SAKARYA UNIVERSITY
INSTITUTE OF SCIENCE AND TECHNOLOGY

MODELING AND SIMULATION OF AN IOT ENABLED COLD CHAIN LOGISTICS MANAGEMENT SYSTEM

M.Sc. THESIS

Dini ABDURAHMAN

Department	**:**	**COMPUTER AND INFORMATION ENGINEERING**
Field of Science	**:**	**ENGINEERING**
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This thesis has been accepted unanimously by the examination committee on 31.05.2016

Associate Professor	**Assistant Professor**	**Professor**
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Head of Jury	**Jury Member**	**Jury Member**

DECLERATION

I declare that all the data in this thesis was obtained by myself in academic rules, all visual and written information and results were presented in accordance with academic and ethical rules, there is no distortion in the presented data, in case of utilizing other people's works they were refereed properly to scientific norms, the data presented in this thesis has not been used in any other thesis in this university or in any other university.

DINI ABDURAHMAN

31.05.2016

ACKNOWLEDGEMENTS

In the name of ALLAH, the Most Gracious, The Most Merciful, To Him belongs all praise.

Every work is a great effort, mine no less than anyone else's. I would therefore like to use this space thank those whose assistance has been invaluable to me. First and foremost, I would extend my gratitude to my advisor Prof. Dr. Celal Çeken for his endless and on-going efforts and supports he has providing me with throughout this work. Finally I would like to thank my family, friends and colleagues who supported me during this journey.

And all praise belongs to ALLAH, The Most Gracious, and The Most Merciful.

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LIST OF SYMBOLS AND ABBREVIATIONS

ASLT	: Accelerated Shelf-Life Test
BE	: Backoff Exponent
CA	: Collision Avoidance
CC	: Cold Chain
CCL	: Cold Chain Logistic
CD	: Collision Detection
CDMA	: Code Division Multiple Access
CRFID	: Computational Radio Frequency Identification
CSMA	: Carrier-Sense Multiple Access
CW	: Contention Window
DST	: Decision Support Tools
ED	: End Device
FDMA	: Frequency Division Multiple Access
FFD	: Full Functional Device
GSM	: Global System for Mobile Communications
GTS	: Guaranty Time Slot
IERC	: International Energy Research Centre
IERC	: IoT European Research Cluster
IMARC	: International Market Analysis Research & Consulting Group
IoT	: Internet of Things
M2M	: Machine to Machine
MAC	: Medium Access Control Layer
maxBE	: Maximum Backoff Exponent
NB	: Number of backoff
PAN	: Personal Area Network
QPSK	: Quadrature Phase Shift Keying

RFD	: Reduced Function Devices
RFID	: Radio Frequency Identification
SD	: Superframe Duration
SDMA	: Space Division Multiple Access
TDMA	: Time Division Multiple Access
ZC	: Zigbee Coordinator
ZED	: Zigbee End Device

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SUMMARY

Keywords: Cold chain logistics, Internet of Things, decision support, RFID, IEEE 802.15.4, Riverbed, Shelf-life

The Dramatic growth of world economy results growth in the supply chain which demands logistics service to be agile, flexible and responsive in the face of uncertainty, especially for temperature sensitive products that need to be monitored and managed in the cold chain. To achieve this, Logistics companies must be supported by appropriate information technologies. Internet provides an effective means of driving information between customer and logistics provider, however, existing gap between products flow and information flow in logistic service has created a problem in getting real-time information about temperature sensitive items which make logistics management more challenging for decision makers.

The growth of internet of things (IoT) gives a potential solution for monitoring, managing, and achieving real-time visibility and sharing information with the appropriate level of intelligence in cold chain industries. This paper demonstrates IoT enabled cold chain logistics that helps to enhance the decision support of all actors through managing, monitoring the real-time ambient temperature of the cold chain and predicting the shelf-life of temperature sensitive products inside the cold chain. In the study, real-time data of ambient parameters are gathered using IEEE 802.15.4 based wireless sensor networks and sent to the remote server through a gateway so that the shelf life of the products can be predicted by the decision support system developed. Radio Frequency Identification (RFID) is also used for identification of perishable goods inside the cold chain. All the devices and protocols employed in the study are modeled and simulated using event-driven Riverbed Modeler software.

NESNELERİN İNTERNETİ TABANLI SOĞUK ZİNCİR LOJİSTİĞİ YÖNETİM SİSTEMİNİN MODELLENMESİ VE BENZETİMİ

ÖZET

Anahtar Kelimeler: Soğuk zincir lojistiği, Nesnelerin İnterneti, karar destek, RFID, IEEE 802.15.4, Riverbed, raf ömrü

Dünya ekonomisinin etkileyici bir şekilde büyümesi, soğuk zincirde izlenmesi ve yönetilmesi gereken özellikle sıcaklık duyarlı ürünler için belirsizlik durumları karşısında etkin, esnek ve duyarlı olabilmek amacıyla lojistik hizmetleri talep eden tedarik zincirinde artış sağlamıştır. Bunun gerçekleştirilebilmesi için Lojistik şirketerinin uygun bilişim teknolojileri ile desteklenmesi gerekmektedir. İnternet kullanımı ile müşteri ve lojistik sağlayıcı arasında etkili bir bilgi akışı ortamı sağlanmaktadır; ancak lojistik hizmetindeki bilgi ve ürün akışı arasındaki mevcut açıklık, sıcaklık duyarlı nesneler hakkında gerçek zamanlı bilginin elde edilmesinde karar vericiler için lojistik yönetimini daha zor duruma getiren bir problem oluşturmaktadır.

Nesnelerin İnterneti alanındaki gelişmeler soğuk zincir sanayilerinde izleme, yönetme ve gerçek zamanlı görünürlük sağlama ve uygun zeka seviyesi ile bilgi paylaşımı alanında potensiyel çözümler sunmaktadır. Bu çalışmada soğuk zincirin gerçek zamanlı ortam sıcaklığını izleme, yönetme ve soğuk zincir içerisindeki sıcaklık duyarlı ürünlerin raf ömrünün tahmin edilmesi aracılığıyla tüm karar vericilerin karar desteklerini geliştirmeye yardımcı olan IoT erişimli soğuk zincir lojistiği gösterilemektedir. Çalışma içerisinde, gerçek zamanlı ortam verileri IEEE 802.15.4 kablosuz algılayıcı ağ yapısı kullanılarak elde edilmiş ve toplanan veriler bir ağ geçidi aracılığıyla sunucuya, ürünlerin raf ömürlerinin geliştirilen karar destek sistemi yardıyla tahmin edilebilmesini sağlamak üzere, gönderilmiştir. Ayrıca, soğuk zincir içerisindeki bozulabilir ürünlerin tespiti için Radyo Frekanslı Tanıma (Radio Frequency Identification-RFID) kullanılmıştır. Çalışma içerisinde kullanılan tüm cihazlar ve protokoller olay-güdümlü Riverbed Modeler yazılımıyla modellenerek benzetimleri yapılmıştır.

CHAPTER 1. INTRODUCTION

1.1. Background

Today's economy is driven by high competitiveness which requires manufacturing and logistics organizations to be agile, flexible and responsive in the face of uncertainties. An efficient supply chain is mandatory for improving business metrics, such as delivering high-quality materials and products within the agreed deadlines. Logistics is utmost important for supply chain operations and many times considered as one of the main sources of uncertainty for the organizations that form supply chains.

When logistics includes transporting perishable materials and products, such as food industry and pharmaceutical industry products, challenges faced by supply chain organizations are even more difficult to deal with and logistics practices of these goods are in public scrutiny. It is crucial to ensure the proper management of ambient temperature through the entire logistic process due to the short shelf life and perishability of food, temperature sensitiveness of medicine and biological products. Hence, every link such as storing, loading, transporting, and packaging becomes more difficult. Therefore, demand for controlling temperature sensitive goods using cold chain logistics (CCL) become an important topic for researchers and concern of the government and enterprises.

These challenges are related to the CCL that can affect the material and product quality when shipped from sellers, manufacturers or distributors to customers. The transportation of temperature sensitive materials and products using the established standard model, where no real-time control or monitoring is employed, can have severe undesired consequences. These challenges led businesses on the path to work towards improving their understanding about cold chain operations and seek new solutions to implement visibility and control of their supply chains. According to some report, annual losses in the global food industry are more than 750 billion USD [1] and in U.S only $35 Billion (industry estimate) food wastes in supply chain [2] .The above losses mainly resulted from the absence of proper facilities, improper food safety handling procedures, and lack of well-educated personnel in the area of the cold chain. Additionally, according to IMARC group's latest report titled "Global Healthcare Cold Chain Logistics Market Report and Forecast (2016-2020)" the annual global sale of pharmaceutical, medical and biological product which are dependent on CCLs are nearly 130 billion USD [3].

Through the past years, several technologies and methods have been used in monitoring CCLs. CCL services use Radio frequency Identification (RFID) applications for various temperature sensitive goods like pharmaceutical and food [4] [5] [6]. However, introducing IEEE 802.15.4 wireless sensor network (WSN), RFID and internet of things (IoT) paradigm can give a great possibility to be cognizant of CCL, by enabling real-time traceability and visibility of physical assets, thus make CC smarter like smart homes, smart city, smart grids and etc. [7].

1.2. Objective

This study aims to implement an IoT enabled CCL management system, which has the potential to enhance the decision support of both logistics providers and customers and is capable of improving operational processes, reducing costs and risks by means of real-time and continuous supervision and shelf-life prediction of temperature sensitive products using IoT enabling technology like RFID and WSN. For more realistic performance evaluation, the whole models and scenarios are implemented using discrete-event network simulator called Riverbed Modeler. In the study, basic characteristics and feasibility of deploying RFID and IEEE 802.15.4 devices are also examined. Riverbed simulation models for RFID and IEEE 802.15.4 devices are designed based EPCglobal Gen 2 and IEEE 802.15.4 standards, respectively.

1.3. Related Work

Information is more than power in supply chain industries, several works of literature has been studied and technologies, methods, and processes are already current practice and have been implemented. At present, cold chain monitoring is mainly performed by the use of data loggers and typically only during transport and not throughout the entire supply chain [8] [9]. Another still common approach found today is using data loggers that are read-out via a PC on a regular interval (daily, weekly), and all information is downloaded into a spreadsheet and printed. These kind of temperature monitoring systems are usually expensive and not automated, thus requiring manual inspection.

In [10] , besides RFID’s short-range product identification, the authors explained the new phase of RFID technology outfitted with sensors to extend its functionalities. Thus, helps for improving the performance of the cold chain through tracking and monitoring of perishable items. Computational Radio Frequency Identification (CRFID) tags are used to synthetically sense ambient temperature and detect abnormal event in cold chain management, thus, reduce the amount of lost and damaged perishable goods within developed IoT enabled environment [6].

Over the last decade, we saw the rapid development of wireless sensor networks in the cold chain. In [11], Sensor networks have been explored as powerful IoT enabling device for many applications, such as surveillance, tracking, locating, measuring, cold chain, and medical care, etc. Wireless sensors are used for demonstrating IoT paradigm through sensing the ambient temperature of the inside the cold chain for web-based real-time monitoring cold chain of blood [12]. The concept of an intelligent container that helps to reduce the food losses related to cold chain logistics are discussed in [13], the intelligent container employ smart sensors which enable to detect the critical situation of perishable items through collected temperature values. The temperature is measured directly from each pallet inside the container. If the remaining shelf of a pallet is known, it will help to reduce the food losses by implementing First-Expire First-Out (FEFO) strategy.

1.4. Structure of the Work

This thesis is organized in the following parts:

- CHAPTER 2. Gives a brief overview on internet of things concept at first and followed by introducing about the most common architecture of IoT, its enabling technologies and its applications, respectively.
- CHAPTER 3. Introduces IoT enabling devices and protocols such as; IEEE 802.15.4/Zigbee and RFID.
- CHAPTER 4. Focuses on the design and implementation of Riverbed simulation models of IoT enabled cold chain logistics, methodologies used for predication of shelf-life and depiction of simulation results and discussion.
- CHAPTER 5. Gives our conclusion with final remarks.

CHAPTER 2. INTERNET OF THINGS AND ITS' APPLICATIONS

2.1. Internet of Things

The main aim of IoT is rendering capability to things in order to communicate each other without restrictions of a time and place using certain infrastructure [14]. It is defined as a dynamic global network infrastructure where physical and virtual "things" are having unique identities, and physical attributes to incorporate with information network make things to be part of business and day to day's activities [4]. And also defined "A network of items each embedded with sensors which are connected to the internet [15]." IoT enables the gathering of real-time data which would be sensed through an environment such as humidity, localization, temperature, brightness, vibration and noise [5]. Thus, IoT applications are changing the way we work and live by saving time and resource and opening new approach for growth and innovation.

IoT application that needs sophisticated analysis, refined decisions and immediate replays, like context aware automation, resource allocation and optimization and asset tracking, needs IoT enabling device with an appropriate level of intelligence to sense or understand external environment and take necessary action to the external event without the help of human intervention [16]. Most commonly used IoT enabling device with technology that enables "things" to acquire and process contextual information is sensor networks, Nano electronics, RFID, M2M, mobile Internet etc.

IoT markets and stakeholders are extending in energy, manufacturing, automation, health, logistics as shown in Figure 2.1. and others take this device's capability as an advantage to improve their company's work.

