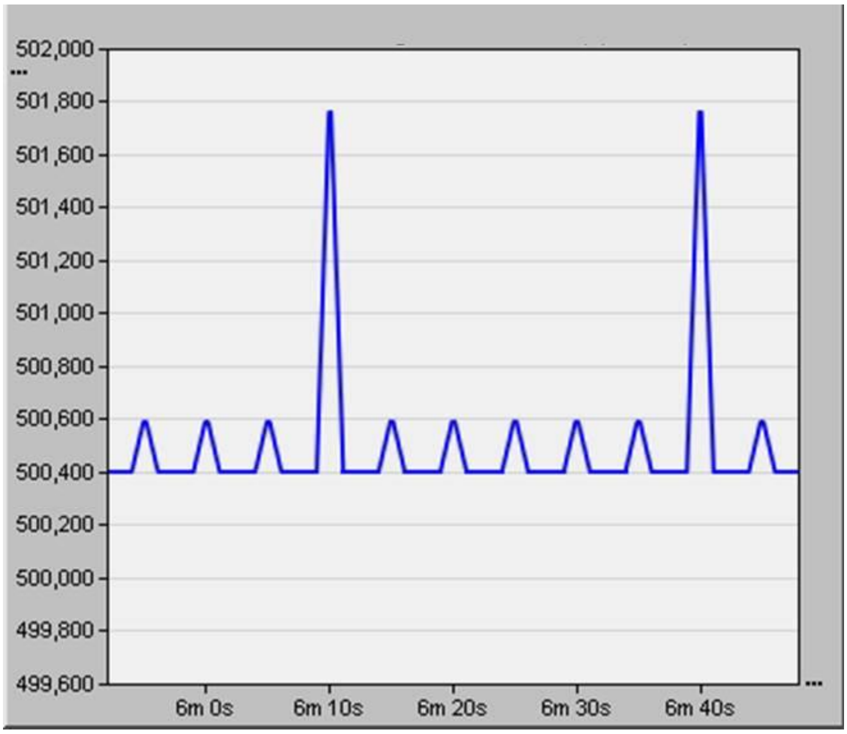

Figure 4.1.1.3 Traffic Received by the Controller in Bytes verses Time in Minutes and Seconds When APs in Cell 2 and 4 are Active [Elnadi 2022]

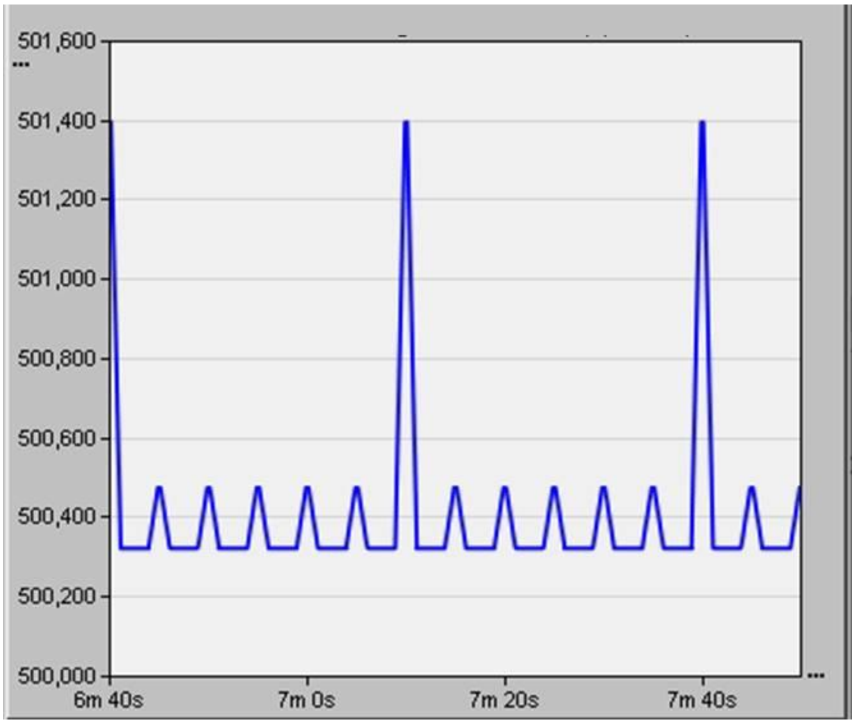

Figure 4.1.1.4 Traffic Received by the Controller in Bytes verses Time in Minutes and Seconds When APs in Cell 1 and 2 are Active [Elnadi 2022]

