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Simulation Modeling of An IoT Based Cold Chain Logistics Management System

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Abstract

The dramatic growth of the world economy has been accelerated the supply chain industry which demands logistics service to be agile, flexible and responsive. Internet technology is quite successful in transferring information between customer and logistics provider. However, the existing gap between goods flow and information flow in logistic service has created a problem in getting real-time information about temperature-sensitive items, which makes logistics management more challenging for decision-makers. Internet of Things technology seems a promising solution for monitoring, managing, and decision making in cold chain industries. This study proposes an Internet of Things based cold chain logistics that help 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. In this preliminary study, real-time data of ambient parameters are gathered using the developed wireless sensor network and transferred to the remote server through a gateway so that the shelf life of the products can be predicted by a decision support system. Radio Frequency Identification (RFID) is also modeled for further considerations related to the identification issue of perishable products inside the cold chain.

Keywords: Internet of Things, Cold Chain Logistics, Wireless Sensor Networks, Shelf Life.

IoT Tabanlı Soğuk Zincir Lojistik Yönetim Sisteminin Benzetim Modellemesi

Öz

Dünya ekonomisinde görülen çarpıcı büyüme, lojistik hizmetin çevik, esnek ve duyarlı olmasını isteyen tedarik zinciri endüstrisinide hızlandırmaktadır. İnternet teknolojileri, müşteri ve lojistik sağlayıcı arasındaki bilgi aktarımı konusunda oldukça başarılıdırlar. Bununla birlikte, lojistik hizmetindeki mal akışı ile bilgi akışı arasındaki mevcut boşluk, sıcaklığa duyarlı ürünler hakkında gerçek zamanlı bilgi edinme konusunda bir sorun teşkil etmektedir ve bu da lojistik yönetimini karar vericiler açısından daha zorlu hale getirmektedir. Nesnelerin İnterneti teknolojisi, soğuk zincir endüstrisinde ortam görüntüleme, yönetim ve karar alma süreçleri açısından umut verici bir çözüm gibi görünmektedir. Bu çalışma, soğuk zincirin gerçek zamanlı ortam sıcaklığını yöneterek, izleyerek ve sıcağa duyarlı ürünlerin raf ömrünü tahmin ederek tüm aktörlerin karar desteğini geliştirmeye yardımcı olan Nesnelerin İnterneti tabanlı bir soğuk zincir lojistiği önermektedir. Bu ön çalışmada, ortam parametrelerinin gerçek zamanlı verileri IEEE 802.15.4 tabanlı kablosuz algılayıcı ağları kullanılarak toplanmış ve bir ağ geçidi üzerinden uzak sunucuya aktarılarak ürünlerin raf ömrünün karar destek sistemi tarafından tahmin edilebilmesi sağlanmıştır. Geliştirilen uygulama çerisinde, soğuk zincirde bulunan bozulabilir ürünlerin tanımlanmasıyla amacıyla radyo frekanslı tanımlama (RFID) sistemi de modellenmiştir.

Anahtar Kelimeler: Nesnelerin İnterneti, Soğuk Zincir Lojistiği, Kablosuz Algılayıcı Ağlar, Raf Ömrü.

1. Introduction

An efficient supply chain plays a vital role in delivering high-quality materials and products within the agreed deadlines. In the case of transporting perishable items like foods and pharmaceuticals, supply chain organizations face even much greater difficulties [1]. 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. Therefore, the demand for controlling temperature sensitive goods using cold chain logistics (CCL) becomes an important topic for researcher and concern of government and enterprises. According to some reports, annual losses of the global food industry is more than 750 billion USD [2] and in U.S only $35 Billion (industry estimate) food west in the supply chain [3]. These losses mainly result from absent of proper facilities, improper food safety handling procedures, and lack of well-educated people in the area of cold chain. Additionally, annual sale of pharmaceutical, medical and biological product which are dependent on cold chain logistics are nearly 130 billion USD.

Through the past years, several technologies and methods have been used in monitoring CCL. CCL services use Radio Frequency Identification (RFID) applications on various temperature sensitive goods like pharmaceutical and food [4-6]. 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 asset, thus make cold chain smarter like smart homes, smart city, smart grids and smart regions [7].

This preliminary study aims to design an IoT supported 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 technologies like RFID and WSN. For more realistic performance evaluation, the whole models and scenarios are implemented using discrete-event network simulator called Riverbed Modeler. Riverbed simulation models for RFID and IEEE 802.15.4 devices are designed based on EPCglobal Gen 2 and IEEE 802.15.4 standards, respectively.

This paper is organized as follow: Section 2 summarizes the IoT supported Cold Chain and presents related works to the IoT and cold chain in the literature. Section 3 introduces IoT enabling technologies such as IEEE 802.15.4 and RFID, briefly. In Section 4, our proposed IoT supported cold chain logistics architecture is given with simulation results and discussions. The paper is concluded with last section providing final remarks.