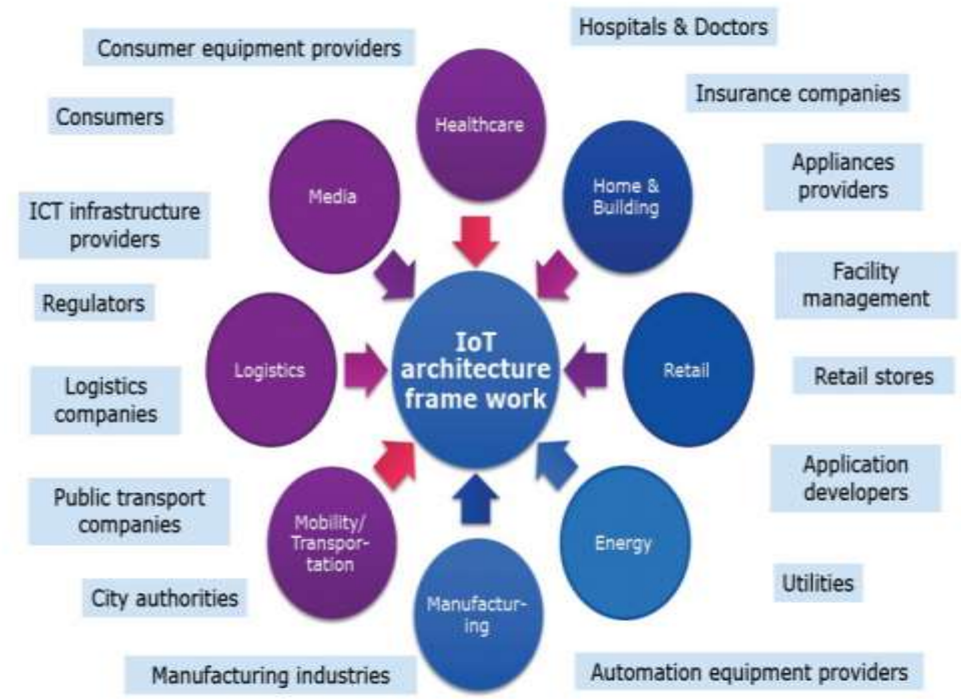

Figure 2.1. IoT market and stakeholder [8]

2.1.1. Architecture of IoT

Even though the concept of the Internet of Things has been under research for over a decade now, still many aspects are not clearly defined. For example, today there is no standardized and specific architecture according to globally recognized standard setting body for the IoT. Despite this lack of common agreement, there is a lot of studies are taking place, among studies The IEEE P2413 standards project currently considering the architecture of IoT as a three-tiered [15], with the layers explained in Figure 2.2.

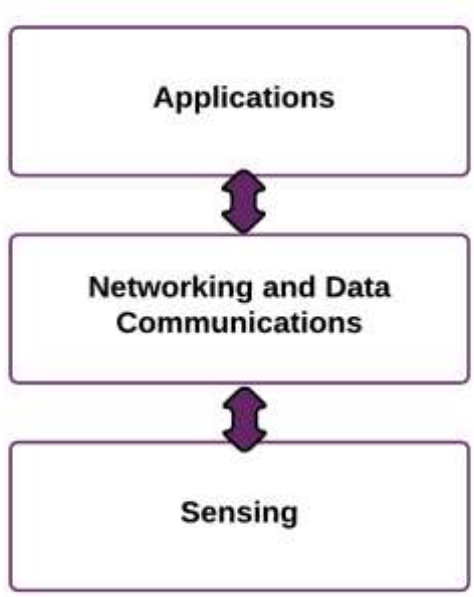

Figure 2.2. Three-tiered architecture

a. The Sensing layer: this layer is used for object identification and data collection from the real world such as temperature, location, speed, moisture, pressure, light, etc. it uses various sensing device and convert this information into digital signals which can be easily transmitted through digital communication networks and stored. The objects of this layer can have sensing abilities, object identification abilities, and actuating abilities. An actuator is a device which can receive programmed commands and perform tasks at specific times [17]. This layer has the same functionality as perception layer in [18]. This layer comprises bar code labels and reader, camera, terminals and sensor networks, RFID tags and reader-writer and sensors.

b. The Networking and data communications layer: it's the brain of IoT with a function of transmitting and processing data, includes convergence network of communication, network management center and intelligent processing center. Core layer is another name of layer 2 in [19] which comprise the network access and the internet. Another name of this layer is gateway layer in [20] because of its establishment of communication channels for heterogeneous sensors and RFIDs.

c. The Applications layer**:** is a combination of IoT's social division and industry demand. It provides a user interface and intelligent application services according to different needs, enabling intelligent control to the items and building an intelligent perceptional world.

2.1.2. Enabling technology

The fast development of IoT rely upon the technological development of enabling technology in the discipline of technology used to connect every object and devices to massive databases and networks, technology used for data collection with capacity to locate change within the physical status of items, technology enable to do a certain action via embedded intelligence in object, and sooner or later to make smaller and smaller things with the capability of two side communication. The aggregate of a lot of these developments made the powerful and efficient communications on IoT packages [21]. Radio-frequency identification (RFID), sensor technologies, smart technologies and nanotechnology are described as the most important technological enabler in [22].

1. Tagging things: RFID

To connect every object and devices to big databases and networks and to the Internet, a necessity of simple, cheap and effective identification system is indispensable. The achievement of the internet of things is, however, currently constrained through our incapacity to gather raw data of a thing, their location and status. Radio-frequency identification (RFID) gives simple one of this functionality and is a key enabler of a ubiquitous communication environment.

2. Feeling things: Sensor technologies

Sensors are one of the key building blocks of IoT. As ubiquitous systems, they can be deployed everywhere from military battlefields to vineyards and redwoods and on the Golden Gate Bridge. They can also be implanted under human skin, in a purse or on a t-shirt. Some can be as small as four millimeters in size, but the data they collect can be received hundreds of miles away.

3. Thinking things: Smart technologies

Embedded Intelligence in the things themselves can improve the energy consumption of the network by devolving information capabilities to the sides of the network. Smart materials incorporate sensors and actuators, as they sense stimuli and respond accordingly

4. Shrinking things: Nanotechnology

Nanotechnology focuses on the design, characterization, manufacturing and application of structures and devices thru the manipulation and characterization of matter at the Nano scale. Potential blessings include increased speed and memory capacities, and a decrease in power intake within particular size.

2.2. IoT Applications

IoT has an incredible potential for social, environmental and economic effect; exact information about the status, location, and identity of things lead us to a smarter decision and more intelligent activities. The uses of the IoT are various and broadened in every aspect of ordinary life of individuals which comprehensively covers society, commercial enterprises, and environment. As per [21] the real destinations for IoT are the formation of a smart environment and mindful things and all the IoT applications developed so far goes under these three wide ranges as appeared in Table 2.1.

It is difficult to envision all potential IoT applications having at the top of the priority list the advancement of innovation and the various needs of potential clients. In the accompanying areas, we exhibit a few applications, which are among the essential application list picked by IERC.

Table 2.1. IoT Applications Domain area

Domain	Description	Applications
Society	Activities identified with the improvement and advancement of society, urban areas and individuals.	Smart cities, smart animal farming, smart Agriculture, Healthcare, Domestic and home automation, independent living, telecommunications, energy, Defense, Medical technology, ticketing, smart buildings
Environment	Activities identified with the assurance, monitoring and advancement of all natural asset.	Smart Environment, smart metering, smart water recycling, disaster alerting
Industry	Exercises related to financial, business exchanges between organizations, association and different elements	Retail, logistics, supply chain management, automotive, industrial control, aerospace and aviation

2.2.1. Smart cities

A smart city is characterized as a city which utilizes IoT empowered technologies to monitor and incorporates most basic infrastructures, including streets, spans, burrows, rail/metros, airplane terminals, seaports, communications, water, power, even major buildings, can better improve its assets and arrange its preventive upkeep activities. An illustrative case of smart city idea is showed in Figure 2.3. Among different smart urban communities' applications which are practical in various part of the world are smart parking, structural health, smart home, smart lighting, waste administration, smart transportation frameworks and smart building [21].

Figure 2.3. Smart city concept [17]

2.2.2. Smart grids

Smart grid is transmission system that can effectively route and manages the energy which is delivered from distributed plants to the last client with high security and nature of supply principles. Subsequently, the smart grid is expected to be the implementation of a sort of “internet” in which the energy packet is overseen comparatively to the data packet across router and gateways. It can choose the best pathway for the packet to achieve its destination [21]. Smart grids use IoT for giving, more proficient and effective power administration and environmentally friendly energy with reduced production expenses [23].

2.2.3. Smart mobility and transport

Implementing IoT concept in transportation and mobility offers new conceivable outcomes and applications which convey new functionalities to the people with reliable, efficient and safe transportation service. Vehicle control and management system, smart traffic management and control are among the most known IoT enabled applications.

2.2.4. Smart health

Smart health contributes a big role healthcare services application through installing sensors in patients for collecting physiological status without obstruction for monitoring health parameter, which helps to give the right medical support at the perfect time by avoiding extra health care cost.

2.2.5. Smart agriculture

IoT can help in enhancing the quality and amplifying the production of fruits and vegetables by monitoring soil moisture, controlling climate condition and keeping up the measure of vitamins and studying climate conditions in fields to forecast ice information, downpour, dry season, wind changes , controlling of moistness and temperature level for preventing fungus and other harmful microbial.

2.3. IoT Enabled Cold Chain Logistics

Cold chain is a part of supply chain which focuses on cold processing, cold storage and cold transportation of temperature sensitive goods through thermal and refrigerated packaging method in protecting the temperature sensitive products from damage. These products can be transported by refrigerated railcars and trucks, refrigerated cargo ships as well as by air cargo [24]. Now a day the contribution of cold chain system in global trade is crucial in perishable product and health supplies, however, due to a poor cold chain system in developing country each year, billions of tons of fresh food product and billions of dollars' worth export are lost. While millions of people are starving, billions of dollars are spent to help those people by improving agricultural process to get efficient amount food. In contrary, nearly half of all food never makes it reach a consumer [25].

To solve aforementioned problem, IoT enabled cold chain play a crucial role in managing, monitoring, receiving real-time data and receiving abnormal event detection from temperature sensitive goods starting at production stage up to customer shelf. The flow diagram in Figure 2.4. depicts pharmaceutical cold chain management stage, which needs a controlling vicinity temperature of the goods using a sensor.

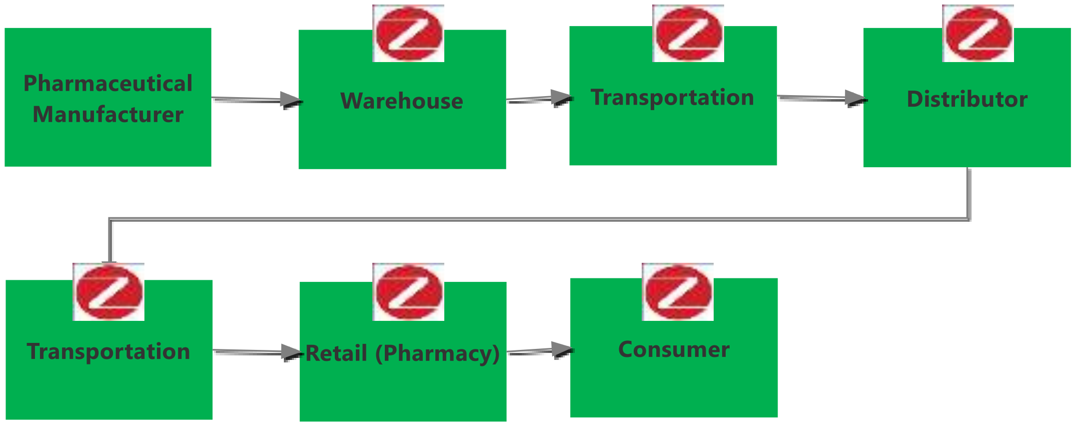

Figure 2.4. Pharmaceutical cold chain management stage

The IoT in logistics has many advantages, including monitoring quality of, shipment conditions, item location, storage incompatibility detection, fleet tracking [21]. Substantial challenges of keeping temperature sensitive goods in appropriate temperature imply the importance of using IoT enabled CCLs, which contain emulator inside the truck during transportation to monitor the condition of the goods and generating of alarm when acceptance criteria are no longer maintained [26].

In the last decade, WSN got a great focus on reducing, improving food safety and losses and wastes by real-time environmental monitoring through processing of collected data, which will not only help in identifying recommended manufacturing, storage conditions but also helping to estimate the shelf life of the product. Implementation of above mentioned real-time monitoring of CCL needs, enabling devices which fulfill basic IoT building blocks like having the capability of sensing, computation and the communication among the devices without involvement of human to deliver specific task [27].

In this study, we demonstrate IoT enabled CCL scenario as it shows in Figure 2.5. It includes; i) WSN structures which send measured ambient temperature to the gateway, ii) RFID technology for identification of sensitive good inside the CC and iii) a gateway which has WSN, RFID Reader, and GSM interfaces to send collected data to remote Server.

