An IoT Smart System for Cold Supply Chain Storage and Transportation Management

Abdulrahman Alshdadi
Department of Information Systems and Technology, College of Computer Science and Engineering, University of Jeddah, Saudi Arabia
alshdadi@uj.edu.sa

Souad Kamel
Department of Computer and Network Engineering, College of Computer Science and Engineering, University of Jeddah, Saudi Arabia
skamel@uj.edu.sa (corresponding author)

Eesa Alsolami
Department of Cyber Security, College of Computer Science and Engineering, University of Jeddah, Saudi Arabia
eaalsulami@uj.edu.sa

Miltiadis D. Lytras
Management of Information Systems Department, Deree College, The American College of Greece, Greece
miltiadis.lytras@gmail.com

Sahbi Boubaker
Department of Computer and Network Engineering, College of Computer Science and Engineering, University of Jeddah, Saudi Arabia
sboubaker@uj.edu.sa

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ABSTRACT

Cold supply chains are becoming more and more attractive due to the high demand induced by increased consumption. To fulfill standards and customers' requirements regarding the conditions under which cold supply chain products (mainly foods and pharmaceuticals) are stored (in warehouses) and transported to the end-users, tracking those conditions is a necessity. To ensure a high level of visibility, fostering emerging technologies can improve the quality of service in supply chains in terms of delivery time, cost, and quality. In this paper, a global framework for monitoring the conditions of storage and transportation of cold products across the whole supply chain is designed and implemented practically. The proposed solution is built around low-cost and low-energy consumption devices such as sensors and microcontrollers which are connected to cloud storage to allow a high level of visibility in the supply chain allowing all parties, including the end-consumers, to follow the products during their transfer, providing a conceptual framework that monitors the performance on a real-time basis and enhances decision making. A prototype using an embedded temperature/humidity sensor, a tiny microcontroller equipped with a Wi-Fi connectivity device, and a mobile 4G/5G network is designed and implemented. The proposed system is connected to a cloud-storage platform continuously accessible by the main parties of the cold supply chain including the provider, the transporter, and the end-consumer. The proposed framework may be handled as a smart contract during which any party can assume its responsibility for the assurance of the best conditions of the supply chain operation. A small-scale real-life scenario conducted in Jeddah City, Saudi Arabia is introduced to show the feasibility of the proposed framework.

Keywords-cold supply chain; tracking; monitoring; microcontroller; sensors; cloud storage

I. INTRODUCTION

Internet of Things (IoT) has attracted much attention over the last few years in various domains, including the supply-chain. The main applications that contributed to the development of the supply-chain domain include traceability and tracking of the conditions under which various goods are stored and transported [1]. Food and pharmaceutical supply-chain involves products that require careful attention during their storage and transportation. The concept of food supply-chain virtualization refers to the opportunities provided by the IoT technology to the cold product sector decision-makers helping them to remotely control and monitor products that are prone to unpredictable events that may affect their safety [2]. While being transported from the source to the destination or warehouses, foods and pharmaceutical products should be kept at prescribed levels of temperature and humidity [3]. Warehouse management systems are in the heart of supply-chain operations to ensure compliance with Industry 4.0 requirements which are nowadays revolutionizing the logistics domain towards efficiency and sustainability [4]. As reported in [5], emerging logistics may include coupling between IoT and blockchain to ensure high efficiency of logistics and transportation operations. Logistics systems are progressively integrating Cyber Physical Systems (CPSs) and information technology as well as communication technologies like 5G. At the design stage of a supply-chain management system, the integration of cloud storage platforms and CPSs has emerged to cut with the traditional logistics systems that focused on vehicles, distribution centers and the characteristics of relevant distribution tasks [6]. In this direction, smart (intelligent) logistics (also called logistics 4.0) has attracted researchers and practitioners and has shown a high potential to ensure efficient tracking, control and automation of the supply-chain [7].