2. Internet of Things Enabled Cold Chain

The aim of IoT is rendering capability to things in order to communicate with each other without restrictions of a time and place using certain infrastructure [8]. It is also determined as a dynamic global network infrastructure where physical and virtual “things” having unique identities and physical attributes to incorporate with information network [4]. IoT enables gathering of real-time ambient data such as humidity, localization, temperature, brightness, vibration, noise etc.[9]. The application that requires sophisticated analysis, refined decisions and immediate replays such as context-aware automation, resource allocation/optimization, asset tracking etc., needs IoT enabling device with an appropriate level of intelligent to sense or understand the external environment and take necessary action to the external event without any help of human intervention [5].Most widely used IoT technologies are WSN, RFID, NFC, Wi-Fi, beacon, bluetooth, cellular, mobile Internet etc. Different business sectors like energy, manufacturing, automation, health, logistics, and others take this device’s capability as an advantage to improve their company’s work.

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 [10]. Nowadays, the contribution of cold chain system in global trade is significantly big. However, due to the poor cold chain systems in developing countries, billions of tons of fresh food product and billions of dollars’ worth export are lost, each year. While millions of people are starving, billions of dollars are spent to help those people by improving agricultural process to get an efficient amount of food. On the other hand, nearly half of all food never reaches a consumer [11].

In order to address aforementioned problems, IoT supported cold chain seems to be the strongest candidate of deployment options for managing, monitoring, receiving real-time data and determining abnormal events regarding temperature sensitive products. In the literature, there are few studies regarding IoT supported cold chain logistics. Ding et al. [6] employed Computational Radio Frequency Identification (CRFID) tags to synthetically sense ambient temperature and detect any abnormal event, which reduces the amount of lost and damaged perishable goods within the developed IoT enabled environment. Substantial challenge of keeping temperature sensitive goods in appropriate temperature implies the importance of using IoT enabled CCL which contains emulator inside the truck during transportation to monitor the condition of goods and to give acceptance criteria is no longer maintained [12].

In this study, we developed an IoT enabled CCL system similar to the one given in Figure 1. It includes; i) WSN structure which sends measured ambient temperature to the gateway, ii) RFID technology for identification of sensitive good inside the cold chain and iii) a gateway which has WSN, RFID Reader, and GSM interfaces to send collected data to remote server.

WSN have initiated a new set of potential applications in such areas as industrial, medical, military, environmental etc. Comparing with the traditional wireless network, WSN are suffering from resource limitation in order to fulfill intended application. This challenge is raised especially due to the limited energy since sensor devices are basically powered by a small embedded battery with such expectations as prolonged network lifetime, assurance of real-time data delivery, managing dynamic topology, and providing scalability in terms of network size and density. In our simulation study, we have deployed IEEE 802.15.4 based WSN with a star topology.

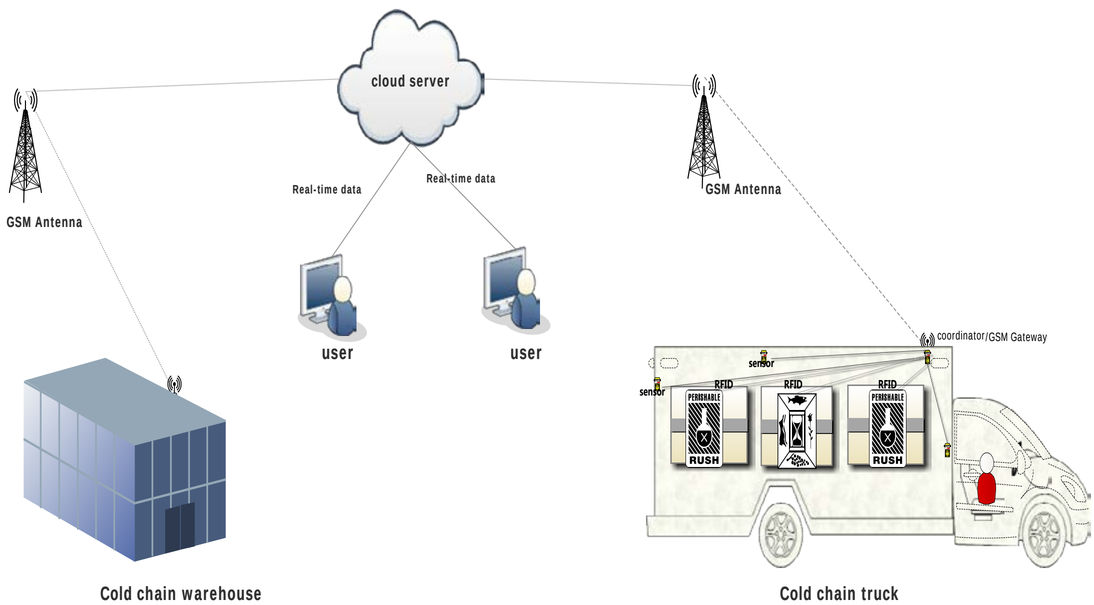

Figure 1 Outline of an IoT enabled cold chain logistics

Radio Frequency Identification is prominently emerging automated identification technology widely used for military applications, supply chain management, asset tracking, animal identification, payment systems etc. RFID compromise of an application host, a reader, and tags. Reader and tag utilize electromagnetic waves to communicate with each other. RFID tag contains a microchip to store certain information and antenna to receive and send the data.