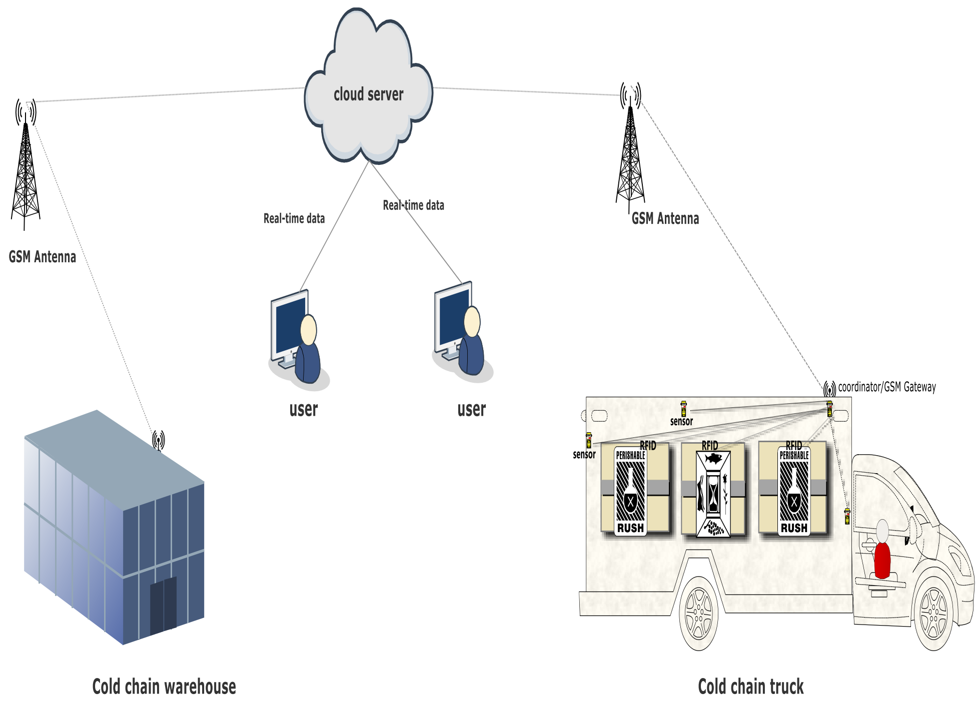

Figure 2.5. IoT enabled cold chain logistic scenario

CHAPTER 3. IEEE 802.15.4/ZIGBEE AND RFID

In this part, the study will introduce the most important feature of IEEE 802.15.4/Zigbee and RFID protocols, followed by pointing how they fit in IoT enabled CCL.

3.1. IEEE802.15.4/Zigbee

WSN is a part of the emerging wireless networking application that has reformed the outline of embedded systems and start a new set of potential applications in medical systems, environmental monitoring, and new home solutions. Since a large number of nodes participate in this kind of network, nodes are organized in a multi-hop wireless network [28].

Comparing with the traditional wireless network, WSN is severing with resource limitation in order to fulfill the intended application. This challenge is raised due to inefficient energy since sensors are basically powered by a small embedded battery with the expectation of prolonged network lifetime, assurance of real-time data delivery, dynamic topology, scalability in the network size and density.

The development of Low-Rate Wireless Personal Area Networks (LR-WPANs) protocol stack by the teamwork of IEEE 802.15.4 Task Group [29] and the Zigbee Alliance [30] have a big contribution as an enabling technology of WSN [31] [32]. As shown in Figure 3.1., Physical layer and medium access control sub-layer specifications are specified by IEEE 802.15.4 standard, Zigbee alliance also specified the framework of the network layer and application layer.

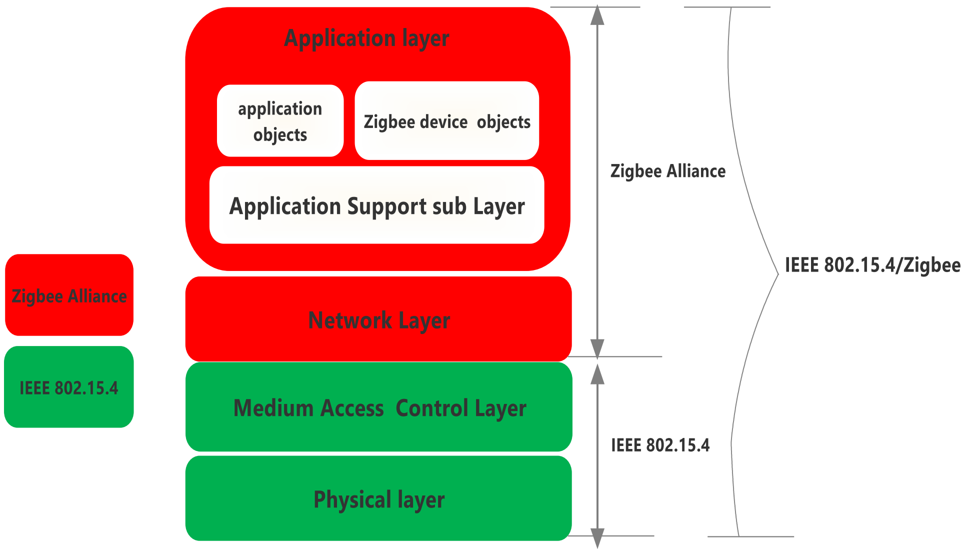

Figure 3.1. IEEE 802.15.4/Zigbee protocol stack

3.1.1. Relevant feature of IEEE 802.15.4/Zigbee protocol stacks

3.1.1.1. IEEE 802.15.4 physical Layer

The primary obligation of the physical layer is transmitting and receiving data using unlicensed radio frequency band 2.4 GHz (worldwide), 866 MHz (Europe) and 915 MHz (North America) with data rates of 250 Kbps, 40 Kbps, and 20 Kbps respectively. Direct sequence spread spectrum modulation technique is used for the above-mentioned frequency. The higher data rate of 2.4 GHz is attributed to a higher-order modulation scheme, higher throughput or lower latency or lower duty cycle. Lower frequency gives a longer range because of lower propagation losses. A low rate can be changed into better sensitivity and bigger coverage area. Table 3.1. shows the summary of this information.

Lower recurrence gives a longer range because of lower proliferation misfortunes. A low rate can be deciphered into better affectability and bigger scope territory. Table 3.1. demonstrates the synopsis of this data.

Table 3.1.Frequency band and data rates

PHY (MHz)	Frequency Band (MHz)	Spreading parameters		Data parameters		
		Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
868/915	868-868.6	300	BPSK	20	20	Binary
	902-928	600	BPSK	40	40	Binary
2450	2400-2483.5	200	O-QPSK	250	62.5	16-ary Orthogonal

The channel between 868 MHz and 868.6 MHz is one, between 902 MHz and 928 MHz is ten and between 2.4 GHz and 2.4835 GHz is sixteen as shows in Figure 3.2. The protocol also allows dynamic channel selection, a channel scan function in search of a beacon, receiver energy detection, link quality indication and channel switching [33].

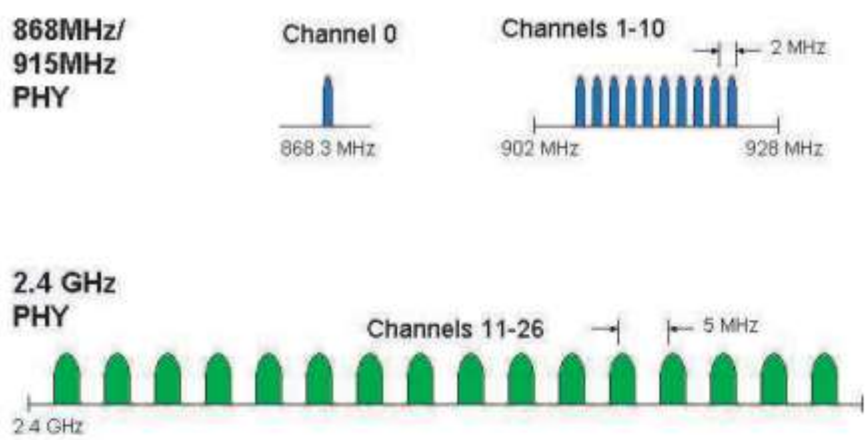

Figure 3.2. Operating frequency bands

3.1.1.2. Zigbee application layer

Zigbee application layer comprise of Application object; this is a part which contains different manufacturer with define user application that developed based on Zigbee application profile one single device, Zigbee device object (ZDO) is a part which helps Application to give its service object by managing Zigbee device through providing suitable networking environment and security management service. Also, this Application support sublayer which provides an interface between network layer and application layer and it's also responsible for maintaining a table of devices that are connected to each other a binding table.

3.1.1.3. IEEE 802.15.4 medium access control layer

IEEE 802.15.4 devices operate either as a full functional device (FFD) that's equipped with a full set of IEEE 802.15.4 protocol stacks or reduced Function Devices (RFD) which operates basic functionality of the protocol stack. FFD has a capability to work as an end device and PAN coordinator, when a FFD device works as PAN coordinator it supports both Beacon-enabled and non-beacon enabled operational mode of MAC protocol which shows in Figure 3.4.

Non Beacon-enabled mode is a mode which the MAC sends its data using non-slotted CSAM/CA mechanism that can't provide any time guarantees to reach their destination. However, in Beacon-enabled mode, PAN coordinator synchronize nodes that connected with it and helps the nodes to distinguish its PAN by sending its beacon. Using Superframe structure is obligatory as part of managing communication between PAN coordinator and associated device in a beacon enabled environment.

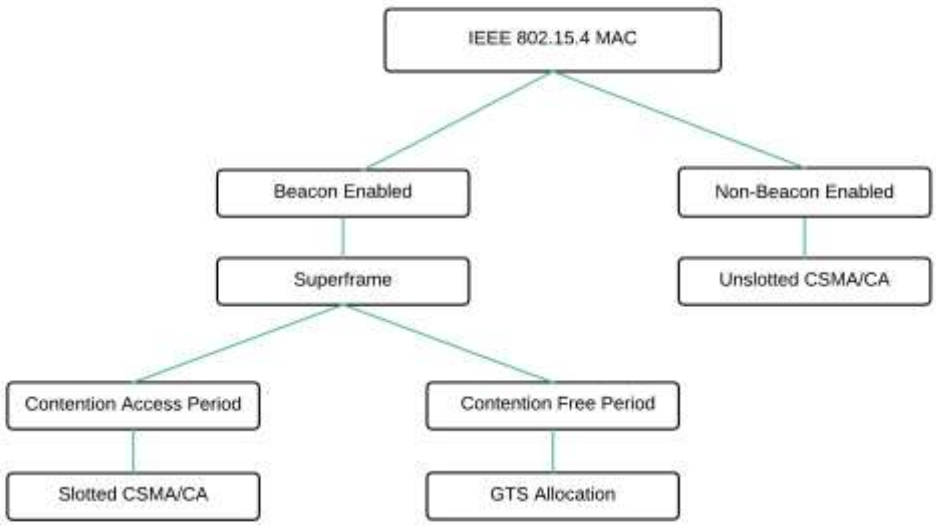

Figure 3.3. IEEE 802.15.4 operation modes

a. Superframe structure

The Superframe in [33], is the time between two consecutive beacons, comprising an active period, which is called Superframe duration (SD) and an inactive period. SD is divided into 16 equally sized time slots that used during for frame transmission. Active period by itself contains a Contention Access Period (CAP) and Contention Free Period (CFP). The communication of devices during CAP must take place using slotted CSMA/CA, while, the CFP contains Guaranteed Time Slots (GTSs). Figure 3.4. Depict Superframe structure. The GTSs always appear up toward the end of the active Superframe starting at a slot boundary instantly taking after the CAP. The PAN coordinator may apportion up to seven of these GTSs and a GTS can occupy more than one slot period. The minimum CAP length is assigned by the standard to 440 symbols.

The Beacon Interval (BI) is determined by Beacon Order (BO) parameter while Superframe Duration (SD) is determined by Superframe Order (SO) parameter. The beacon interval is defined as follows:

$BI = aBaseSuperframeDuration.2^{BO}$, for $0 \leq BO \leq 14$

The Superframe Duration, which related to the active period, is characterized as takes after:

$SD = aBaseSuperframeDuration.2^{SO}$, for $0 \leq SO \leq BO \leq 14$

In the above equation, aBaseSuperframeDuration indicates the minimum duration of the Superframe, related to SO = 0. This duration is settled to 960 symbols [34] related to 15.36 ms, assuming 250 kbps in the 2.4 GHz frequency band. In this situation, every time slot has a duration of 15.36/16 = 0.96 ms.

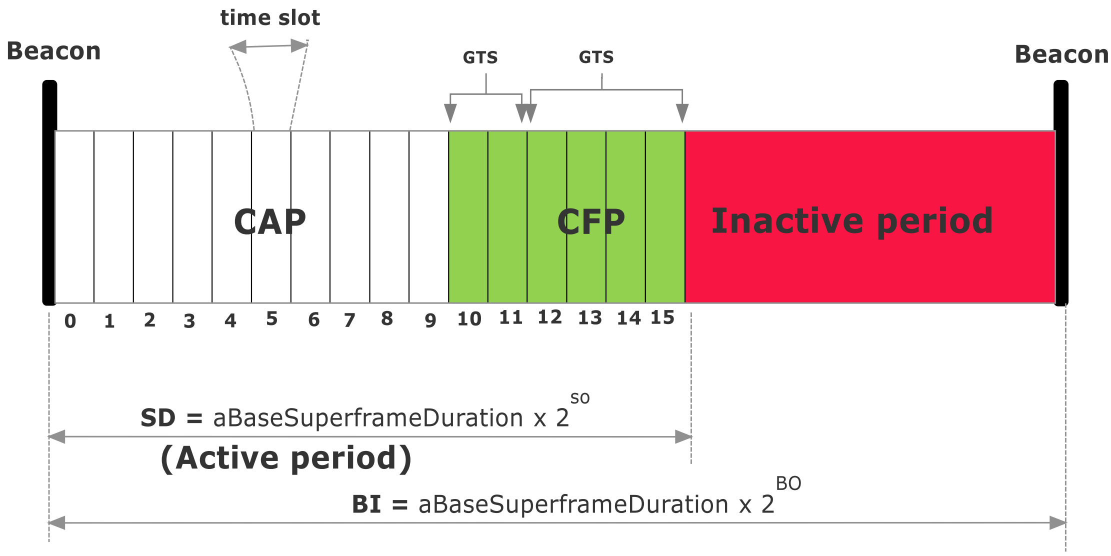

Figure 3.4. Superframe structure of IEEE 802.14.5

Beacons are playing vital for the establishment of the whole network by broadcasting beacons within the selected frequency channel, which is possible for building diverse topology. PAN coordinator or coordinators send beacons to enable nodes, which need to associate with a designated channel performs an active scan of the channel and also the associated device receives the transmitted beacons throughout that period. In the meantime, the associated device retrieves all important info regarding available parent devices (coordinator or PAN coordinator) in the selected frequency channel. Therefore, depending on the requirements, the associating node can choose an appropriate parent.

b. The CSMA/CA mechanisms

At the point when more than one station tries to transmit a simultaneously, a collision happens, and the afterward all frames get corrupted. The standard mechanism for contention resolution in computer networks is a called carrier-sense multiple access (CSMA). CSMA algorithms endeavor to break symmetries of failing transmissions being restarted at almost the same time by using randomized binary exponential backoff technique. While wired, devices can listen to their own particular transmissions and use CSMA with collision detection (CSMA/CD), stations in wireless networks usually, it can't listen to their own transmissions, and consequently colliding transmissions can only be identified after they have been occurred [35] , thus, IEEE 802.15.4 employ CSMA mechanism with collision avoidance (CSMA/CA). Figure 3.5. shows a basic flowchart diagram of basic CSMA/CA algorithm which used in IEEE 802.15.4 standard, comprising two different CSMA/CA mechanisms such as:

- The slotted CSMA/CA. Employed in the beacon-enabled mode.
- The unslotted CSMA/CA. employed in the non-beacon-enabled mode.