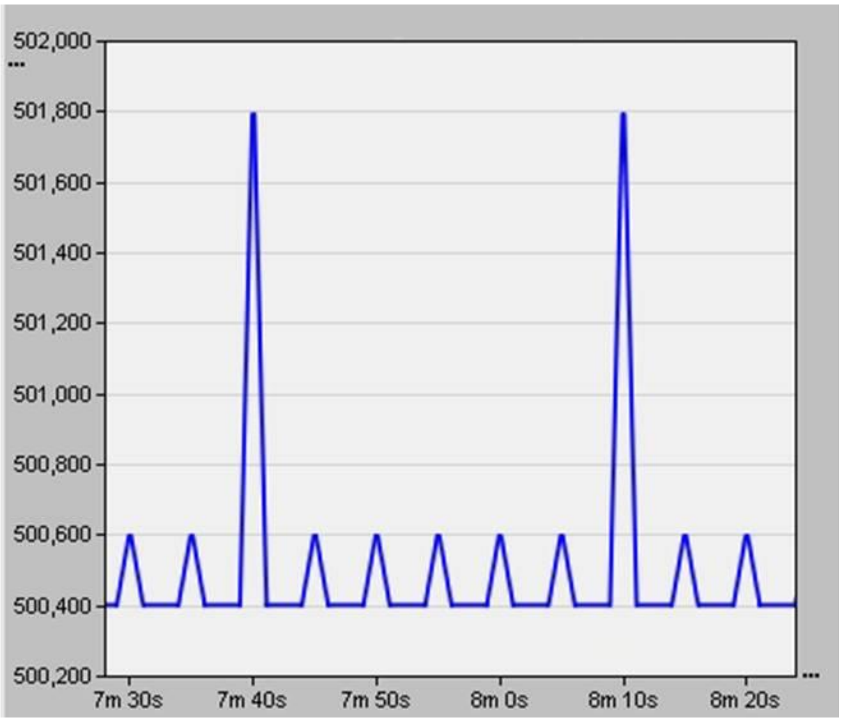

Figure 4.1.1.5 Traffic Received by the Controller in Bytes verses Time in Minutes and Seconds During the Failure of AP in Cell 5 [Elnadi 2022]

Notice that the expected data received at the controller is equal to 1800 Bps plus the cameras' traffic. This number is calculated based on the number of sensors inside the greenhouse and their different sampling rates. For illustration, as mentioned in the table of sensors sampling rates in chapter 3 that sensors send 2 bytes every 1 second, 1 byte every 5 seconds and 6 bytes every 30 seconds. Hence:

Number of sensors is 200
200 X 2 bytes = 400 bytes
200 X 1 bytes = 200 bytes
200 X 6 bytes = 1200 bytes

Therefore, the total number of bytes equal to 1800 and the data sent by the cameras to the controller equal to 20 (number of cameras) X 25 KBps which is 500 kBps.

It is noticed in figure 4.1.1.2 that the long spike represents the traffic received by the controller every 30 seconds, however, the received traffic is not the expected due to the increase in the PLR value over the threshold value by 0.22% during the operation of access point in cell 3; this is the only active access point in the whole greenhouse. Since it is the worst-case scenario, these losses are acceptable because the system is truly operating in an extreme case. In figure 4.1.1.2, it is noticeable that the traffic received at the controller side when only access point in cell 1 and 2 are active, is experiencing great loses due to the lower value of PLR that ranges between [19.520, 19.383] as shown in table 4.1.1.3 since the PLR value exceed the 2% threshold, this case is not acceptable and it is recommended to change the positions of these access points to be place in cell 2 and cell 4 since they provide lower PLR value as shown in figure 4.1.1.3. Finally, figure 4.1.1.5 represents the traffic received by the controller during single access point failure in cell 5 where the expected traffic is fully received at the controller end with a lower PLR value.