RFID tags are classified as active, passive and semi-passive. Passive tags are widely used ones and have no built-in power source. They need radio waves transmitted by RFID reader to be activated and carried out a process. Active tags comprise self-sustained power or battery to keep the entire tags chip active through the whole communication between reader and tags, while semi-active tag is an integration of active and passive tags [14]. We focus in this study on passive tags. Simultaneous transmission attempt of tags may cause a collision and lost since passive tags are not capable of sensing shared communication channel. Similar to the other radio systems, RFID also requires Medium Access Control (MAC) protocol to avoid different types of collision. Anti-collision algorithms are used to solve the collision problem of RFID communication. Slotted Aloha (SA) algorithm is a widely used MAC protocol in RFID communication standard defined by EPCglobal [15].

In Gen 2 protocol, a reader uses three basic operations to manage tag population: **Select** is a process of selecting tag population in the vicinity for the inventory and access purpose. Reader sends a select command to the tags, which gives rise to power up the tag, assert or deassert SL flag and set inventoried flag that gets the tag ready for next state. **Inventory** is a process of identifying tags by using query, query repeat, and query adjust commands. **Access** is a process of accessing (writing to/reading from) identified tags.

3. Simulation Study

All the simulation scenarios, devices, and protocols are implemented using Riverbed Modeler and details of them are given in the following subsections.

3.1 Simulation Scenario

IoT enabled CCL model comprises of 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 2.

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 sense ambient temperature and to transfer it to the PC which is responsible for coordinating the network and has a GSM and RFID interfaces.

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 standard PC device 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 also includes an RFID tag for further considerations. The server node in the scenario is employed 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 3.2.

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 products in IoT enabled CCLs. IEEE 802.15.4 based WSN structure employed in this study has been derived from the one developed by IPP-HURRAY Research Group [16]. 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 includes a physical layer with a wireless radio receiver (rx) and a transmitter (tx). It supports 250 Kbps data rate, works at 2.4 GHZ frequency band and uses Quadrature Phase Shift Keying (QPSK) modulation technique. The Media Access Control Layer (MAC) of the node model supports Slotted CSMA/CA mechanism and beacon-enabled mode in which PC sends a beacon to synchronize associated nodes in order for helping nodes determine their PC and organizing the sleeping times for saving on energy.

