A Fog Computing Framework for Scalable RFID Systems in Global Supply Chain Management

by

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Abstract

With the rapid proliferation of RFID systems in global supply chain management, tracking every object at the individual item level has led to the generation of enormous amount of data that will have to be stored and accessed quickly to make real time decisions. This is especially critical for perishable goods supply chain such as fruits and pharmaceuticals which have enormous value tied up in assets and may become worthless if they are not kept in precisely controlled and cool environments. While Cloud-based RFID solutions are deployed to monitor and track the products from manufacturer to retailer, we argue that Fog Computing is needed to bring efficiency and reduce the wastage experienced in the perishable produce supply chain.

This paper investigates in-depth: (i) the application of Fog Computing in perishable produce supply chain management using blackberry fruit as a case study; (ii) the data, computations and storage requirements for the fog nodes at each stage of the supply chain; (iii) the adaptation of the architecture to the general perishable goods supply chain; and (iv) the benefits of the proposed fog nodes with respect to monitoring and actuation in the blackberry supply chain.

Keywords – **Radio Frequency Identification (RFID), Supply Chain Management (SCM), Internet of things (IoT), Fog Computing (FC).**

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Chapter 1

Introduction

The Internet of Things (IoT) is based on the idea that the physical environment will be seamlessly merged with the virtual environment. One key technology used to realize this is the Radio Frequency Identification (RFID) devices [37]. The most data rich and intensive RFID application is the supply chain management system, in which a tagged product is tracked from manufacture to final purchase.

A supply chain represents the sequence of organizations involved in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customers. Supply chain management consists of planning, implementing and controlling the operations of the supply chain as efficiently as possible. It aims at improving collaboration among supply chain partners, so that inventory visibility and inventory velocity can be improved. Types of supply chains include domestic and global supply chains. Managing a global supply chain is much more difficult than managing a domestic supply chain because of the rules and regulations that differ between countries and the need for additional service providers to help shipments find their way to their ultimate destinations. Global supply chains also tend to be spread over a greater distance, which allow opportunities for variability (with respect to demand, cost and weather) to intervene and affect shipments. Therefore, building an agile or flexible supply chain would help handling disruptions due to day-to-day variability stemming from globalization, outsourcing and shorter product lifecycles [19].

RFID differentiates itself from the traditional barcode through its possibilities for bulk registration, identification without line of sight, unambiguous identification of each individual object, data storage on the object, and robustness toward environmental influences and destruction [62]. Potential benefits of implementing RFID for the supply chain stakeholders include obsolescence prevention, counterfeit prevention, decreased inventory, reduced stock-outs, reduced shrinkage by theft, improved asset visibility and real-time decision making [65].

The perishable produce supply chain is one of the fastest growing sectors of supply chain. Continued success relies upon effective management of the cold chain, a term used to describe the series of interdependent operations in the production, distribution, storage and retailing of chilled and frozen produce. The control of the cold chain is very important to preserve the safety and quality of cooled and refrigerated foods. The cold chain is complex, time-critical, and dynamic. It possesses several characteristics such as high perishability of products, seasonality in production, necessity of conditioned transportation and storage, and safety concerns [69]. Nowadays, the distance that food travels from producer to consumer has increased as a result of globalization in food trade. Perishable produce are sensitive to temperature conditions in which they are handled and require special storage conditions in order to preserve their freshness. The variation of temperature arises when items move through supply chain actors (manufacturing, transportation, distribution stages). The freshness of perishable produce is tracked by their 'lifetime' (also known as Shelf Life). Once an item surpasses its lifetime, it is no longer safe for use. Therefore, keeping safety and quality along the food supply chain has become a significant challenge.

Food chain integrity not only includes safety concerns but also origin fraud and quality concerns. Consumers demand verifiable evidence of traceability as an important criterion of food quality and safety. When insufficient refrigeration of perishable food is known and reported, the food is then discarded, thus mitigating concerns about food safety and quality but creating food waste. The United Nations estimates that each year approximately 1/3 of all food produced for human consumption is wasted, while other reports indicate that food waste accounts for 40% of production [56]. Similar amounts of food waste were reported in [40], indicating that improvements aimed at reducing food waste have been minimal over the last decade. The annual economic impact of food waste is estimated at $218 billion in the U.S., $143 billion in Europe, and $27 billion in Canada [41, 26, 40]. Such an amount of food waste is unacceptable, especially given the world's growing population, the saturation of land resources used for agriculture, and the already significant concerns about food security and greenhouse gases in many regions of the world.

Sensor-enabled RFID tags are deployed to monitor and track the produce from manufacturer to retailer in large-scale applications. However, global supply chain management is not only about getting products faster, cheaper, and of better quality but also getting managers the right information at the right time, so that they can make better informed supply chain decisions. RFID tags and sensors generate data at a fast pace and analyses must be very rapid. This entails use-cases where minimizing latency and conserving network bandwidth while offering privacy and security are mission critical for success. However, today's cloud models are not designed for the volume and velocity of data that RFID tags and sensors generate. Thus, there is a need to analyse the data close to the devices that generate them (at the edge). This is known as Fog Computing [14].

1.1 Research Motivation

Global supply chain scenarios are typically characterized with use cases in which massive amounts of data are collected for processing from myriad geographically dense endpoints. For example, consider a large retailer with global suppliers that span several countries and track objects placed at the item level. Such a retailer sells millions of items per day through thousands of stores around the world and for each item, it records the complete set of movements between locations, starting at factories in producing countries, going through the transportation network, and finally arriving at a particular store where the item is purchased by a customer. Figure 1.1 shows the flow of an object in the supply chain [10].

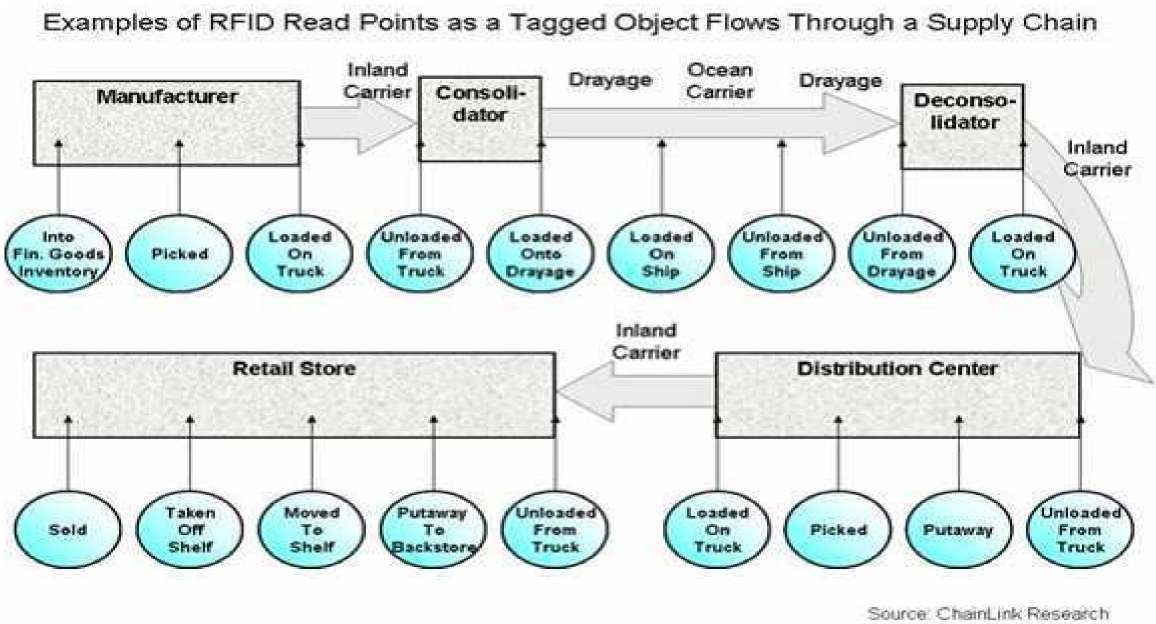

Figure 1.1: A tagged object as it moves through the supply chain

For each object movement, there could be many properties, such as humidity, weight loss and temperature recorded. In such cases, storing and analyzing all the data in a centralized, remote data center may be less than optimal for the following reasons. Firstly, the data volume generated by the sensors may exceed the network bandwidth, thus introducing delays. Secondly, for latency-sensitive applications, data transmission to a remote cloud would introduce unacceptable delay, especially when the data analysis is designed to trigger a local, real-time response (e.g., automatically alerting the shipping manager when the temperature of perishable produce in transit goes above the optimal temperature). Thirdly, to survive in today's competitive market, retailers need to make it easy for consumers to buy anywhere, receive anywhere, and return anywhere. The key to this cross-channel order promising is the ability, in real-time, to locate and allocate available inventory from any location, whether in the store, in distribution centres, in transit, or on order from the manufacturer. This requires having a very accurate, real-time, and item-level picture of inventory at all these sources. In this context, global supply chain integration has higher requirements for real-time information sharing, response speed, and flexibility in agile management than local supply chains [73]. Furthermore, the network journey introduces risk of dropped or corrupted packets, potentially compromising the data [77].

In addition, network and computation resources may need to be configured in a more suitable architecture, in which computation resources are split between local sites (where data is temporarily stored as it undergoes preliminary filtering or analytics) and the cloud (where it is further analyzed and stored).

The purpose of Fog Computing is therefore to place a handful of computation, storage and communication resources in the close proximity of users, and accordingly provide fast-rate services to users via local short-distance high-rate wireless connections.

In this thesis, we propose a framework for a Fog- computing RFID-based solution that limits network-induced delays, controls network costs, and minimizes risks of data loss or corruption.

1.2 Research Questions

Our work seeks to address the following questions.

1. **What is the need for integrating fog computing into cloud based RFID systems in distributed global supply chains?**

   Truly meaningful data identifies events while they are happening, and allows companies to change routes or find other solutions to mitigate delays. When trouble hits the supply chain, shippers need to react immediately. This speed is especially important for globally distributed shipments, because it is easier to lose visibility. Fog nodes (i) analyze the most time-sensitive data at the network edge, close to where they are generated instead of sending vast amounts of RFID data to the cloud, (ii) act on RFID data in milliseconds, based on policy, and (iii) send selected data to the cloud for historical analysis and longer-term storage.

2. **Effective Load Balancing: Where should computing for planning and actuation be carried out?**

   Fog computing extends cloud computing by introducing an intermediate fog layer between intelligent readers or RFID middleware and the cloud. By performing critical latency sensitive operations in the fog nodes, the network latency is reduced.

3. **What are the advantages of integrating Fog Computing in RFID-enabled perishable produce supply chains in terms of monitoring and actuation?**

   We explore the benefits of this integration by using a blackberry fruit supply chain as a case study. The shortcomings of cloud based RFID systems are highlighted and a fog computing model is devised to tackle these shortcomings.

4. **What are the challenges arising from such integration?**

   In these early days of IoT and even earlier days of Fog computing, enterprises are largely on their own to do the configuration, that is, to determine how to split the data processing, where to locate the edge nodes for optimal cost and performance, and so on. It can be complex, and requires a lot of time and cost to get it right. The challenges are formidable and they include but are not limited to:

   (a) Capital costs: Unlike cloud computing, Fog deployments require capital investments in edge hardware.

   (b) Hardware maintenance burden: Although edge systems are hardened for remote, unattended deployment, they still require site visits for deployment and hardware maintenance.

   (c) Site design: Because fog equipment is not deployed in a traditional data center, design and engineering may be complex. For example, equipment may require line-of-sight access to sensors, may need to be deployed on top of poles or rooftops, and may require zoning variances, permits, and/or leased space or access rights.

1.3 Methodology

We adopt the following approach:

1. Using a cloud-based RFID enabled supply chain for perishable products as a case study, we examine all the activities and operations involved. Benefits and

shortcomings of cloud-based RFID are also addressed;

2. We examine critical time sensitive operations and actuations that require local processing at each stage of the supply chain; and

3. We present a *fog-based RFID* system framework to address the shortcomings of cloud-based RFID in perishable produce global supply chain.

1.4 Thesis Organization

This chapter introduces the research scope, the motivation for the research study and describes the research questions. The following chapters are structured to address the research questions and methodology.

Chapter 2 discusses the literature on RFID technology, perishable supply chain management, and Fog Computing.

Chapter 3 discusses the case study where sensor-enabled RFID tags are used to monitor blackberry fruit deterioration from the farm (field) in Mexico to the distribution centers in California.

A solution architecture is proposed in Chapter 4, describing the distinct parts which compose the framework.

Chapter 5 describes the integration of the framework in a perishable supply chain using blackberry fruit as a case study. It also examines the adaptation of the architecture to the general perishable goods supply chain and the exploration of data models for constraints in IoT system with the example of a truck cooling system.

Finally, Chapter 6 draws the main advantages of the fog nodes in the blackberry supply chain. It also highlights the potential challenges of implementing the fog architecture in the perishable produce supply chain.

Chapter 2

Literature Review

This chapter reviews the literature on RFID technology. The components of an RFID System (the tag, reader, middleware and backend server) are examined. Classification of tag standards and frequencies as well as characteristics of data collected from RFID system, the perishable produce supply chain system, and the role of RFID in the perishable supply chain are discussed. The Fog Computing literature is also reviewed.

2.1 Internet of Things

The term Internet of Things was first coined by Kevin Ashton in 1999 in the context of supply chain management [3]. However, in the past decade, the definition has been more inclusive, covering wide range of applications like healthcare, utilities, transport etc. [64]. Although the definition of 'Things' has changed as technology evolved, the main goal of allowing computers to sense information without the aid of human intervention remains the same. The current Internet has undergone a radical evolution into a network of interconnected objects that not only harvests information from the environment (sensing) and interacts with the physical world (actuation/command/control), but also uses existing Internet standards to provide services for information transfer, analytics, applications, and communications. Fueled by the prevalence of devices enabled by open wireless technology such as Bluetooth, Radio Frequency Identification (RFID), Wi-Fi, and telephonic data services as well as embedded sensor and actuator nodes, IoT has stepped out of its infancy and is on the verge of transforming the current static Internet into a fully integrated Future Internet [74]. Two key technologies supporting this technological advancement are RFID and Wireless Sensor Networks (WSN). They are used to automatically identify people, objects, and animals, as well as monitoring environmental parameters, and area monitoring.

RFID is a system made up of electromagnetically responsive tags that can be picked up by specialised readers. Each tag can be embedded with unique information and attached to objects in order to track their presence and movement. In the supply chain industry, RFID tags have traditionally been attached to shipping containers to track their arrival or departure. Tags may be attached to components, such as car parts in an automotive plant, which can then be tracked as they move along the production line [37]. For the Internet of Things, this development of a cheap way to identify an object and its location has huge implications. For example, livestock can be tracked through an agricultural facility, the nearest security or safety staff could be identified to deal with an incident at an event, and medications could be tracked in hospitals reducing theft and misuse. While smart sensors enable us to access a variety of information gathered in real time, their cost and size limit their application. Although the cost of basic IoT sensors has come down to a matter of dollars (smarter versions in the tens of dollars), some classes of RFID tags only cost a few cents. These economics mean that a fashion retailer can tag every piece of clothing in a store and a supermarket could tag all of their tens of thousands of products [71]. If the Internet of Things is to become the Internet of Everything, then RFID could play a major role in its future.

2.2 RFID Technology Overview

RFID dates back to the 1940s. Advancement in electromagnetic theory formed the basis for understanding radio frequencies which can reflect waves from objects [11, 37, 74]. This understanding of radio frequencies also led to the development of Radio Detection And Ranging or Radar. Radar uses the fact that radio waves reflect off an object enabling their range, height, and bearing to be determined. This technology was greatly employed during World War II. Another advancement in radio communications is the airplane transponder and its military counterpart, the Identify Friend or Foe (IFF) systems. These systems communicate with base stations, such as observation points or airplane control towers, to provide real-time monitoring and identification of airplanes. IFF systems are used by the military to distinguish between friendly or hostile forces and can be classified as active RFID systems. A brief overview of the development of RFID technology over the years is shown in Table 2.1.

Table 2.1: RFID history timeline

Date	Event
Late 1940's	Radar technology was first used to identify enemy and friendly aircraft.
1948	A scientist and inventor, Harry Stockman, creates RFID and is credited with the invention.
1950's	Inventor, D.B. Harris creates a different variation of the technology with a passive responding chip.
1966	Security checkpoint and security tags/anti-theft devices using RFID technology are first produced for commercial establishments.
1973	The first Radio Frequency Identification Transponder system is created.
1979	The first Radio Frequency Identification chips that can be implanted into other things are created.
1990's	Emergence of standards. RFID widely deployed. RFID becomes a part of everyday life.
2003	Walmart makes announcement that it will require RFID to be used by its supplying companies by the year 2006.
2005	Near field communication (NFC) is introduced in the United States.

2.3 RFID System

An RFID system contains four basic components [62, 65, 71, 74]. The first is the RFID tag that is attached to an asset or item. The tag contains information about the assets or items and may incorporate sensors. The second is the RFID interrogator/reader, which communicates with the RFID tags. The third component is middleware which performs filtering and aggregation of RFID data collected from the tags. Finally, the backend servers link the RFID readers to a database.

2.3.1 RFID Tags

An RFID tag is a small microchip, supplemented with an antenna, that is capable of transmitting a unique identifier in response to a query by a reading device. A tag, which is generally attached to an object, typically stores information about the object. This information may range from static identification (serial number) to user written data (cost of the item) to sensory data (temperature of the object).

2.3.2 RFID Tag Classification

RFID tags can be classified by power source, memory type, frequency and standard.

2.3.2.1 RFID Tag Classification by Power Source

RFID tags are usually of three types under this category and they include: (i) passive; (ii) active; and (iii) semi-passive.

Passive RFID tags typically do not possess an onboard source of power and therefore rely on a reader or interrogator to “wake it up”and supply the power necessary to respond and transmit data. Because of their dependence on external reader energy fields and their low reflected power output, passive RFID tags have a much shorter read range (less than 3 meters) as well as longer tag life when compared to active RFID tags [13]. Passive RFID tags are less costly to manufacture than active RFID tags and require almost zero maintenance. They are usually smaller in size, mechanically flexible and much cheaper compared to the other types. These traits of long-life and low-cost make passive RFID tags attractive to retailers and manufacturers for unit, case, and pallet-level tagging in supply chains.

Active RFID tags have their own battery power source. They broadcast a signal to the reader and can transmit over long distances compared to passive tags (100+ meters). Additionally, active RFID tags are continuously powered, whether in the reader field or not, and are therefore able to continuously monitor and record sensor status. This is particularly valuable in measuring temperature limits and container seal status. They are characterized with very high read rates due to their higher transmitter output, optimized antenna and reliable source of on-board power. Active RFID tags can provide tracking in terms of presence (positive or negative indication of whether an asset is present in a particular area) or real-time location. One major source of interference for passive tags is metal, and in environments with high amounts of metal, such as shipping containers, active tags are often used. Active tags are also used in real-time tracking of high-value assets such as medical equipment, electronic test gear, computer equipment, reusable shipping containers, and assembly line material-in-process. Of the several applications, the main application of active RFID tags is in port containers for monitoring cargo [39].

Semi-passive tags refer to a class of RFID tags that contain a power source, such as a battery, to power the microchip circuitry. Semi-passive RFID tags overcome two key disadvantages of pure passive RFID tag designs: (i) the lack of a continuous source of power for onboard telemetry and sensor asset monitoring circuits; and (ii) short range. They may also contain additional devices such as sensors. Unlike active tags, semi-passive tags do not use the battery to communicate with the reader. Communication between reader and tag is completely similar to passive tags. Semi-passive tags might be dormant until activated by a signal from a reader. This conserves battery power and can lengthen the life of the tag. Because the tags are self powered they can transmit their data over greater distances (about 30 meters) and they reply more quickly to the reader. However, semi-passive tags are more costly than their passive equivalents [62].

2.3.2.2 RFID Tag Classification by Memory Type

There are two types of RFID tags under this category:

Read Only tags: Information on the tag is factory programmed, and the memory is disabled to prevent any future changes.

Read Write tags: Information can be read and flexibly altered by the user. These tags typically contains more memory and are more expensive than read only tags.

2.3.2.3 RFID Tag Classification by Frequency

RFID tags operate at different frequencies and the most common are outlined below.

Low Frequency tags operate at 125 KHz and have a read range less than 0.5 meters. They are the least expensive of all the tag types but have a slow data read rate. Such tags are used in applications which require close range reading as in access control and item level tracking.

High Frequency tags operate at 13.56 MHz and have a read range of less than one meter. Although high frequency tags can read data faster than low frequency tags they are often deployed in similar applications of low frequency tags.

Ultra High Frequency tags operate at 433 MHz or 865-956 MHz and in long ranges as many as 100 tags can be concurrently read by a reader. As these tags operate at a frequency more than 900 MHz, this improves the read rate as data from the tag is read in a shorter time interval avoiding collision with data from other tags [70].

Microwave tags operate at 2-30GHz and have a long read range of up to 10 meters [51].

2.3.2.4 RFID Tag Classification by Standards

There are two main international RFID standards bodies or standardization bodies: (i) ISO - International Standards Organization; and (ii) EPCglobal - Electronics Product Code Global Incorporated. The ISO RFID standards fall into a number of categories according to the aspect of RFID that they are addressing. These include: air interface and associated protocols; data content and the formatting; conformance testing; applications; and various other smaller areas.

In 1999, a number of industrial companies created a consortium known as the Auto-ID consortium with the aim of researching and standardizing RFID technology. In 2003, this organization was split with the majority of the standardization activities coming under a new entity called EPCglobal. The Auto-ID Center retained its activities associated with the research into RFID technologies.

Auto-ID tag standards: In order to be able to standardize the RFID tags, the Auto-ID Center devised a series of classes for RFID tags. They include:

Class 0/1: Class 0/Class 1 tags are read-only passive identity tags.

Class 2: Class 2 tags are passive tags with additional functionality like read-write memory or encryption.

Class 3: Class 3 tags are semi-passive RFID tags. They may support broadband communication.

Class 4: Class 4 tags are active tags. They are capable of broadband peer-to-peer communication with other active tags in the same frequency band and with readers.

Class 5: Class 5 tags are essentially readers. They can power other classes (1, 2 and 3) as well as communicate with class 4 and be able to communicate with each other via wireless means [6].

2.3.2.5 The EPCglobal Network

EPCglobal network is a global standard for RFID supply chain networks providing a platform for trading partners to share product information [10]. As a participant of the EPCglobal Network, a company publishes event information of products into the EPCglobal Network to share with other companies. This information gives EPCglobal

Network participants visibility of the location and movement of objects within supply chains. The architecture of EPCglobal Network is made up of many components outlined below:

1. Electronic Product Code (EPC): This is a globally unique key used to retrieve information from the EPCglobal Network. EPC, standardized by EPCglobal, is a set of coding schemes for RFID tags [48]. The EPC standard represents a numbering framework that is independent of specific hardware features, such as tag generation or specific radio frequency. This is shown in Figure 2.1 [10].

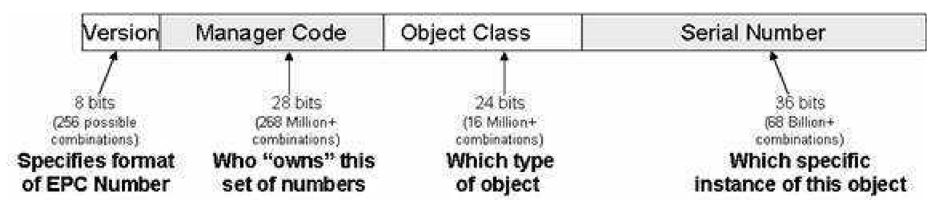

Figure 2.1: Electronic Product Code (EPC)

2. EPC Information Services (EPCIS): EPCIS defines interfaces for sharing supply chain event data between applications that capture event information and applications that need access to such information. With EPCIS, all trading partners control their own data and may share it with only those they choose. In order to be able to leverage the full potential of the information distributed among the EPCIS servers of different trading parties, it is necessary to derive the exact addresses of the EPCIS servers that possess information about a particular item, i.e., EPC. The EPCglobal Network defines two information systems that provide such kind of functionality, namely the EPC Discovery Service and the

Object Name Service (ONS).