In both cases, the CSMA/CA algorithm is implemented based on backoff periods, where one backoff period is equivalent to aUnitBackoffPeriod = 20 Symbols. The backoff period boundaries of each device in the PAN are aligned with the superframe slot boundaries of the PAN coordinator for accessing a channel in slotted CSMA/CA mechanism. Where In unslotted CSMA-CA, backoff period of one device is not necessary to be synchronized to the other device.

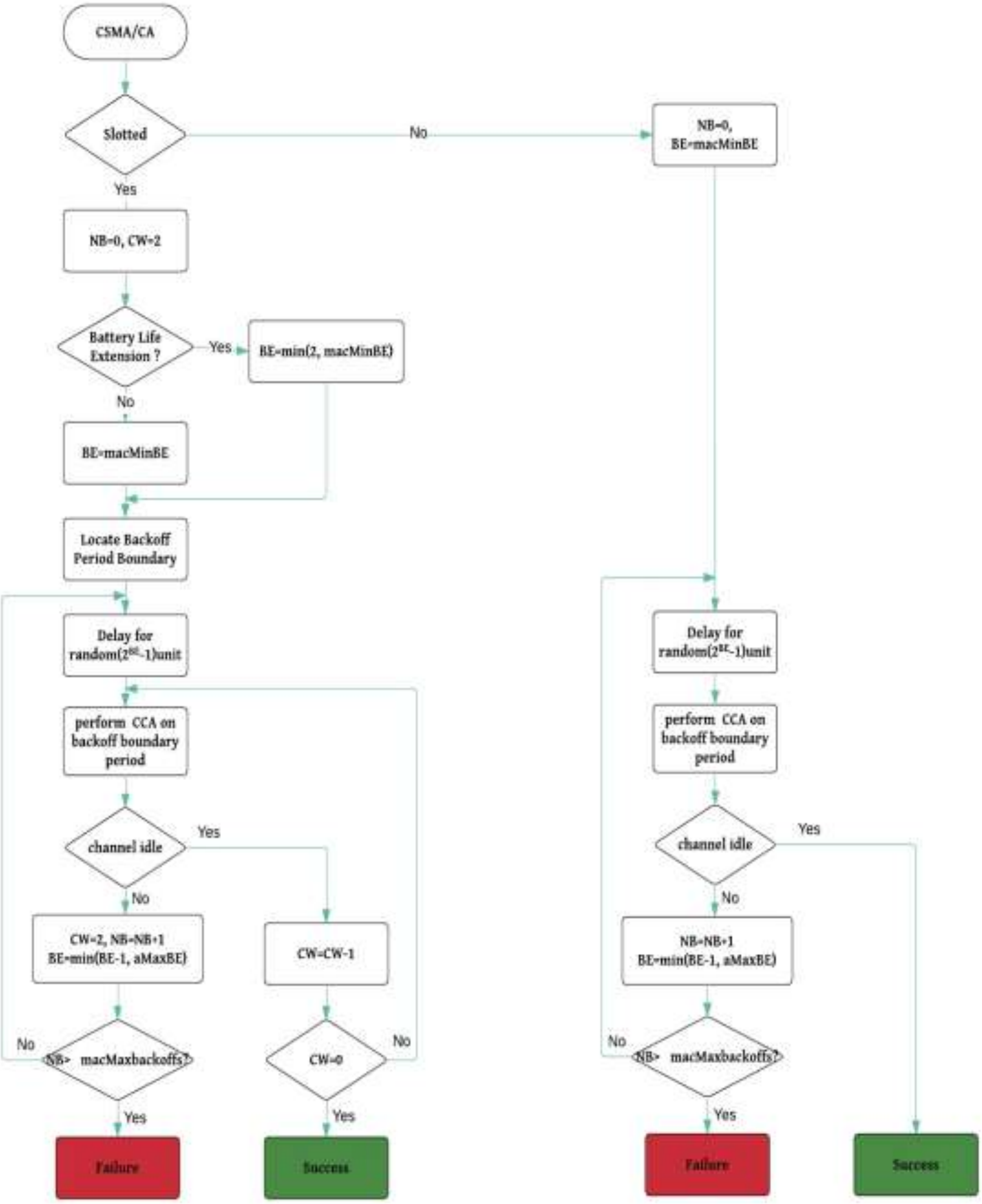

Figure 3.5. CSMA/CA Algorithm

NB is the Number of Backoffs in CSMA/CA algorithm which representing the number of failed attempting the current transmission. NB will be reset to 0 at the beginning of a new transmission. BE is Backoff Exponent, helps to compute backoff period which a device should wait before an attempt to assess the channel. Thus, devices should wait for a random number of backoff period between 0 and 2BE-1 before transmitting. CW is Contention Window showing the number of backoff periods that need to be clear before transmission started. The value of CW will be 2 at the beginning of each transmission and reset to 2 each time the channel is assessed to be busy. Until the channel is idle the process repeats again by incrementing NB until maxBE is less than NB.

3.1.1.4. Zigbee network layer

The Network layer ensures reliable and secure transmission by managing network, routing and security related services. Zigbee defines three types of devices based on the role of devices in a network:

- Zigbee Coordinator (ZC): Is a Full Functional Device which has a responsibility to form and manage network infrastructure. It can be used as PAN Coordinator and Zigbee Router (ZR) once the network is formed. In a beacon enabled environment, ZC takes responsibility of synchronization among the node in data transfer process. There is only one ZC required for each Zigbee network.
- Zigbee Router (ZR): is a full functional device, routing of a message in the mesh and cluster tree is handled by ZR by associating with ZC and also act as PAN coordinator.
- Zigbee End Device (ZED): is a just sensor/actuator node with reduced functionality, which couldn’t have the capacity to route and connect another device with it.

3.1.2. Topologies supported by Zigbee network layer

IEEE 802.15.4/Zigbee support three network topologies such as a star, mesh and cluster-tree topologies [33]. IEEE 802.15.4 standard in the beacon-enabled mode supports only the star topology, the Zigbee specification has proposed its extension to the multi-hop cluster-tree and mesh topologies.

3.1.2.1. Star topology

Star topology is a topology with centralized communication paradigm which is suitable for small scale network, i.e. only one node may act as ZC with the responsibility to manage the nodes those need to join the network and communicate each other must pass through ZC as shows in Figure 3.5. Among the most important advantages of a star topology is its simplicity and predictable and energy efficient behavior. The disadvantages are constrained scalability and ZC as a single point of failure. ZC spends high battery resource since all activities route through it.

3.1.2.2. Mesh topology

The communication paradigm in mesh topology is decentralized, i.e. the network incorporate ZC that recognizes the whole network with the ability of a direct node to node communication inside its radio range. The mesh network usually operates in an ad-hoc fashion that causes unpredictable end-to-end connectivity between nodes. In contrast with the star topology, the mesh topology gives great extensibility and avoid single point failure with ensured fair resource usage. Contrary to mesh topology's improved network flexibility and power efficiency, it increases network complexity.

3.1.2.3. Cluster-tree network topology

The cluster-tree network topology is a special case of a tree network in which a parent with a child forms a cluster. In this topology, each cluster has its own ZR and any cluster in the network may allow the end device to join the network at the end of the leaf node of a branch and only one ZC available in the network.

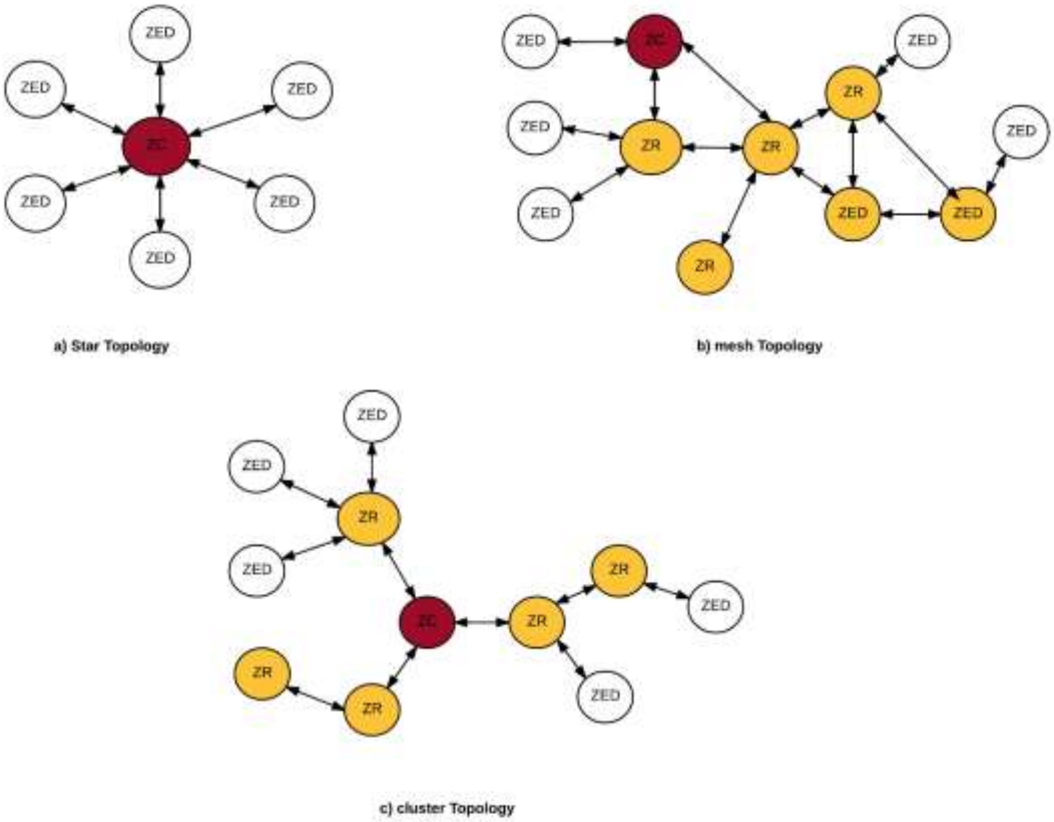

Figure 3.6. Network topology

3.2. Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) is prominently emerging automated identification technology which conquered challenges of other identification systems. It includes barcode systems, optical character recognition systems, smart cards, and biometrics and are widely used for military applications, supply chain management, asset tracking, animal identification and payment systems due to low cost and power efficiency, ability to resist harsh environment and no line of sight is required for communication, RFID system compromise of an application host, Reader, and Tag. Reader and Tag's uses electromagnetic waves to communicate each other, thus enable to exchange data between them with the help of RFID application host. A RFID reader acts as a master for the tag and a slave for the application host [36]. This master–slave idea is shows in Figure 3.6.

RFID is seen as a prerequisite of IoT because of the functionality it has like object identification, tracking and monitoring tagged object in real time [37]. RFID Tag contains microchips which store certain information that will be processed, modulated and demodulate signal and comprise of Antenna to receive and send those data.

Mostly tags are classified as passive, semi-passive and active tags. Passive tags are most commonly used one which has no built-in a power source that needs radio wave generated by the reader to be activated and carried out a process, thereby passive tags luck of medium sensing mechanisms at the time of communication between reader and tags. Active tags comprise self-sustained power or battery to keep the entire tag chip active through the whole communication between reader and tags. While the semi-active tag is an integration of active and passive tags [38]. This study focuses on passive tags since it uses them in this paper. Simultaneous tags transmission causes a collision and lost due to the limitation of passive tags to sense shared communication channel and cooperation with other tags to avoid a collision.

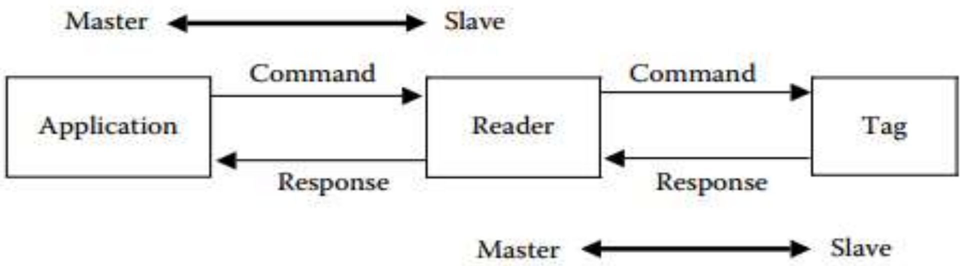

Figure 3.7. Master–slave architecture of the RFID system

3.2.1. Medium access control (MAC) of RFID

Like other Radio system, RFID requires Medium Access Control (MAC) protocol to avoid various sort of collision. Conventional collision avoidance techniques, for example, Carrier Sense Multiple Access (CSMA) can't be adapted for RFID system, particularly when passive tags are utilized because of energy limitations and its basis of reflection-based communication.