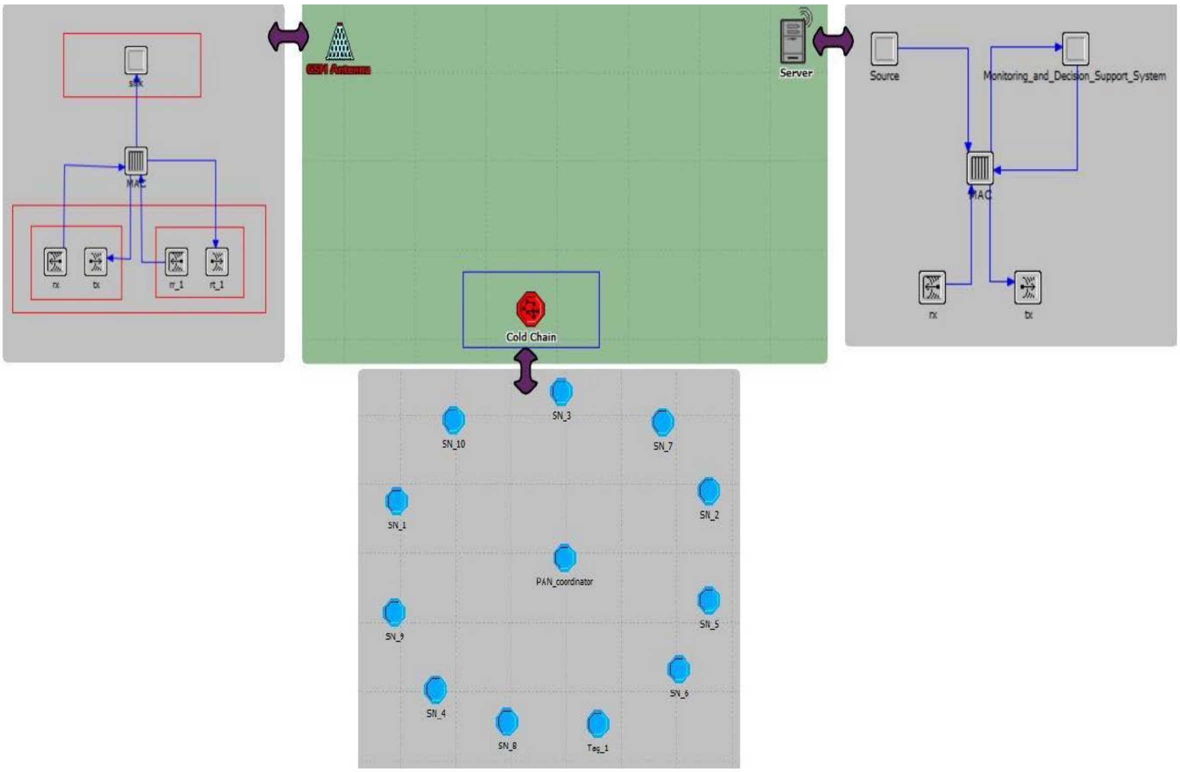

Figure 2 Internet of things enabled cold chain logistics: An example scenario

Since the MAC layer has a beacon-enabled mode, Guaranteed Time Slot (GTS) service for time-critical service also can be supported by the WSN structure. However, we have employed only the Contention Access Period (CAP) to provide communication between nodes since delivering the ambient temperature is not a time-critical service. The traffic source in the node model produces data frames, i.e. ambient temperature, transferred by the slotted CSMAC/CA during CAP period. 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 includes additional modules as a GSM interface, an actuator interface, and a RFID reader module, as can be shown in Figure 3.

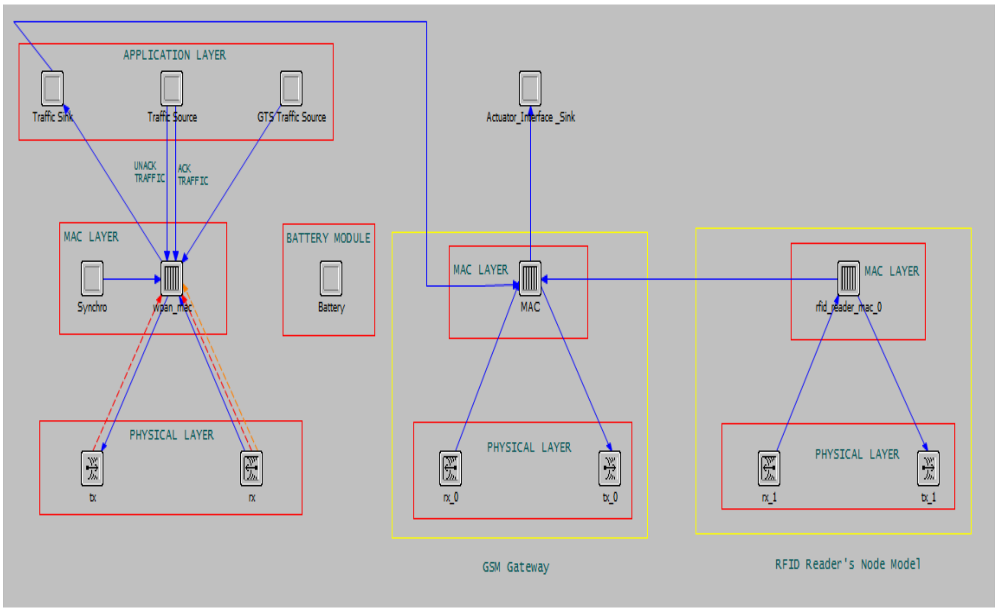

Figure 3 PAN coordinator node model

GSM interface in the PC node model is responsible for providing communication between the network in vehicle and the remote server. All the sensed temperature values and RFID tags' information are sent to the remote server using GSM interface incorporated into the PC. The actuator interface in the PC is capable of getting any control signal produced by the Monitoring and Decision Support System employed in the remote server and of delivering it to the control system in the vehicle. The detail of algorithm employed in the Decision Support System is given in subsection 3.2.

Figure 4 and Figure 5 show the process models of RFID reader and tag, respectively. The process models are modeled with a Finite State Machine (FSM) and developed based on probabilistic anti-collision resolution protocol, called adaptive slotted aloha, according to the EPCglobal Gen 2 specification. The details of RFID system can be found in [15].