3. EPC Discovery Service (EPCDS): The EPC Discovery Service standard is currently in development by the EPCglobal Data Discovery Working Group. Its main purpose is finding and obtaining all of an item's relevant visibility data as it moves through the supply chain. It offers trading partners the ability to find all parties who had possession of a given product and share RFID events about the product [48]. Given an EPC, it returns a list of URLs of the query interfaces of EPCIS servers which are in possession of information related to the particular EPC. With this functionality, authorized and authenticated clients are able to reconstruct traces of items and track the current locations of items.

4. Object Name Service (ONS): The ONS matches the EPC ID to a location on the Internet (or possibly the intranet) that provides additional information about that particular object. ONS is based on the Internet's existing Domain Name System (DNS), which routes information requests to appropriate Internet locations. For a given EPC, the ONS Framework will point to the EPC Information Service that contains the information for that EPC [48]. There are two levels to the ONS service: (i) The root ONS service responsible for finding the local ONS server for any given EPC; and (ii) The local ONS service that returns the actual URL for the EPCIS.

Object information retrieval in the EPCglobal Network is illustrated in Figure 2.2 [10] and the steps involved are explained below:

1. In supply chain systems, the information about the product can be stored at every phase in the supply chain. The manufacturer places RFID tags with EPCs

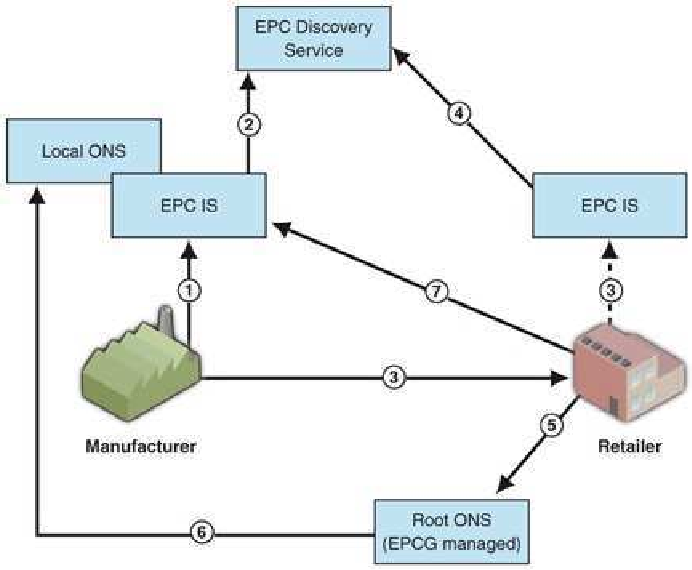

Figure 2.2: Electronic Product Code routing in a supply chain

on products or in packaging and records the tag with its local EPCIS to enable item tracking, history file creation and future trading partner use (e.g., retail point-of-sale).

2. The local EPCIS informs the global EPC Discovery service of a tag that has been read.

3. The manufacturer sends the tagged product to the retailer. As the product progresses through the supply chain, the information on these tags can be altered by the supply chain participants such as the distributor. Upon getting to the retailer, the retailer registers receipt with his local EPCIS.

4. The retailer's local EPCIS registers the tag read with the global EPCIS Discovery service.

5. The retailer requires the product information, so he queries the Root ONS that

is deployed by EPC Global.

6. The Root ONS points to the appropriate manufacturer's local ONS that points to the manufacturer's EPCIS.

7. The retailer connects with the manufacturer's EPCIS and gets the required information.

Therefore, EPC allows for monitoring location, movement and trigger events. Operational efficiencies could be gained by a near real-time view throughout the supply chain, such as improved inventory control, increasing throughput, and lowering cost of the products.

2.3.2.6 Generation 1 and Generation 2 Tags

The EPC Class One Generation One (Gen 1) standard was ratified in 2004. The major feature of this standard was the write once/multiple read limitation of the tags. However, ignoring this distinction, most modern compatible tags actually allow multiple writes and reads. Gen 1 tags were designed to operate in the 860 MHz - 930MHz spectrum, which limits the allowable distribution of these tags due to differing telecommunication zones. The memory capacity was set at either 64 or 96 bits due in part to limits in technology and partially to reduce the costs of individual tags to a minimum.

Due to the sudden increase in RFID usage and the rate at which the technology was improving the second generation was proposed in the same year as the Gen 1 standards were ratified. This led to confusion amongst potential adopters, as many wondered if they should purchase the available Gen 1 technology or wait for the second generation hardware to be made available. EPC addressed this issue by claiming that Gen 1 equipment would be accessible by Gen 2 tags with the correct software.

The obvious benefit of the generation two standards was in the area of available memory, with the Gen 2 tags allowing an accessible memory of up to 256 bits. Beyond this, both password lengths were extended from the eight bits of generation one to thirty two bits. Also, Gen 2 tags are designed to work in the spectrum of 860 MHz - 960 MHz [6]. The addition of an extra 30 MHz to the tag operation frequency decreases the likelihood of the 10 channels being flooded and causing tag communication difficulties. A further improvement was the increase in the size of the 96 bit item ID to a 512 bit version in generation two, along with the allowance for unlimited user memory in anticipation of future class 2 and class 3 improvements.

The reader operations for Gen 2 are fairly similar to that of a Gen 1 tags. Both use frequency hopping as well as listening before talk operations. Nevertheless, generation two tags have an additional dense reader mode. Dense reader mode was specifically designed for enterprise deployment (such as a warehouse or distribution centre) with many readers. The mode offers a communication function that claims to practically eliminate the usual interference associated with a large number of readers communicating with their concurrent tag population, resulting in a maximum overall system stability, and reliability [6].

2.3.3 RFID Reader

The reader uses radio signals to communicate with a tag in order to access information on that tag. RFID readers have two interfaces. The first one is a RF interface that communicates with tags in their read range in order to retrieve tag identities. The second one is a communication interface, generally IEEE 802.11 or 802.3, for communicating with the servers. The RFID reader is either mounted (fixed) or handheld. RFID readers can read data from or write data to a tag.

2.3.4 RFID Middleware

The management of numerous RFID readers as well as the management of the data they generate usually requires a special intermediate software layer known as Middleware. RFID middleware applies routing, filtering, formatting or logic to tag data captured by a reader so the data can be processed by a software application. It also acts as a reader interface to the application software.

2.3.5 Backend System

Finally, one or several servers constitute the third part of an RFID system. They collect tags identities sent by the middleware and perform calculation such as applying a localization method. They also embed the major part of the middleware system which connects the reader to the backend server.

Figure 2.3 shows the basic components of an RFID object .

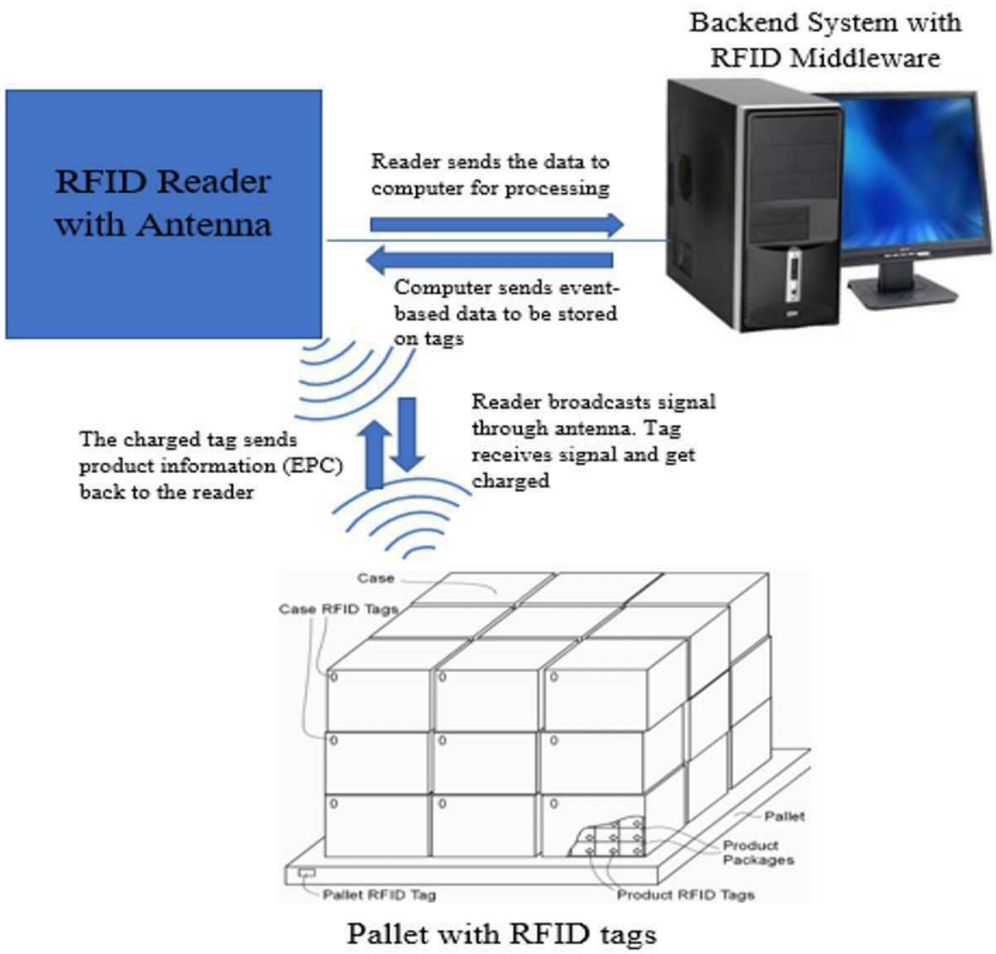

Figure 2.3: Basic components of an RFID system in a supply chain

2.4 Perishable Produce Supply Chain

Perishable items are defined as items which have a limited useful life. Some examples of perishable items are human blood, photographic films, fresh fruits and vegetables (FFVs), cold chain products (meat, fish), flowers and drugs [5, 9, 54]. Perishable products are broadly categorized into:

1. *Fixed-lifetime Perishable Products*: For perishable produce under this category, the duration in which the products are alive or useful is relatively short but is a fixed period. Examples include high technology products, fashion apparel, medicines, and canned food products.

2. *Random-lifetime Perishable Products* : This category involves perishable goods which are subject to deterioration that is non-uniform over a short period because of the significant impact of environmental factors on the quality of perishables. The random lifetimes observed in practice are largely the result of variability in the time it takes for the product to flow through the supply chain, as well as the product's temperature history (along with other environmental factors like humidity, handling, and lighting). Examples include fresh fruits and vegetables.

FFVs are sensitive to temperature conditions in which they are handled and require special storage conditions in order to preserve their freshness. The variation of temperature arises when items move through supply chain actors (manufacturing, transportation, distribution stages). The freshness of perishable products is tracked by their 'lifetime' (also known as Shelf Life). Once an item reaches its lifetime, it is considered to be lost (no longer safe for use). In practice, the lifetime is determined by keeping the product at a pre-specified level of temperature and observing throughout a specified duration the microbial development under this condition.

While random-lifetime perishable products make up about 38% of total store sales, they contribute up to 65% of total store shrink [61]. Clearly, the problem for suppliers is how to maintain product availability while avoiding excessive product loss and food contamination.

A number of frameworks have been proposed for perishable supply chain design. One of the first was introduced by Fisher [23], who devised a taxonomy for supply chains based on the nature of the demand for the product. For innovative products (volatile demand, short life cycle, fast 'clockspeed'), he maintained that the supply chain should be designed to be fast and responsive. Lee [44] expanded upon the taxonomy proposed in [23] by suggesting that the supply process should be either stable or evolving. A stable supply process has a well established supply base and mature manufacturing processes. In an evolving supply process technologies are still early in their development with uncertain or limited suppliers. The authors in [22] made a significant contribution to supply chain strategy by introducing the concept of delayed product differentiation, or postponement. They showed that delaying final product definition until further downstream in the chain reduces variety in the early stages (in effect, making the product more functional). This creates opportunities for supply chain designs that can be efficient in the early stages and responsive in the final stages.

These studies suggest that supply chain strategies based on a simple choice between efficiency and response can be inappropriate when the product undergoes substantial differentiation or change in its value as it moves through the chain. In the analysis that follows we show that this is the case for perishable produce: the value of the product changes significantly and the appropriate supply chain structure is a combination of responsiveness and cost efficiency. For perishable produce, the maximum quality (and value) of the product is largely determined by actions taken in the early stages of the process: seed production, growing conditions, planting practices, and harvesting methods. As perishable products, quality begins to deteriorate once they are picked, and the supply chain management problem is to control the loss in product quality over the remaining stages in the chain — from the field to the customer [5].

2.4.1 Factors affecting the Quality of Perishable Produce

Shelf Life is a common term that relates to the time period for the product to become unacceptable from sensory, nutritional or safety perspectives. It is also referred to as the period during which a fruit or vegetable maintains its desired quality attributes. The desired quality attributes, however, depend on grower, retailer and consumer perceptions. For example, in berry yield, absence of defects and firmness are major concerns for growers, whereas retailers are concerned with the fruit's appearance and suitability for purchase by consumers upon arrival at the store [17]. Consumers, on the other hand, look for an attractive fruit with uniform colour, good eating quality and a reasonable refrigerator shelf life [76].

Product shelf-life is estimated by: (1) identification of quality and safety parameters; (2) determining the stress variables; (3) survey of kinetic models and degradation mechanics; (4) accelerated shelf life testing; and (5) computational shelf life determination. Quality parameter identification is the first and most important part, because the accuracy of the shelf life depends upon the monitored variables and responses (quality parameters). Several representative quality parameters should be chosen from the following groups: (a) microbiological, (b) physical, (c) chemical, (d) biochemical, and (e) sensory.

Temperature is a significant factor affecting shelf life. It affects the rate of respiration, activity of enzymes and degradation of nutritious substance [24]. The rate of chemical reactions is closely related to temperature. In addition to chemical aspects, low temperature may cause chilling or freezing injury to fresh vegetables or fruits as well [17]. To maximize shelf life, there is a prescribed storage temperature for different FFVs. In berries, for example, maximum shelf life is attained when fruits are held at 0 degrees Celsius. At 10 degrees, shelf life is lost 3 times faster and at 30 degrees, over 9 times faster [17]. This is known as accumulated accelerated shelf life loss or advanced shelf life loss. A key problem with temperature related advanced shelf life loss is that the loss is invisible until the FFVs start to deteriorate quickly that there is little that can be done to avoid losses [17]. If time and temperature data are available from the time of harvest, then accumulated accelerated shelf life loss can be calculated locally and used to differentiate one pallet/case of fruit from another.

Atmosphere also plays an essential role in reactions taking place in perishables.

It is known that reducing O_2 (oxygen) and raising CO_2 (carbon dioxide) concentration helps to slow down respiration rate and prolongs shelf life of fresh fruit and vegetables[45, 76]. Some of the chemicals can affect the ripening process as well as shelf life of some fruits. For instance, ethylene is found to be a key factor for ripening of fruits and vegetables. However, some fruits are not affected by ethylene such as blackberries, grapes, cherries etc. [45].

High humidity is essential for some FFVs to prevent shriveling and loss of weight. Although high humidity is essential, moisture promotes the growth of disease-causing organisms. This can be prevented by maintaining adequate air circulation and applying the coldest storage temperatures allowable for each fruit without freezing [17].

2.4.2 Factors affecting the Quality of Perishable Produce inside a Refrigerated Truck

Several factors influence the temperature of produce loaded inside a semi-trailer or truck: the heat sources within and outside the trailer; the type of refrigeration; the amount of air circulation and its distribution; and the packaging and loading arrangement of the produce.

1. Temperature Control: There are three sources of heat that have to be controlled in order to maintain produce temperature during transport. These are described below:

- Residual heat load (denoted as H_R) includes any heat initially held within the truck before loading as well as the field heat contained in the produce and its packaging materials [2]. The cooling unit installed in a trailer is generally designed to remove only the external and internal heat loads in transit. It does not have the extra capacity to handle the residual heat load in addition to the external and internal heat load at the same time. Therefore, to be able to maintain produce at its optimum temperature, the truck and the produce itself have to be pre-cooled to the recommended transport temperature prior to shipment.

- External heat load (denoted as H_E) results from the interaction between the trailer and its external environment. It is usually the most significant heat load which influences produce temperature during transport. External heat enters the trailer through conduction, convection, infiltration or radiation. To reduce the amount of conduction heat load, insulation materials are used. Physical damage and moisture penetration usually decreases the insulation value of materials. Therefore, damages on trailer surfaces must be immediately repaired and drain holes have to be maintained free of debris to prevent water accumulation.

- Internal heat load (denoted as H_I) in a trailer includes respiration heat generated by the produce during transit. Biological materials respire as part of their metabolic process. Fresh fruits and vegetables continue to respire even after harvest. As produce respires, carbon dioxide, moisture and heat are released. Generally, the shelf life of a fruit varies inversely with its respiration rate, allowing fruits with lower respiratory rates to be stored longer than those with higher rates. Therefore, the total amount of heat that must be absorbed by the refrigeration system (T_O), required to maintain the produce during transit is given in Equation 2.1:

$$T_O = H_R + H_E + H_I \tag{2.1}$$

2. Type of Refrigeration: The most common refrigeration system in use for refrigerated food transport applications today is the mechanical refrigeration with the vapour compression cycle. The main components are the evaporator, compressor, condenser, expansion valve and blower. The compressor sucks refrigerant vapour from the evaporator and compresses the refrigerant vapour which subsequently flows to the condenser at high pressure. The condenser ejects its heat to a medium outside the refrigerated transport container while condensing the refrigerant vapour. The liquefied refrigerant then flows to the expansion device in which the refrigerant pressure drops. The low pressure refrigerant then flows to the evaporator where the refrigerant evaporates while extracting the required heat from the refrigerated transport container. Thus, the truck volume is cooled, due to the heat exchange with the refrigerant flowing through the evaporator. Accordingly, cooling is also provided for produce stored in the truck volume. Finally, the refrigerant is once again supplied to the compressor unit. A blower/fan recirculates the conditioned air back into the trailer through a fabric chute attached to the ceiling that directs the air at the rear door.

Remote evaporators can be installed inside separate compartments in the trailer to enable multi-temperature hauling of both fresh and frozen commodities at the same time. A defrost cycle eliminates ice buildup on the evaporator coil by automatically switching from refrigeration to defrost. Reducing the accumulation of ice, keeps air moving efficiently over the coil.

The mechanical refrigeration system can be operated at continuous or automatic (start/stop) mode. In continuous mode, the compressor and the blower operate continuously and temperature is maintained very close to the set-point. In the automatic mode, the compressor works intermittently, but the blower that circulates air inside the trailer operates continuously. The use of automatic mode results in fuel savings, but creates a wider temperature fluctuation around the set-point compared to the continuous mode. Continuous setting must be used for perishable produce loads, as they need continuous air flow to handle the heat of product respiration. It also allows for more consistent temperature throughout the trailer for the duration of transport. Thermostats are used to regulate the air temperature inside the trailer. The choice of set-point temperature is a function of the type(s) of produce present in the load. Different products have different optimum holding temperatures. For example, highly perishable produce such as blackberries and strawberries should he maintained at $0^0C(32^OF)$.

3. Air Circulation: Inefficient air distribution is more likely to be the main reason for improper cooling of the load during transport [2]. For this reason, air circulation plays a critical role in maintaining produce temperature during transport of fruits and vegetables. Refrigerated air has to be circulated uniformly through and around

the load to absorb internal and external heat loads. On the whole, circulating air around the load retards heat flow, isolates the load from warm/cold surfaces within the trailer and allows cold air to remove heat faster from around and within the load to the refrigeration unit. This also reduces the temperature gradient across the evaporator and prevents frequent defrosting of the refrigeration unit.

Aside from a high airflow rate, uniform air distribution is needed to maintain the desired produce temperature throughout the entire load. Uneven air distribution results in over-warming or over-cooling at different parts of the load that could lead to shorter shelf life and eventual spoilage.

The overhead or top-air delivery system is the most widely used method of air circulation in refrigerated semi-trailers [66]. This system delivers high velocity, low-pressure airflow longitudinally inside the trailer. Air travels above the load from the front to the rear of the trailer. Along the way, some of the air flows down between the sidewalls and the load. As the air reaches the rear end of the trailer, it flows downward between the rear door and the load. Air then moves underneath the load from the rear to the front along the floor; when it reaches the front wall, air flows upward behind the load and returns to the evaporator. As air circulates along the surfaces of the trailer and through the load, it picks up heat coming into the trailer and heat generated by the produce. Figure 2.4 shows the flow of air in a semi-trailer [2].

Several features are available which assist air circulation within refrigerated semi-trailers. Semi-trailers can be equipped with an air-delivery duct, a deep channel floor and a pressure return-air bulkhead.

Figure 2.4: Top-down air delivery in a semi-trailer

The air-delivery duct helps to distribute air from the outlet of the refrigeration unit to the rear and both sides of the load. The duct is connected to the blower discharge through an adapter. It is mounted on the middle and slightly off to the side of the ceiling using velcro, grommets or nylon. The use of these features enhances air circulation above and below the load, as well as at front and rear of the semi-trailer. In terms of the air duct design, the National Perishable Logistics Association/Refrigerated Transportation Foundation (NPLA/RTF) recommends a minimum cross-sectional area of 0.15 m^2 (240 in^2). Progressive air spills are placed along the length of the duct, except at the first 3 m (10 ft) near the refrigeration system. The air spills are used to divert the airflow and allow some air to flow sideways. For the first 3 m, the edges of the duct are fastened tightly to the ceiling. If the connection is not tight, air can short circuit to the bulkhead which affects the thermostat reading and causes poor regulation of temperature. The size of the air duct is normally matched to the type of refrigeration unit used and the ceiling area of the trailer. Information on the proper size of the air duct is usually available through the manufacturer of the trailer refrigeration system.

In a top-air delivery system, the space between the load and the floor of the trailer acts as a plenum for returning air to the evaporator. If there is insufficient amount of return air space between the floor and the load, airflow will be throttled and the fan will rotate without discharging any conditioned air to the load. In [66], it is stated that around 0.15 m^2 (240 in^2) of return air space is required for the fan of an average trailer to operate at 100% capacity. The most common types of floor found in refrigerated semi-trailers are flat floor (without any channels), duct board floor, duct-T floor and T-beam floor. None of these floor designs provide sufficient air passage for return air. Therefore, it is recommended to load produce on pallets or wood racks when these types of floor are used [66].

A return-air bulkhead is basically a false wall that provides a clear pathway for air to return to the evaporator. It serves to isolate the load from the front wall, to prevent the load from blocking the air return to the evaporator and to force air to go around and under the load without short-circuiting [66]. The bulkhead can cover the full width and half the height of the front wall. Frame and solid/pressure bulkheads are commonly used. In terms of temperature management, solid/pressure bulkhead is better than frame bulkhead since the latter may allow some air to by-pass the load. The NPLA/RTF recommends a space of at least 76 mm (3 in) between the bulkhead and the front wall and a minimum open space of 152 mm (6 in) between the bottom edge of the bulkhead and the trailer floor [2]. Bumpers or pallet stops may be installed at the bottom opening to prevent blockage due to load shifting. The airflow may be blocked at the bottom due to improper loading or load shifting. The top of the bulkhead must have an open area of 0.02 m^2 to 0.03 m^2 (30 to 50 in^2) to allow mixing of top and bottom-air, as well as allowing some air flows to the thermostat in case of blockage at the bottom of the bulkhead [2].

4. The Packaging and Loading Arrangement of the Produce: Two important factors have to be considered when stacking boxes/cases on a pallet: (i) the alignment of vent holes in the boxes in the direction of airflow; and (ii) the stability of packages piled in layers. Unstable cases may fall while in transit and block air circulation channels. Properly stacked pallets do not only provide good air circulation but also protect the produce from physical injury. Corrugated fiberboard boxes are used in boxing clamshells of blackberries. The boxes can be column stacked or cross stacked on the pallet. After stacking cases on pallets, they are loaded into the semi-trailer. The loading pattern affects air circulation, the amount of contact between the load and the inner walls, and the stability of the load. The way in which pallets are loaded influences air circulation and consequent removal of all heat loads on the trailer. The availability and direction of air channels is dependent on the loading pattern, which affect the airflow pattern around and across the load. The loading pattern also determines the amount of produce warming or freezing due to conduction. Finally, the loading pattern influences the number of produce pallets that can be transported in a given length of trailer. Various loading patterns are used by the industry. Produce pallets can be sidewall loaded, offset loaded, pinwheel loaded or centerline loaded by

a forklift or a pallet truck. Centerline loading prevents heat conduction between wall and product as it creates a gap between the wall and the product where air can flow to remove heat that penetrates the wall. Figure 2.5 shows the diagrams of common loading patterns in a refrigerated truck [47].