4.2 The Used Methodology to Balance Between System Cost and Steady State Availability.

4.2.1 System Reliability and Availability

There is no doubt that the great advancements in technologies such as Internet of Things, remote sensing, and artificial intelligence have transformed the agriculture sector. In greenhouse systems, these technologies have helped farmers to increase their profit and crop yields while minimizing production costs, plant crops in a more environmentally friendly way and mitigate the risks caused by climate changes. However, in developing countries, especially in the Mediterranean region, there are many challenges that might impact building such systems and gain from their benefits. One of the most highlighted challenges is the system cost along with an inefficient maintenance. In fact, the owner/supervisor is not only investing in building a greenhouse with the latest equipment and control system but also, he is investing in introducing cutting – edge technologies that need trained and qualified personal able to uptake these new technologies and take advantage of it. Therefore, system reduction cost is number one priority for these countries. Hence in this research, the steady state availability is used to calculate system uptime to system cost (regarding access points).

A reliable system means that the system can be operational during failure and in the presence of minimum available components [SMITH 2005, KOREN 2007]. While, availability is an important metric used to assess the performance of repairable systems, accounting for the reliability and maintainability properties of a component or a system. There are a number of different classifications for availability including steady state availability [SMITH 2005, KOREN 2007]. The most common used formula for the steady state availability is:

$$AV_{ss} = \frac{U}{U+L}$$

Where U is the access point repair rate and L is the access point failure rate.

A lot of research and work has already done to study the nature of failures along with ways of mitigations and preventions. So, it is important to understand in details some reliability properties and service metrics that values the efficiency of a system such as P(t) which is the probability of survival, mean time to repair (MTTR), mean time to failure (MTTF) and mean time between failures (MTBF).

Mean-Time-To-Failure (MTTF) is the average time duration before a non-repairable system component fail. The MTTF will be the inverse of failure rate; the following formula to calculate the MTTF:

$$MTTF = \frac{\text{Total hours of operations}}{\text{Total number of units}}$$

$$MTTF = \frac{1}{L}$$

Mean-Time-To-Repair (MTTR) is the average time taken to fix a failed component and return it back to its operational state. MTTR includes the time spent during the alert and diagnostic process before the repair is initiated. MTTR is the inverse of repair rate. So, the average time just spent on the repair process is calculated as follows:

$$MTTR = \frac{\text{Total hours of maintainace}}{\text{Total number of repairs}}$$

$$MTTR = \frac{1}{U}$$

Mean-Time-Between-Failures (MTBF) is MTTF + MTTR where “T” is a random value for the time in which the system is still alive. So, the probability in which the system is a live for time “t” is R(t) = P(T>t). R(t) always satisfy the following conditions:

$$0 < R(t) < 1$$

$$R(t) = 0; \text{ if } t = \infty$$

$$R(t) = 1; \text{ if } t = 0$$

Hence, the steady state availability formula is:

$$AV_{SS} = \frac{MTTF}{MTTF+MTTR}$$

Bathtub Curve

This curve in figure 4.2.1.1 is widely used in reliability for determining the condition of an equipment by being represented as the probability of failures [SMITH 2005]. It comprises of three main parts. The first part known by early failures or infant failures which is the decrease in failure rates. The second part is the constant failure rate also known by random failures and finally the third part is wear-out-failures where the failure rate increases by the time the device reaches to the end of its lifecycle.