In this paper, an IoT-based storage and transportation system applied to cold supply chain products (including foods and pharmaceuticals), will be designed and implemented under the specific conditions of Jeddah City, Saudi Arabia. The main contributions of this study are:

- The design and implementation of a cost-effective management system for cold supply-chain allowing tracking the conditions under which cold products are stored and transported.
- The designed solutions are based on low-power consumption sensors and microcontrollers which makes them deployable in various and multiple supply-chain operations.
- A major feature of the proposed system is the possibility to extend it to implement smart contracts, where the violation of the contract conditions may lead to canceling the contract or any related operations.

II. LITERATURE REVIEW

Cold supply-chain management systems have attracted much attention due to their high ability to involve/integrate various technologies including IoT, blockchain, information technology, and cyber physical systems in unified frameworks. Authors in [8] integrated IoT and blockchain for efficient traceability in a frozen aquatic product. The developed system was reported to overcome difficulties faced by traditional systems involving security, decentralized data management, and easy tampering of the exchanged data relevant to the logistics operations. As part of an efficient supply-chain, packaging related issues were considered in [9] using tools from the Model-Based Engineering (MBE). The IoT technology components, including sensors, were implemented in the pallets used to handle the products along the supply-chain. The collected information is expected to improve the control capabilities of the whole system. High-price shipment management and tracking systems in the smart city context were considered in [10]. To ensure a high level of transparency, a completely automated smart-contract was implemented involving all supply-chain parties and including all operations such as contract creation, money deposit, and the possibility of cancellation if any of the agreed conditions is violated. To prevent perishable products spoilage which accounts for high amounts of waste worldwide, real-time tracking and monitoring was considered in [11]. The main aim of the developed system was to detect anomalies in order to allow involved parties to react in order to limit waste and prevent dangers to consumers. The developed system architecture included four layers, namely perception, network, processing, and application. Additional applications of IoT in cold supply-chain included vaccine supply-chain during COVID-19 pandemic [12] and sensor agricultural for Chinese medicine logistics [13]. From a managerial perspective, the IoT combined with other technologies such as blockchain, has contributed to improve the management of supply-chain various operations including warehousing, manufacturing and delivery [14].

Table I summarizes the relative works and emphasizes on the controlled ambient parameters, involved technologies including datalogging, communication and related applications.

III. METHODOLOGY

A. System Design

Based on the literature review, it is seen that the trend in cold supply chain applied research focuses on the application of emerging technologies (IoT and blockchain) to two of the main components of a logistics framework, storage and transportation. Although the cold supply chain structure includes product manufacturing and transportation from the factory to the storage warehouse (Figure 1) and since the temperature is the main factor that may affect the quality of cold products, this paper will focus only on the temperature tracking and product management during the storage and transportation phases since they are more prone to difficulties. Factories are usually taking care about the conditions of their products manufacturing. In this section, the IoT-based system for tracking and monitoring the temperature in cold supply-chain is presented in detail. To design the system, a structured process including five steps is devised. The choice of the system components is based on the users' requirements, determined from those proposed in previous studies, our own observations, direct meetings with the stakeholders, or electronic surveys. Once the requirements are well-understood, the next step consists of choosing the system components that are able to fulfil the requirements while considering several criteria and constraints such as functionality, ease of use, technology, ease of implementation, component availability, cost, etc.

TABLE I. SUMMARY OF SELECTED STUDIES ON IOT IN COLD SUPPLY-CHAIN

Reference	Ambient parameter(s)	Technologies	Datalogging	Communication	Applications
[15]	Temperature, Relative Humidity (RH), O_2, CO_2, shock and vibration	IoT	Sensor nodes	Wireless communication networks	Fresh fruit and vegetables
[16]	Temperature (low values) for frozen products	IoT, Radio-Frequency Identification (RFID), blockchain	Sensor nodes	Wireless Sensor Networks (WSNs)	Fishery traceability and safety
[17]	Temperature, humidity, luminosity, and gas concentration	Real time monitoring and notification based on IoT + Artificial Neural Networks (ANNs) for classification	Multi-sensor system	Bluetooth, Internet	Management of cold product storage
[18]	Pressure	IoT, ANNs	Microcontrollers	WSNs in the distribution service layer	Coordination in the distribution of cold products based on IoT
[19]	Temperature, biosensors, gas sensors, freshness indicators	IoT and Communication	Not included	Various communication tools	Management of food supply chain
[20]	Freezing temperature	IoT, 5 G communication technology	FPGA	5 G networks, GPS system	Cold supply chain logistics system
[21]	Temperature, location, humidity, pressure, light exposure	Blockchain, IoT	Not included	RFID, Ethereum wallet, cloud messaging services	Smart contract based on IoT and blockchain