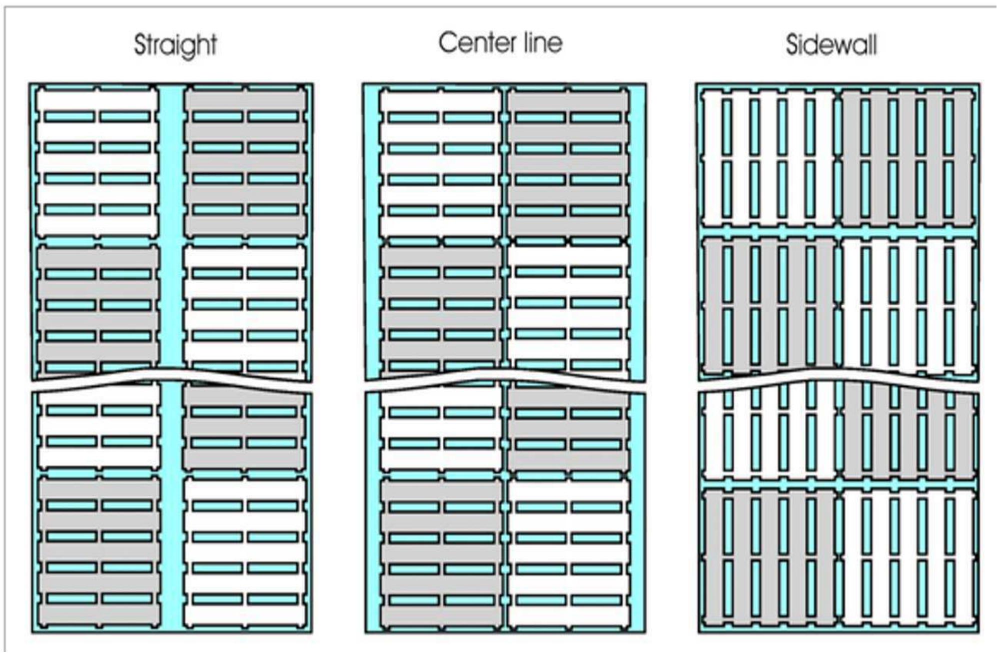

Figure 2.5: Diagrams of common loading patterns in a refrigerated truck.

2.4.3 Tools used in Monitoring Environmental Parameters

Various types of environment parameter measurement and recording equipment have been used in the literature for reducing spoilage in perishable produce supply chains. They are discussed below.

Chart Recorders : Refrigerated transportation vehicles and shipping containers used for perishable goods transfer have recording chart thermometers for recording the temperature of the interior space. These charts are specific for each vehicle in the cold chain and do not capture the product consignment temperature and time as the product moves between vehicles in the supply chain. The paper feature also presents its major disadvantage in that data must be processed and interpreted manually [57].

Data Loggers: These are smaller compared to chart recorders and are equipped with integrated sensors for measuring and tracking environmental parameters (mostly temperature over time). Data loggers are placed in perishable product consignments by the shipper to be retrieved later and the stored temperature and time data then downloaded by either linking to a programmed personal computer or by removing a printed chart. These robust portable recorders are expensive and need to be returned to the shipper on consignment completion. Additionally the data is not accessible until the logger is ultimately read and this may be after a product recall or temperature abuse has occurred.

Time-temperature Integrators (TTI) : TTI are monitoring tools that provide a visual, non reversible, indication of time and temperature exposure above a pre-set threshold temperature. The underlying functional principle is an incorporated dye that diffuses or a color-changing chemical substance that begins to flow along the quality-indicator range. These strips are typically 96 mm by 20 mm and while relatively inexpensive, only indicate products exhibiting time temperature abuse sensitivity and represent a signal as to when product quality should be checked prior to use. While a TTI can visually indicate temperature abuse, it does not show when and where it happened. TTI labels have no means to communicate with a reading device to automatically transfer data to an information system. Therefore, manual data acquisition is required [35].

2.4.4 RFID in the Perishable Produce Supply Chain

Wireless sensor technologies used in environmental monitoring include WSN (Wireless Sensor Networks) and RFID (Radio Frequency Identification). These technologies have been attracting many research efforts during the past few years, driven by the increasing maturity and adoption of standards, such as Bluetooth [20] and ZigBee [4] for WSN, and various ISO (International Organization for Standards) standards for RFID (ISO 15693, ISO/IEC 18000, ISO 11784, etc.) [30]. Sensor embedded RFID offers several advantages over WSN such as (i) RFID sensors can transmit both an ID number and the sensor data so the data from multiple sensors can be associated with the sensor tag, while wireless sensors only transmit the sensor data, with no ID number; (ii) RFID readers can read multiple tags simultaneously while this is not possible with wireless sensor networks; and (iii) RFID systems are less expensive to set up while WSN are costly to set up in global supply chains [57].

Recently, several solutions for implementing temperature managed traceability systems using RFID tags with embedded temperature sensors have been reported [36, 43]. One technical challenge is the management of the huge data amount generated from sensors. For this purpose, more attention has been paid to Cloud-based RFID [1, 11, 27]. Cloud computing provides computing services that are scalable and virtualized [65]. Guinard et al. (2011) [27] explored the application of RFID systems, RESTful interfaces and Web 2.0 mashups for surveillance in retail stores. The authors employed the Electronic Product Code Information Services (EPCIS) using Fosstrak software platform to create the cloud based traceability application. In another study [1], a cloud-based tracking and tracing system for Returnable Transport Items (RTIs) was proposed. The system features Hybrid AutoID process and a cloud repository while adopting the EPC standard. In [11], the design and implementation of an RFID tracking solution based on web services and cloud computing resources was presented. The emphasis was on shifting a greater part of data processing to the readers and cloud resources. Present works using cloud-based RFID are insufficient in that they are focused on functionalities, lacking in considerations about latency and real-time actuations to reduce the inefficiencies in the perishable supply chain.

2.4.5 Fog Computing

Fog Computing was first introduced by Cisco in 2012 to describe a compute, storage and network framework for supporting Internet of Things applications. The metaphorical term highlights that compute resources are close to the ground (that is, proximate to the data sources), in contrast to cloud computing, in which compute resources are centralized and remote [67]. The main feature of fog computing is its ability to support applications that require low latency, location awareness and mobility. This ability is made possible by the fact that the fog computing systems are deployed very close to the end users in a widely distributed manner, making it suitable for global supply management. By orchestrating and managing compute and storage resources placed at the edge of the network, fog computing can deal with the ever increasing demand for real time analytics in perishable produce global supply chain management.

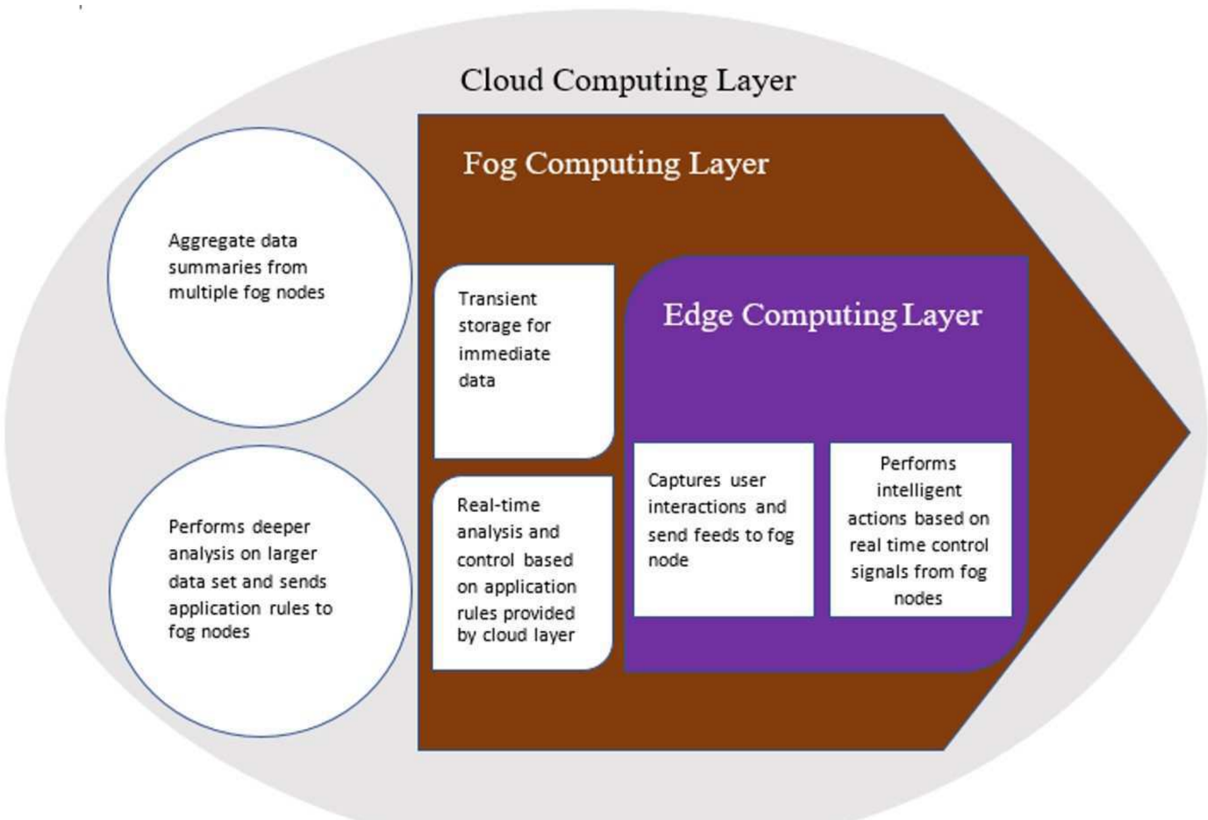

Figure 2.6: Fog computing overview

While Fog and Cloud Computing use the same resources (networking, compute, and storage), and share many of the same mechanisms and attributes (virtualization, multi-tenancy), there exist certain key differences highlighted below [12]:

- Storage: In cloud computing, storage is primarily allocated to large scale data centers while fog computing carries out a substantial amount of storage near the user or at the network edge ie., (the endpoint that provides an entry point into enterprise or service provider core network).

- Architecture: Traditional cloud computing architecture is mostly centralized. However, fog architecture is made up of layers that may be distributed, centralized or a combination thereof.

- Latency/Network Jitter: Fog computing performs the required computation near the end-user. Thus, latency and network jitter in fog computing is relatively low compared to cloud computing.

- Communication: In fog computing, communication is carried out at the network edge as opposed to cloud computing where all communications are routed and synchronized through the backbone network to the cloud.

According to [12], fog computing is an extension of cloud computing. Therefore, choosing between a cloud and fog is not a binary decision. They form a mutually beneficial, inter-dependent continuum. Traditional backend clouds will continue to remain an important part of computing systems as fog computing emerges. In many of these systems the fog and cloud will both be implemented. The segmentation of what tasks go to fog and what goes to the backend cloud are application specific, and could change dynamically based upon the instantaneous state of the network, in areas like processor loads, link bandwidths, storage capacities, fault events, security threats, etc.

2.4.6 Fog Computing Components

A fog node consists of two main components: Hardware and Software. Fog hardware provides the following functionalities.

- Network connectivity;
- Processor capacity sufficient to perform fog application execution (often basic analytics or filtering);
- Storage capacity for temporary collection and aggregation of data;
- Security; and
- Management and analytics platforms.

Fog hardware can be static at a fixed location, e.g., inside a shop installed similar to a WiFi access point, or mobile e.g., placed on a moving vehicle as the Greyhound BLUE system [8]. Cisco offers a range of products that act as fog hardware and they include ruggedized routers, switches and compute modules.

Fog software comprises host management and monitoring platforms, security, and analytics software. For example, in Cisco's fog solution, the fog nodes use the Cisco IOx application framework to host fog applications, provide application security, and integrate data analytics. The node collects and processes two types of data: contextual data (the data points generated by the IoT devices), and control data (results of monitoring and healthchecks of the IoT devices; e.g., ensuring that each connected device is authorized and generating notifications if a device fails to report in).

Because the workload is split between the network edge and the cloud, the application software must enable seamless data sharing and processing, even when different protocols are used by data sources. For this reason, the OpenFog Consortium [1] was launched in November 2015, under Cisco's leadership, to develop APIs and standards to enable functionality such as device authorization, security, monitoring, and analytics to adapt to specific IoT applications [14].

To our knowledge, there are no references in the literature where fog computing has been applied to perishable produce supply chain management. In this thesis, fog computing is superimposed onto cloud computing to create a distributed computing architecture to tackle the slow data access and constrained network resources presently experienced by global supply chain managers.

[1] openfogconsortium.org

Chapter 3

Case Study: Use of RFID tags in Monitoring a Blackberry Supply Chain

3.1 Type of RFID tags Suitable for Monitoring the Perishable Produce Supply Chain

Perishable Produce Supply Chains require tags that can be read around metal or high water content packages in addition to long read ranges. Passive RFID tags performance suffers in these instances. For these applications, focus shifts to active RFID tags which perform well in RF challenging conditions and offer the ability to add sensors. However, the improved performance comes with some notable drawbacks. For instance, active RFID tags do not adhere to a single interface standard, often have greater tag size and complexity, and are significantly more expensive than passive

RFID solutions.

In [9], a list of requirements that RFID tags must satisfy to be employed in perishable produce monitoring is given. They include: (i) RFID tags with temperature sensors should be able to withstand temperatures between -22^0F and 140^0F; (ii) the RFID system should operate at Ultra High Frequency (UHF), preferably at 915 MHz to be compatible with other wireless technologies already in place; (iii) commercially available RFID handheld readers and the tags should communicate using a standard and passive protocols; (iv) a battery life of 3 years for RFID tags to properly record the entire temperature history; (v) the solution needs to be portable and fully stand-alone; and (vi) the read range from the sides of the pallet should be at least 6 to 10 feet. Therefore, semi-passive tags such as Intelleflex XC3 tags from Zest Labs (Intelleflex changed its name to Zest Labs, Inc.) are used in monitoring the fresh produce supply chain. Zest Labs tags and readers, as part of their Zest Fresh solution, support the new ISO 18000-6C Class 3 standard and the existing EPCglobal Class 1 Gen 2 standard, thus enabling other compliant tags to be read. It features a large user read and write memory of 60 kbits allowing the logging of over 3000 data points/readings. These features are illustrated in Figure 3.1 [75] .

Other RFID tags available in the market that satisfy the key requirements include CAEN RFID [1] and Infratab [2]. The accuracy of sensor-enabled RFID data loggers is a critical issue in cold chain management (temperature controlled supply chain).

[1] http://www.caenrfid.com
[2] http://www.infratab.com

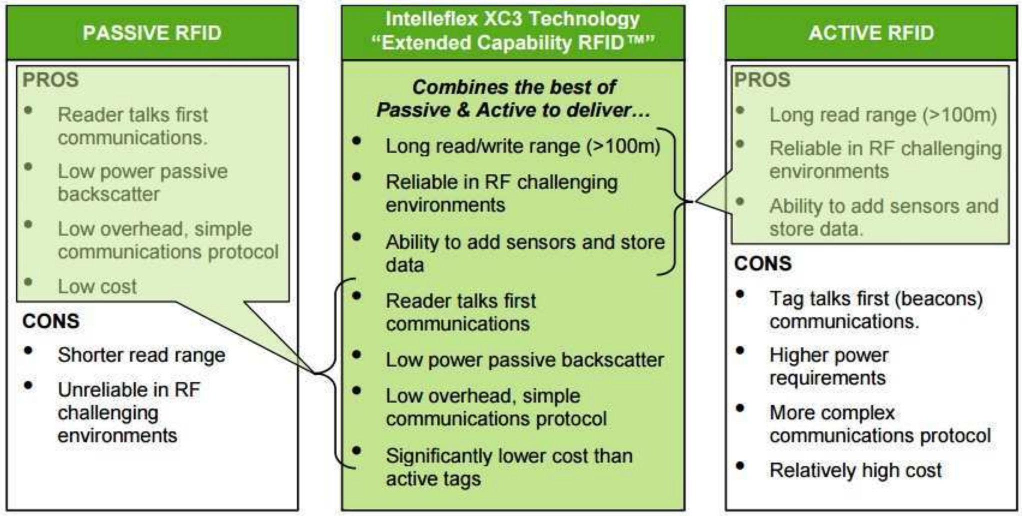

Figure 3.1: Semi-passive tags combining the best features of active and passive tags. Intelleflex is now Zest Labs and this figure is reproduced with their permission.

This accuracy becomes even more important if the objective is early detection of temperature changes and gradients. Standards for food distribution allow deviations of +0.5 or -0.5^0C from the set point [63]. Ismail Uysal et al. [9] compared three different RFID loggers in order to find the most appropriated one for monitoring cold chain logistics. Using wireless temperature sensors, remote monitoring (RFID), algorithms, and diagnostics, it was demonstrated that Army First Strike Rations (a semi-perishable food with significant degradation under high temperature conditions) shelf life can be automatically calculated in real time using web-based computer models. Several tests were carried out in a climate chamber. A fully functional prototype RFID system was developed as a result of extensive testing. Intelleflex tags were selected because they showed high accuracy in both temperature and environmental simulation tests, had a longer communication range than other tested tags, and are based on an advanced class 3 communication protocol, making them future-ready in terms of adaptability to other systems and RFID readers.

Some tags also come with the reader software integrated in portable handheld edge devices. An example is the Motorola MC9090 handheld reader. It comes with an Intel XScale PXA270 processor at 624 MHz, a memory of 64 MB RAM and 128MB ROM and a Windows Mobile Operating System. The application software runs on the Windows Mobile operating platform. It comes with the inbuilt functionality to use the intelleflex reader module to communicate with the TMT-8500 tags. This can be used to start, stop, record RFID tags and run a temperature-based shelf-life algorithm on the downloaded data. The tags and readers used are shown Figure 3.2 [75].

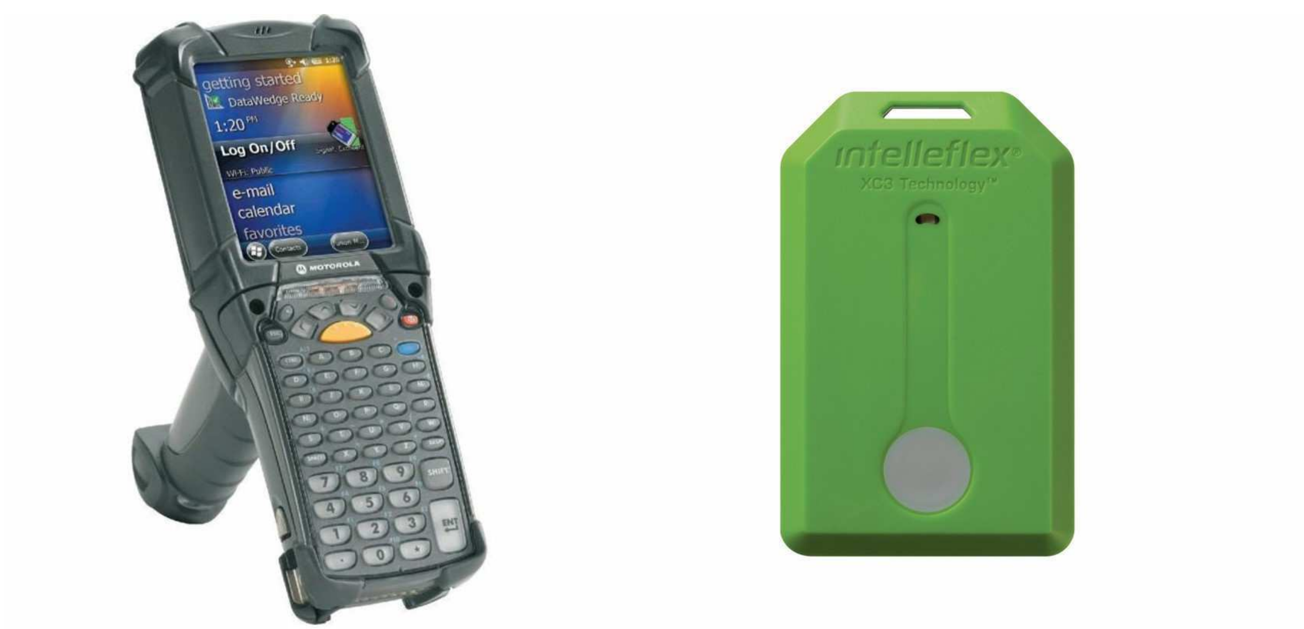

Figure 3.2: Motorola MC9090 and TMT-8500 Intelleflex tag. Intelleflex is now Zest Labs and this figure is reproduced with their permission.

Type of Sensing/Reading: Most commercial RFID sensor tags fall into two sensing categories:

1. Interval sensing: The sensors of this kind wake up periodically and sense the environment. This sensing mode can be used for long distance transportation and/or long-term storage in general.

2. Immediate/Waypoint sensing: The sensors of this kind are woken up and made to sense the environment according to a user's request. This sensing mode can be used to sense the environment at essential and/or obligatory logistic points in order not to miss those points using interval sensing. Critical points for sensing in the blackberry supply chain as an example include: placing the berries into cases in the field; loading the berries into the truck; at the packing house receiving dock; at the point of pre-cooling; upon leaving the packing house for distribution centres; at the distribution centres, and from distribution centre to the retail centre (this is further described in Section 3.4).

3.2 Issuing Policies in Perishable Produce Supply Chain

Much of the research in perishable items inventory management has focused on the First-In-First-Out (FIFO) issue process. In [54], a study on the issuing policies for a blood bank with random supply and demand showed that FIFO is better than Last-In-First-Out (LIFO) for maximizing utility and reducing inventory stock-outs. FIFO is the most commonly adopted approach ensuring the oldest stock is shipped out based on its arrival date at each individual distribution centre (DC). This approach makes the often-criticized assumption that all products arriving on a particular date have the same shelf life potential, which all too often is not the case. The reality is that the normal quality control visual inspection process is not adequate to see the "invisible"shelf life loss introduced earlier in the supply chain due to improper temperature controls [29]. While FIFO works effectively for perishable products with fixed shelf life, the same cannot be said for perishable products with random shelf life. LIFO ensures that the newest stock is shipped out according to their arrival time. The items which arrived last in the distribution centers are thus shipped first to the retail stores.

In addition to FIFO and LIFO, other policies for perishable goods such as FEFO (First-Expired-First-Out), LQFO (Lowest-Quality- First-Out), LEFO (Latest-Expiry-First-Out), SIRO (Service-in-Random-Order) and HQFO (Highest-Quality-First-Out) were studied in [58]. FEFO means that products are selected by their shelf-life or rather best before date. LQFO means that products are selected by their quality. SIRO means that the distribution centre selects products to be shipped to the retail store randomly and completely independent of product age or quality. These policies were studied in a simulation study that compares the performance of these policies for perishable goods to the common policies FIFO, SIRO and LIFO. The simulation model represents customer demands, lead times for logistics, the initial quality and products' deterioration of quality. Within this analysis LIFO, LEFO and HQFO constantly showed high percentages of spoilage while FIFO, FEFO and LQFO were the best policies concerning spoilage. The highest rate of sold products used LQFO and the second highest used FEFO. Due to real-time monitoring of the quality of perishable goods FEFO can be extended to a so-called 'dynamic FEFO' that enables the representation of the actual quality of the product. Contrary to the currently employed FIFO or static FEFO strategy which uses static best before dates, dynamic FEFO takes the dynamically changing shelf-life into account by using information acquired during storage and transport from an appropriate sensor system. Hence, a quality-driven distribution can be carried out which results in a minimum of waste of perishable goods.

Dynamic-FEFO will only ship products depending on their shelf life potential in relation to their end destination, thus ensuring only high-quality products arrive at their destination and eliminating product loss during transport. The transition to a strategy of FEFO requires the implementation of information-sharing highways across supply chains between trading partners which is enabled by Fog Computing. This enables a data-driven supply network that will give the DC manager more information about the integrity (shelf life) of all incoming goods and, as a result, the DC manager may then choose to distribute goods based on their remaining shelf life [58].