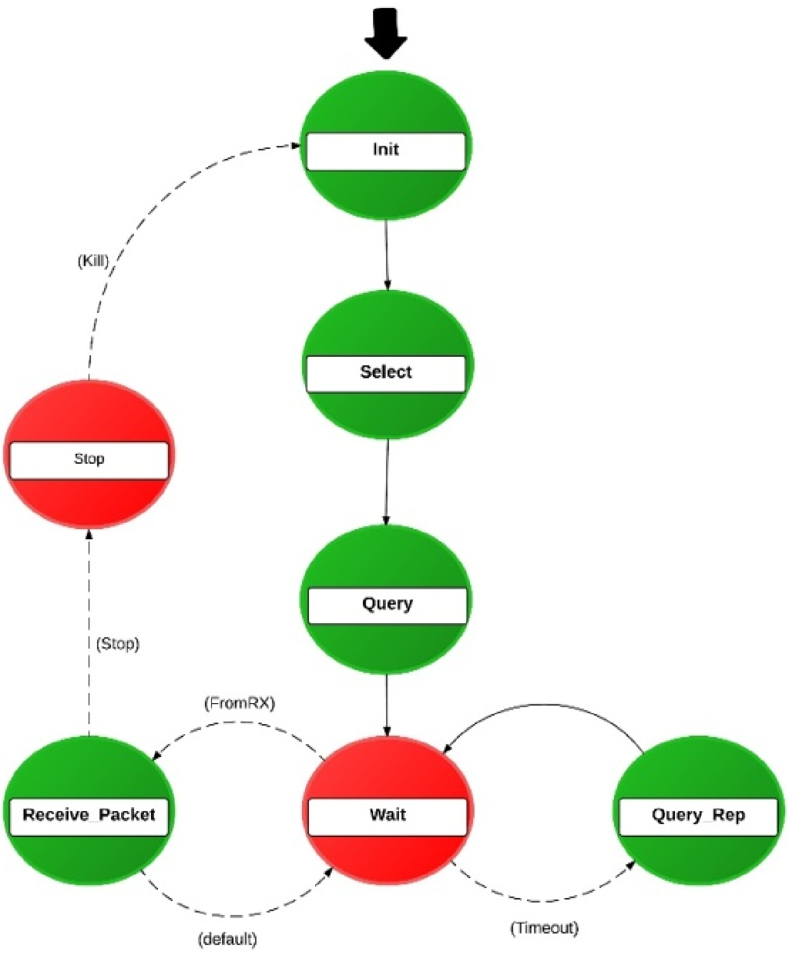

Figure 4 RFID reader process model

3.2 Shelf Life Predication of Perishable Foods

Food products start to deteriorate the moment they are harvested, so it is important to use the cold chain to ensure 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 2 shows the shelf-life of common perishable food product under optimal temperature [10].

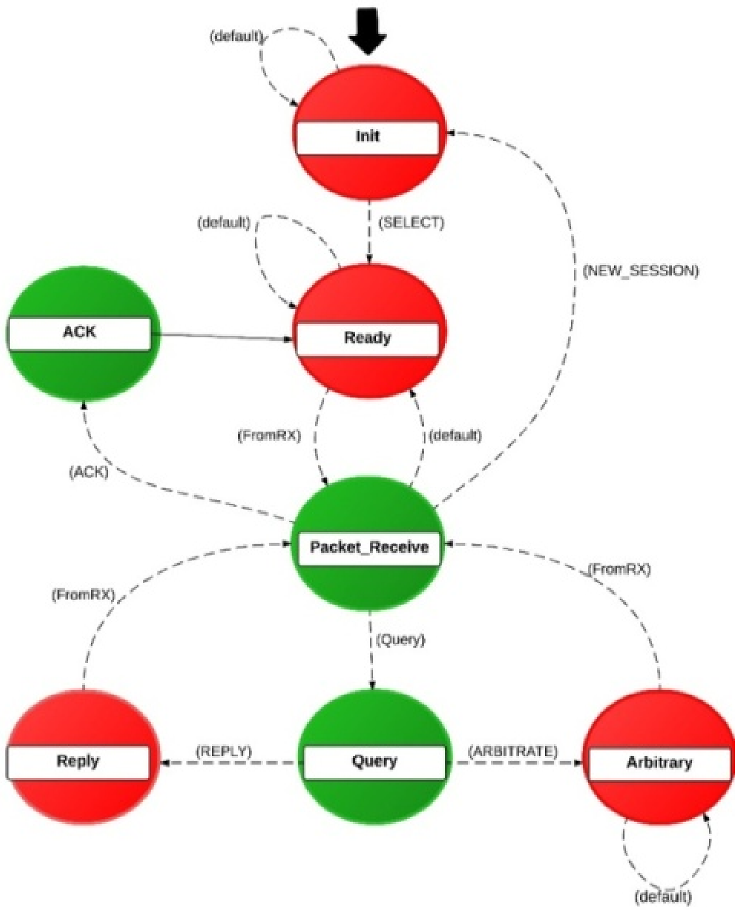

Figure 5 RFID tag process model

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.