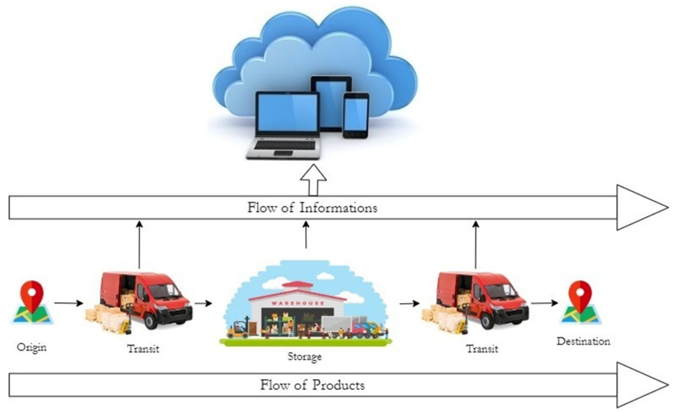

Fig. 1. Block Diagram of an IoT-enabled cold supply-chain management system.

B. Hardware Specifications

Once all components are chosen, the next step is to allocate to the prototype development which will be the base for later testing the efficiency of the system at small-scale before deploying it. The system architecture is provided as a block diagram in Figure 2. The chosen components (hardware), their technical specifications, and their related requirements are provided below.

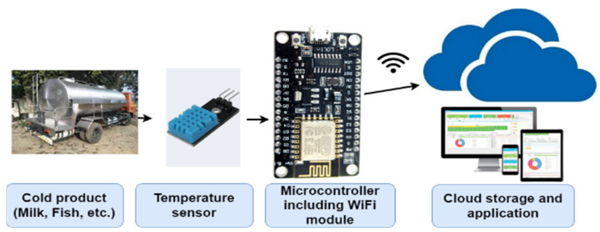

Fig. 2. System architecture.

1) Temperature Sensor

DHT22 was chosen as the temperature sensor for many reasons. First, the sensor provides the temperature in a reasonable range (-40 °C to 50 °C) which corresponds to a variety of cold and frozen products. As indicated in the foods' transportation regulations, the majority of fresh vegetables, foodstuff, fresh fruit and chilled dairy and dairy products transportation temperatures are covered by the DHT22. It is affordable, particularly for small-scale prototyping which is the case of our study. The sensor accuracy is defined as ±0.5 °C (for temperature) and ±1% (for humidity) which can be considered as good values, since even the regulations are not so strict in terms of accuracy. In addition, the operating voltage (3.5 V to 5.5 V) and the operating current (0.3 mA (measuring) and 60 uA (standby)) are easily provided by small batteries that can be embedded on the transportation mean.

2) NodeMcu (ESP8266)

The NodeMCU (Node Microcontroller Unit) is an open-source hardware that can be programmed by the Arduino Integrated Development Environment (IDE). The microcontroller is built around a low-cost device called ESP8266. The ESP8266 is a 32-bit microcontroller that includes the crucial small-scale elements of a mini-computer such as a microprocessor and RAM. In addition, the microcontroller contains a networking (Wi-Fi) device that allows connectivity to the Internet. Those specifications made this microcontroller an excellent choice for the IoT-based tracking and monitoring system for supply-chain management developed in this study. The NodeMcu was chosen against other microcontrollers such as the Raspberry Pi for its affordable price, being open-source and the availability of a lot of materials and applications in various fields including online monitoring.