Using conventional MAC techniques in reflection based communication results failure as tags can’t sense the medium, detect a collision, or sense the existence of other channel traffic. This implies no collision avoidance techniques could be implemented at the tags. The conceivable answer for resolution for collision in RFID system at the reader side. Particular to RFID system, a collision can be classified as follow.

Tags-to-reader collisions: Occur when more than one tag inside a reader's vicinity tries to answer to the reader's request simultaneously. Tags-to-reader collisions are the most common one, particularly when passive tags are included. They bring about reduced reading rates, wasted resources, and increased delay.

Readers-to-tag collisions: Occur when one tag is communicated by more than one reader. In such a situation, numerous reader attempts to access a single tag which results in corruption of the tag's interior state. Accordingly, the tag may not be recognizable.

Reader-to-reader collisions: Are aftereffect of the conventional frequency interferences, that is, multiple readers inside each other's interference zones are locked on the same frequencies.

3.2.2. RFID Anti-Collision Protocols

Among all effectively existing techniques and procedures of collision avoidance literature, there no techniques which guarantee absolutely collision free RFID communication system. This thesis we use the most dominant anti- collision protocol in RFID communication. Before describing its detail, we introduce the existing anti-collision or multiple access techniques for the sake of general understanding. Different studies categorize the techniques of handling multi access issues into four different techniques. These multiple-access techniques are Space Division Multiple Access (SDMA) technique, Time Division Multiple Access (TDMA) technique, Frequency Division Multiple Access (FDMA) technique, and Code Division Multiple Access (CDMA) technique. This we shall briefly review these four techniques.

1. Space Division Multiple Access (SDMA) Technique: In this technique the total number of tags which present inside interrogation zone is spatially isolated to decrease the interference caused by the tags. It uses an electronically controlled directional antenna. Various tags will be distinguished based on their angular positions.

2. Time Division Multiple Access (TDMA) Technique: Time Division Multiple Access technique allocates the available channel bandwidth to readers and tags with respect to time. Based on the time allocated by the reader, tags respond in their corresponding time slots with the reader. In this technique, reader talks first, tags listen. Later tags respond to the reader based on the time allocated. Because of simplicity, low processing overhead from passive tags, and low complexity (computational, processing, and monetary cost) it's the dominant medium protocol in RFID system compared with other existing procedures such as FDM, CDMA, OFDMA.

3. Frequency Division Multiple Access (FDMA) Technique: In this method, the existing resource i.e., channels bandwidth into smaller bandwidths which in turn are dedicated to individual tags until the communication among the tag and the reader is completed. Having noninterfering frequencies is the biggest advantage of this technique for simultaneous communication of tags and readers, even though, it has not been significantly utilized in RFID system because of impracticality for tags and relatively high cost of readers for such kind of techniques.

4. Code Division Multiple Access (CDMA) Technique: This technique works basically on the principle of cellular mobile communication. Readers are identified by their unique codes and works in synchronization with each other. This technique is too complicated to implement for RFID system as the computation time required is more for both tags as well as the reader.

Tag-collision is the most dominant collision which occurs at the time when multiples of tags which found inside the interrogation zone are replayed simultaneously to the command of the reader. Therefore, Tag collision are resolved by implementing anti-collision techniques at the side of the reader. This thesis has been laser focused on Tag anti-collision procedures only. Hence, other collision avoidance procedures are not used for implementation of our scenario. Collision avoidance or anti-collusion protocols for Tags are mainly classified into two types: (a) probabilistic, and (b) deterministic.

a. Deterministic protocol is a protocol which classified under tree base algorithm because of the splitting approaches used by the reader to identify a set of tags to respond in a given period or the tags in the protocol are treated as nodes in the binary tree [39]. The tags are identified based on their unique ID's where the reader scans all the nodes of the tree in every round. This protocol is very successful in identifying the tags inside the vicinity. However, the reader will be busy and took more time in the process of identifying tags [36].

b. Probabilistic protocol: is anti-collusion protocol developed based on one of the basic medium access control protocol that is called ALOHA protocol, and also uses time division multiple access (TDMA) technique to manage collision of the Tag. Tags in ALOHA waits for transmission time after generated random number is assigned to each tag. If transmitted data by tag reached to the reader with collision, then the reader will identify the tag and continue assigning generated a random number and randomly transmit the data to the reader. In such random communication, collision is inevitable. Thus, ALOHA has different enhanced version to decrease the probability of a collision. Among different enhanced version of this protocol adaptive slotted aloha algorithm is widely used in RFID communication standard, which defined by EPCglobal [40].

Since we used EPCglobal standard for modeling RFID system using Riverbed simulator, EPCglobal is explained in the following part.

3.2.3. Basic EPCglobal Gen 2 protocol model

Physical and logical specification of passive-backscatter, the interrogator-talk-first (ITF), and RFID system operate in the 869 MHz-960 MHz frequency is defined by EPCglobal. Transmitted information from the Reader by modulating RFID signal to the tag is used as both information and operating energy for the tag, this commutation between Reader and Tag is half-duplex [41].

A reader uses three basic operation to manage tag population.

- Select: Is a process of selecting tag population in the vicinity for the purpose of inventory and access.
- Inventory: - is a process of identifying tags by sending, query, query repeat, and query adjust commands to one of four sessions. The Interrogator (Reader) identifies a single Tag reply and requests the Tag's EPC.
- Access: - is a process of getting to particularly distinguished tag. The Interrogator may perform a core operation, for example, reading, writing or killing the Tag; a security-related operation such as authenticating the Tag; or document related operation such as opening a specific file in the Tag's User memory. Access comprised multiple commands.

In this section, the mandatory commands of slotted aloha are described and reader-tag communication is illustrated based on [41] using sequence diagram as shown in Figure 3.7.

1. The first communication between reader-tag initiated by the reader by sending select commands to the tags, thus power up tags, assert or desert a tags SL flag and set inventoried flag which makes the tags ready for the next state

2. The reader issue Query/QueryAdjust/QueryRp command to start new inventory round in one of four sessions, among sessions, tags that have the same Sel and Target fields with Query command shall load random value ranging (0, 2^{Q}-1) into their slot counter.
3. The tag with zero slot counter respond with 16 bits random number RN16, others with non-zero slot counter will not respond
4. The reader sends ACK back to tag with the same RN16 with the previous one as an acknowledgment
5. The reader receives 96 bit EPC + CRC-16 bit from the tag, if the tag received valid RN16 from the reader.
6. The reader requests to access handle of the same RN16 using Req-RN command.
7. The tag respond with the handle of RN16 if it receives valid RN16 for the reader.
8. Finally, the tag permits the reader to access the handle, by checking the validity of handle parameters. Aforementioned reader-tags communication steps will repeat once again.

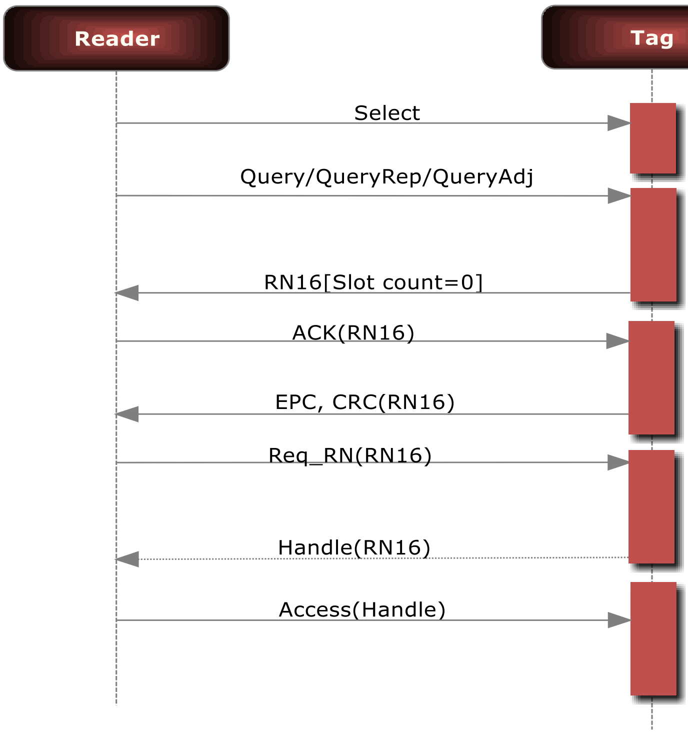

Figure 3.8. Sequence diagram for reader-tag communication

CHAPTER 4. SIMULATION MODEL FOR IOT ENABLED COLD CHAIN LOGISTICS

Simulating and modeling are important approaches in the development and evaluation of the systems regarding time and expenses. The simulation demonstrates the expected behavior of the system based on its simulation model under different conditions. Hence, the purpose of this simulation model is to determine the precise model and anticipate the behavior of the real system under. All the simulation scenarios, devices and protocols are implemented using Riverbed Modeler and details of them are given in the following subsections.

4.1. Simulation Scenario

IoT enabled CCL model comprises WSN and RFID models that are developed based on the IEE 802.15.4 and EPCglobal Gen 2 standards, respectively. The system also contains a GSM network and a Server as it can be shown in Figure 4.1. The relevant parameters for WSN simulation are tabulated in Table 4.1. The RFID simulation parameters are similar to those of provided in subsection 3.2.3.

Table 4.1. Simulation Parameters

Parameter	Value
GTS	Enabled
Beacon	Enabled
Frequency band	2.4 MHz
Simulation time	60s
Packet Interval Time(seconds)	Exponential (1.0)
Packet Size (bits)	Constant (500)
Data rate(bps)	250,000
Beacon order	15

Table 4.2. Simulation Parameters (continued)

Superframe order	15
Initial energy	2 AA Batteries (1.5V, 1600 mAh)
Maximum Backoff Number	4
Minimum Backoff Exponent	3

The simulation model includes two types of IEEE 802.15.4 nodes; a PAN Coordinator (PC) and a Sensor Node (SN). According to our scenario, the main functionality of SN is to collect ambient temperature and to send this data to the PC which is responsible for coordinating the network and has a GSM and RFID interfaces.

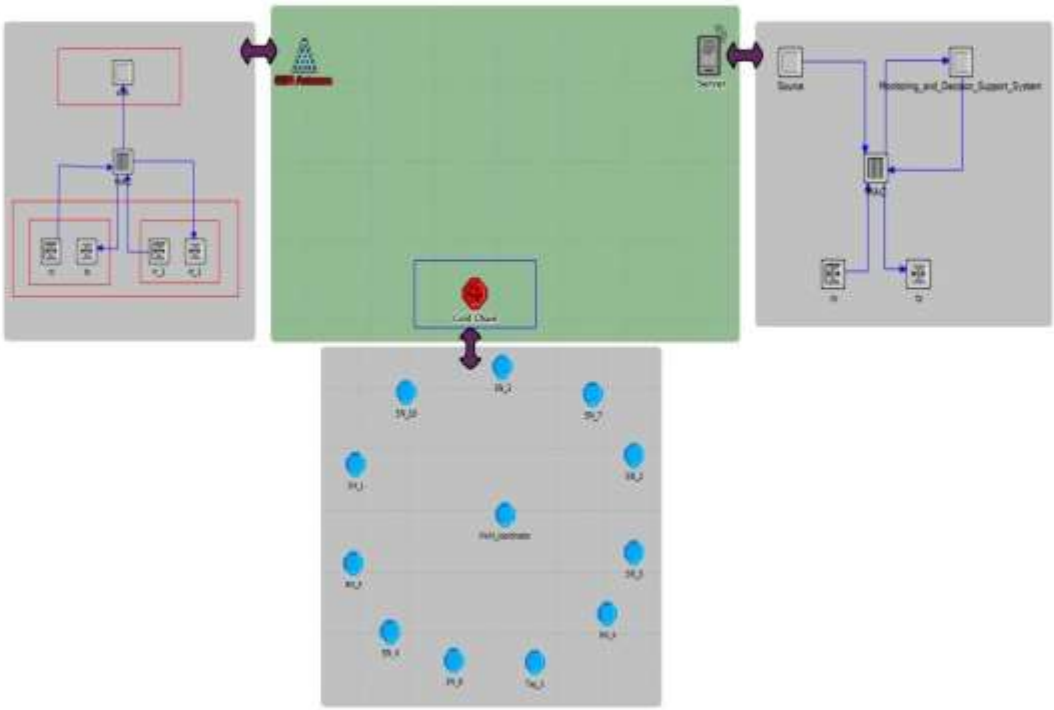

Figure 4.1. Internet of things enabled cold chain logistics Riverbed Network model

The WSN structure in the simulation scenario has a star topology in which only one PC is available for controlling all network activities. The WSN has also ten SNs which are capable of generating network traffic to emulate the sensed temperature from the environment and of sending the traffic to the PC using IEEE 802.15.4 protocol. The PC is modified to have additional capabilities like sending and receiving data from GSM network and reading RFID tag information, i.e. RFID reader functionality. The scenario is also include a RFID tag. The server at simulation scenario is used to monitor, manage and access real-time data of IoT enabled CCL. It also includes the decision support system whose detail is given in subsection 4.2.

The fundamental point of this simulation is to examine the practicality of deploying IEEE 802.15.4 and RFID to control, monitor and gather real-time data of temperature sensitive goods in IoT enabled CCLs. Among the application of IEEE 802.15.4 and RFID in CC industry, there are more similarities than the difference in functionality, environment and structure. Thus, the simulation model is focused on some parts of CCLs.