Table 2 Shelf-life of common perishable food products [9]

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..,)	14-65	-2
Oranges	21-90	7
Pears	120-180	-0.6
Potatoes	30-50	10
Seafood (shrimp, lobster..,)	120-360	-17.8
Strawberries	5-10	0.6
Tomatoes	7-14	12

Accelerated Shelf Life Testing (ASLT) is a common method to be able to calculate the shelf life of the products, rapidly. In this study, ASLT is exploited to predict the real-time shelf life of perishable products. According to ASLT, 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 represented by Q10=2 [17-18]. Considering this theorem, the shelf life of a perishable product can be determined using Equations 1 and 2.

$$Q10 = \left(\frac{\text{Shelf-life at elevated T}}{\text{Shelf-life Claimed}}\right)^{\frac{10}{\text{elevated T(°C)} - \text{optimal T(°C)}}} \quad (1)$$

$$\text{shelf-life at elevated T} = \frac{\text{Shelf-life Claimed}}{2^{\frac{(\text{elevated T(°C)} - \text{optimal T(°C)})}{10}}} \quad (2)$$

The algorithm used in our simulation models related to self life calculations is given below.

1. Store the values of standard shelf life of a product “Shelf-life Claimed”, an appropriate temperature for a product “optimal T(℃)”, and a 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. If the “shelf-life at elevated T” value of the product is in standard condition, continue monitoring the shelf life for a specified time.
5. If calculated “shelf-life at elevated T” is below a certain threshold, send an alert to the cold chain and repeat the process within specified time.

4. Results And Discussions

Figure 6 depicts local statistics of WSN model to measure end-to-end delay which indicates the elapsed time while any data packet is sent from an 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 an expected result since the network load is very light in size and the network has enough capacity to transfer all the generated packets.

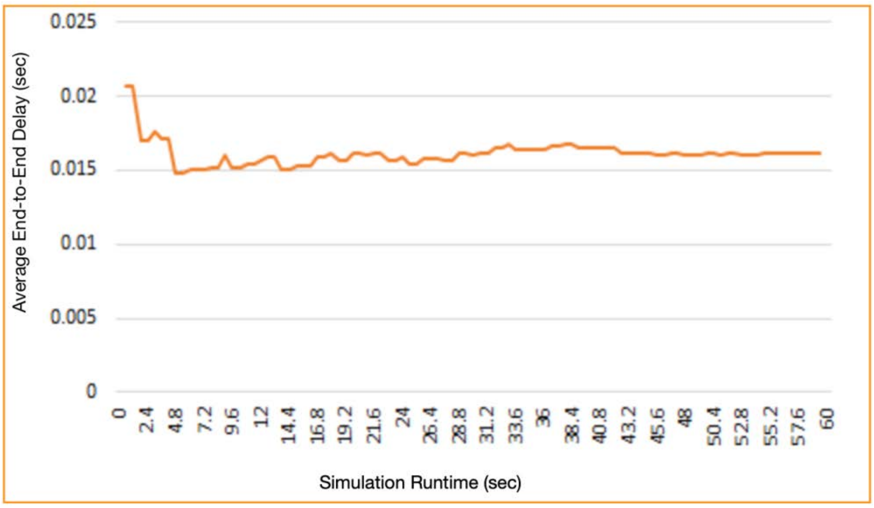

Figure 6 Average End-to-End delay result

The whole network output load of WSN in our IoT enabled CCLs model is given in Figure 7. 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.

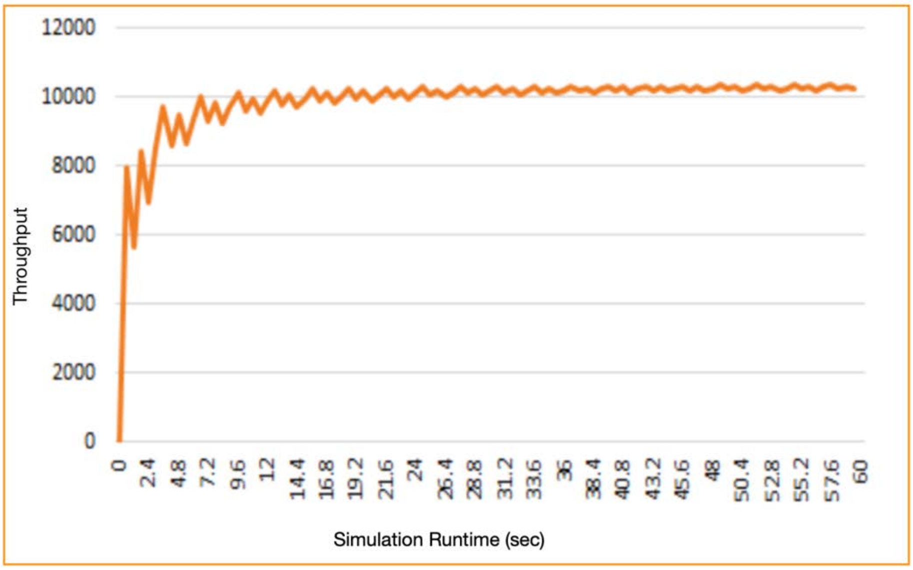

Figure 7 Network output load

In the scenario, IoT gives the possibilities for logistics managers, quality managers, and other actors, to manage and monitor real-time ambient parameters of cold chain through the whole life cycle. Figure 8 illustrates real-time ambient temperature of the cold chain which is collected at a specified time using WSN. The collected temperature data is stored in designated server across the chain, which used for preparing automated compliance report of the products.