3) Battery

The battery is highly required for feeding the system, particularly during the product transportation. A 3.7 V Lithium-Ion battery was chosen for this system due to its reasonable capacity (2600 mAh) and affordable price (around 7 USD). In addition, this battery is able to feed the NodeMcu microcontroller as well as the temperature sensors for acceptable periods of time.

C. Software Specifications

For the software components, the Arduino IDE to develop the application code and upload it in the microcontroller flash memory and the free cloud platform Adafruit were utilized. Adafruit is an IoT platform that provides cloud services including analytical tools for data collection, visualization, and analysis. At some extent, the provided services are free of charge which allows simple prototyping mainly at small scale. Although Adafruit can provide large-scale applications (paid services), this study will be limited to the free available services for cost limitation reasons.

IV. RESULTS AND DISCUSSION

A. Prototype Development

After completion of the system's various hardware and software components, the preliminary prototype was implemented. The prototype is depicted in Figure 3. The designed system consists of three layers including perception, network, and application [22-24].

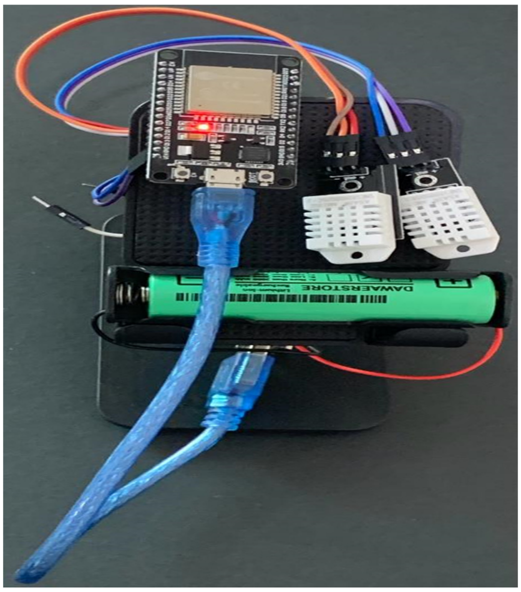

Fig. 3. The prototype of the cold supply-chain management system based on IoT.

The perception layer is composed of two sensor nodes (DHT22) that allow measuring the temperature as a key parameter in the cold supply-chain. It can be recalled here that the temperature is used to illustrate the concept of monitoring in cold supply-chain and that other sensors can be included (RFID, GPS, vibration sensor, etc.) if there are additional standard requirements. In this study, the DHT22 sensor is only used as a temperature sensor although it can also measure humidity. To overcome the issue of sensor calibration, two temperature sensors were used. The network layer includes all devices and protocols that facilitate the data transmission. As depicted in Figure 3, the NodeMcu microcontroller is equipped with a Wi-Fi module integrated to the microcontroller board to wirelessly send the sensed data (temperature in this case) to the cloud storage. Through the microcontroller particular edge computing of the data can be performed to improve system performance. Among those computing actions, the storage of redundant data can be prevented (such as the case when the temperature doesn't change from one sample to another). The application layer consists of the features supported by the cloud such as storage and visualization. To illustrate the usability of the designed system, several use-case scenarios were practically implemented under Jeddah City, Saudi Arabia conditions. Jeddah climate is characterized by a relatively high temperature accompanied with a high level of humidity due to its proximity to the Red Sea. Under those conditions, cold supply-chains may face several problems during the product storage or transportation. In what follows, the results of a case scenario will be detailed.

At the beginning, a cold supply-chain monitoring channel has been created on the Adafruit platform. As general settings, the channel ID and the Application Programming Interface (API) key are unique references to the channel. They are later required for programming purpose. Two fields mapped to temperature and humidity (the two parameters measured by the DHT22 sensor) are set up, even though only the temperature was considered in this study. Several parameters related to the data visualization can be modified via the platform. The private view mode has been chosen in this scenario. However, sharing the channel view with specific users is possible and this will be implemented in practice to support smart contract terms of the cold supply-chain. In fact, in real-life scenarios, only the allowed parties/stakeholders such as the product supplier, transporter, retailer, and end-user can view the conditions under which the product is stored/transported. The channel settings include the location (latitude, longitude, and elevation) of the sensor node of the variable being monitored. If a Global Positioning System (GPS) module is used, the tracking of the transported cold product will be possible. A specific field will then be created.