The original Riverbed simulation model of IEEE 802.15.4, we used in this study, was developed by IPP-HURRAY Research Group [42]. In our study, the original model is modified and additional functionalities such as RFID reader and GSM gateway are incorporated into the coordinator, i.e PC. The GSM networks components and RFID Tags are also modeled and integrated to the simulation scenario for more realistic performance evaluation. SN node model is depicted in Figure 4.2. It consists a physical layer with wireless radio receiver (rx) and transmitter (tx) with data rates of 250 Kbps and working at frequency band of 2.4 GHZ using Quadrature Phase Shift Keying (QPSK) modulation technique.

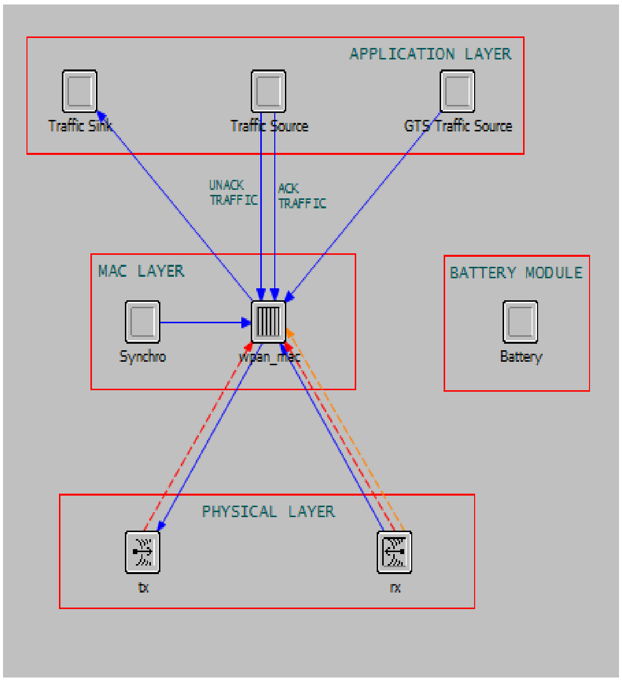

Figure 4.2. Simulation model for Zigbee end user node

The Media Access Control layer of the node model supports Slotted CSMA/CA mechanism and beacon enabled mode in which PC sends a beacon to synchronize associated nodes and to help the nodes for identifying their PC. Since the MAC layer has a beacon enabled mode, GTS service for time-critical service also can be supported by the WSN structure.

The application layer comprises of two traffic sources and a traffic sink. The traffic source, in the node model, produces data frames transmitted to the destination by the slotted CSMAC/CA during CAP period and the GTS traffic source generates time critical data frame delivered by GTS mechanism. The traffic sink module is employed to collect statistic from the arriving packets. The battery module is also incorporated into the node model in order to determine consumed and remaining energy of any WSN node. Added to its common functionalities, the PC also provided with additional modules as a GSM interface, an actuator interface and a RFID reader module, as can be shown in Figure 4.2.

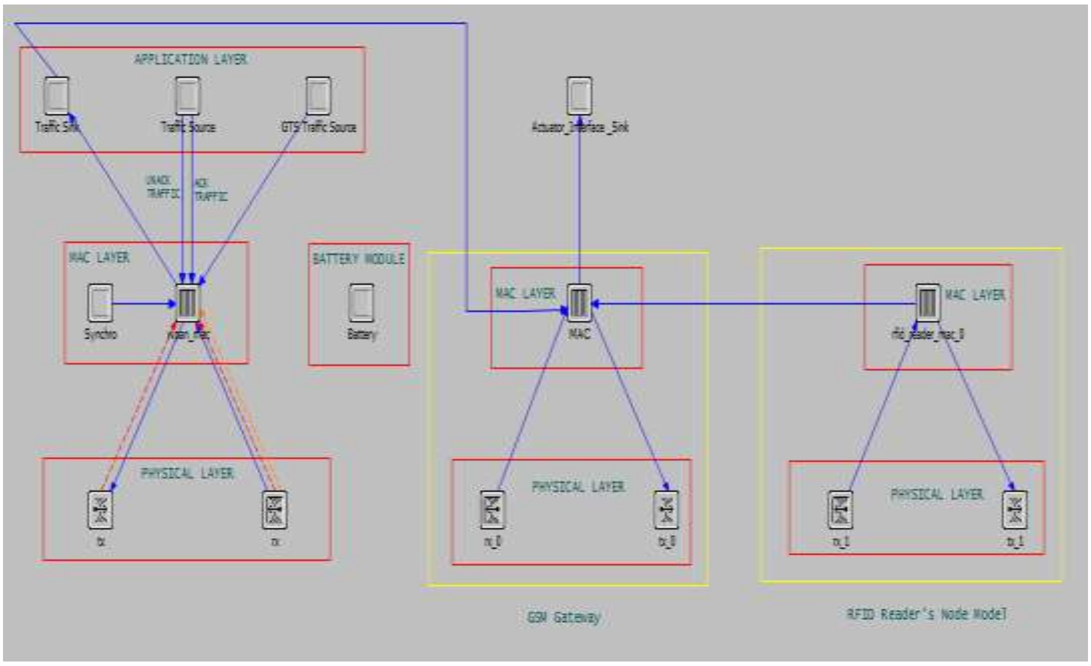

Figure 4.3. Node model for PAN coordinator

GSM interface in the PC node model is responsible for providing communication between the network in vehicle and remote server. All the sensed temperature values and RFID tags' information are send to the remote server using GSM interface incorporated into the PC. Actuator interface in the PC gets any control signal produced by the Monitoring and Decision Support System employed in remote server (Figure 4.1.) and delivers it to the control system in the vehicle. The details of algorithm employed in the Decision Support System is given in subsection 4.2.

Figure 4.4. and 4.5. show the process models of RFID Reader and Tags, respectively. The process models are modeled with a Finite State Machine (FSM) and developed based on probabilistic anti-collision resolution protocol, which is called adaptive slotted aloha according to the EPCglobal Gen 2 specification. Figure 4.6. and 4.7. show the node models of RFID reader and Tag, respectively, which contain a MAC layer and physical layer with a wireless radio receiver (rx) and transmitter (tx) that operate in the 860 MHz-960 MHz frequency range. The details of RFID protocols can be found in [41].

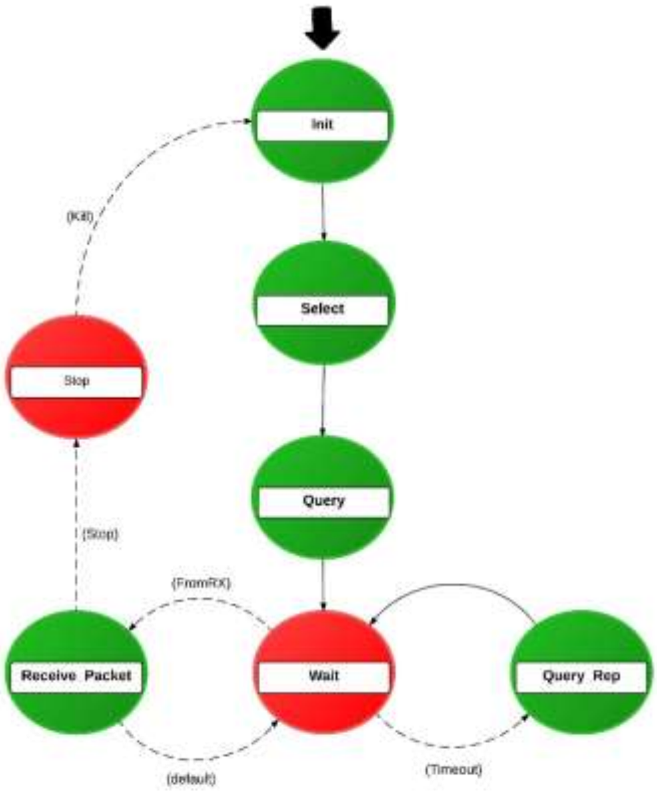

Figure 4.4. Riverbed Simulation model of RFID reader

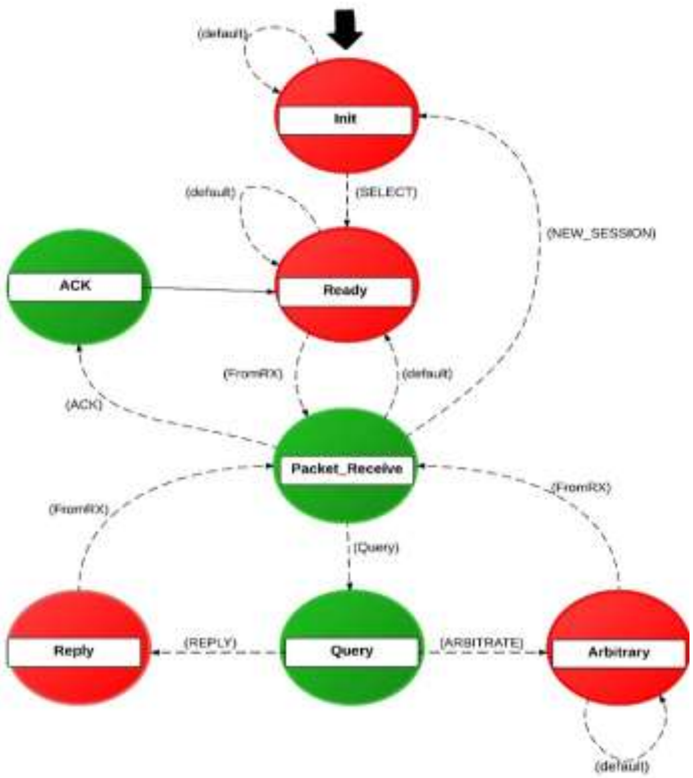

Figure 4.5. Riverbed Simulation model of RFID Tag

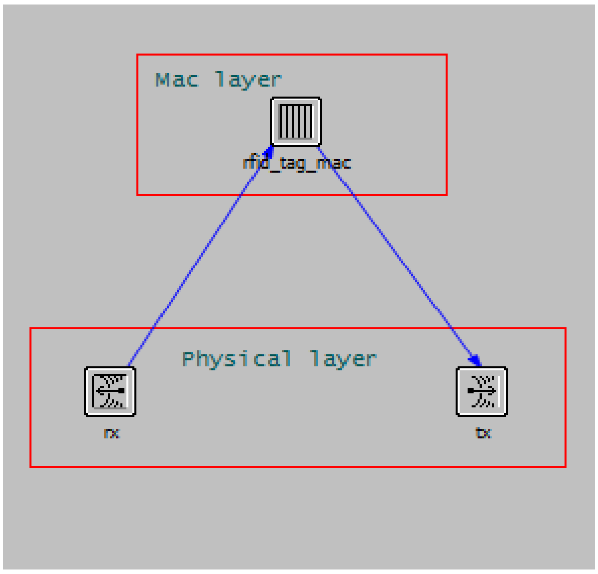

Figure 4.6. Riverbed Simulation Node model of RFID Tag

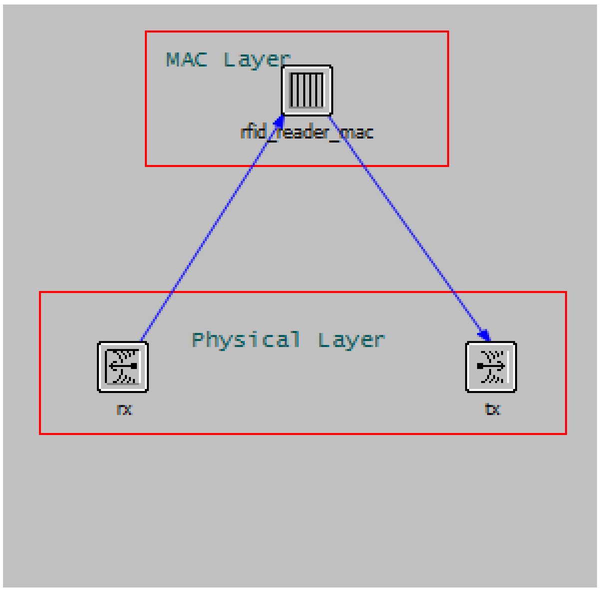

Figure 4.7. Riverbed Simulation Node model of RFID reader

4.2. Shelf-Life Predication of Perishable Foods in IoT Enabled Cold Chain

Food products start to deteriorate the moment they are harvested, so it is important to use the cold chain to insure the quality of the product by keeping under optimum storage temperature. An important parameter to evaluate product freshness through the whole life cycle of a product is the shelf-life, which is the length of a time that perishable product stored without becoming unsuitable for the human use. Table 3.1. shows the shelf-life of common perishable food product under optimal temperature [43].

Table 4.3. Shelf-life of common perishable food products [43]

Product	Shelf-life(days)	Optimal temperature(Celsius)
Apple	90-240	0
Bananas	7-28	13.5
Bell Peppers	21-35	7
Cabbage	14-20	1
Eggs	180	1.1
Onions	30-180	1
Lettuce	12-14	0.6
Fresh Meat (beef, lamb, pork, poultry)	14-65	-2
Oranges	21-90	7
Pears	120-180	-0.6
Potatoes	30-50	10
Seafood (shrimp, lobster, crab)	120-360	-17.8
Strawberries	5-10	0.6
Tomatoes	7-14	12

In order to develop a mathematical model and predict the shelf life of the perishable product, different experimental test on the physical, chemical and microbiological parameter of the specific perishable product have taken place. Evaluating the shelf-life of a product depends on the characteristics, the natures of the intended product, and the environmental factors involved in its degradation, such as temperature, light and humidity. Even though, all products have no the same decay rate, the general rate law given in equation 4-1.

$$r = -\frac{dA}{dt} = k(A)^n \tag{4.1}$$

Where dA/dt is the change in the measurable quality factor A with time, n is the order of the reaction where for most quality attributes in food products is either zero, first or second order [44], A and k is the reaction rate depending on several variables (depending on the reaction).