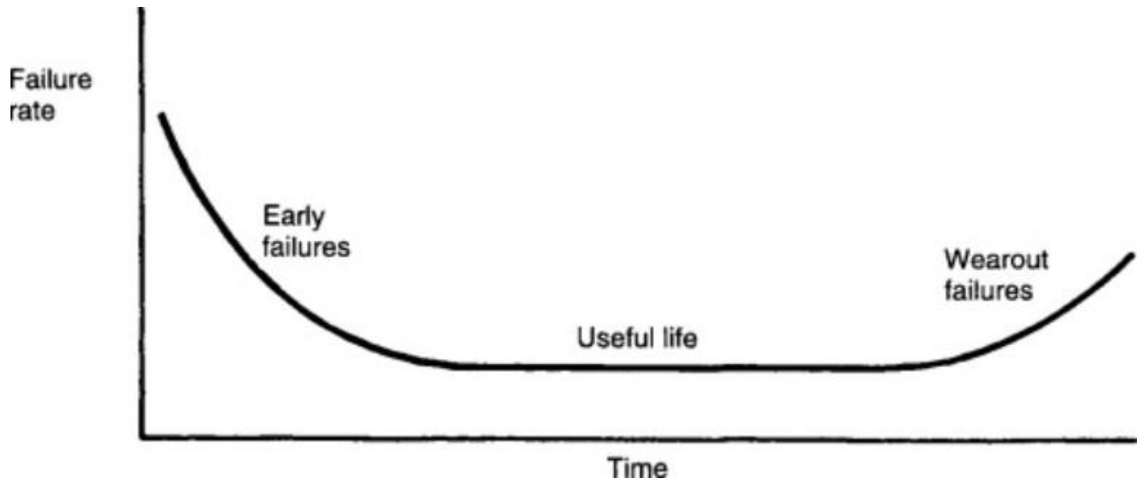

Figure 4.2.1.1 Bathtub Curve [SMITH 2005]

4.2.2 Optimistic Scenario vs. Pessimistic Scenario

As mentioned in the previous section that the greenhouse architecture can tolerate up to four access point failures as long as it keeps its PLR value within the preferred range (PLR≥ 2%). For only one access point available, the system performance will be affected since its best obtained PLR = [1.8% ~ 2.2%] as shown in table 4.1.1.3. For this reason, two scenarios have been studied to calculate and compare between the steady state availability of a system consisting of one working access point which is the optimistic scenario and a system consisting of two working access points which is the pessimistic scenario.

A. *Optimistic scenario*

In the case of quadruple access point failures where only one access point is available. failures could occur in any cell so; it is recommended to relocate the active access point to cell 3. Since it was shown earlier that active access points located in cell 1 and cell 2 are experiencing an unacceptable PLR value, greater than 40% and 20%, respectively. The same thing goes for the scenarios with active access points in cell 4 and cell 5, since they are both symmetrical to scenarios with access points in cell 2 and cell 1, respectively. Therefore, cell 3 is the ideal place in this case. The time needed to relocate the only active access point to its ideal location, cell 3, is enough so that crops won't suffer from serious damages during system downtime. The steady state availability can be calculated using the following formula:

$$AV_{ss\text{-}o} = \frac{U}{U+L}$$

Generally, a good quality access point should last from three to five years according to the datasheets of high-quality access points from top rated brands. In developing countries, the life span of access points maybe affected and reduced due to many reasons such as:

1. high environment temperature, especially for the Mediterranean region, where heat is one of the most common causes of network equipment failure.
2. Power supply is not always reliable and it is subject to failure in harsh environmental conditions.
3. Faults at power stations and short circuiting.
4. Unexpected power surges, power grid instability and inconsistent maintenance strategies.

Additionally, in the meantime, importing high-quality access points has become a challenge because of COVID-19 pandemic and its global impact. the worldwide supply chain has greatly affected by the challenges related to COVID-19 including delays and disruption. Moreover, the pandemic has been one of the primary reasons for the on-going global chip shortage crisis (semiconductor chips). Where the demand for integrated circuits exceeds the supply affecting many industries including automobiles, computers and other products that need semiconductor. It has been estimated that chip shortage might last for a year or two until supplies return to normal. This in return will lead to increase the access point failure repair time. Therefore, in the view of these global situations, and according to professionals in this fields who are aware of what situations are look like in the developing countries, the access point MTTR varies between two weeks and one month, while the access point MTTF can be as low as six month and as high as three years. Hence, to calculate the steady state availability (AV_{SS}), there are two values used for the MTTR which are: 2 weeks (U = 2/month) and one month (U = 1/month) and for the MTTF there are three values which are: six months (L = 0.1667/month), one year (L = 0.0833/month) and three years (L = 0.0278/month). The results of AV_{SS-O} are presented in the table below.