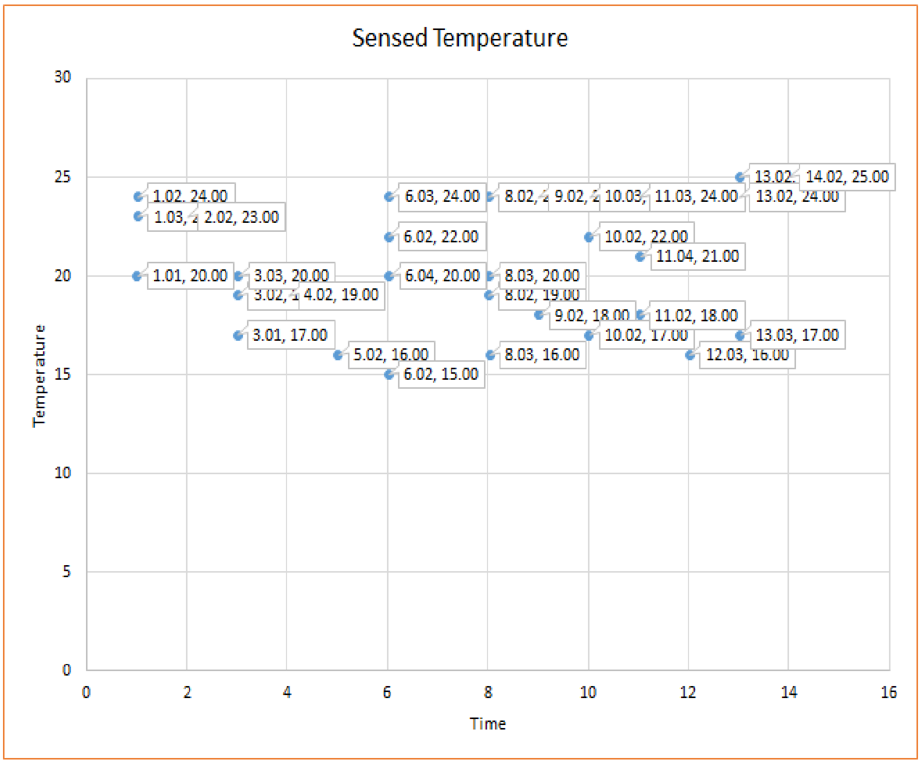

Figure 8 Ambient temperature of the cold chain

Even though managing and monitoring real-time ambient temperature and others key CC parameters provide 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 measured ambient temperature of the CC is utilized to determine the remaining shelf life of temperature sensitive products. Calculated shelf life value of temperature sensitive product is depicted in Figure 9. The developed algorithms in the previous section were used for predicting the remaining shelf life of the products. The developed decision support system can filter out the ambient temperature of the CC and remaining shelf life of the product with the values that couldn't fulfill the pre-defined thresholds. Since both temperature and shelf life have a direct effect on the quality of temperature sensitive products, decision makers could use these real-time results in order to take appropriate measures ensuring safety of the products.