3.3 Granularity of Monitoring Perishable Products

Truck-level monitoring: This involves monitoring the ambient temperature of the trailer during transportation of FFVs. Truck-level monitoring does not capture variations in how individual pallets/cases are handled at each step throughout the end-to-end process. Consider for example the step of loading the reefer trailer. Often the driver has not pre-cooled the truck. They turn on the refrigeration unit just before they start loading the trailer. The first pallets loaded into the trailer help to cool down the trailer, but in the process those pallets are warmed up as well. Finally, after the last pallet is loaded, the driver puts the temperature monitor into the trailer and pushes the button to start recording the temperature. The truck's temperature recording device missed all of those events during the loading process and the dramatic variations of temperature that each pallet was exposed to. To understand the true temperatures that a product has been exposed to, it is therefore important to monitor the temperature at the product itself rather than the surrounding environment.

Pallet-level monitoring: In pallet-level monitoring, a tag is affixed to a pallet. When the pallet is ready for shipment, a tag ID is programmed into the tag. This tag ID is typically cross-referenced to a purchase order and a list of the inventory on the pallet. At the shipment destination, the tag ID can be cross-referenced again to the database record that contains the pallet information. This was found to improve product movement visibility, streamline distribution, and aid in forecasting. While the pallet is the most economical unit for measuring temperature very near the product itself, case-level end-to-end monitoring gives a much more precise picture of the remaining shelf life, enabling a First Expired, First Out (FEFO) approach, which is smarter and more accurate. The remaining shelf life is calculated, based on the complete temperature history inside the case from the time of harvest to the present [32].

Case-level monitoring: In case-level monitoring, tags are placed on cases. As in pallet-level tagging, the tag typically cross-references the purchase order and inventory information. The primary advantage of case-level tagging over pallet-level tagging is that it allows more detailed tracking. Case tagging also saves labor time by automatically reporting case counts and thus making manual counting of cases unnecessary.

3.4 Blackberry Supply Chain

In order to effectively answer our research question of the application areas/use cases of Fog Computing in RFID-enabled supply chain management, we consider the blackberries global supply chain network. The dynamics of the berries supply chain are different compared to other supply chains due to the following reasons: (i) the high respiration rate of the fruit; (ii) the ability to quickly lose water and weight from the lack of a protective peel or rind; and (iii) the need for the fruit to be rapidly cooled and kept cold during the handling process since they are highly susceptible to mold and decay.

Blackberries may be held in cold storage for 2 to 20 days depending on the cultivar, handling and ripeness of the fruit. Berries are harvested directly into retail containers which are transferredointo clamshells to reduce bruising that comes with handling the berries. The clamshells are further loaded into cases and finally transferred onto pallets. Once harvested, the clock starts ticking and shelf life begins to deteriorate based on the prevailing environmental conditions. For blackberries, the amount of heat produced as a natural consequence of respiration depends on the storage temperature [76]. This is shown in Table 3.1. Blackberries (highlighted) have the highest respiration rates compared to other berry fruits:

Table 3.1: Respiration rates of berry fruit

Berry	*Resp. Rates at* 0^0C	*Resp. Rates at* 10^0C	*Resp. Rates at* 20^0C
Blueberry	1,300	3,900	15,000
Strawberry	3,500	16,000	33,000
Blackberry	5,100	17,000	39,000

Therefore, tracking and monitoring the environmental conditions of blackberries from the field to retailer is critical. This can help the grower, distribution manager and retailer calculate the remaining shelf life, identify any potential quality issues and help route produce quickly. The blackberry supply chain process workflow is illustrated in Figure 3.3. The process is divided into the following stages:

1. *Harvest in the Field*: Fresh blackberries are usually handpicked and harvested into the final containers to reduce stress associated with handling. The containers/clamshells are then loaded into flats/cases and placed on pallets. A forklift is used to load the pallets into trucks. This implies that inspection and grading occur at the field. The most important factor affecting the shelf life/quality of the berries is the temperature, followed by the humidity. After

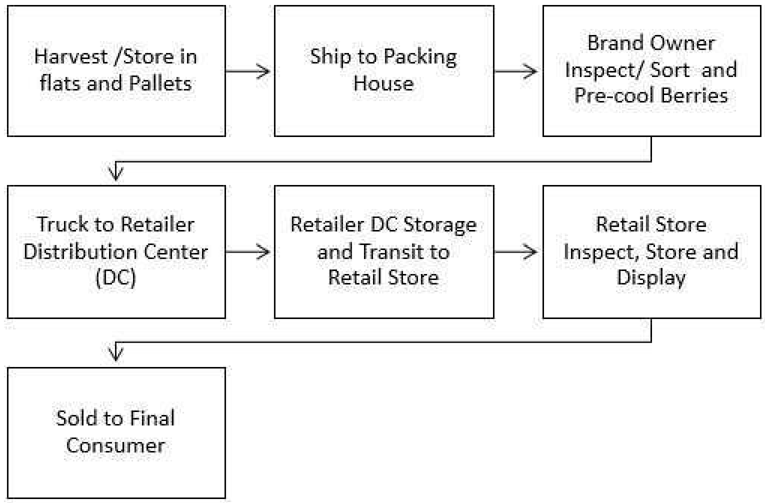

Figure 3.3: Blackberry supply chain process workflow

harvest, every hour out of refrigeration can reduce the shelf life by one day. It is therefore extremely important to remove the field heat in the fruit, thereby lowering respiration and transpiration rates significantly. To maximize shelf life, the produce should be protected from the sun and transported to the packing house quickly.

2. *Shipping to Packing house*: Transport is often done by refrigerated road vehicles and containers equipped with embedded cooling systems. In such environments, temperatures rise very quickly if a refrigeration unit fails [38]. The refrigerated truck should be able to provide the required cooling and humidity control while in transit. In rare situations, the pallets are transported to the shipping house in flatbed trucks without a refrigeration unit. This may introduce temperature abuses leading to food waste or raising quality concerns.

3. *Inspection and Sorting at the Packing House*: Upon arrival at the packing house,

the products are further inspected based on their weight, color and size. It is critical that this process be done quickly to minimize delays before cooling.

4. *Pre-cooling*: Pre-cooling (rapid removal of field heat) is necessary to suppress enzymatic degradation, slow respiration, slow or inhibit water loss and the growth of decay-producing microorganisms. Reducing the delay from harvesting to pre-cooling has been shown to improve the shelf-life of perishable food significantly, as this is generally the period when perishable food is at its highest temperature and loses shelf-life at the highest rate [17]. As an example, Pelletier et al [52] monitored the quality of strawberries along the cold chain and reported that a delay of 4 hours between harvesting and pre-cooling increased water loss by approximately 50% and significantly decreased the visual quality of the food at its arrival at the distribution center. Nunes et al [50] reported similar results for delays of 6 and 8 hours before pre-cooling. Pre-cooling methods include room cooling, hydro-cooling, forced-air cooling, vacuum cooling, and the use of ice.

Forced-air cooling is recommended for most of the FFVs and is especially appropriate for berries that are susceptible to wilting. An additional benefit to forced-air cooling immediately after harvest is that it tends to dry wounds, which decrease the chances for decay growth. In forced-air cooling, the pallets are stacked in two rows in a cold room with space left between the two rows to form a tunnel. A box fan is placed on one end of the tunnel, and a tarpaulin is placed over the cartons at the other end. Negative pressure created by the tunnel pushes the warm air out of the cartons and into the room. The produce are promptly removed from the forced-air pre-cooler upon achieving 7/8 cooling.

Commercial pre-cooling for perishable fresh produce aspires to rapidly remove at least 7/8 of the field heat from the crop. Field heat can be defined as the difference in temperature between the temperature of the crop harvested and the optimal storage temperature of that product. The time required is known as the '7/8 Cooling Time'. It has been estimated that removing seven-eighths of the field heat from fruit takes three times as long as it takes to remove half of the excess heat [59]. This prediction is based on the idea that the rate of cooling is constant. Thus, if the fruit were one-half cooled in one hour in the pre-cooler, it would take three hours to make it seven-eights cool. In the absence of a good pre-cooling facility, growers/packing house manager can expect shelf life of the fruits to decrease. Removal of the remaining 1/8 will occur during subsequent refrigerated storage and handling, with little detriment to the product.

5. *Truck to Retail Distribution Centers*: During this phase, the berries are transported in refrigerated trucks/containers depending on the mode of transportation (the dominant means of transportation is road). In the U.S. it is estimated that food transported by land travels more than 2000 km before it arrives at the retailer [55]. In Canada [46], it was reported that the average total transportation time for fresh-cut lettuce from production to retail was approximately 38 h, which, assuming an average speed of approximately 65 km/h, corresponds to a distance of nearly 2500 km. Given the long distances traveled and, therefore,

the long duration of land transportation, keeping the temperature of perishable food in the desired range during this step in the cold chain is critical.

Controlled Atmosphere (CA) is usually administered to further slow down the respiration process during transportation in long distances. In these, the concentrations of O_2 and CO_2 are monitored and maintained at predetermined levels. Initial low O_2 concentrations may be achieved through the use of nitrogen generators or O_2 scrubbers, or the fruit may be allowed to reduce the O_2 concentration through respiratory activity. To prevent the O_2 concentration from becoming too low, air can be exchanged with the atmosphere. CO_2 accumulates from respiration, but can be prevented from increasing excessively by absorbing it with lime, by removal with an activated carbon scrubber or by purging from the truck with nitrogen.

A more recent approach to CA storage is termed dynamic CA storage, in which the O_2 concentration in the store is determined by the response of the fruit. Dynamic CA optimizes the CA process, since using a predetermined atmosphere tends to err on the side of safety by setting the O_2 concentration well above the lowest safe level to allow for the variability in low O_2 tolerance amongst fruit from different orchards or seasons. Although this eliminates the risk of fruit becoming anaerobic, it also reduces the potential benefit. While early attempts at dynamic CA utilized ethanol sensors to detect if fruit metabolism was becoming anaerobic, it was the development of a fluorescence sensor [72] that could give a rapid measurement of the fruit response to low O_2 stress that allowed the commercialization of dynamic CA. The sensor is placed over a sample of the fruit in the truck, the O_2 concentration is decreased until a response is detected from the fruit and then the O_2 concentration is increased slightly above the low O_2 stress point. The procedure can be repeated throughout the transit period so that the O2 concentration can be continually matched to the capacity of the fruit to withstand low O_2.

An alternative way of utilizing the beneficial effects of low O_2 and high CO_2 is termed Modified Atmosphere (MA) storage. In this system, fruit respiration is used to reduce the concentration of O_2 and increase that of CO_2 inside an enclosed space, usually the export box or retail packs. The fruit is prevented from becoming anaerobic by making such enclosures out of plastic films that are partially permeable to O_2 and CO_2. Both gases come to an equilibrium based on respiration rate, the specific permeability of the film, the surface to volume ratio of the package and the amount of fruit in the package. Hence, this form of storage is highly dependent on being able to control the fruit temperature, since this determines the rate of respiration. The independence of having fruit in smaller packages that can be moved intact throughout handling and retailing suggest that MA may be more versatile than CA, although in practice any inability to maintain adequate cold-chain conditions can result in fruit spoilage as packages turn anaerobic at higher than desired temperatures [16].
The environmental parameters to be monitored at this stage include: temper-

ature, humidity, carbon-dioxide and light intensity.

6. *Retailer DC Storage and Transit to Retail Store*: The berries are unloaded quickly and temporarily stored in a cooling room before they are finally transported to retail stores.

7. *Retail Store Inspection, Store and Display*: Upon arrival at the retail store, the berries are finally inspected for defects before they are displayed for purchase by the consumers.

In summary, accumulated shelf life loss can be introduced in all these stages if environmental conditions are not strictly controlled. Table 3.2 below shows the factors affecting the quality of berries, environmental parameters to be monitored and sensors required at each stage of the supply chain:

3.5 Blackberry Case Study

Intelleflex (Now Zest Labs)[3], in conjunction with ProWare Services [4] conducted a case study with an international berry grower with operations in Central Mexico that documented issues and ways to reduce temperature related loss in the cold chain. The project studied two phases in the supply chain: (1) from the field to the packing house in Mexico; and (2) from the packing house to the distribution centers (DC) in the USA [31]. The distribution centers are located in Southern California, Texas and Pennsylvania. The predominant type of blackberry grown was 'erect', particularly

[3]http://www.zestlabs.com
[4]https://www.prowareservices.com

Table 3.2: Factors affecting the quality of blackberries in the supply chain

Stage	Challenges Associated	Sensors Required
Field	(i) Produce may be left in the field for too long. (ii) Produce may be exposed directly to the sun	Temperature and humidity sensors are placed in the cases after the berries are harvested.
Shipping from field to packing house	(i) Malfunctioning or turned off refrigeration unit in the truck (ii) Inadequate cooling in the truck	Temperature and humidity sensors used at the field are retained for use during this stage
Transport to distribution centers	(i) Carbon dioxide levels may exceed thresholds in case of controlled atmosphere (ii) Inadequate cooling in the truck (iii) Refrigeration unit may be turned off (iv) Uneven or poor air circulation in the truck (v) Truck doors may not be properly closed	New temperature, humidity, light and carbon dioxide sensors are placed in each case at the packing house
Distribution centers	(i) The product may be left at ambient temperature for too long(at the loading dock)	Temperature and humidity sensors from previous stage are retained in the cases.
Retail stores	(i) Inadequate cooling facilities (ii) Exposure to ambient store temperature	New temperature and humidity sensors are installed in freezers and cold display units.

'Tupy'. In the most optimal conditions, once harvested, blackberries have at most 17 days of shelf life, depending on the harvest conditions.

3.5.1 PHASE 1: From Field to Packing House

Approximately 150 growers in the area harvest their blackberries and then ship them, using a variety of vehicle types, to the packing house and cold storage facility in central Mexico. The distance from the growing fields to the packing house varies significantly, with the transportation taking from less than an hour to more than four hours. The blackberries are harvested at different temperatures throughout the day. This variation in temperature and time to pre-cool results in a significant variation of shelf life for each pallet. Intelleflex XC3 Technology temperature monitoring tags were placed in the individual pallets of blackberries at harvest in the field in order to monitor the temperature from harvest to the packing house and then determine the remaining shelf life once the pallets reached the packing house. The time and temperature of the pallets were sampled at a frequency of 15 mins and saved in the memory of the tags. Upon arrival at the packing house, the time and temperature data were read while in the inspection cooler area, and shelf-life loss was calculated based on the accumulated time and temperature. It was found that the temperature varied on a pallet-by-pallet basis due to the differences in distances from the field to the packing house and the types of vehicles used (e.g. refrigerated or flat bed trucks), as well as the ambient temperature which, of course, varies by time of day and year. Any pallets received at the packing house with less than 14 days of remaining shelf life (based on the customer's supply chain routing profiles) required special handling because if they were shipped to California or Pennsylvania, they may not meet the maximum routing profile requirements.

The steps involved in Phase 1 is described in Figure 3.4

Approximately 70% of the pallets were determined to have 14 or more days of remaining shelf life when they arrived at the packing house and could therefore be safely shipped to any of the distribution centers using any route and still have sufficient shelf life upon arrival at the DC to ship to any retailer. However, 30% of the pallets had less than 14 days of shelf life at arrival, indicating these pallets require special routing to ensure their shelf life matches that required by the routing profile. These pallets are termed as "Pallets-at-risk".

3.5.2 PHASE 2: From Packing House to the Distribution Centers (DC) in the USA

Pallets with Intelleflex temperature monitoring tags were loaded into the truck for distribution to the US distribution centers. Each trailer was also equipped with a traditional temperature monitor to log the ambient temperature inside the trailer. On the pallets, temperature was monitored on a 3-hour basis and saved on the internal memory of the tag. There is a significant variation in the time it takes for the berries to travel to the US-based distribution centers:

1. For Southern California, it takes about 3-4 days by truck.

2. For Texas, it takes 2 days by truck.

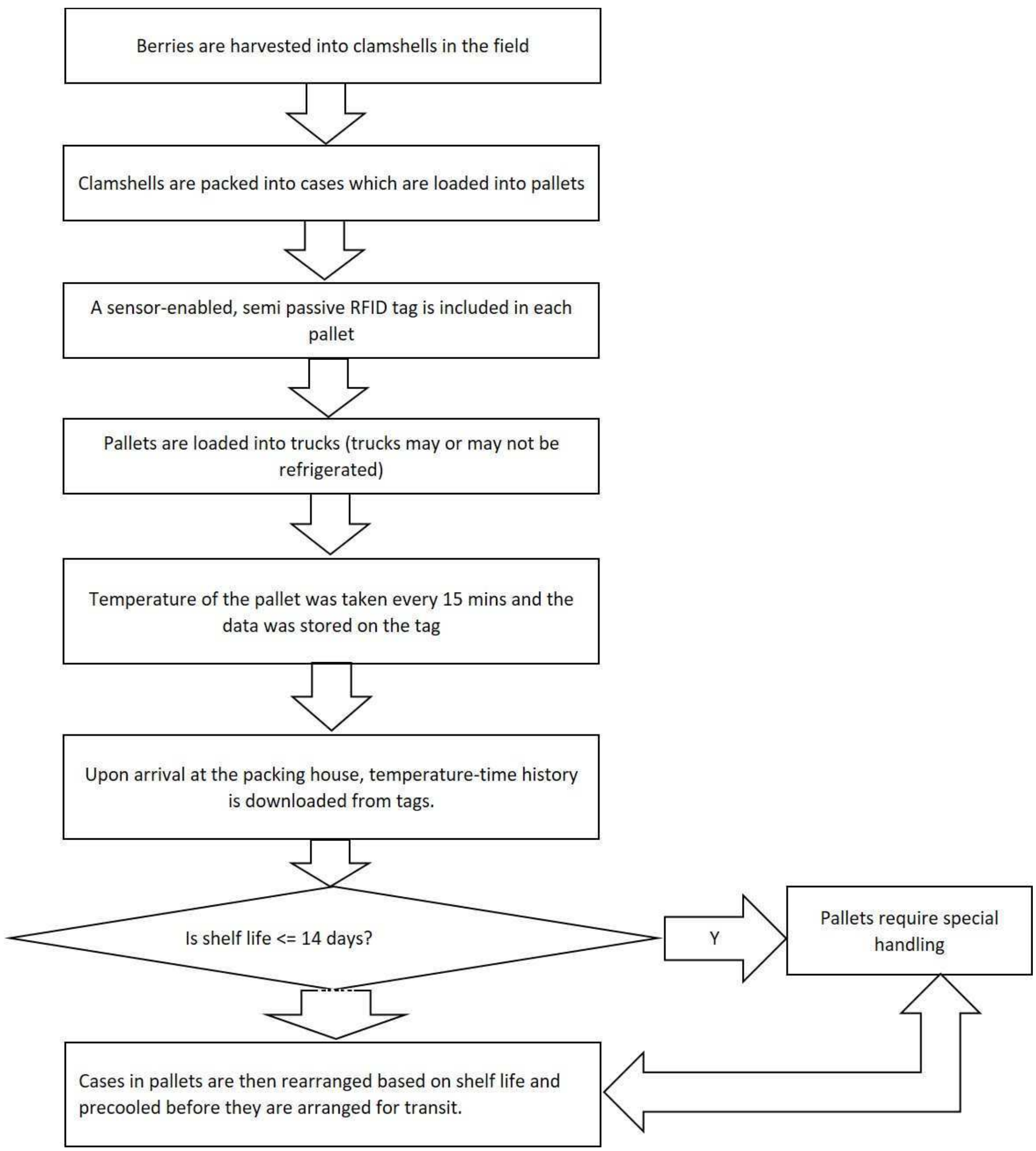

Figure 3.4: Phase 1: From Field to the Packing House

Pallet Remaining Shelf Life After QC at Mexico Pack House

Shelf Life (days)	>16	15	14	13	12	11	10	<10
% of Total Pallets	23.2%	19.7%	27.1%	12.3%	7.9%	5.4%	2.5%	1.5%

14 days shelf life at shipment required for optimal sales

70% (>16, 15, 14) — 30% (13, 12, 11, 10, <10)

Source: Intelleflex

Figure 3.5: Pallet remaining shelf life at Mexico Pack House. Intelleflex is now Zest Labs and this figure is reproduced with their permission.

3. For Pennsylvania, it takes 4-5 days by truck.

Upon arriving the distribution centers, the time-temperature history on tags was downloaded and the shelf life for each pallet calculated. The actual pallet-level temperature data, however, demonstrated that there was a wide variation in pallet temperatures within the trailer and therefore there was a loss in shelf life while the pallets were en-route to the DC. Figure 3.6 shows 21 pallets of blackberries on the three day trip from the packing house in Mexico to the DC in Southern California [31]. This truck took approximately 5 days (4.94 days) for the trip, almost a day longer than the average time. This means that *all* pallets on this truck have experienced an additional day of shelf life loss. Also, as a result of the temperature variation inside the pallets in the trailer, 5 pallets (Pallets 2, 3, 9, 10, and 11) experienced temperatures greater than 40^0F resulting in accelerated shelf life loss. The ambient temperature of the truck however remained constant during the trip. The high temperature experienced by the pallets was a result of heat generated by the fruits due to poor air circulation of the truck. These ‘Pallets at Risk’ require special handling as they are highly susceptible to spoilage. These pallets will continue to lose shelf life at an accelerated rate through the distribution centers to the retailer's custody [31].

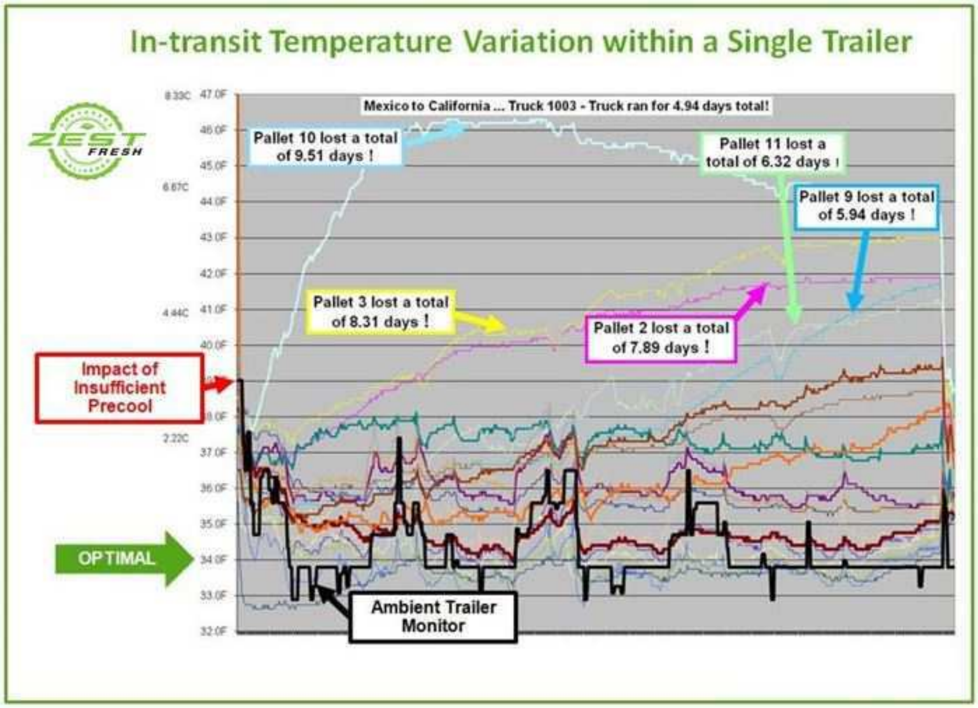

Figure 3.6: Time-temperature monitoring from Mexico to Southern California. Intelleflex is now Zest Labs and this figure is reproduced with their permission.

3.5.3 PHASE 1: Process Optimizations

At the end of the Phase 1, it became apparent that advanced shelf life loss was heavily incurred during the transportation of berries from the field to the packing house. Quality loss is a function of environmental parameters (temperature, time and humidity) abuse. At the end of Phase 1, it was revealed that 30% of avoidable loss occurred even after the pallets were monitored. This was due to the following reasons: (i) environmental parameter sensing systems (sensor enabled RFID tags) logged the data to be retrieved at a later time (at the packing house), but did not prevent shelf-life loss from occurring to goods in the field and in-transit. Table 3 below summarizes the type of sensing, parameters to be monitored, conditions to trigger the alert and required actuation to prevent losses.