B. Experimental Setup

On November 25, 2023, an experimental test of the designed cold supply-chain system based on IoT was conducted under Jeddah City conditions. The experiment was implemented in two phases. First, the NodeMcu microcontroller was connected to the WiFi router and then it was connected to an Android smartphone to simulate the real conditions of a cold product being transported. In real conditions, the smartphone can belong to the truck driver or can be a dedicated one. The values of the temperature during the test phase are shown in Figure 4. Two scenarios simulating the storage and the transportation of a cold product are implemented as shown in Table II. As the entries are being collected, alerts on thresholds were implemented depending on the transported cold product temperature as required by the related standards.

TABLE II. IOT COLD SUPPLY CHAIN MANAGEMENT SCENARIOS: STORAGE AND TRANSPORTATION

Scenario	Start location	End location	Start time	End time
Storage	Alsulaymaniyyah	Alsulaymaniyyah	8:02 PM	8:56 PM
Transportation	Alsulaymaniyyah	Alfaysaliyyah	8:56 PM	9:43 PM

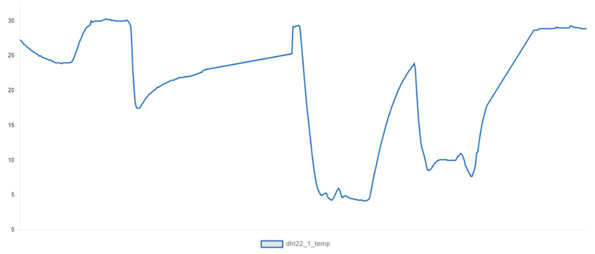

Fig. 4. Records of the temperature of the cold supply-chain channel collected on November 25, 2023 (Jeddah, Saudi Arabia), starting at 8:02 PM.

C. Limitations

During the cold supply-chain monitoring system development, several limitations were faced. Those limitations are summarized as follows:

- Before using any sensor (including the temperature sensor DHT22), its calibration should be performed with a calibrating sensor. One of the difficulties faced in this study is the unavailability of such a sensor. As a solution, two sensors were used almost in the same location [25].
- When connected to a smartphone WiFi network, particularly in the case of long-distance product transportation, the system may face energy consumption issues which can be solved using appropriate power banks/batteries.
- The IoT free channel on Adafruit allows a relatively limited number of entries [26]. In order to provide more storage space, a paid channel may be required depending on the number of the required entries and on the number of used sensor nodes.

D. Cost Analysis

The cost of the cold supply-chain system based on IoT is a primary key of its usefulness. The costs of the system components are shown in Table III.

TABLE III. IOT COLD SUPPLY CHAIN PROTOTYPE COST ANALYSIS

Component	**Price (SAR)**
NodeMCU microcontroller	70
Temperature sensor DHT22 (2 items)	90
Battery	15
Cable and wires	5
Total cost	180

As can be seen, the cost is relatively affordable and the system is therefore deployable and extendable, especially to high price shipments.

V. CONCLUSION

In this paper, a cold supply-chain monitoring system based on Internet of Things was designed and tested experimentally. The system was based on low-cost devices and free cloud platform services for prototyping purpose. The prototype was tested under Jeddah (Saudi Arabia) conditions and was found to be efficient in monitoring the temperature as the key parameter of cold products (food and pharmaceutical) storage and transportation. This system can be adopted as a basis for smart contracts in supply chain where the various parties, including the supplier, transporter, retailer, and end-user can track/monitor the product during its journey from the factory/store to the consumer. The designed system is found to be extendable to other applications in logistics and supply-chain by including more sensors and adding other features, particularly in the application layer. As future work, more features can be added to the system, e.g. the required cloud storage space could be minimized by pre-analysis of the collected data as soon as they are received in order to store only significant changes or the use of artificial intelligence techniques to extract only the most significant data features. By implementing those improvements, the designed system can support smart contract implementation as a part of the cold supply chain.

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