As describe above temperature is among the most important parameter for perishable product storage. Even short disruption of temperature in the cold chain could bring a big change in the shelf-life of the perishable product. This significant change due to the temperature is not visible for different participant. In equation 4.1 the rate k is referred to quality of degradation which is directly depend on temperature T according to Arrhenius law as shows in below equation 4-2 [45].

$$k = We^{\frac{-E_a}{RT}} \tag{4.2}$$

Where W is the pre-exponential factor, Ea. the activation energy and R the gas constant. The Arrhenius law parameter should be determined with a non-linear regression of empirical data in an adequate confidence interval [46]. For n=0 in the equation 4.1, meaning for zero order reaction the shelf-life of the product is calculated as follows:

$$t_s = \frac{A_e - A_O}{k_O} \tag{4.3}$$

Where A_O stands for recommended food quality, A_e stands for minimum food quality level, t_s for shelf life time and k for the quality of degradation speed which depends on the Arrhenius law in equation 4.2. And when the value of a temperature is evaluated beyond appropriate value we could get the value k (the new degradation speed) using the same equation.

In the case of missing the common food science kinetic parameters such as rate constant and activation parameters, which is used to describe microbial changes in a food during processing and storage. Also in a time developing a sound, scientific test takes a great deal of time and resources, Accelerated shelf-life test (ASLT) is used. ASLT describes the temperature dependence of a reaction as the factor by which the reaction rate changes when the temperature is increased based on the assumption that chemical reaction in material follows the Arrhenius reaction rate function. This function states that every 10°C increase or decrease in temperature of a homogenous process results in a 2x or 1/2x change, respectively, in the rate of a chemical reaction. This chemical reaction rate is denoted Q10=2. This applies to a shelf-life as the following equation 4.4 and 4.5:

$$\mathrm{Q10} = \left(\frac{\text{Shelf−life at elevated T}}{\text{Shelf−life Claimed}}\right)^{\frac{10}{\text{elevated T(℃)−optimal T(℃)}}} \tag{4.4}$$

$$\text{shelf} - \text{life at elevated T} = \frac{\text{Shelf−life Claimed}}{2^{\frac{(\text{elevated T(℃)−optimal T(℃)})}{10}}} \tag{4.5}$$

In this study, predicting the shelf-life of temperature sensitive product through comprehensive monitoring of temperature along the entire cold chain life cycle is fruitless without mathematical models used to predict the shelf-life through real-time collected environmental parameters. Thus, ASLT is utilized to develop algorithms which gives capability to IoT enabled CCL for predicting real-time shelf-life of perishable products. Developed algorithms are structured as follow.

1. Store input data about standard shelf-life of a product “Shelf-life Claimed”, an appropriate temperature for a product “optimal T (℃)”, and certain “threshold”.
2. acquire the value of “elevated T (℃)” from WSN which is the elevated temperature of the cold chain.
3. Calculate the “shelf-life at elevated T” of the product using ASLT.
4. Identify if the “shelf-life at elevated T” of the product is in standard condition, continue monitoring the shelf life based on specified time.
5. If calculated “shelf-life at elevated T” is below a certain threshold send alert to the cold chain and repeat the process within specified time.

4.3. Simulation Results and Discussions

To evaluate the performance of aforementioned enabling technologies, 60s simulation time interval is chosen since we can get needed stable result within this period. Figure 4.8. shows a graph that helps to compare the total number of packets introduced to the network by PC with respect to total number packet received by the remote server. The graph depicts that sensed and identified ambient parameters using ten SNs and an RFID have the same Figure with those reached to the remote server which means all the data could be delivered without any loss as desired.

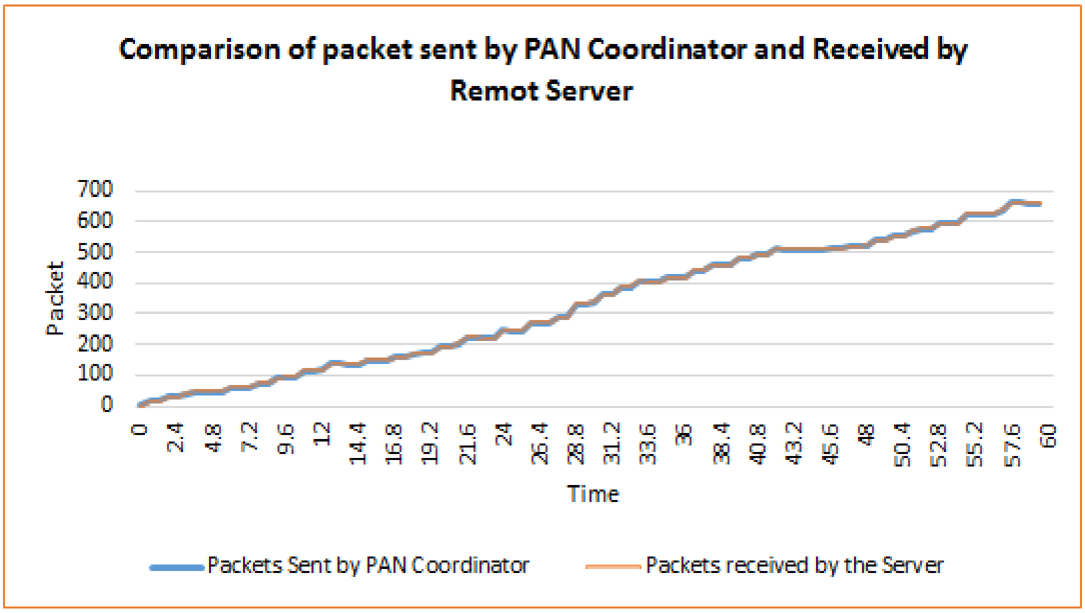

Figure 4.8. Packet submitted by PAN vs packet received by remote server

Figure 4.9. depicts local statistics of WSN model to measure end-to-end delay which indicates the elapsed time while any data packet is sent from a SN to the PC. As it can be seen from the Figure, the end to end value took approximately 0.015 second, to attain a stable condition. According to our scenario, this is expected result, since, the network load is very light in size.

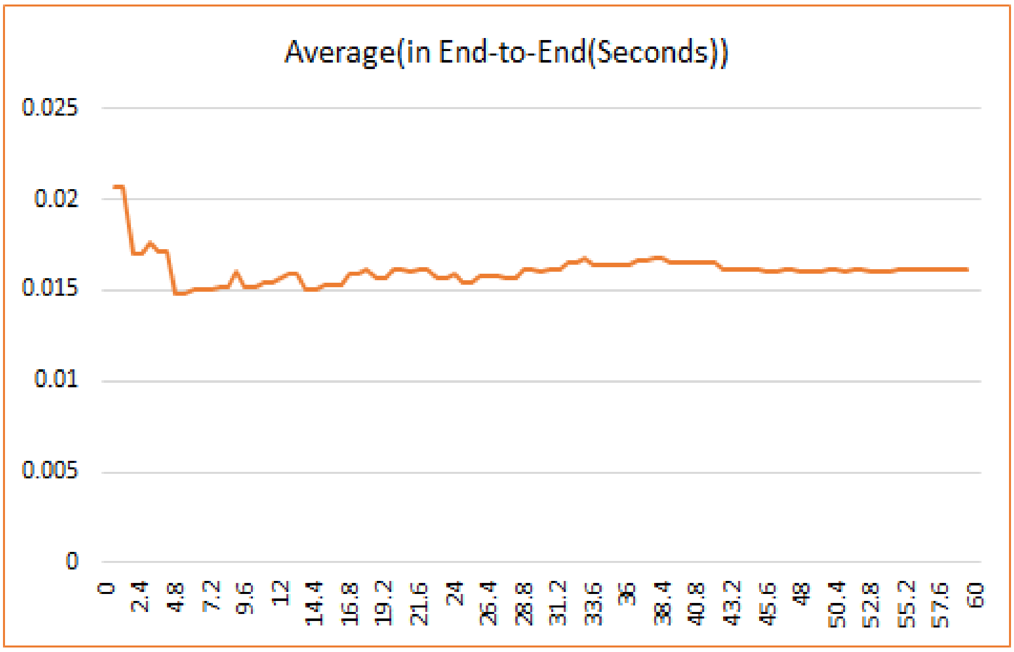

Figure 4.9. End-to-End delay

Figure 4.10. presents the total network throughput results of the WSN, which is the amount (packet) of data transmitted with no error from the SNs to PC within a specified time (second).

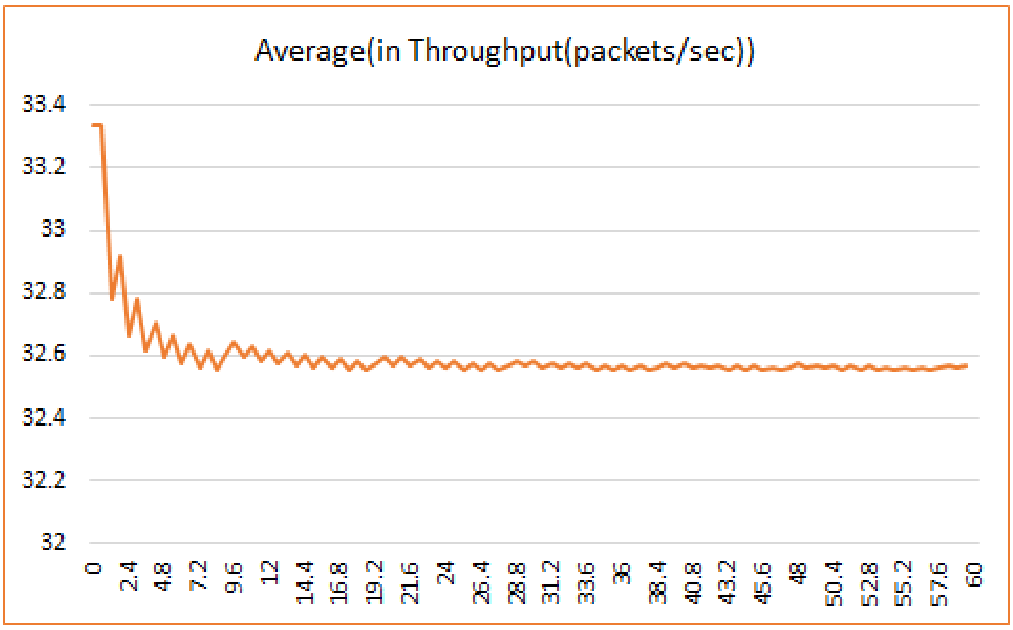

Figure 4.10. Throughput

The whole network output load of WSN in our IoT enabled CCLs model is given in Figure 4.11. The average network output load value is approximately 10Kb/s in stable condition. As can be shown in the Figure the network can easily transmit all the measured data since the maximum bandwidth value, i.e. 250 Kb/s, is never reached.

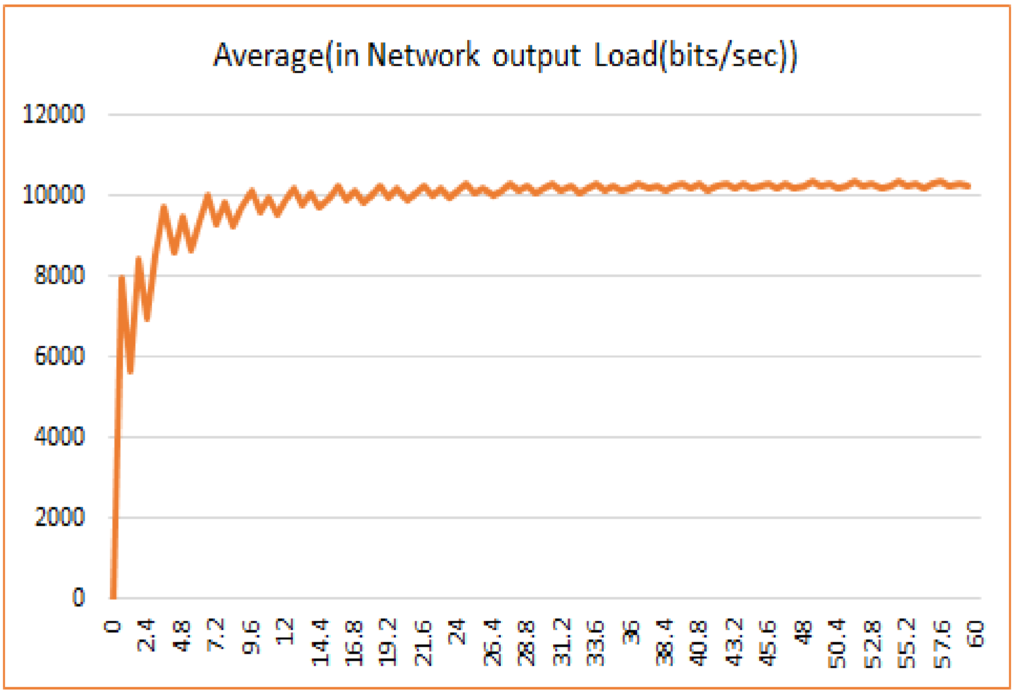

Figure 4.11. Network output load

In demonstrated scenario, IoT gives the possibilities for logistics managers, quality managers and other actors for the CC, to manage and monitor real-time ambient parameters of cold chain through the whole life cycle. Figure 4.12. illustrates real-time monitored real-time ambient temperature of the cold chain which collected at specified time using WSN in the CC that visually dispelled to the users. The collected temperature data is stored in designated server across the chain, which used for preparing automated compliance report of the products.