Table 3.3: PHASE 1: Process optimizations

RFID tag use	Parameters to be monitored	Condition to trigger alert	Actuation type
Field	Temperature and humidity	(i) Shelf life exceed threshold value. (ii) Time cases spend in the field exceed 30 mins. (iii) Humidity values fall below or exceed threshold values.	Manual: transport cases/ pallets to packing house for immediate pre-cooling.
Shipping from field to packing house	Temperature, humidity, and geolocation	(i) Inadequate cooling in the truck. (ii) Humidity values fall below or exceed threshold values.	Automatic: reduce or increase the temperature/humidity to keep the produce within the required range.

3.5.4 PHASE 2: Process optimizations

The key factor responsible for the shelf life losses in Phase 2 was primarily due to poor air circulation. It is therefore important that the supply air of the refrigeration unit in the truck strongly correlates with the actual temperatures within the cases of fruits in the truck. Apart from the temperature sensor, other sensors required during this stage include light, humidity, O_2 and CO_2 sensors.

Table 3.4: PHASE 2: Process optimizations

RFID tag use	Parameters to be monitored	Condition to trigger alert	Actuation type
Truck from packing house to distribution center	Temperature, humidity, carbon dioxide, oxygen and light.	(i) Shelf life exceed threshold value. (ii) Poor/insufficient air circulation in the truck. (iii) Humidity values fall below or exceed threshold values. (iv) Oxygen and carbon dioxide values fall below or exceed threshold values.	Manual: (i) ensure ventilated cases are stowed in a way that does not impede air movement. (ii) reload the pallets in a way that is compatible with designed airflow requirements. (iii) ensure that the set point is correctly configured in the truck. Automated: (i) automatic ventilation can be used to let in fresh cool air when oxygen levels drop below set point. (ii) vacuum pump can be used to extract excess carbon dioxide when levels fall above set point.

Chapter 4

Architecture

4.1 Fog-Computing Model

The OpenFog Consortium specified key objectives for Fog Computing. This includes:

1. Security: additional security to ensure safe, trusted transactions.
2. Cognition: awareness of client-centric objectives to enable autonomy.
3. Agility: rapid innovation and affordable scaling under a common infrastructure.
4. Latency: real-time processing and cyber-physical system control.
5. Efficiency: dynamic pooling of local unused resources from participating end-user devices.

We propose a Fog Model which comprises a three-level layer of fog nodes to resolve the inefficiencies observed in the perishable produce supply chain. This model is in compliance with the EPCglobal standard.

4.2 Layers in the Fog Node

4.2.1 *Layer 0 (Data Producers/Consumers)*

The data producers include the RFID embedded sensors that produce telemetry data to be consumed by the monitoring and control layer. Data produced by the tags in this stage include the Electronic Product Code (EPC) ID of the pallet/case monitored, time, temperature, humidity, internal and/or external pressure, vacuum level, air-purity (oxygen, nitrogen, carbon dioxide, and other gases levels), fermenting gas level (such as ethylene), light exposure/brightness, and other environment parameters measured by the sensors. The embedded sensors should also monitor non-environmental parameters such as the truck-door open/closed status. The tags should be rugged and be able to withstand harsh environmental conditions as well as mechanical stress. At least RFID Class 1 Generation 2 tags should be used to allow for internal memory within the tags.

The data consumers include 'dumb or passive readers' that are purely limited to 'listening' and do not perform additional tag interrogations. They simply provide a power source and medium for the tags to operate and transmit data. These readers are installed at critical way points which include the truck, dock doors, pre-cooling rooms and the retail display unit.

4.2.2 *Layer 1 (Monitoring and Control Layer)*

The main responsibility of this layer is to execute control logic (generate actuator command) through stateful inspection of the sensor readings. This involves generating events, which may trigger workflows through machine-to-machine or human intervention. Fog devices in this stage include active or smart readers and the Intelligent Gateway as a Mobile-fog-node. We will describe the roles and models of each of these components below.

4.2.2.1 Smart Readers as Fog Nodes (also referred to as 'Fog Node 1')

The most basic function of the RFID Reader is to read RFID tags and to give a user or application access to a list of these tags. Smart readers are readers that do not only interrogate the tags but also possess in-built programmable microprocessor with extended processing capabilities. To serve as a fog node, a smart RFID reader should have the capability to host robust applications that enable smart applications directly from the reader. These applications include the ability to store and forward data at specified intervals when network connection is inherently poor and the ability to support business intelligence within the reader. Smart readers also have the capability of hosting applications, allowing customers to deploy RFID technology without a middleware computer or separate device for each reader. We further highlight the hardware and software characteristics of the smart reader.

(a) **Hardware Requirements**: They include the following: (i) the reader should operate seamlessly in radio frequency unfriendly environments including containers and pallets around metal, liquids, people and clothing; (ii) it should have a long read range (read ranges of 100 meters or greater) to allow for accurate reading of tags; (iii) it should have a low profile form factor to allow for easy and flexible installation; (iv) it should have an integrated cellular modem for GSM, GPRS and SMS communications for easy deployment at remote or mobile worksites (e.g at the field) and (v) it should be ruggedized to withstand the extreme heat, cold and moisture of outdoor environments as well as high humidity, dust and vibrations encountered in harvesting, warehouse or enclosed environments (a storage and operating temperature of -40^0C to -65^0C). The readers are connected to the upper layer fog node via a multitude of interfaces. However, these should be standard open interfaces like USB, Ethernet and PCI and other wireless technologies like GPRS. The data is transferred to the next fog node in the hierarchy.

(b) **Software Requirements**: An RFID reader will frequently sense multiple RFID tags within its detection range. While it seems like the reader is capable of reading hundreds of tags immediately, it actually must read them sequentially in order to comprehend each individual identity. In perishable produce supply chain environments, readers are expected to bulk read. Therefore, they must be programmed with collision detection to formulate a protocol to scan and organize each tag; otherwise the time to identify each item grows polynomially. In general, tag anti-collision protocols can be grouped into two broad categories: aloha-based protocols and tree-based protocols. The former is composed of aloha, slotted aloha, and frame slotted aloha that reduce the occurrence probability of tag collisions since tags transmit at distinct times. The latter is composed of the binary tree protocol and the query tree protocol. We consider the popular dynamic framed slotted ALOHA algorithm (DFSA) due to its high performance of tag identification [21].

In a dynamic frame length ALOHA anti-collision algorithm, the interrogator initiates a read cycle by broadcasting a request command to all tags under its coverage. This request command also includes a dynamic parameter, called the frame length, by which each tag randomly selects one of the available time slots and transmits its RN16 (a 16-bit random number from the tag pseudo-random number generator) at the selected time slot. For a given time slot, there are only three possible outcomes: idle, successful transmission and collision. The channel is idle if no tag transmits its RN16 in the time slot. A successful transmission means a single tag sends its RN16. If two or more tags transmit in the same time slot, the interrogator suffers from collision and no tag can be read.

After a read cycle, the interrogator can observe empty slots, singly occupied (or successful) slots, and collision slots. If the number of collision slots is greater than zero, the interrogator needs to estimate the number of tags that are present at the beginning of the read cycle and forecast the number of unread tags. According to the number of unread tags, the interrogator then determines an appropriate frame length for the next read cycle. When the number of slots with collision is over the upper threshold, the interrogator increases the number of slots. If the collision probability is smaller than the lower threshold, the interrogator decreases the number of slots. The read process stops when there is no collision in the read cycle. In the presence of a large number of collision slots, it is reasonable to assume that the number of tags is great. In this case, the number of empty slots should be very small. In contrast, a large amount of empty slots means that just a few tags are present.

Upon receipt of the tag RN16, the reader sends an acknowledge (ACK) command with the same random number attached for the tag to validate the data integrity and uniquely identify the tag. After verifying the RN16 is a match, the tag sends its unique item identifier or EPC. Once a tag is uniquely identified, the reader can choose to perform different operations ranging from read/write to a specified memory bank using a Read or a Write command, lock a tag for secure access using Lock command to prevent or allow access to a specific memory band or permanently disable the tag.

The reader also includes an embedded software comprising of the following modules:

(i) The Data Collection Module: In scenarios where multiple RFID readers are used, a smart reader can serve as a processing hub for dumb readers that do not have processing capabilities. It is a key instrument of the connection with the dumb readers and the upper layer fog applications. Moreover, it is used to control the readers, add data to the tags and also format them in a single format. To control the readers, this module has an embedded LLRP (Low Level Reader Protocol) driver. LLRP is a standard that facilitates the communication between the software and the readers. It should also be able to support readers that are custom built and do not follow the LLRP standard. Data collected in this layer include a list of tag IDs, their EPC codes and sensor readings.

(ii) Reader Administration Module: The administration module concerns the settings of the RFID Readers, antennas and sensors settings which can be modified such as IP address, power, and the number of antennas. In addition, each reader's operation specification can be altered: Start/Stop trigger, number of tag reports, transmit power, receiver/transmit sensitivity and priority. Business rules can be added, edited or removed. Finally, reader supervision will be embedded in this module. The supervision is a module which consists of logging each event about a reader. When there is a problem with any of the readers, an alert is sent via email or SMS message to designated personnel, leading to quick response and resolution when issues arise. This reduces downtime in RFID read zones and eliminates the costs associated with manually recovering missed data transactions.

(iii) Data Processing Module: RFID data captured by an RFID reader is often duplicated because an RFID tag can be read multiple times in the reading zone of a reader. To remove the duplicate (and redundant) data, it has to be filtered. For example, consider a sceneraio where multiple actors in the same location use RFID tags. In order to only keep the interesting tags, filter rules would remove tags that we do not need. A filter defines rules that allow or stop tags' reading during the reading process. Filtering can be on specific serial numbers of tags, or in the business number of a tag.

RFID systems generate significant amount of data that can be aggregated in a number of different ways. RFID data can be aggregated in the time domain, e.g. by generating entry and exit events, and in the space domain, e.g., by combining data from different readers and reader antennas that observe the same location or by detecting the movement of a tagged object. Since RFID permits identification at the instance-level rather than at the class-level, there is also the possibility to report the quantity of objects belonging to a specific category.

Tags Interpretation, which is the mapping between the Tag Number (TID) and the business data we have in a database, is also carried out during this phase. The tag number is just an ID but it is always linked to personal or business data. For example, the box with the RFID XXX (UID) contains three YYY items (Business Data).

In some cases, some tags' EPC are encoded following a strict format. There are multiple formats for RFID tags such as binary and hexadecimal encodings . The data processing module should include encoding and decoding algorithms in order to get back the information.
(iv) Connectors: Tag reads, after being treated in the data processing module, will be transmitted via connectors such as a database connector, files or queues. The connectors allow external application (such as fog applications) to get the aggregated data from the reader.
An example of this fog node is the Alien ALR-F800[1] new fifth-generation reader architecture that intelligently adapts and configures based on its environment.

[1]http://www.alientechnology.com/products/readers/alrf800/

4.2.2.2 Intelligent Gateway as a Mobile Fog Node (also referred to as 'Fog Node 2')

We propose an intelligent gateway with cognitive features that would allow quality problems to be detected in real time, and alarms to be triggered when specific environmental parameters cross a threshold. Automated quality assessment systems would free the transport operator from the task of manually analyzing traditional temperature charts. If the system were implemented on a locally embedded platform close to the sensor itself, it could greatly reduce the amount of communication data and costs. Only alarm notifications or state flags would need to be transferred over mobile networks. The required density of the measurement network depends on the setting. For a setting with an even distribution of thermal mass and airflow, the amount of sensors might be reduced to cover the core and each surface side, but in settings like delivery trucks, one sensor per meter could be necessary for reliable detection of local pallet/cases temperature peaks [35].

The system should take into account three key challenges for managing goods: Tracking, Tracing, and Real-time Monitoring (TTM). Tracking focuses on the ability to locate trucks and containers at any time. Tracing allows both distribution centres and retailers to know product movements from source to end users. Finally, the most recent challenge is monitoring, which enables logistics companies to assure product quality during transportation. Monitoring should not be limited to simple measurements, but should also evaluate data in the sensor network and make decisions locally. By making decisions locally using decision support tools, the amount of data transferred is drastically reduced, from hundreds of temperature data, to just 'temperature is OK' and 'remaining shelf life is within/outside threshold'. An intelligent gateway consists of RFID tags, smart RFID readers and the following elements.

(a) **Onboard Decision Support Unit (ODSU)**: This is the most intelligent component of the vehicle on-board equipment. At the point of loading, it should be able to download the shelf life model for the specific produce and other business rules related to the produce. It has the function of defining an item's default profile for each of the environment parameters that must be maintained during transportation and storage and the variations that may be tolerated thereof. It should be able to enforce these business rules based upon the stream of data received from 'Fog node 1'. The business rules should contain specific guide and instructions on how temperature and quality deviations should be handled in the event where a case/pallet is in peril as well as the resulting issuing of alerts. These alerts may be audiovisual or a very audible beep. The beeps may indicate the level of urgency required. For instance, a single loud beep may indicate the violation of a default parameter and requires external attention while two loud beeps indicates that at least one item is spoiled and needs to be removed, re-routed, or destroyed.

The ODSU receives filtered readings from 'Fog node 1' and matches them against the perishable produce default temperature and humidity profile. If the values exceed the maximum or fall below the minimum temperature and humidity, it triggers an alarm and issues corrective actions. These actions include: (1) lower or raise temperature, then recompute shelf life; (2) increase or decrease humidity, then readjust shelf life; and (3) adjust parameters and re-route truck to the nearest distribution centers. The ODSU is also responsible for synchronizing time-temperature history with the locally distributed fog nodes as well as the cloud database upon arriving at the distribution center. This is to ensure that subsequent transportation of goods would allow efficient tracking and monitoring.

An example of this unit is the Advantech IoT Gateway UTX-3115 [2] embedded box. Bundled with Intel Gateway solutions for the IoT, a pre-integrated software and hardware platform containing a Linux operating system and security and management features, UTX-3115 allows secure data aggregation and analysis from edge devices to the cloud through WiFi and/or 3G technologies. It is also a perfect fit for installation in a truck environment due to its wide temperature support (-20^0C – 60^0C).

(b) **Event Notification Unit**: The event notification manager is triggered by the ODSU after corrective actions have been carried out in the event of a threshold violation. The Event Notification unit sends alerts in form of messages and emails to the distribution/warehouse manager and the driver. The packing house manager also gets messages in form of feedback if several cases are experiencing high temperatures while the ambient temperature of the truck is constant. This could be a clear indication that the berries were not properly pre-cooled before they were dispatched to the distribution center.

The core aspects of the fog node can also be viewed as compute, storage, network

[2] http://www.advantech.com/products/utx-and-systems/

and control. In terms of computation and storage on the mobile fog node, the supervision of spatial temperature deviations inside a truck or container can produce large datasets. However, the share of information that is of interest for the transport operator in the end can be expressed with a few bytes: the number and location of pallets-at-risk with out-of-range temperature conditions and corrective actions as needed. In order to save costs for external communication and energy consumption of the fog nodes, it is most useful to process the data directly on the tag or in the subsequent fog node. Data compression techniques include: (i) simple shelf life models, which evaluate the effect of temperature deviations according to the Arrhenius Law for reaction kinetics or by a simple exponential relation to temperature [33] and (ii) the Derivative-Based Prediction (DBP) model, which allows the processor to check after each measurement if the rate of temperature change per time unit has changed. This has been shown to suppress data up to 90%. An analysis of required CPU time and memory showed that the hardware of typical RFID sensor nodes, such as the Wireless Intelligent Sensing Platform (WISP) passive RFID tags and the Intelleflex XC3 semi-passive tags, are fully sufficient to host such algorithms. The fog node requires at least a program memory of 408 bytes and a RAM of 122 bytes in computing a look-up table for the Arrhenius model [34].

In terms of network, the RF interface allows for easy communication between 'Fog node 1' and tags. The communication between 'Fog node 1' and 'Fog node 2' should be carried out over cellular networks such as GPRS. 'Fog node 2' should come with an upgradeable firmware and software that allows for remote update. The fog nodes should also come with a health check indicator that is monitored by the cloud sytems such that the health status of the nodes can be ascertained.

4.2.3 *Layer 2 (Cloud Servers)*

The primary responsibility of this layer is to store and analyze the entire history of the supply chain operations that span multiple systems. Data offloaded by the mobile fog node include: (i) the history of sensor readings that exceed threshold; (ii) the shelf life of the cases; (iii) the number of expired cases; and (iv) the alert history. Based on these data, possible computation carried out in this layer involves determining the amount of produce to be delivered to downstream retail stores/distribution centers and optimal routes at each level of the supply chain. Big Data Analytics can be performed with the history of sensor readings which can enable transit points and transportation routes to be managed efficiently on a day-to-day basis. This involves capacity planning for trucks as well as shift planning for personnel in distribution centers and packhouses. Often operational planning tasks are based on historical averages or even on personal experience, which typically results in resource inefficiency. Instead, using the capabilities of advanced analytics, the dynamics within and outside the distribution network are modeled and the impact on capacity requirements calculated in advance.

Real-time information about shipments (items that are entering the distribution network, are in transit, or are stored) are aggregated to predict the allocation of resources for the next 48 hours. This data is automatically sourced from warehouse management systems and sensor data along the transportation chain. Furthermore, detection of ad-hoc changes in demand is derived from externally available customer information (e.g., data on product releases, factory openings, or unexpected bankruptcy). Additionally, local incidents are detected (e.g., regional disease outbreaks or natural disasters) as these can skew demand figures for a particular region or product. This prediction of resource requirements helps operating personnel to scale capacity up or down in each particular location. A precise forecast also reveals upcoming congestions on routes or at transit points that cannot be addressed by local scaling. Simulation results give early warning of this type of congestion, enabling shipments to be reassigned to un-congested routes, mitigating the local shortfall.

Other responsibilities in this layer include: (i) Device Management: to ensure that all IoT devices (the sensors and actuators) are performing optimally and delivering the services that are expected from these devices; and (ii) Application Management: for managing the behavior and functionality of the application and also managing the information collected by the application. The application management layer is typically custom built to meet the needs of a specific application. The proposed fog computing model is compatible and adaptable to other sectors of the perishable produce supply chain such as blueberry, raspberry, lettuce, fish etc. The hierarchical fog layer is shown in Figure 4.1:

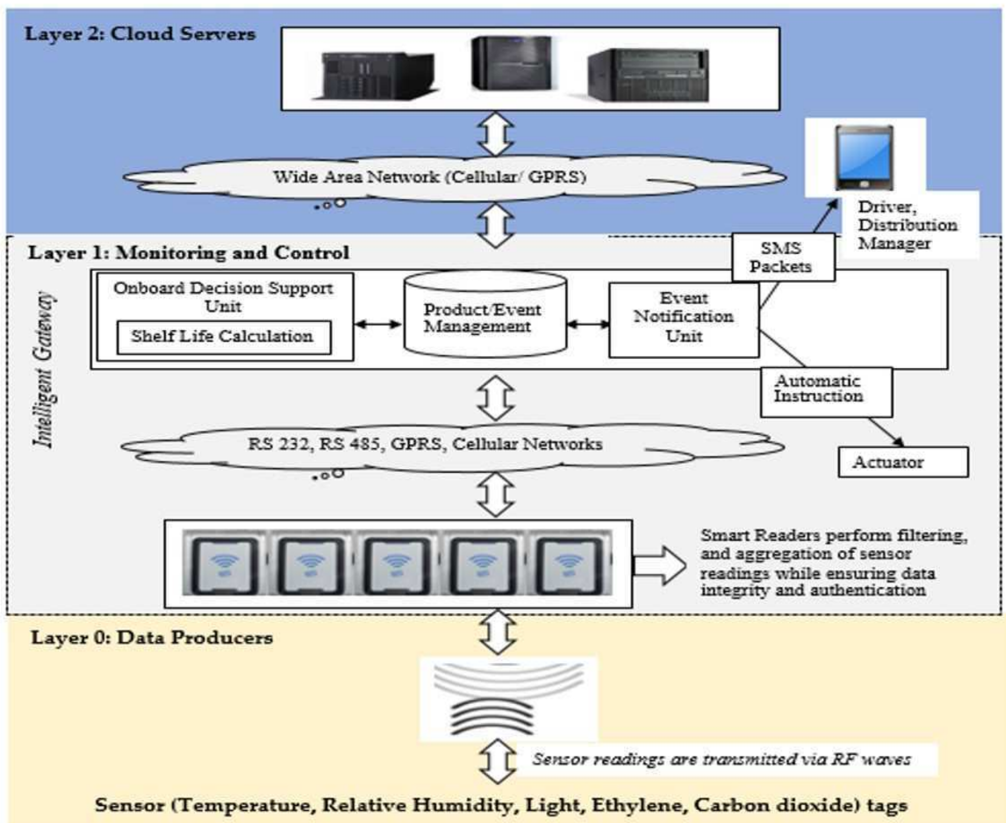

Figure 4.1: Fog layers for perishable produce supply chain

Chapter 5

Integration of Fog-based RFID Solution to the Blackberry Supply Chain

This chapter describes the integration of the proposed fog computing framework to address the limitations observed in the blackberry supply chain. It also examines the adaptation of the framework to general perishable goods supply chains. Finally, we explore data models for constraints in IoT systems using the example of a truck cooling system.

5.1 PHASE 1

The process begins with tagging the cases. In addition to the EPC stored on an RFID tag, most tags are built with CMOS integrated circuits with Electrically Erasable

Programmable Read-Only Memory (EEPROM) [7] which facilitates the reading and writing of additional data on the tag. This helps to store additional information about an object on the tag attached to the object without depending on the network database for more information. The tags for UHF standard have four memory banks as shown in Table 5.1.

Table 5.1: Memory banks in an RFID tag

Bank	Memory Definition
Bank 00	Reserved
Bank 01	EPC
Bank 10	TID
Bank 11	User

- EPC Memory: this stores the Electronic Product Code. It is the first writable memory bank. It has a minimum of 96 bits of writable memory.
- Reserved Memory: this stores the kill password and the access password (each is 32 bits long). The kill password permanently disables the tag (very rarely used), and the access password is set to lock and unlock the tag's write capabilities. If the application does not require the use of kill or access passwords, this memory location should contain zero values.
- TID (Tag Identifier) Memory: this is used only to store the unique tag ID number by the manufacturer when the IC is manufactured. Typically, this memory portion cannot be changed.

- User Memory: this is the second writable memory bank. The user memory can store additional information about the items the tag is attached to. There is no standard for how many bits of memory are writable on each tag. Typically, the user memory is no more than 512 bits, but there are some high memory tags with up to 64 kilobits of memory. This memory can usually be locked to prevent overwriting of data. To write data on the tag, the specific address of the memory bank and the block within this bank need to be identified. All the data to be written on the tag are considered as a single data string and written entirely within the tag's user memory location. This is because the user memory of a tag is a single string of bits. The data stored on the tag contains extra 'framing' information which separates one piece of data from another and identifies what each piece of data is. Also, the data is compressed before storing on the tag so that as few bits as possible are required. This allows less expensive tags to be used in any given application, and also improves performance because fewer bits need to be communicated between the RFID tag and the RFID interrogator (reader). This can then be read by an application program which retrieves the different pieces of information from that data string.

  With read-write chips, the user memory should contain quick information such as: the batch/lot number, sensor ID, degradation rate history, alert history, weight and the shelf life left (in days) of cases. This can be added to the tag or written over existing information when the tag is within range of a reader.

An important piece of data is cut-to-cool times. This is how long a harvested produce is exposed to ambient temperature before it is pre-cooled. This can vary significantly by pallet (even those from the same field, using the same process). For instance, it can take roughly 12 minutes to pick and build a pallet of berries in a field operation. If the crew assembles 12 pallets to fill a flat-bed truck, the first pallet would have been harvested roughly 150 minutes before the last pallet. At summer time temperatures, this can result in a variation of roughly 3 days of remaining freshness between the first and last pallets from the same load. Harvested crops remain in the field even longer, severely impacting the freshness of the product. In the case study, sensor tags were used to monitor the temperature. However, the shelf life computation did not happen until the truck arrived at the packing house. As a result, up to 30% loss was recorded after reception at the packing house. This was detected by downloading the temperature data from the RFID loggers and computing the shelf life. We build a process flow for integrating fog computing into enhancing this process so as to increase the freshness.