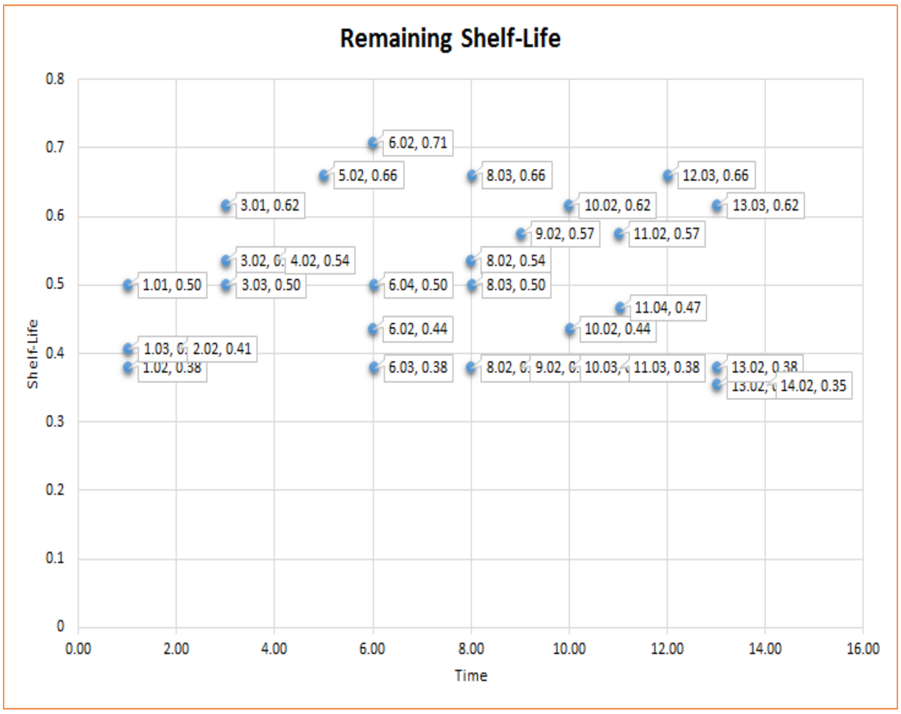

Figure 9 Remaining shelf life of the products

5. Conclusions

This study has introduced an IoT enabled CCLs that is capable of monitoring and analyzing the ambient temperature of perishable products and calculating the remaining shelf life of them, in real-time. We developed an access point which includes WSN, GSM, and RFID reader interfaces. An RFID system is also modeled for further considerations related to the identification matter of perishable products inside the cold chain. Additionally, we have integrated the ASLT based remaining shelf life prediction algorithm into the system proposed. The results show that IoT supported cold chain systems have a big potential for managing, monitoring, receiving real-time data and determining abnormal events regarding temperature-sensitive products.

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References

[1] S. Mejjaoulia and R. F. Babiceanu, "RFID-wireless sensor networks integration: Decision models and optimization of logistics systems operations," Journal of Manufacturing Systems, vol. 35, pp. 234-245, 2015.

[2] Food wastage footprint: Impacts on Natural Resources, 2013. [Online]. Available: http://www.fao.org/docrep/018/i3347e/i3347e.pdf. [Accessed: 2019].

[3] Cost-Effective, Real-Time System to Tackle $35 Billion Annual Waste in U.S. Perishable Goods, 2006. [Online]. Available: http://www.prnewswire.com/news-releases/cost-effective-real-time-system-to-tackle-35-billion-annual-waste-in-us-perishable-goods-56420232.html. [Accessed: 2017].

[4] J. C. Park, "Mobile RFID reader-initiated LLRP connection," IEEE Int. Conf. Comput. Convergence Technol, pp. 1205-1209, 2012.

[5] F. Li and Z. Chen, "Brief analysis of application of RFID in pharmaceutical cold-chain temperature monitoring system," Proceedings 2011 International Conference on Transportation, Mechanical, and Electrical Engineering (TMEE), pp. 2418–2420, 2011.

[6] H. Ding, R. Li, S. Li, J. Han and J. Zhao, "MISS: Multi-dimensional Information Sensing Surveillance for Cold Chain Logistics," IEEE 10th International Conference on Mobile Ad-Hoc and Sensor Systems, pp. 519-523, 2013.

[7] R. Porkodi and V. Bhuvaneswari, "The Internet of Things (IoT) Applications and Communication Enabling Technology Standards: An Overview," 2014 International Conference on Intelligent Computing Applications, pp. 324-329, 2014.

[8] Internet of Things European Research Cluster, "The Internet of Things," New Horizons, 2012.

[9] B. Yan and D. Lee Lee, "Application of RFID in cold chain temperature monitoring system," ISECS International Colloquium on Computing, Communication, Control, and Management, pp. 258-261. 2009.

[10] J. P. Rodrigue and T. Notteboom "The Cold Chain and its Logistics," The Geography of Transport Systems, 2017. [Online]. Available: https://people.hofstra.edu /geotrans/eng/ch5en/appl5en /ch5a5en.html. [Accessed: July 2019].

[11] Outlook on the Logistics & Supply Chain Industry. World Economic Forum, 2013.

[12]S. Nechifor, A. Petrescu, D. Damian, D. Puiu and B. Târnaucă, "Predictive analytics based on CEP for logistic of sensitive goods," International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), pp. 817-822, 2014.

[13] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari and M. Ayyash, "Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications," IEEE Communications Surveys & Tutorials, vol. 17, pp. 2347-2376, 2015.

[14] J. Banks, M. A. Pachano, L. G. Thompson and D. Hanny, "RFID Applied," John Wiley & Sons Inc. 2007.

[15] EPC™ Radio-Frequency Identity Protocols Generation-2 UHF RFID, GS1 EPCglobal Inc., 2013.

[16] A. Van Nieuwenhuyse, A. Koubaa and M. Alves, "On the use of the ZigBee protocol for Wireless Sensor Networks," IPP-HURRAY Research Group, 2006.

[17] M. A. V. Boekel, "Kinetic Modeling of Food Quality : A Critical Review," Comprehensive Reviews in Food Science and Food Safety, vol. 7(1), pp. 144–158, 2008.

[18] T. P. Labuza, "Application of chemical kinetics to deterioration of foods," J. Chem. Educ, vol. 61(4), pp. 348, 1984.