Table 4.2.2.1 AV_{SS-O} APs for Optimistic Scenario [ELNADI 2022]

L (/month)	U (/month)	AV_{SS-O} (%)
0.1667	2	92.31
0.1667	1	85.71
0.0833	2	96.00
0.0833	1	92.31
0.0278	2	98.63
0.0278	1	97.30

B. Pessimistic scenario

In this scenario, having at least two working access points is a necessary. The system architecture will be more powerful and reliable in covering the failed whole cells. Additionally, as shown in the previous section, having two working access points in specified locations; cell 2 and cell 4 yield to lower PLR values (table 4.1.1.3). However, if any of these two access points fail, resulting in having only one access point available either in cell 2 or cell 4, the whole system will be stopped and the failed access point should be replaced and the operational one should be relocated to cell 3. Hence, the following formula will be used to calculate the steady state availability.

$$AV_{ss\text{-}p} = \frac{U}{U+2L}$$

Notice that the failure rate (L) has changed to (2L) for the same reason mentioned above. The results are presented in table 4.2.2.2

Table 4.2.2.2 AVss-p APs Failure for Pessimistic Scenario [Elnadi 2022]

L (/month)	U (/month)	$AV_{ss\text{-}p}$ (%)
0.1667	2	85.71
0.1667	1	75.00
0.0833	2	92.31
0.0833	1	85.72
0.0278	2	97.30
0.0278	1	94.73

From the results obtained for $AV_{ss\text{-}o}$ and $AV_{ss\text{-}p}$ presented in table 4.2.2.1 and 4.2.2.2, it is noticed that $AV_{ss\text{-}o}$ is always greater than $AV_{ss\text{-}p}$. It is also noticed that with a lower failure rate value (L) (higher access point MTTF) and higher repair rate value (U) (lower access point MTTR), the smaller the difference between $AV_{ss\text{-}o}$ and $AV_{ss\text{-}p}$. For example, when L is equal to 0.0287/month and U is equal to 2/month, the value of $AV_{ss\text{-}o}$ is slightly higher than $AV_{ss\text{-}p}$ by only 1.37%. So, in this case, it is the management to decide whether to accept suboptimal performance with a lower downtime or operate using pessimistic scenario and increase the downtime.

4.3 Three Working Access Points Within a Greenhouse

According to Riverbed simulations, as the number of the working access points within the greenhouse increase, the PLR values decrease and the system would be more reliable and efficient. The simulations also showed that system architecture with three access points operating in cell 1, cell 3 and cell 5, yields lower PLR values. A reliable system means that it can operate successfully with two access points when one of the three access points fail. These two access points should be placed in cell 2 and cell 4 so that lower value of PLR could be obtained. In this case, Markov models has been used to model the probabilities of different states and the rate of transitions among them as well as to calculate the steady state availability for three access points.

Markov Model

Markov Model is a stochastic model used to represent randomly changing systems assuming that future states do not depend on past states, however, they depend only on the current state [ZIMMERMANN 2010]. So, the difference between Markov chain and any other stochastic method is that Markov chain is a "memoryless". The model shows all possible stats, transitions, rate of transitions and the probabilities between them and it can be expressed in the equation as the one below or in graphical model.

$$P(X_n = i_n \mid X_{n-1} = i_{n-1}) = P(X_n = i_n \mid X_0 = i_0, X_1 = i_1, \ldots, X_{n-1} = i_{n-1})$$

4.4 Markov Model Results

All Markov Models were simulated using SHARPE [SHARPE 2020]. SHARPE is abbreviated for "Symbolic Hierarchical Automated Reliability and Performance Evaluator". It is a modeling tool that was developed by Duke university for analyzing stochastic models and calculating system reliability, availability and performability. Figure 4.4.1 shows the Markov Model graphical representation used to calculate the steady state availability for greenhouse with working three access points AVss-3AP.