5.1.1 Monitoring in the Field

Sensor embedded (temperature) tags are attached to each of the cases after they are filled with berries in the field before they are arranged into pallets. The tags are triggered to start monitoring immediately. Fog Node 1 and Fog Node 2 should be positioned at strategic points in the field to allow reading of tag and sensor measurements. Every 5 minutes, the fog node reads EPC code and sensor readings for all cases within its range. It is also equipped with a unique identifier, which in the case of immobile readers relates to its location. Finally, an internal clock lets the reader mark the time of observation. Thus, each time a tag is sensed a quadruplet of the form

$$(EPC_i, loc_i, t_i, temp_i)$$

is generated, where EPC_i denotes the Electronic Product Code of the tag, loc_i is the location of the reader, t_i is the current time and $temp_i$ is the current temperature of the case. This data stream of quadruplets is filtered and aggregated based on requirements prescribed by the fog applications of Fog Node 1 before it is sent to Fog Node 2 for analysis. In Fog Node 2, the fog application retrieves the specific temperature and water loss profile for blackberry crops and performs shelf life and water loss computations described in the next section. The result summary comprises: Shelf life days left, high/low temperature thresholds exceeded, water loss thresholds exceeded and time elapsed per case (the elapsed time from the field to point of packing may exceed pre-defined limits). It then looks for exceptions by comparing the summary to conditions pre-configured by the user and finally to alert (via sms/email) the field manager and packing house manager when exceptions are observed. The field manager can take immediate action to load the pallets into the truck and transport them to the packing house for pre-cooling. Shelf Life left, time-elapsed, degradation rate, exception and alert conditions are to be communicated quickly to Fog Node 1 and is put into the RFID tag memory as quick information. Once quick information are in the RFID memory, they are read like any other RF data, even when the sensor is asleep or in an otherwise low power state. Figure 5.1 below shows the functional operations of fog nodes in the field.

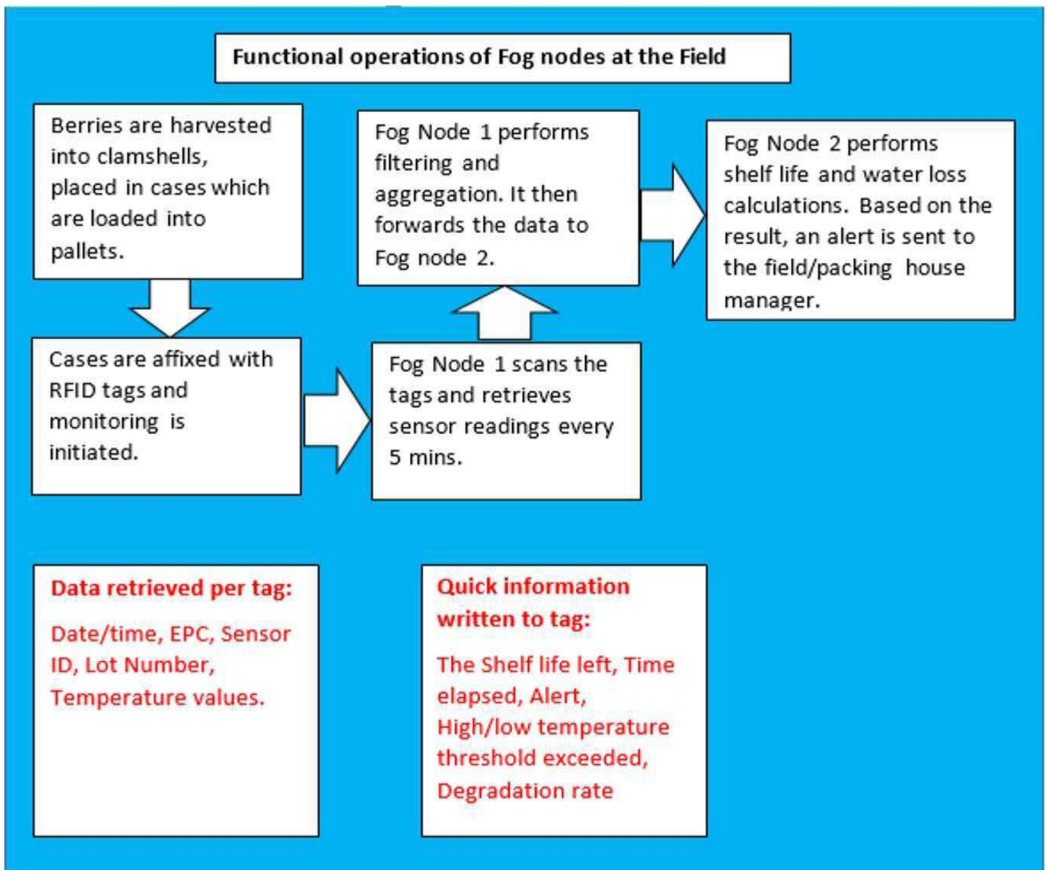

Figure 5.1: Functional operation of Fog nodes in the field

5.1.2 Computations Carried out in Fog Node 2 at the Field

Upon receipt of tags' data from Fog Node 1, Fog node 2 performs shelf life and water loss computations. The process for deriving the algorithms for these computations are described below:

a. The Shelf Life of the produce: Fresh fruit starts to degrade once it is picked. The rate and the degree of degradation depend on both the composition and the environmental conditions during storage and distribution [25]. In general, the loss of food quality or shelf life is evaluated by measuring the concentration of a quality index, A. The change of quality index A with time (dA/dt) is given in Equation 5.1 [42, 68]:

$$\frac{-dA}{dt} = kA^n \tag{5.1}$$

where k is called a rate constant or degradation rate that depends on temperature, product and packaging characteristics and n is a power factor called reaction order which defines whether the rate of change is dependent on the amount of quality left. If environmental factors are held constant, n also determines the shape of the deterioration curve. (dA/dt) is the rate of change of quality with time. A negative sign is used if the deterioration is a loss of quality and a positive sign is used if it is for the production of an undesirable end product.

If the value of n is 0 in Equation 5.1, the equation is called a *zero-order kinetics*. This implies that the rate of loss is constant with time. However, this equation does not hold for blackberry fruit, rather, there is an exponential decrease in the rate of shelf life loss as the quality decreases. This is known as *first order kinetics*. For this case, n is equal to one. The amount of quality left as a function of time is not a straight line as illustrated in Figure 5.2 [42]. The y-axis shows the amount of quality A remaining and the x-axis shows the time.

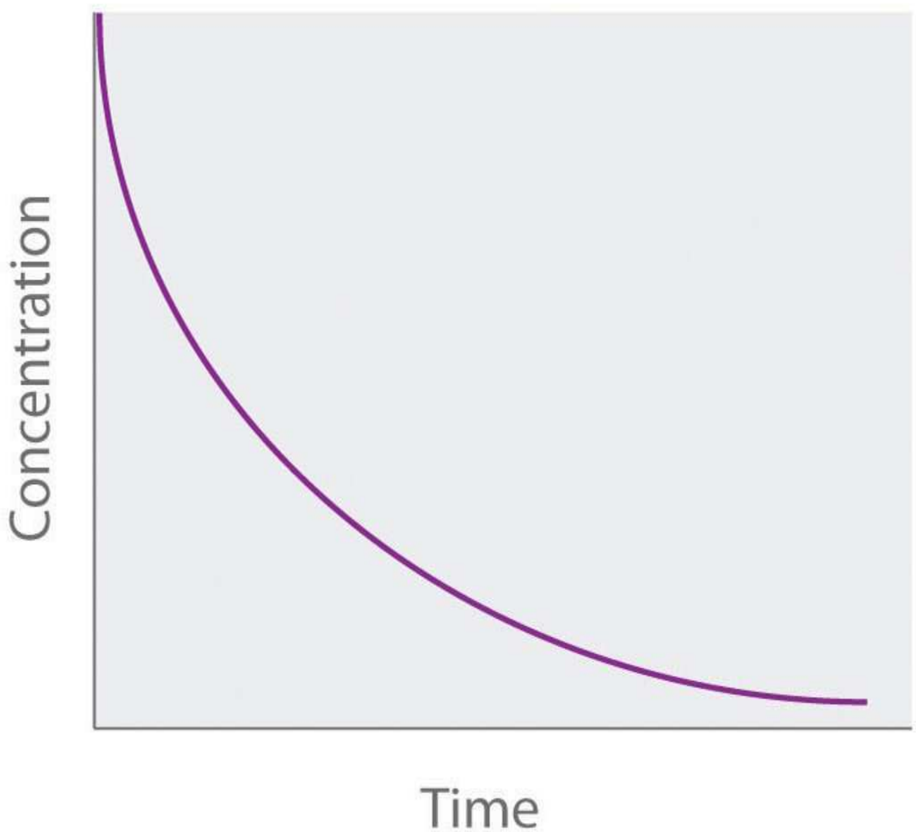

Figure 5.2: First order degradation

For first order kinetics, Equation 5.1 becomes:

$$\frac{-dA}{dt} = kA \tag{5.2}$$

To integrate Equation 5.2, we need to separate the variables A and t. This is expressed as follows :

$$\frac{-dA}{A} = k \times dt \tag{5.3}$$

We integrate the left side of Equation 5.3 using (A_0) and (A) as lower and upper limits. We also integrate the right side using 0 and t as lower and upper limits to derive Equation 5.4:

$$-ln\frac{[A]}{[A_0]} = k \times t \tag{5.4}$$

where A is the amount of quality left at time t and A_0 is the initial quality.
Equation 5.5 is derived by making A the subject of Equation 5.4

$$A = A_0 \times \exp^{-kt} \tag{5.5}$$

Re-writing Equation 5.4 using a property of logarithms which state that ln $A/B = lnA - lnB$, the left hand side of the equation can also be written as:

$$-(lnA - lnA_0) = (lnA_0 - lnA) = ln\frac{[A_0]}{[A]} \tag{5.6}$$

Therefore, Equation 5.4 can be given as:

$$ln\frac{[A_0]}{[A]} = k \times t \tag{5.7}$$

At the end of the shelf life S_L which is the same as t, the quality attribute concentration would be A_e. Substituting A_e for A and S_L for t in Equation 5.7 gives:

$$ln\frac{[A_0]}{[A_e]} = k \times S_L \tag{5.8}$$

For first order kinetics, the shelf life at a given reference temperature r can be calculated as:

$$S_L = \frac{ln\frac{A_0}{A_e}}{k_r} \tag{5.9}$$

The Arrhenius relationship [25] is often used to describe the influence of temperature on the degradation rate whether for zero or first order reactions:

$$k = k_o exp(-E_a/RT) \tag{5.10}$$

where k is the degradation rate (is the amount of change in quality in a unit of time that depends on the ambient conditions), k_o is a pre-exponential factor, E_a is an activation energy in Joules per mole (J/mol) or calories per mole (cal/mol), R is the gas constant in Joules per mole Kelvin ($J/molK$) or calories per mole Kelvin ($cal/molK$), and T is an absolute temperature in Kelvin $K(273 +^0 C)$ [25].

Taking the natural log of both sides in Equation 5.10, we have:

$$ln(k) = ln(k_o) - \frac{E_a}{RT} \tag{5.11}$$

Rearranging Equation 5.11 to conform to the equation of a straight line $y = mx + b$, we have:

$$ln(k) = -\frac{E_a}{R}(\frac{1}{T}) + ln(k_o) \tag{5.12}$$

Using Equation 5.12, at one specific temperature T, we have a specific rate constant k. At another reference temperature T_r, we have a specific rate constant k_r. Therefore it can be written as:

$$ln(k_r) = -\frac{E_a}{R}(\frac{1}{T_r}) + ln(k_o) \tag{5.13}$$

Subtracting Equation 5.13 from Equation 5.12, we have:

$$k = k_r \cdot exp(-\frac{E_a}{R}(\frac{1}{T} - \frac{1}{T_r})) \tag{5.14}$$

Once the kinetic parameters have been determined, if k_r is the k value at a reference temperature, its value at any temperature is given by Equation 5.14.

The shelf life for blackberry fruit can be determined using the algorithm given below:

- Identify the quality parameter to determine the shelf life e.g. anthocyanin content.
- Identify the environmental stress level: temperature (T).
- Define the kinetic model: zero order or first order. Blackberry follows a first order kinetics model [68].
- Get threshold values of temperature ($0^0C - 2^0C$), the activation energy E_a, the gas constant R, A_0, A_e, k_0 and the minimum shelf life threshold (set to 14 days).

- Calculate the degradation rate at the ambient temperature (k_r) using Equation 5.10.

- Calculate the shelf life at the prevailing ambient temperature S_L using Equation 5.9.

- WHILE S_L != 0, start the monitoring loop.

- Acquire current values of environmental variables. The temperature of the cases ($C_1, C_2, \ldots, C_j$) will be measured in each of the pallets ($P_1, P_2, \ldots, P_i$). Thus, a temperature matrix is formed accounting for each of the cases within the pallet:

$$\begin{pmatrix} P_1: & T_{11} & T_{12} & T_{13} & \ldots & T_{1j} \\ P_2: & T_{21} & T_{22} & T_{23} & \ldots & T_{2j} \\ \vdots & & & & & \\ P_i: & T_{i1} & T_{i2} & T_{i3} & \ldots & T_{ij} \end{pmatrix}$$

  - FOR each element in the matrix, compare T_{ij} with the reference values;
    - IF temperature falls within threshold,
    - THEN degradation rate and the shelf life remains the same.
    - ELSE calculate: (a) the new degradation rate (k) with equation 5.14; (b) the new quality attribute concentration with equation 5.5; and (c) the new shelf life with Equation 5.9.
  - Check if new shelf life falls below the required threshold.
  - Send an alert if shelf life falls below the minimum shelf life threshold.
  - END

- END WHILE

b. Water loss of the Produce: Transpiration of fresh fruits and vegetables is a mass transfer process in which water vapor moves from the surface of the plant organ to the surrounding air. The driving force of transpiration is the gradient of water vapor pressure (WVP) between the tissue and the surrounding air. The water vapor pressure deficit (VPD) of the air is the difference between the WVP of air and that of saturated air at the same temperature. The SI (Systeme International d'Unites) unit for expressing WVP is the pascal (Pa or newton per $meter^2$) or millibar $mbar$. Relative humidity (RH) is the most popular term for expressing the water content of air. It is defined as the ratio of actual WVP in the air to the saturation WVP possible at a given temperature, expressed in percent. This definition makes clear that RH is a function not only of the amount of water vapor in the air but also of temperature. Thus, for the same RH, air at higher temperature has higher VPD than air at lower temperature.

The rate of water loss from fruits and vegetables is affected by the shape and structure of the produce and the plant factors as well as the environmental conditions. These plant factors are quantified by the transpiration coefficient or T_{value}. The rate of water loss (with unit in '% per time') can be expressed as:

$$T_{value} \times VPD \tag{5.15}$$

The T_{value} is fixed for specific fruits. VPD is increased by increasing temperature and decreasing relative humidity. A psychrometric chart (see Figure 5.3 on next page) gives a graphical representation of the relationship between temperature, RH and water vapor pressure. Therefore, if the temperature of the produce is known and the RH is assumed to be 100% (saturated) the WVP can be determined. Likewise the WVP of the atmosphere can be determined using temperature and RH. The difference between these two values is the VPD [18].

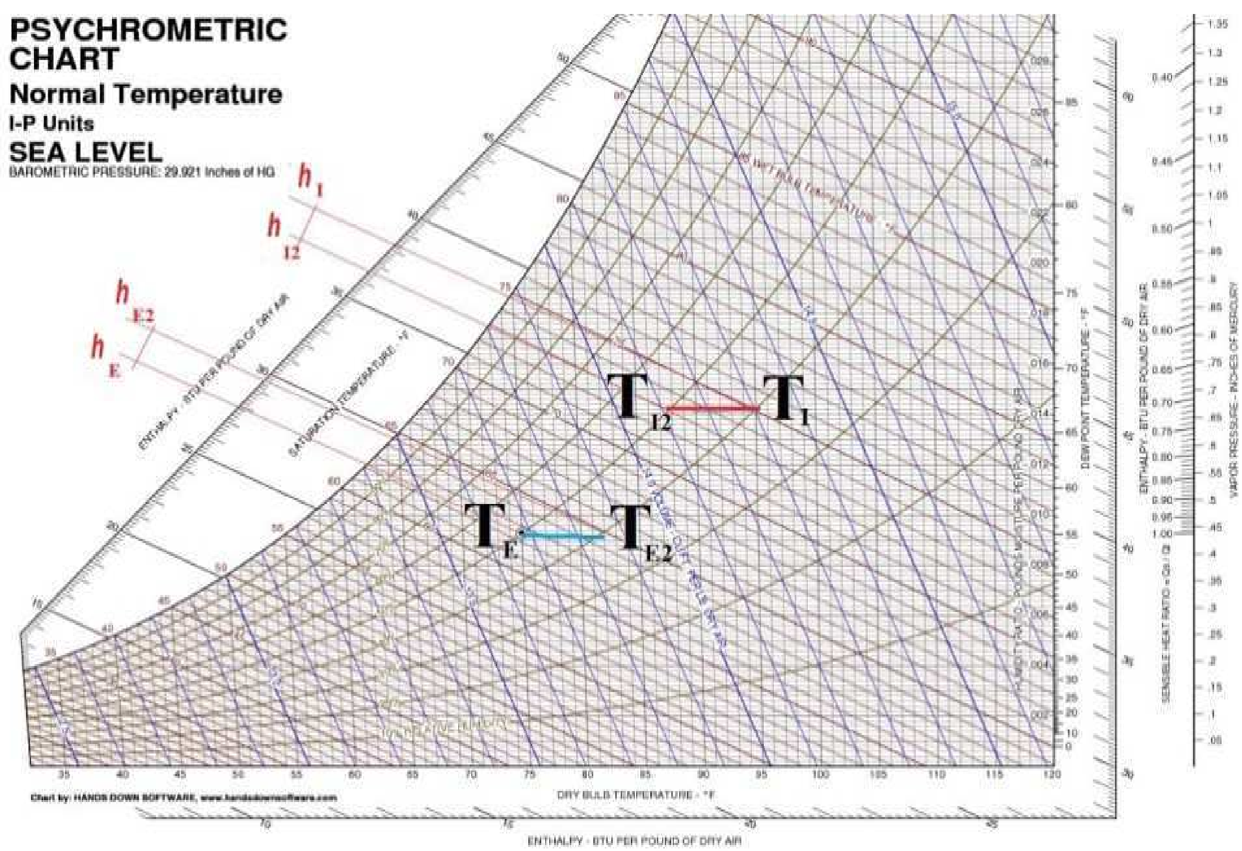

Figure 5.3: Psychrometric chart. Reproduced under Public Domain from Wikimedia Commons.

The maximum permissible water loss at which blackberries become unsalable is 6% [18]. The rate of water loss is determined from the algorithm below:

- Get the transpiration coefficient T_{value} for blackberry fruit, the maximum permissible water loss (Water loss threshold), the vapor pressure of the ambient air based on the relative humidity (V_a).
- REPEAT
  - Start the monitoring loop
  - Acquire current values of environmental variables. The temperature of the cases $(C_1, C_2, \ldots, C_j)$ will be measured in each of the pallets $(P_1, P_2, \ldots, P_i)$. Thus, the temperature matrix used during the calculation of the shelf life is retrieved:

$$\begin{pmatrix} P_1 : & T_{11} & T_{12} & T_{13} & \ldots & T_{1j} \\ P_2 : & T_{21} & T_{22} & T_{23} & \ldots & T_{2j} \\ \vdots & & & & & \\ P_i : & T_{i1} & T_{i2} & T_{i3} & \ldots & T_{ij} \end{pmatrix}$$

  - For each element in the matrix, fetch the vapor pressure of the cases (V_c) at 100% relative humidity. This can be retrieved from a psychometry lookup table stored in Fog node 2.
  - Subtract (V_a) from (V_c) to get the vapor pressure deficit.
  - Compute the water loss using Equation 5.15.
  - Send an alert if rate of water loss falls above the required threshold days.
- UNTIL rate of water loss reaches the threshold for each of the cases.

5.1.3 Alert/Notification

The packing house manager, the field manager and the truck driver are alerted if the following events are detected: (i) shelf-life within the case drops below the reference values; or (ii) water loss falls below predefined threshold. This method of alert is known as Single Threshold Shelf-life Alert (STSA) and uses one single input, which is the threshold Shelf-life in days. This value based on the cultivar of blackberry, was set at 15 days. The new shelf life or 'Time-to-expire' is also communicated via their mobile devices or through e-mail. In summary, if the fog device (Fog node 2) detects a temperature below the said minimum threshold or above the maximum threshold, it should preferably (i) make a decision i.e. to output a good-specific characteristic indicating that due to the event the good is outside the defined legal specification; and (ii) store the event for backtracking (this is to allow the user to trace back deficiencies or 'temperature abuse' in the transport and/or storage history). However, if the temperature and humidity parameters fall within the required threshold, the data does not need to be stored except for regulatory or compliance purposes.

5.1.4 Monitoring during Transportation of Berries to Packing House

Sensor embedded RFID tags are deployed to monitor the supply air from the refrigeration equipment to ensure that the ambient temperature of the truck is within the required range. A relative humidity sensor is installed in the truck to monitor the relative humidity of the ambient air. After the truck is loaded, the fog nodes resume monitoring of the shelf life. Every 5 minutes, Fog Node 1 reads EPC code, location and sensor readings for all cases within its range. It also retrieves the degradation rate and shelf life (stored as quick information) from the user memory in the tag. Finally, an internal clock lets the reader mark the time of observation. Thus, each time a tag is sensed, a data stream of the form

$$(EPC_i, loc_i, t_i, temp_i, hum, k_i, S_{Li})$$

is generated, where EPC_i denotes the Electronic Product Code of the tag, loc_i is the location of the reader, t_i is the current time, $temp_i$ is the current temperature of the case, hum is the relative humidity of the truck, k_i is the current degradation rate of the case, and S_{Li} is the current shelf life of the case. This data stream is filtered and aggregated based on requirements prescribed by the fog applications of Fog Node 1 before it is sent to Fog Node 2 for analysis. In Fog Node 2, the fog application retrieves the specific temperature and humidity profile for blackberry crops and performs shelf life and water loss computations. The steps for monitoring the shelf life at this stage is described below:

- Get threshold values of temperature ($0^0C - 2^0C$), the activation energy E_a, the gas constant R, A_0, A_e and the minimum shelf life threshold (set to 14 days).
- Set the degradation rate at the ambient temperature k_r as k_i.
- Set the shelf life at the prevailing ambient temperature S_L as S_{Li}.
- WHILE S_L != 0, Start the monitoring loop.
- Acquire current values of environmental variables. The temperature of the cases $(C_1, C_2, \ldots, C_j)$ will be measured in each of the pallets $(P_1, P_2, \ldots, P_i)$. Thus, a

temperature matrix is formed accounting for each of the cases within the pallet:

$$\begin{pmatrix} P_1: & T_{11} & T_{12} & T_{13} & \dots & T_{1j} \\ P_2: & T_{21} & T_{22} & T_{23} & \dots & T_{2j} \\ \vdots & & & & & \\ P_i: & T_{i1} & T_{i2} & T_{i3} & \dots & T_{ij} \end{pmatrix}$$

- FOR each element in the matrix, compare T_{ij} with the reference values;
    * IF temperature falls within threshold,
    * THEN degradation rate and the shelf life remains the same.
    * ELSE calculate: (a) the new degradation rate (k) with equation 5.14; (b) the new quality attribute concentration with Equation 5.5; and (c) the new shelf life with equation 5.9.
    * END IF
- Send an alert if shelf life falls below the required threshold.

• END WHILE

Although similar to the algorithm used in computing the shelf life in the field, this algorithm differs in that it factors the shelf life and degradation rate of the produce computed in the field in determining the 'new shelf life'. This allows for an accurate estimation of the shelf life at any point during the supply chain. The rate of water loss is determined from the algorithm below:

• Get the transpiration coefficient T_{value} for blackberry fruit, the maximum permissible water loss (water loss threshold).

- REPEAT
  - Start the monitoring loop.
  - Acquire current relative humidity value and supply air temperature.
  - Fetch the vapor pressure of the ambient air in the truck based on the relative humidity (V_a).
  - Acquire current values of environmental variables. The temperature of the cases $(C_1, C_2, \ldots, C_j)$ will be measured in each of the pallets $(P_1, P_2, \ldots, P_i)$. Thus, the temperature matrix used during the calculation of the shelf life is retrieved:

$$\begin{pmatrix} P_1: & T_{11} & T_{12} & T_{13} & \ldots & T_{1j} \\ P_2: & T_{21} & T_{22} & T_{23} & \ldots & T_{2j} \\ \vdots & & & & & \\ P_i: & T_{i1} & T_{i2} & T_{i3} & \ldots & T_{ij} \end{pmatrix}$$

  - For each element in the matrix, fetch the vapor pressure of the cases (V_c) at 100% relative humidity. This can be retrieved from a psychometry lookup table stored in the fog memory.
  - Subtract (V_a) from (V_c) to get the vapor pressure deficit.
  - compute the water loss using Equation 5.15.
  - Send an alert if rate of water loss falls above the required threshold days.
- UNTIL rate of water loss reaches the threshold.