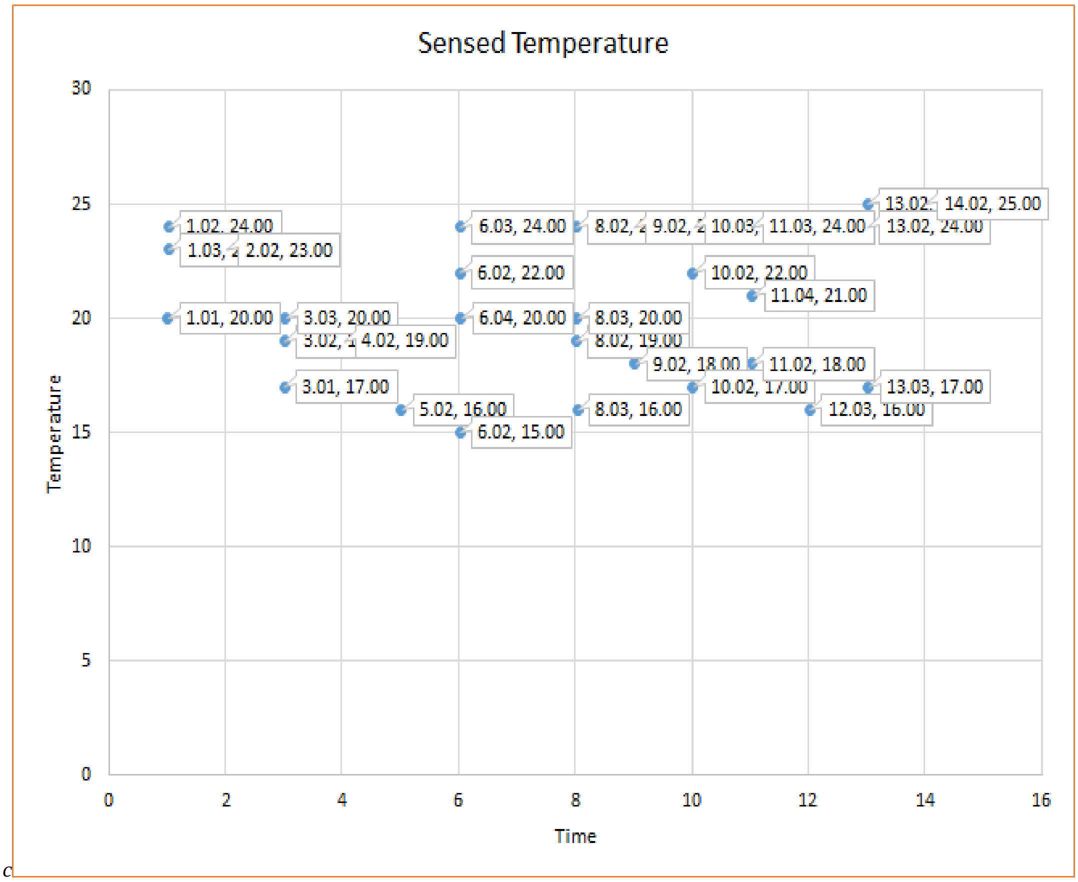

Figure 4.12. Ambient temperature of the cold chain

Even though managing and monitoring real-time ambient temperature and others key CC parameters provides a lot of possible solutions for enhancing the decision support of all actors, the most important advantage of IoT enabled CC is analyzing and interpreting the collected parameters. In this study, the accessed Real-time ambient temperature of the CC through WSN, is utilized to calculate the remained shelf-life of temperature sensitive products in the cold chain, calculated shelf-life value of temperature sensitive product is depicted by Figure 4.13. The developed algorithms in the previous section were used for predicting the remaining shelf-life the product.

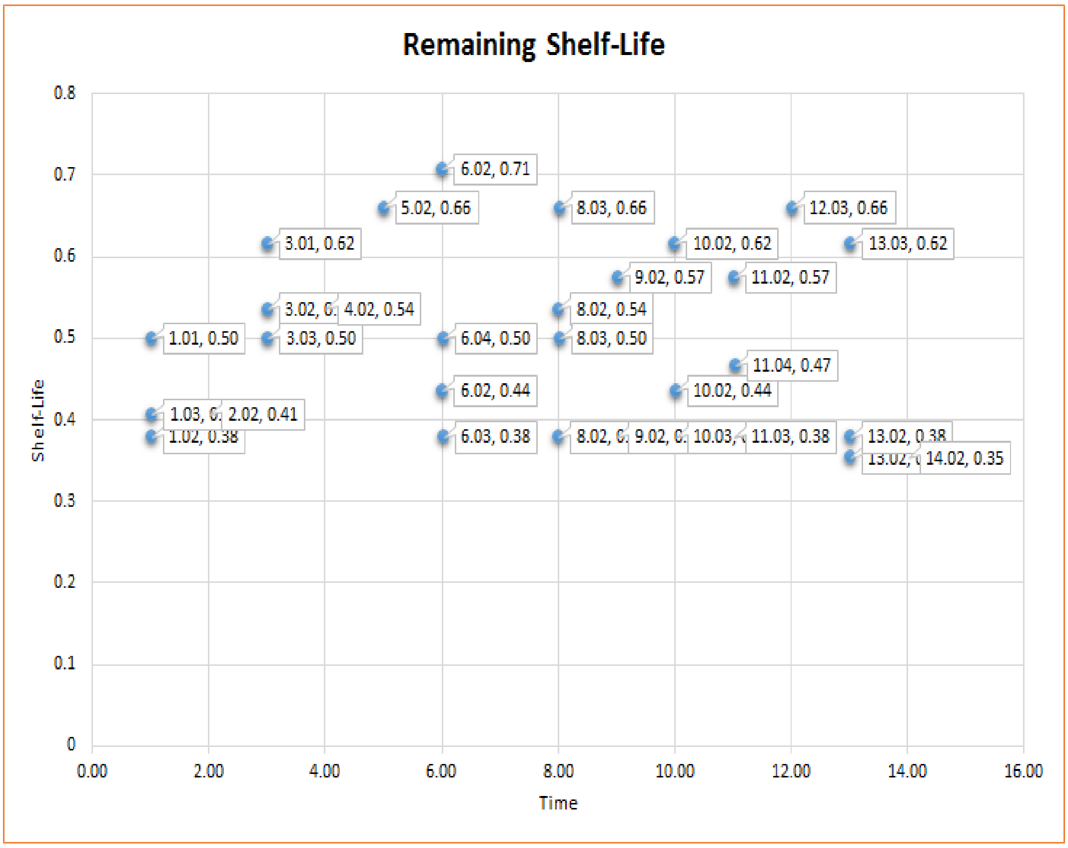

Figure 4.13. Remained shelf-life

The developed decision support system can filter out the ambient temperature of the CC and shelf-life of the product with the values that couldn't fulfill the pre-defined thresholds. Since both temperature and shelf-life of a product has a direct effect on the quality of temperature sensitive products, the decision makers could use this real-time results in order to take corrective measures for insuring the safety of the products, it could be manual or automated. Figure 4.14. and 4.15. show filtered out values of ambient temperature and its remaining shelf-life the product, respectively.

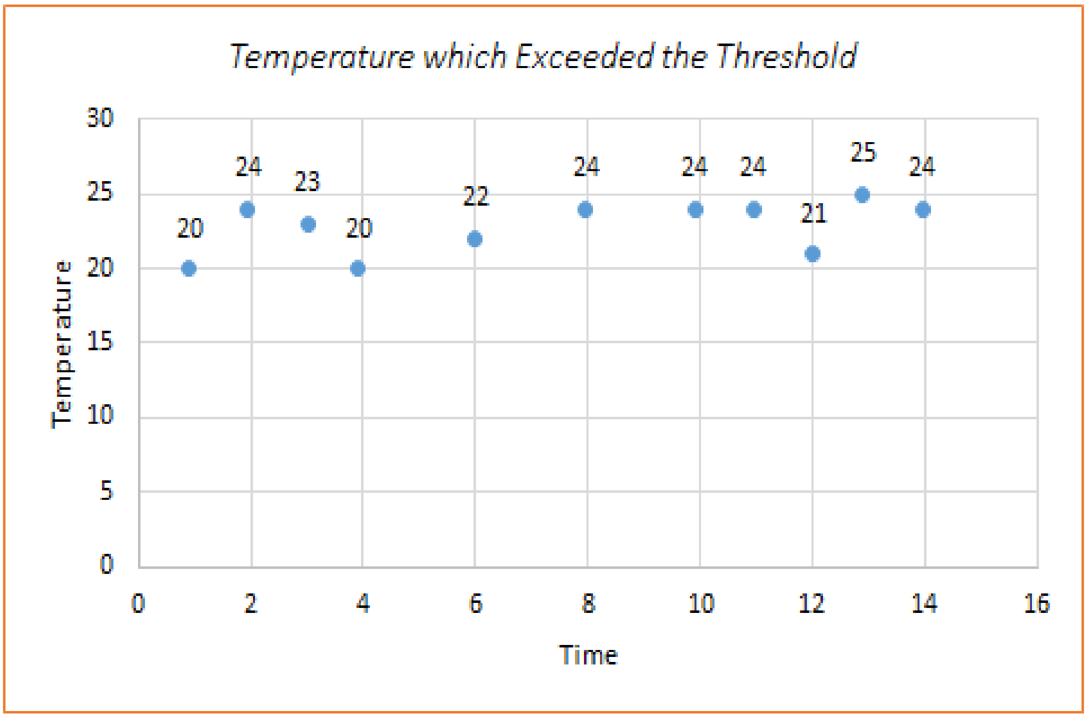

Figure 4.14. The value of temperature which exceeded the pre-defined threshold

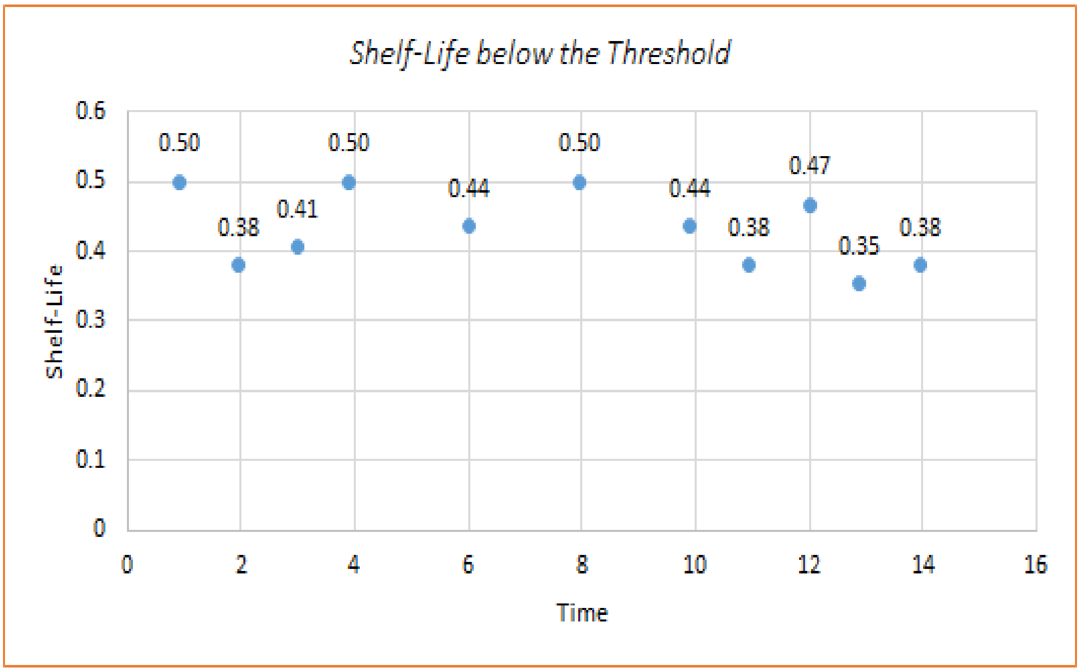

Figure 4.15. The shelf-life below the threshold

CHAPTER 5. CONCLUSION

In this thesis, internet of things vision, basic features, applications, enabling technologies and related work was first introduced. Taking into account our scenario IoT enabled cold chain logistics application and its previous studies are investigated, IEEE 802.15.4 and RFID’s standards, significant features and flexibility of deploying enabling devices for IoT applications were briefly examined.

The study has demonstrated IoT enabled CCLs that provide the capability to all actors to monitor, manage, gather real-time data and analyze ambient temperature of temperature sensitive item with the intelligence of providing a real-time alert for an abnormal result from the expected shelf-life of the product inside the CC. The scenario is modeled and simulated using Riverbed modeler, which is one of the appropriate network simulators for researchers. Thus, the first contribution of our study is, examining the Basic characteristics and flexibility of deploying IoT enabling technologies like WSN and RFID through developed the simulation model. We developed access point which compromises WS interface, GSM interface, and RFID reader interface. The second contribution of our study is also analyzing different way of predicting the shelf-life of perishable product and developed algorithms based on ASLT which helps to calculate the shelf-life of perishable product by utilizing collected ambient temperature.

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RESUME

Dini Remedan Abdurahman, was born on September, 22, 1983 in Ethiopia in a town named Harar. He went to primary school, secondary and high school in Ethiopia, where he completed in 2004. He entered Arba Minch University the same, where he joined the department of computer sciences and IT from which he graduated in 2007. Up to 2009, he has been working in one of regional state of Ethiopia which called Harari Regional state capacity building bureau as a senior network expert and also he has been working as Director of Center of Competency Bureau at the same regional state up to 2013. In 2014, he left his home country to start a master degree in Computer and Information Engineering at Sakarya University from which his graduation is expected in 2016.