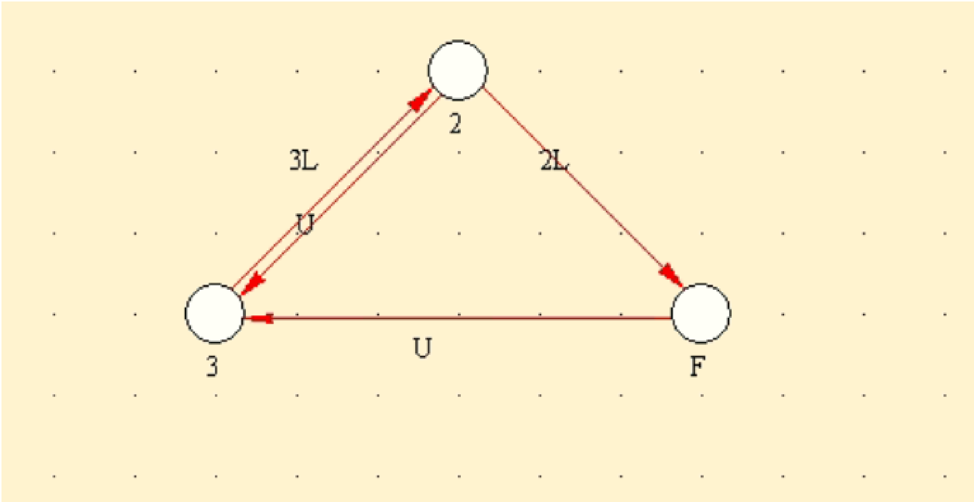

Figure 4.4.1 Markov Model for 3AP [Elnadi 2022]

In this model, the system starts with state “3” in which all the three access points are functioning very well. When one of the three access points fail with the rate of 3L, the system transitioned to state “2” with only two working access points. At this point, the system repair process would start through ordering a new functional access point. As a matter of fact, it takes an amount of time (1/U) for an access point to be purchased, shipped, clear customs and installed in the greenhouse. However; in the case of one access point fails with the rate of 2L while in state “2”, the system has to stop and move to state “F”. So, again another access point is ordered passing by all the factors causing an increase in the repair time, therefore, a transition is made from state “F” back to state “3”. From the Markov Model, Chapman-Kolmogorov equations have been concluded [SIEWIOREK 1998]

Let:

PR = [PR3 PR2 PRF]

Where PRi is the probability of being in state i, where i = (3, 2, F).

$$TR = \begin{bmatrix} -3L & 3L & 0 \\ U & -(U+2l) & 2L \\ U & 0 & -U \end{bmatrix}$$

TR is the Transition Rate matrix [SIEWIOREK 1998], hence:

$$\frac{dPR}{dt} = [PR\ X\ TR]$$

$AV_{ss\text{-}3AP}$ represents the steady state probability values for both being in state “3” or state “2”. The $AV_{ss\text{-}3AP}$ results are presented in table 4.4.1.

Table 4.4.1 Steady State Availability Values for 3 APs [Elnadi 2022]

L (/month)	U (/month)	$AV_{ss\text{-}3AP}$ (%)
0.1667	2	97.14
0.1667	1	91.67
0.0833	2	99.15
0.0833	1	97.14
0.0278	2	99.89
0.0278	1	99.59

Based on what was mentioned, a greenhouse with three working access points has higher availability than greenhouse with two working access points. However, the available resources contribute greatly in deciding which solution is going to work. For example, back to table 4.2.2.2, the value of $AV_{ss\text{-}p}$, when L was equal to 0.0278/month and U was equal to 2/month, is equal to 97.30%. On the other side, the value of $AV_{ss\text{-}3AP}$, when having the same values for L and U, is equal to 99.89%. $AV_{ss\text{-}3AP}$ is higher than $AV_{ss\text{-}p}$ by only 2.66%. Accordingly, the difference is relatively small, the owner/management of the greenhouse might think that its better having two access points inside the greenhouse instead of three;

this will be more cost efficient and also will make the system available, reliable and functioning as desired.

Some crops are rare and very expensive that need much care than others such as certain flower species. Therefore, system with higher values of steady state availability is required. In this case, and as mentioned in the table 4.4.3 below, having access points in cell 1,2,4 and 5 will always produce AV_{ss-4AP} greater than 99% (except the scenario with L equal to 0.1667/month and U equal to 1/month the AV_{ss-4AP} is equal to 96.67%). These values were obtained from Markov Model as shown below in figure 4.4.2.