The packing house manager is alerted if the shelf-life and water loss within the case drops below the reference values.

5.1.5 Monitoring in the Packing House

Upon arrival at the packing house, Fog Node 2 prepares a summary of recommendations and outputs based on the history of shelf life and sensor readings. These include: (i) the unloading sequence for the pallets; (ii) pre-cool load order; (iii) the total time spent in transit; (iv) the total time spent in the field and (v) the shelf life left. The data in the fog nodes (temperature and relative humidity readings per case, alert history, time used in each process as well as shelf life per case) are offloaded to the cloud facilities via WAN or wireless LAN for further storage and analysis.

Analyses carried out in the cloud are process modeling and predictive analysis. This is to answer questions such as, ‘If pallets 1 through 10 sit out an extra hour, so that pallets 11 to 20 can be prioritized in the pre-cool, can we still meet the shelf-life commitments and requirements for those first 10 pallets?’ Analysis can evaluate thousands of potential options and come up with the best combination of actions, guided by the goals, preferences, and constraints of the operation. It also provides summary analytic data. This data is organized by process step (at the field, field to packing house, pre-cooling), and compares performance over time (day to day, week over week, etc.) and by equipment or crew. This allows the grower to optimize performance for each process step, and experiment with new procedures while monitoring performance.

The cases are further re-arranged at the packing house according to their shelf life and pre-cooled. This is to allow uniform shelf-life pallets to be packed up for transit.

Figure 5.4 summarizes the entire process from Field to Packing house:

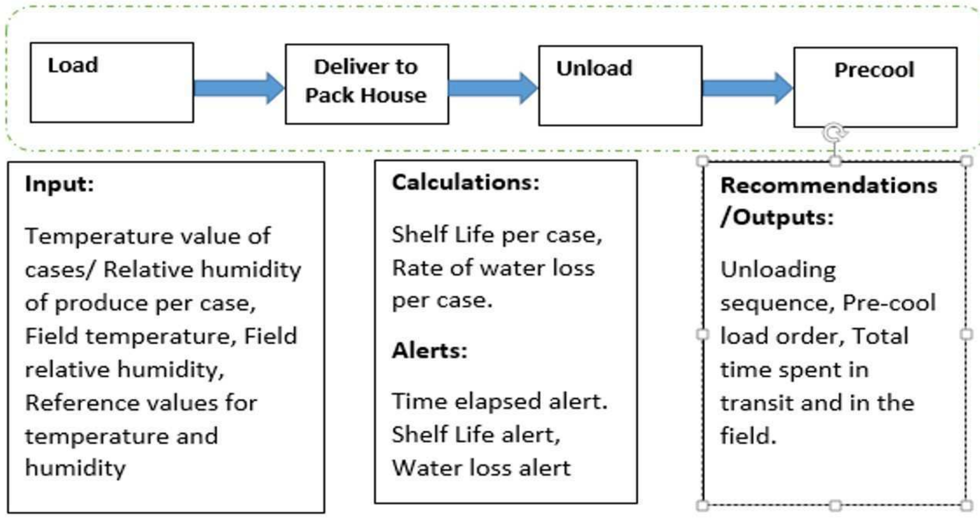

Figure 5.4: Computations and alerts from the Field to the Packing House

5.2 PHASE 2

5.2.1 Monitoring during transit from Packing house to Distribution Centers

We assume the following: (i) the pallets have been pre-cooled to the required pulp temperature; (ii) the refrigerated truck is pre-cooled adequately before it is loaded with the produce; (iii) the truck is airtight; (iv) the refrigerated truck can provide controlled atmosphere thus significantly reducing the heat of respiration; (v) the pallets are properly loaded into the truck (centerline); and (vi) the pallets are properly braced to prevent them from sliding during transit. In this instance, the main function of the fog nodes is to ensure that the temperature of the produce does not exceed a given threshold (this is defined as 1^0C for blackberries), the humidity is maintained at 90-95% and the CO_2 concentrations are kept between 10-20%. In order to achieve this, Fog Node 2 is connected to actuators/controllers programmed to maintain the desired concentrations of O_2, CO_2 and humidity. Additional sensors such as light sensors are also deployed at the doors of the truck to ensure that the truck door stays closed to optimize cooling. At this point, the only heat left to be monitored is the heat accumulated due to improper/poor circulation and solar effect on the indoor temperature. Average sun-shade difference for outdoor temperature reaches more than 7^0C and so, walls exposed to sun radiation show clearly differentiated thermal patterns compared to shaded ones. The environmental parameters to be monitored at this stage include: temperature, humidity, carbon dioxide, oxygen and light intensity.

5.2.2 Computation in Fog Nodes

Estimation of Air-Circulation: Pearson product-moment correlation coefficient: An efficient air circulation system distributes air uniformly throughout a loaded semi-trailer. The air circulation system is a closed loop that starts at the discharge of the blower, through and around the load, and returns to evaporator for conditioning. The uniformity of air distribution is affected by the availability of air channels around and between the pallets. If sufficient air channels are available for air movement, any variation in the supply air temperature will result in a similar variation in air temperature everywhere throughout the entire load. Performance of the air circulation system is independent of the refrigeration system set-point and return air temperature. Its performance can be measured ultimately, by the uniformity of air temperature surrounding the load. The semi-trailers used in the case study had top-air delivery systems. Similarly, most refrigerated trucks use top-air delivery system.

The Pearson product moment correlation coefficient, denoted by r, assesses the relationship between the temperature of the supply air and of air present within the cases inside the trailer. It describes how closely air temperature at various points in the load varies with the supply air temperature. When airflow is uniformly distributed inside the trailer, air temperature at any location within the trailer would remain close to the supply air temperature and a positive correlation would be obtained. To examine the uniformity of air distribution within the truck, air temperature measured at each case is correlated to the supply air temperature over time. This is done by placing new sensor embedded tags within the cases and at the blower of the refrigeration system in the truck. The computation is carried out after the following events: (i) pallets are loaded into the truck; (ii) truck doors are shut tight; and (iii) truck cooling system is stabilized.

The Pearson correlation coefficient is calculated using the following equation

$$r = \frac{S_{12}}{\sqrt{(S_1)^2(S_2)^2}} \tag{5.16}$$

$$= \frac{\sum(X_1 - \overline{X_1})(X_2 - \overline{X_2})/(n-1)}{\sqrt{\sum(X_1 - \overline{X_1})^2/(n-1)}\sqrt{\sum(X_2 - \overline{X_2})^2/(n-1)}} \tag{5.17}$$

$$= \frac{\sum(X_1 - \overline{X_1})(X_2 - \overline{X_2})}{\sqrt{\sum(X_1 - \overline{X_1})^2}\sqrt{\sum(X_2 - \overline{X_2})^2}} \tag{5.18}$$

where:

- r is the Pearson correlation coefficient of variables X_1 and X_2 where X_1 is the supply air temperature and X_2 is the temperature within each of the case.
- S_{12} is the covariance between X_1 and X_2.
- S_1 is the variance of X_1.
- S_2 is the variance of variable X_2.
- X_1 is the first random variable (supply air temperature).
- $\overline{X_1}$ is the mean of X_1.
- X_2 is the second random variable (temperature within the case).
- $\overline{X_2}$ is the mean of X_2.
- n is the number of samples.

The magnitude of r varies from -1 to 1. A value of 1 indicates that the air temperature at a point inside the trailer increases linearly with the supply air temperature. A value of 0 indicates that there is no association. A value of -1 indicates a perfectly negative association between the two temperatures, i.e. air temperature at a point decreases linearly with an increase in supply air temperature.

Sensor readings begin as soon as the truck is loaded and truck doors are closed. Fog Node 1 collects sensor readings from the tags every 5 minutes. The readings include the EPC code, temperature, humidity, O_2 and CO_2 values as well as light intensity. Fog Node 1 also collects the supply air temperature from the blower. These readings are transferred to Fog Node 2 where shelf life computations, relative humidity, O_2, CO_2 and light intensity are analyzed. The results of these readings are communicated to the controller for automatic adjustments where necessary. To monitor the air circulation within the truck, the Pearson product moment of correlation is computed on an hourly basis by correlating the temperature of each case (over the last hour) with the temperature of the supply air.

Table 5.2 shows the flags for triggering alerts within the fog device:

5.2.3 Implementation

In this section, we present the results of a simulation of Fog Computing environment for the blackberry case study to validate the proposed architecture in Chapter 3 [60]. Then, efficiencies of the two placement strategies (i.e. cloud-only and edge-ward) were evaluated in terms of latency and network usage for Phase 2 blackberry case study .

5.2.3.1 Simulation Toolkit

iFogSim is a simulator used to model IoT and Fog environments and measure the impact of resource management techniques in terms of latency, network congestion

Table 5.2: Monitoring and actuation in Fog Nodes

Parameters monitored by sensors	Conditions to trigger alert	Actuation carried out by fog nodes
The supply air temperature from the refrigeration unit and the temperature within the cases in the truck.	If the magnitude of r is less than 0, this implies poor air circulation leading to uneven cooling in the truck.	Shelf life of cases is recomputed by 'Fog Node 2' and the current degradation and shelf life values are stored on each tag. Truck can be diverted to the nearest environmentally controlled facility. Upon arrival, the truck driver checks to see if there are obstructions in the movement of air. If checks to see if there are any, they are cleared.
Relative humidity/ Carbon dioxide	Humidity values fall below or exceed threshold values; Carbon dioxide/oxygen concentrations fall below or exceed threshold values.	Automatic adjustments are carried out by the fog node by sending a signal to the controller to reduce/increase the humidity/carbon dioxide and oxygen levels to the required level.
Light	Light intensity exceeds threshold	Truck driver should ensure that the doors are properly shut.

and energy consumption [28]. iFogSim is packaged with two application module placement strategies – cloud-only placement and edge-ward placement.

- Cloud-only placement: The cloud-only placement strategy is based on the traditional cloud-based implementation of applications where all modules of an application run in data centers. The sense-process-actuate loops in such applications are implemented by having sensors transmitting sensed data to the cloud where it is processed and actuators are informed if action is required.

- Edge-ward placement: Edge-ward placement strategy favors the deployment of application modules close to the edge of the network. However, devices close to the edge of the network – like routers and access points – may not be computationally powerful enough to host all operators of the application. In such a situation, the strategy iterates on Fog devices towards cloud and tries to place remaining operators on alternative devices [28].

5.2.3.2 Performance Evaluation: Latency

The number of sensors for each sensor type (temperature, humidity/CO_2, Light) was varied from 1 to 4. This was done to check the effect of additional sensors in the truck on the latency with fog nodes and actuators. Figure 5.5 [60] illustrates the latency when the truck is equipped or treated as Fog node using the proposed architecture. Fog Node 1 and Fog Node 2 are able to maintain the latency to the minimum even when number of sensors were increased. This is because the data generated by the sensors are minimal and the truck is still able to handle the traffic without additional delay. The difference of latency between humidity/CO_2 and temperature/light is because in case of humidity/CO_2 the action is taken by Fog Node 2 without human intervention and hence it has one less hop [60].

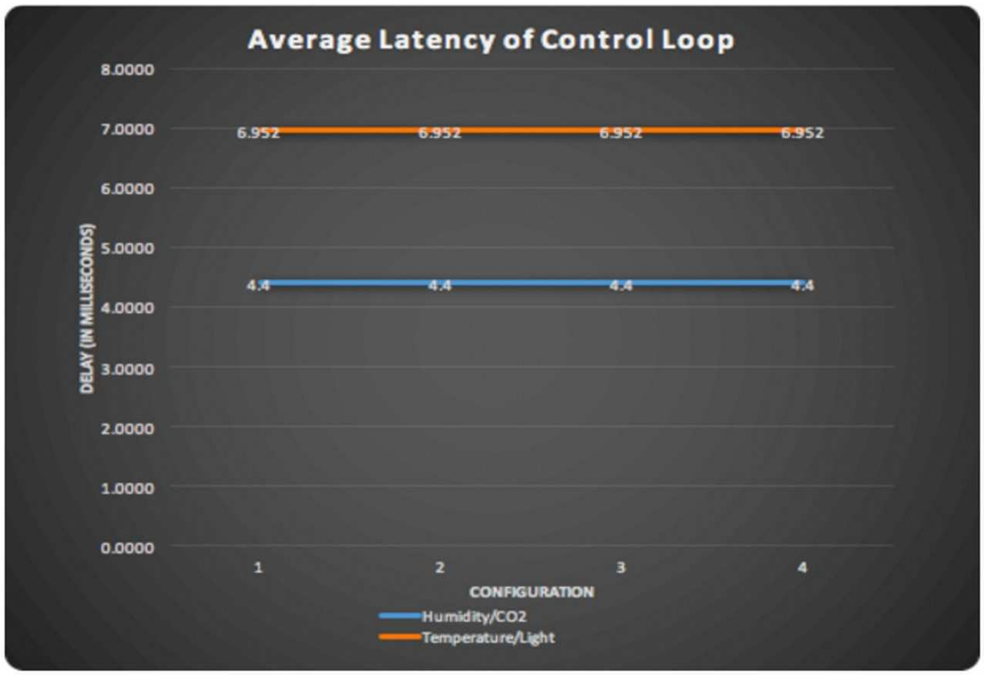

Figure 5.5: Latency in truck with Fog Nodes (Edge-ward placement)

Figure 5.6 [60] depicts the latency without fog node (truck sends data to cloud only). The latency introduced by cloud based deployment is approximately thirty times higher than fog deployment.

5.2.3.3 Performance Evaluation: Network Utilization

In the case of fog deployment, the data is read by Fog Node 1 in real time basis and the estimation of the shelf life is done by Fog Node 2. Due to the analysis and calculation near to the edge the network utilization in fog deployment is significantly less than

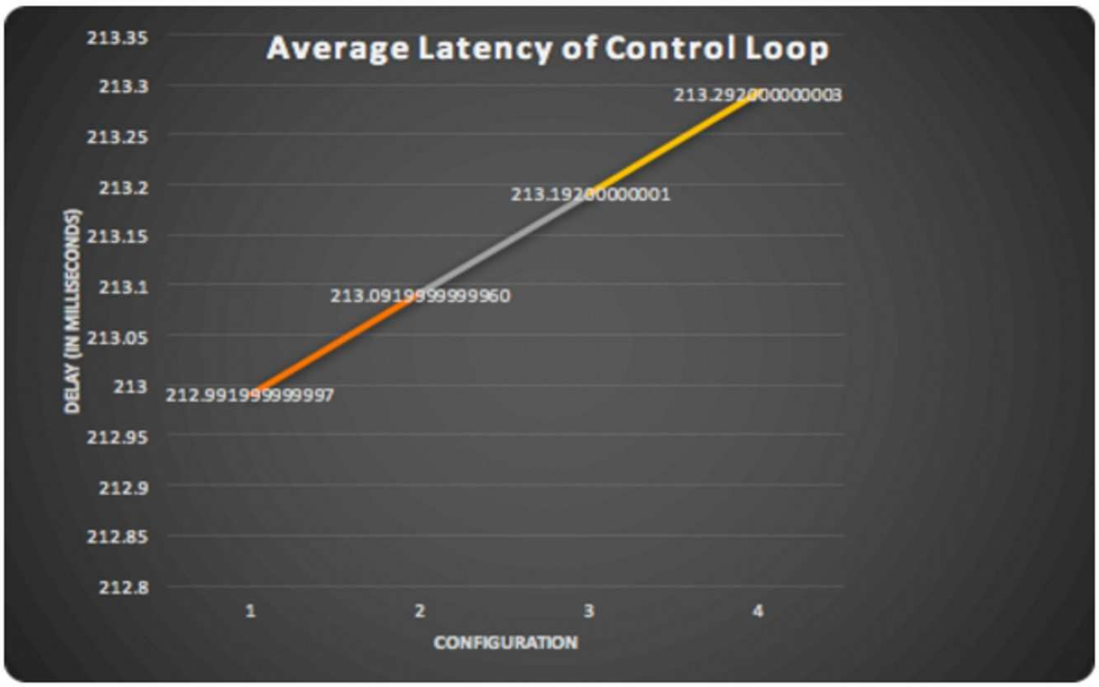

Figure 5.6: Latency in truck without Fog Nodes (Cloud-ward placement)

cloud deployment. The data that is sent by fog node to the cloud is for historical analysis and does not affect the environmental control. The utilization, however, slightly increases with the increase in sensors which is expected as the utilization is calculated for its entirety. In case of cloud-only deployment, the data is stored in the internal memory of the tag in every three hours interval. The amount of data gathered in three hours is significantly higher which contributes to large amount of network utilization.

The comparison of the network utilization can be seen in Figure 5.7 [60].

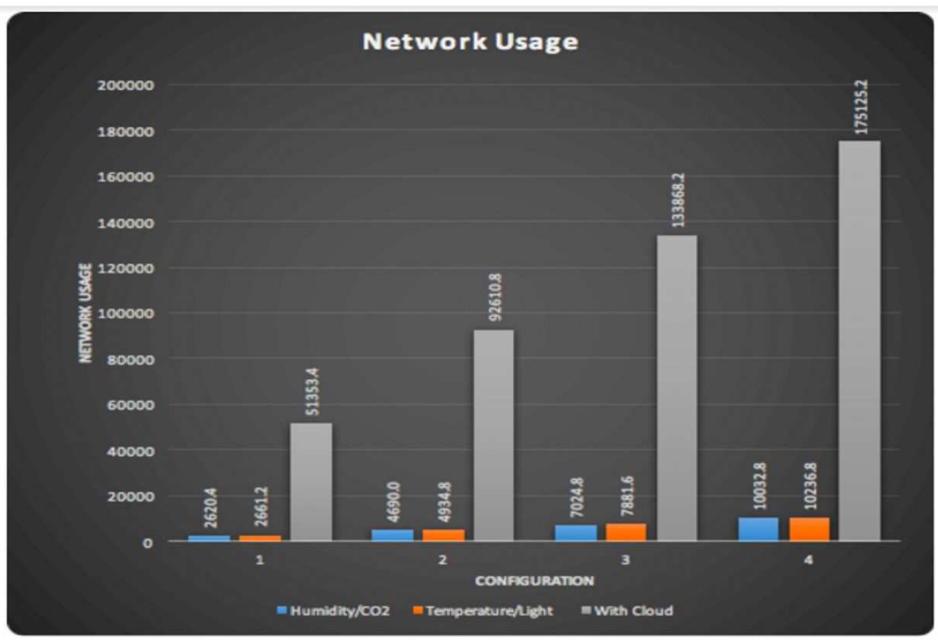

Figure 5.7: Network utilization (in Kb)

5.3 Storage Optimization in the Fog Node

From the blackberry case study, it takes an average of 225 minutes to load the truck on the field and transport it to the packing house. We assume that every case contains a sensor and the truck can take an average of 21 pallets (120 cases per pallet) per trip and that all the data are stored within the duration. If the temperature and humidity sensor readings are streamed every 5 minutes and stored, it would require an average of 4 MB to store the data within this period. However, for optimization of memory, in the absence of regulatory and compliance requirements, it is possible to adjust the frequency of storage according to the degradation rate (k-value) measured. This storage method beneficially allows the sensing of the environmental parameters with the shortest/best possible time interval while keeping the consumption of the fog memory to a minimum. This also allows for a more precise monitoring due to short sampling intervals while the monitoring time can be increased without having to implement costly and/or voluminous storage units.

To optimize storage, the method starts with an initialization, the first temperature and humidity values in fog node 2 are stored, and the degradation rate is computed. Based on this rate, the storage interval is defined with appropriate measured values being stored. The higher the degradation speed or k-value for a specific case, the shorter the interval of storage. The time interval between two stored measurements is preferably in a range, such that the calculated k-value based on the current measured environmental parameter does not exceed a predefined 'degradation step' (this value is defined by the grower based on the type of produce). At the next sampling time, the temperature and humidity values are measured and the degradation difference since the last data storage is calculated. If the degradation difference is greater than the degradation step, the immediate previous sensor readings are stored. If not, the readings are discarded and the method returns to the start of the loop. The algorithm in Figure 5.6 illustrates this.

Algorithm 1 Storage Optimization Function in Fog Node 2 for Shelf Life Computation

Require: Shelf-life (S_L), Temperature (T_{first}), Activation energy of produce (E_a), Gas Constant (R), the pre-exponential factor (K_0) and the Degradation Step (D_{step}).

set *time-counter* = 0
get temperature (T_{first}) readings from sensors
store first time and temperature readings
calculate the degradation rate or k-value using the Arrhenius equation (eqn. 5.10)
increment time counter
get new temperature (T_{new}) readings from sensors
while (S_L) > 0 and $T_{new} > 2^0C$ or $T_{new} < 0^0C$
calculate the new degradation rate: k_{new}
if k_{new} - k-value > D_{step} **then**
    store T_{new}
else
    discard T_{new}
end if
end while

Figure 5.8: Storage function in Fog Nodes

5.4 Arrival at the Distribution Center and Retail

To ensure 'quality-driven' distribution of produce at the distribution center, the application of a FEFO management system requires knowledge of the remaining shelf-life of the food. Therefore, upon arrival at the distribution center, Fog Node 2 offloads the result summary (comprising the shelf life of each case, the degradation rate, sensor readings, and alerts generated) to the cloud, which is integrated into the distributor's planning and reporting system. This is utilized by the distribution manager to distribute the goods to the retailer in a FEFO fashion. It also provides flexibility to adjust the destination of the produce to match its current quality state.

A relevant approach at retail is the implementation of a dynamic shelf-life assessment (DSLA) system. In a DSLA system, the expiration date (or use-by, sell-by, or best-before date) of a food is adjusted considering its time-temperature history [42]. A shelf life that is representative of the food's true quality is thus established, reducing waste caused by conservative expiration dates. In addition to waste reduction, knowledge of the time-temperature history can also be used to identify perishable food that has been subjected to severe temperature abuses that may have compromised its safety. The product at risk can be removed by retailers, and there is thus an additional barrier against food-borne outbreaks resulting from cold chain failure. An additional improvement at retail resulting from knowledge of the time-temperature history of a food is the implementation of a dynamic pricing system. Such a system is based on the assumption that a food product with a longer remaining shelf-life has greater value than a food product that has to be consumed quickly. This system can reduce food waste by providing an economic incentive to buy food with a short remaining shelf-life, which may otherwise be wasted when fresher products are continuously available.

5.5 Adapting the Fog Computing Architecture to General Perishable Goods Supply Chain

We have examined the integration of the fog architecture proposed in Chapter 4 to the blackberry supply chain. This solution can be easily applied to other fruits in the berries family such as raspberry and blueberry. However, the perishable supply chain includes items more diverse than fresh fruits and vegetables. Prompted by regulations and economics, the cold chain has broadened. Other items that require climate-controlled handling include:

- *Pharmaceuticals*: The blood and vaccines supply chain are extremely sensitive to temperature and may become unsafe to use if optimal temperature thresholds are breached. The links in the blood supply chain consists of collection sites, blood centers, distribution centers, as well as points of demand, which, typically, include hospitals. Many of these collection sites are mobile or temporary locations while others are permanent sites. Whole blood (WB) is shipped after being collected at the collection sites to the blood centers. At the blood centers, the collected blood is separated into parts, e.g., red blood cells, platelets and plasma, since most recipients need only a specific component for transfusions. The blood is also tested for multiple infectious disease markers, including but not limited to HIV, hepatitis, and the West Nile Virus. If the result of a test for a specific unit of donated blood at the testing lab turns out to be positive, the remainder of that unit will be discarded. Thereafter, the processed blood is shipped to the Distribution Centers (DCs). Distribution centers act as trans-shipment points, and are in charge of facilitating the distribution of blood to the ultimate destinations.

An efficient cold chain system must be in place to ensure that all blood and blood components shipped by or received into a blood bank or blood transfusion service have been maintained within the correct temperature ranges. Red blood cell components must be kept at a temperature of 2^0C to 10^0C during transportation. All frozen components should be transported in a manner to maintain their frozen state. The transit time for blood and blood components should not normally exceed 24 hours. Upon arrival at the DCs or hospitals, they should be kept at 2^0C to 6^0C. Whole blood is not vulnerable to degradation of shelf life but is susceptible to bacterial contamination if the temperature exceeds the threshold [53].