Table 4.4.3 Steady State Availability Values for 4 APs [Elnadi 2022]

L (/month)	U (/month)	AV_{ss-4AP} (%)
0.1667	2	99.29
0.1667	1	96.67
0.0833	2	99.88
0.0833	1	99.29
0.0278	2	99.99
0.0278	1	99.96

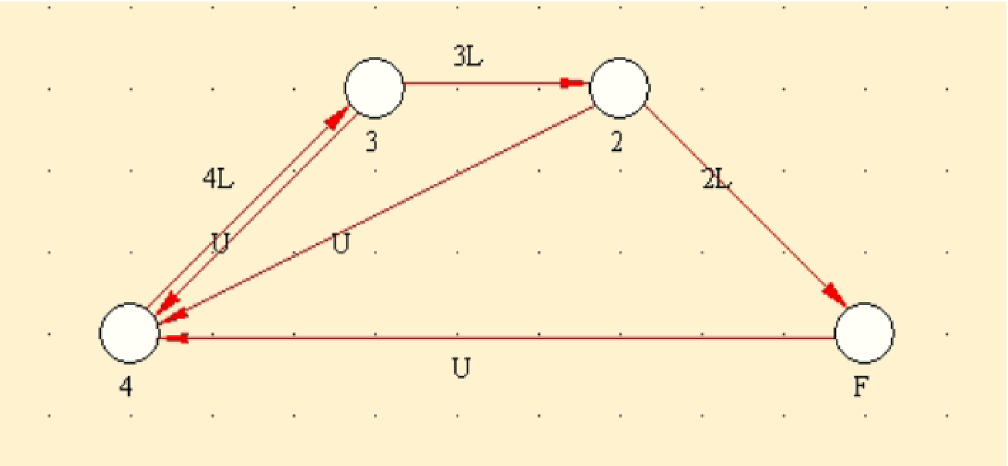

Figure 4.4.2 Markov Model for 4AP [Elnadi 2022]

It is similar to the previous model in figure 4.4.1 but it has four states: 4, 3, 2, and F. Following the path of the Pessimistic approach when there are only two access points available, these two access points should be placed in their ideal location; cell 2 and cell 4.

CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

In conclusion, introducing new generation of agriculture systems such as precision agriculture will definitely help to address climate change adaptation and achieve the goal of increasing crop production, reducing cost, and improving yields. The contributions presented in this research has a fundamental role in developing a support and management tool for the agriculture sector, hopefully these results can be extended to other sectors to make benefits out of it. Additionally, this research has contributed in providing a low-cost alternative for gathering information and processing the collected data to obtain information with added value to improve agriculture productivity.

This research focused on studying a greenhouse system in the context of Networked Control System (NCS) through the deployment of a fault-tolerant model on the access point level. Moreover, studying system maintainability and lifetime which are an important aspects of precision agriculture. The greenhouse architecture is divided into 5 similar cells with the area of 40m x 40m. The total area of the greenhouse is 200m x 40m. Each cell inside the greenhouse is equipped with Wi-Fi sensor nodes, wired actuators, a set of wired cameras and one access point. Additionally, there is a controller for the whole cells which is responsible for collecting the data from sensor nodes, processing and analyzing them, then send proper control commands to the actuators for adjusting the internal climate of the greenhouse. The controller is connected to the access points through Switched Ethernet.

A fault-tolerant model was presented on the access point level focusing on single, double, triple and quadruple access point failures. Furthermore, data handling methods were presented to handle the data loss during system downtime.

The metric used in evaluating the performance of the system during access point failures is the packet loss rate (PLR). It was found in literature that the PLR value should not exceed 2%. Using Riverbed Modeler simulation tool, the results showed that the system can tolerate up to three access point failures with an acceptable PLR value (≤ 2%). in case of quadruple access point failures, the remaining active access point should be placed in the middle cell to obtain a marginal PLR value. Moreover, the simulations showed that the active cell can take over the load of one failed cell, not only the neighbor failed cell but also one cell further.

Additionally, in this research, a new methodology has been introduced to compare between system cost (from the point of view of access point) and system downtime. Steady state availability is used to measure system downtime and Markov model has been used to compare between system cost and system downtime. It has been shown that as the number of access points inside the greenhouse house increase, the system will be more powerful and achieve reliability and high availability. However, it comes with its cost, which mean that having a greenhouse equipped with five access point will increase the system cost and maintainability therefore, system manager/supervisor might find it better to start with two access points instead of five. So that system cost will be reduced without affecting the reliability and availability of the system.

Future work can explore the application of networked control systems in smart agriculture from a cybersecurity standpoint, both in terms of internal threats (on site) or in the IoT link to off-site supervisory nodes. It is also important to extend the simulations conducted by implementing hardware prototypes to gather real-world data, and further strengthen the conclusions of this research.

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