For vaccines, the cold chain distribution process officially begins when a product is released from a manufacturer's warehouse. From that point on, the cold chain process begins. The cold chain is a complex series of multiple touch points, facilities, vehicles, modes of transportation, and personnel that ultimately ends with the administration of a medication to a patient. The optimum temperature for refrigerated vaccines is generally between 2^0C and 8^0C. For frozen vaccines the optimum temperature is -15^0C or lower. Vaccine shelf life is best managed through determination of a minimum potency release requirement, which helps assure adequate potency before expiration. The laws of kinetics such as Arrhenius behavior help practitioners design effective accelerated stability programs, which can be utilized to manage stability after a process change. Therefore, it is possible to accurately determine a vaccine degradation rate and predict the shelf-life of bio-products stored in refrigerated condition after temperature breaches occur [15].

- *Fresh cut flowers*: cut flowers require strictly controlled temperature and humidity levels to preserve freshness and quality. The links in the supply chain are similar to the blackberry supply chain.

- *Fine art and antiques*: controlling humidity and temperature are vital for shipments of art, antiques, collectible vehicles, and other valuable items. These items often travel long distances in a controlled climate of about 70^0F with around 55% relative humidity. Temperature and humidity excursions might result in deterioration which include: (i) dimensional change: paint and other finishes may crack, fibers can break and lamination can get undone; (ii) chemical reaction: paper can disintegrate and turn yellow, metals can corrode, glass could cloud, salts may crystallize and dyes can fade; and (iii) bio-deterioration: mold growth and bacteria growth on art may cause staining or devour the entire piece.

- *Chemicals and engineered materials*: climate control helps to reduce the likelihood of a chemical reaction that could result in a fire or explosion or affect the load's quality.

Primary environmental parameters usually controlled during transit of perishable items are temperature, relative humidity, and concentrations of O_2, CO_2, and ethylene. The 'optimum' storage environment for each commodity is designed to maintain these variables within a set of limits that produces the maximum storage life for most of the individual members of the commodity. These environmental parameters however vary per perishable item as shown in Figure 5.9.

Perishable Items	Environmental Parameters to be Monitored				
	Temperature	Relative humidity	Carbon dioxide	Ethylene	Oxygen
Berry fruits e.g. raspberry, blueberry and blackberry	Yes	Yes	Yes	No	Yes
Blood products e.g. blood plasma	Yes	No	No	No	No
Cut flowers	Yes	Yes	Yes	Yes	Yes
Fine arts/ Antiques	Yes	Yes	No	No	No
Chemical materials e.g. heavy metals, radioactive materials	Yes	Yes	No	No	Yes
Vaccines	Yes	No	No	No	No
Avocado, Brussel sprouts, green onions, and asparagus	Yes	Yes	Yes	Yes	Yes

Figure 5.9: Environmental parameters to be monitored for general perishable items

Computations to be carried out by fog applications, conditions to trigger alerts and actuations for each perishable item is shown in Figure 5.10.

The algorithm in Figure 5.11 describes the method for monitoring quality of perishable items using the proposed architecture.

Perishable Item	Computation to be carried out by Fog application	Condition to trigger alert	Actuation required
Blood products	Check if temperature value of the unit is within the threshold for the product.	Temperature exceeds or falls below threshold values.	Discard the affected blood unit. Fix the refrigeration unit quickly or transport to the nearest cooling facility.
Vaccines	Check if temperature value of the unit is within the threshold for the vaccine and shelf life computation.	Temperature exceeds or falls below threshold values.	Isolate and label affected vaccines with "Quarantine" and date of cold chain break. Fix the refrigeration unit quickly or transport to the nearest cooling facility. Store the vaccines at appropriate temperature and continue monitoring the storage unit conditions.
Fine arts	Check if temperature and humidity values fall below or exceed the threshold for the item.	Temperature and/or humidity exceed or fall below threshold value.	Ensure refrigeration unit is working well to keep items in optimal climate condition. Automatic adjustments can be performed by the controller to restore oxygen and humidity levels to the required threshold.
Chemical materials	Check if temperature, humidity and oxygen values fall below or exceed the threshold for the item.	Temperature exceeds threshold value.	Automatic adjustments can be performed by the controller to restore oxygen and humidity levels to the required threshold. Fix the refrigeration unit quickly or transport to the nearest climate controlled facility.

Figure 5.10: Monitoring and actuation in fog nodes for general perishable items

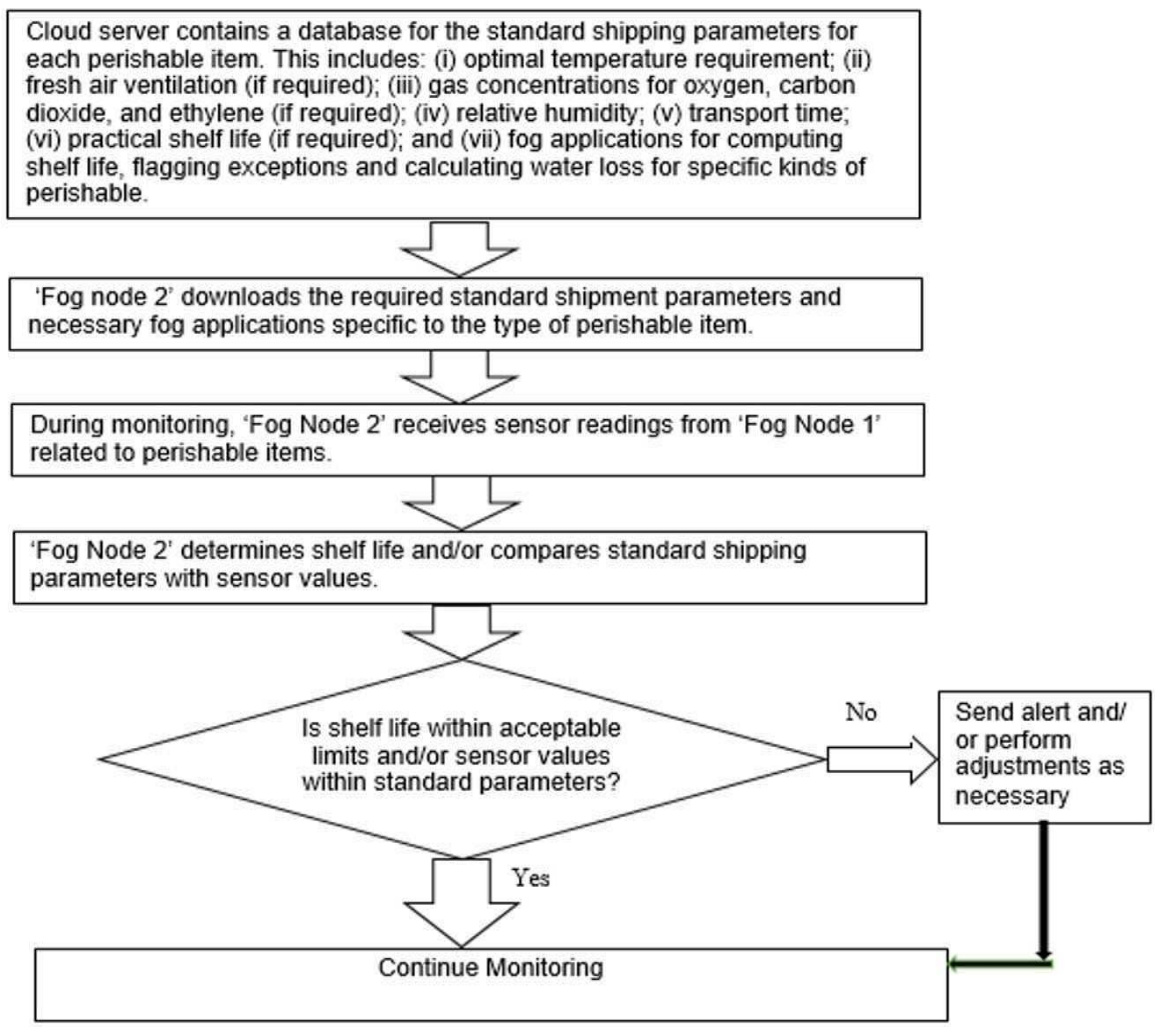

Figure 5.11: Workflow for monitoring other perishable items using the proposed framework

5.6 Enforcing Constraints for Control Applications Using Ontology

Control applications form an essential part of the IoT ecosystem as they enable automation and implementation of high level policies with little oversight. Examples include home heating systems, irrigation systems, drone delivery system, autonomous mining etc. Each of these control applications needs to operate within constraints dictated by the domain. For example, a home heating application needs to control the temperature of air supplied to the house based on external influences such as weather and availability of solar power or energy storage. Moreover, an intelligent control system needs to respond to events from the utility by reducing power demand and sacrificing comfort. User preferences dictate that temperature be within a narrow range when the house is occupied. In addition, the air supplied needs to ensure the humidity, air quality and air flow remain within a comfortable range.

Device to device communication can lead to unprecedented automation. However, to process the data generated by IoT, we need a common data model across different sources. Domain specific schema and ontologies have been proposed to map the IoT data to a standard representation. With a semantic ontology[1], it is possible to represent relationships between system entities and incorporate these dependencies into the data analysis. However, most data models are focused on representing information for data analysis. The data models provide little support for applications that can make actuation decisions within the IoT system, and mechanisms for control are

[1]Semantic Sensor Network Ontology: https://www.w3.org/2005/incubator/ssn/ssnx/ssn

implemented in an adhoc manner by application developers. We explore methods to model such constraints using the example of a truck cooling system.

5.7 Truck Cooling System for Perishable Produce

The refrigerated truck contains an insulated enclosure divided into a cooling space and a transport volume. Typically, the transport volume is loaded with perishable produce such as meat, vegetables and fruit, etc. The setpoint temperature is then chosen to reduce quality degradation of the perishable produce. The cooling space may be separated from the transport volume by a panel equipped with one or more openings to allow a return air flow from the transport volume into the cooling space and a supply air temperature flow from the cooling space into the transport volume. The air flow through the cooling space typically passes by a return air temperature sensor and a supply air temperature sensor. In such systems, the return air temperature sensor typically measures the temperature of air returning from the transport volume while the supply air temperature sensor measures the temperature of air supplied to the transport volume. A thermostat ensures that the supply air temperature is equal to or close to the set point temperature. The thermostat also provides feedback to the users and captures their temperature preferences. For perishable fruits and vegetables, controllers are employed to control the oxygen and carbon dioxide concentrations in accordance with the programmed and desired values dynamically and continuously.

Control knobs present in this system include: (i) thermostat; (ii) humidity regulator; (iii) fan/blower; and (iv) carbon dioxide and oxygen regulator. The cooling control system has to take many constraints into consideration and they include: (i)

User preferences may dictate that temperature and humidity controllers be turned off during the night time if the weather is cool and may resume operations during the day as the temperature increases; (ii) For frozen commodities, typically shipped at setpoints ranging from -10^0C to -20^0C, it is especially important that produce temperature is not too far above the setpoint. Therefore for setpoints below -10^0C, it is common practice to control a measured return air temperature closely to the setpoint; (iii) For chilled commodities, typically shipped at setpoints above -10^0C, both too high and too low produce temperatures are undesirable; and (iv) The temperature of produce within the truck should not fall outside defined limits during defrost cycle. To achieve this, air circulation within the truck should cease during defrost as the temperature of the setpoint is raised by the heater in the refrigeration system.

Semantic ontologies provide a systematic way to model relationships between different entities of interest in a domain and have been successfully used to represent domain knowledge in a wide variety of applications. Figure 5.12 shows the dependencies in a truck cooling system. The dependency graph provides a mapping of entities in the application domain. However, constraints in a system depend not only on the entity relationships, but also the real-time values of these entities. A model of the system state space is needed to precisely define the constraints in the system. Figure 5.13 shows a simple example of a state space model, with five essential entities in the truck cooling example. The current operating point of system can be changed in multiple ways, each of which may violate the specified constraints for blackberries. The state space model can represent the constraints in the system for each transition as shown in the figure. With such a state space model, we can analyze the system

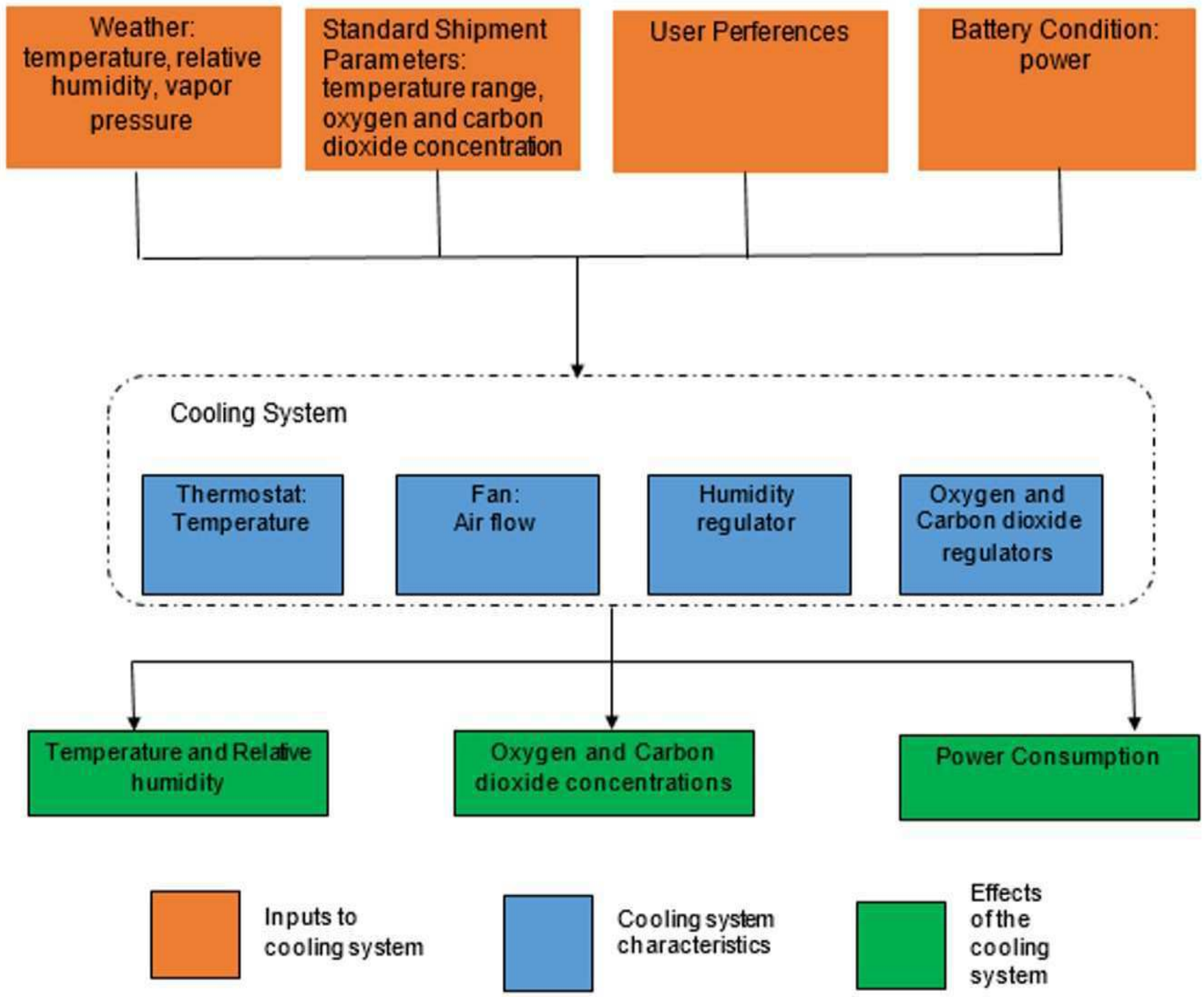

Figure 5.12: Model of dependencies between different entities in a truck cooling system

constraints (safe vs. unsafe) between different actuation decisions.

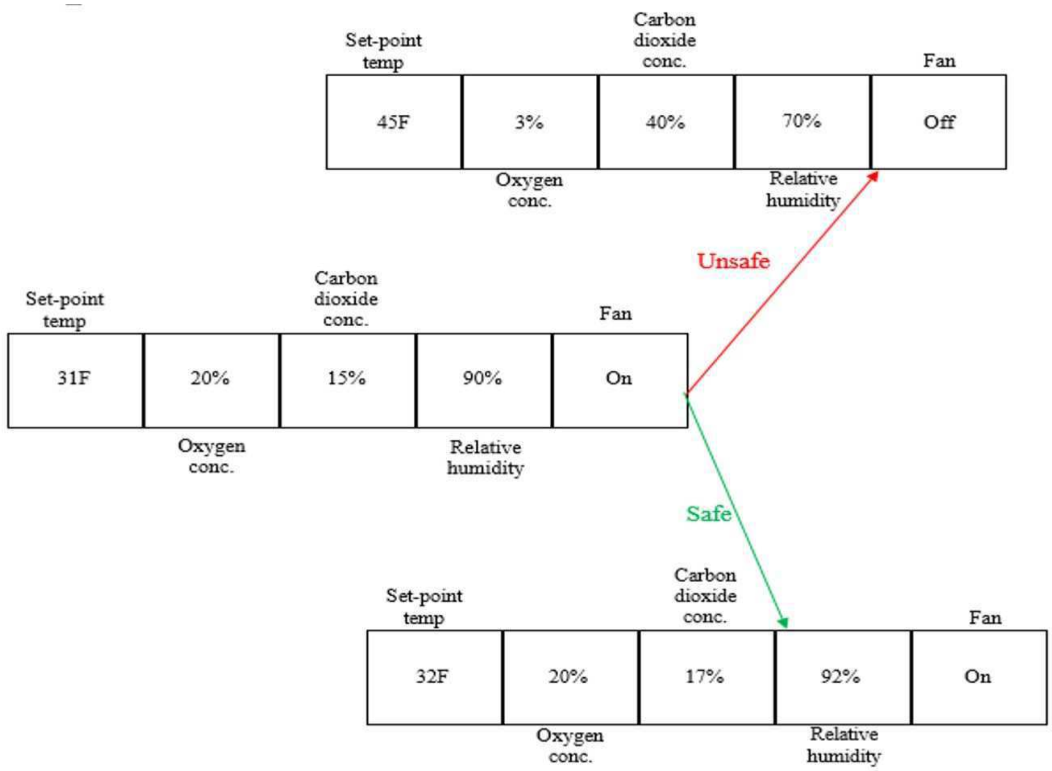

Figure 5.13: State space model capturing constraints specified by standard for blackberry

Chapter 6

Conclusion

6.1 Advantages of Fog nodes in the Blackberry Supply Chain

We examine the advantages of the fog nodes in each process step in the blackberry supply chain.

- *Phase 1*: This phase comprises the following steps: (i) harvesting of berries in the field; (ii) transportation of berries from the field to the packing house; and (iii) pre-cooling of berries at the packing house.

  Monitoring and Actuation without Fog Nodes

  Sensor readings were stored on the tags. No actuations were performed in the field and in-transit. Upon arrival at the packing house, readers were deployed at the receiving dock of the pack house. The readers downloaded the temperature history and uploaded it to the cloud servers via wireless area networks (local WiFi). Reading full temperature charts from the RFID data loggers at the receiving docks may be slow and this may introduce delay in uploading the data to the cloud. Furthermore, network connection and bandwidth may not be guaranteed introducing further delays. Cloud servers carried out shelf life computation for each pallet and provided a report that shows pallets with shelf life below the required threshold. Based on this information, the field manager groups the pallet for pre-cooling and distribution according to their shelf life. Due to the delayed action, 30% of the pallets suffered from shelf life loss.

Monitoring and Actuation with Proposed Fog Nodes

In the Field: Fog nodes deployed in the field can provide real time monitoring of berries. With the local compute and storage resources provided by fog nodes, berries can be monitored on a case level. Also, additional environmental parameter, relative humidity of the berries, can also be recorded by the tags. Major processing performed in this stage are the shelf life estimation of each case based on the time-temperature data and the water loss computation. Upon reception of sensor values, fog nodes compute shelf-life and if the shelf-life falls below a defined threshold, sends a notification to the field manager via his mobile phone. Upon reception of alert, field manager performs immediate loading of the cases/pallets into truck so they can be shipped to the packing house quickly. In other cases, if the berries had been left on the field for too long and their shelf life had expired, the field manager may dispose the berries rather than shipping them to the packing house.

In-transit to the Packing House: Sensor embedded RFID tags used in the field, are also deployed to monitor the refrigerated air to ensure that the ambient temperature of the truck is within the required range. The packing house manager and the truck driver would be alerted about the cases once the shelf-life drops below the reference values. While no actuations are performed in this stage, fine-grained monitoring and computation of shelf life are helpful for the following reason. The longest distance from packing house to the field in the case study is 4 hours. Therefore, at the worst case, the produce may travel for up to 4 hours before arriving at the packing house. Given that the field heat is still present in the produce and active respiration is ongoing, the produce would 'warm up' the temperature of the truck. The truck might take some time to reduce this temperature. The top-down air delivery/circulation would cool the top and front pallets while the middle and bottom temperatures remain warm. Since the shelf life is dependent on the deterioration rate which is also dependent on the temperature, the shelf life needs to be computed frequently.

At the Packing House: The data from the fog nodes are used to determine the priority of pallets/cases for pre-cooling and also for shipping to retail distribution center. The benefits provided by fog nodes are the following: (i) fog nodes eliminate the time delays associated with uploading the data to the cloud; (ii) they ensure that pallets/cases are promptly pre-cooled on a First-Expired-First-Out (FEFO) basis; and (iii) they reduce further degradation of freshness in the berries thus reducing wastage.

- *Phase 2*: This phase involves the shipment of berries from the packing house to the distribution centers.

  Monitoring and Actuation without Fog Nodes

  Upon arrival at the distribution center, the time-temperature history on tags was downloaded and the shelf life for each pallet calculated. The actual pallet-level temperature data, however, demonstrated that there was a wide variation in pallet temperatures within the trailer and therefore shelf life was reduced while the pallets were en-route in the trailer. As a result of the temperature variation inside the pallets in the trailer, 5 pallets experienced temperatures greater than $40^0 F$ resulting in accelerated shelf life loss. The ambient temperature of the truck however remained constant during the trip.

  Monitoring and Actuation with Proposed Fog Nodes

  Fog nodes deployed in the truck would ensure real time monitoring of the environmental parameters leading to real time actuations. Air circulation can be detected by correlating the temperature of the supply air with the actual temperature within the cases leading to immediate detection of uneven air circulation within the truck.

6.2 Potential Challenges facing the Implementation of Fog nodes in the Perishable Produce Supply Chain

The challenges are outlined below.

1. Capital costs: Unlike cloud computing, Fog deployments require capital investments in edge hardware and software.

2. Hardware maintenance burden: Although edge systems are hardened for remote unattended deployment, they still require site visits for deployment and hardware maintenance.

3. Site design: Because fog equipment is not deployed in a traditional data center, design and engineering may be complex. For example, equipment may require line-of-sight access to sensors, may need to be deployed on top of poles or rooftops, and may require zoning variances, permits, and/or leased space or access rights.

4. Tools for fog simulation: Real-world testbeds for evaluating performance of fog based policies are often very expensive to develop and not scalable in many cases. Therefore, for preliminary evaluation of proposed fog computing environments, many researchers look for efficient toolkit for fog simulation. However, very few fog simulators are available.

5. Security and Privacy Concerns: Security vulnerability of fog computing is very high as it resides in the underlying network between end device/sensors and

Cloud data centres. Also privacy mechanisms are needed to protect data in fog nodes closely associated with the users' situation and interest.

6.3 Conclusion

The limited shelf-life of perishable goods and their susceptibility to fluctuations in environmental parameters often lead to high loss rates in the perishable produce supply chain. Using the blackberry supply chain as a case study, the thesis explores the stages of the supply chain and the monitoring and actuation required. A Fog-Cloud model that can be used to provide seamless quality control in real-time from the field to the distribution centers with emphases on when, where and how fog nodes can be integrated into the blackberry supply chain is described. The blackberry supply chain use case was selected on literature review as a suitable candidate to study the Fog-Cloud model. Note that some results in this thesis appear in [49].

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