C2SLDS: A WSN-based perishable food shelf-life prediction and LSFO strategy decision support system in cold chain logistics

Abstract: Temperature monitoring, shelf-life visibility and Least Shelf-life First Out (LSFO) stock strategy are important contents in perishable food cold chain logistics for both cold chain managers and workers in order to reduce quality and economic losses. This paper illustrates a wireless sensor network (WSN) based integrated Cold Chain Shelf Life Decision Support System (C^2SLDS) designed for perishable food product's cold chain management. The system is implemented based on the wireless sensor networks and time temperature indicator (TTI) features and enables perishable food's cold chain temperature monitoring, shelf-life visibility and LSFO stock strategy decision support. System test and evaluation shows that the infield radio transmission is reliable and the whole system meets most of the users' requirements raised in system analysis. This system can be improved by integration with geographic information systems (GIS). By combining with different sensors, this system gain the potential ability to be introduced into controlled atmosphere packaging (CAP) and modified atmosphere packaging (MAP) chain for perishable food.

Keywords: Perishable Food, Cold Chain Logistics, Shelf-life, Decision Support System, Wireless Sensor Network

1. Introduction

Many food products are perishable by nature attributes and require protection from spoilage during their preparation, storage and distribution to give them desired shelf-life (Holley and Patel, 2005). Shelf-life is the time during which a perishable food remains safe, comply with label declaration of nutritional data and retain desired sensory, chemical, physical and microbiological characteristics when stored under the recommended conditions (IFST, 1993). Temperature is one of the most important parameters of quality control and freshness is almost an exclusively function of time and temperature. Thus the temperature is becoming a very important function for perishable food and visibility & traceability is especially important in its cold chains(Zhang et al., 2009).

In order to ensure freshness, extend shelf-life and enhance perishable food safety and security, cold chain management (CCM) methods are established. Cold chain monitoring and control are essential parts in CCM systems (Kuo and Chen, 2010). Time Temperature Indicator (TTI) and information technology such as Wireless Sensor Networks (WSN) are currently highly researched method in cold chain monitoring.

TTI provides the possibility to continuously monitor and record the time-temperature history along the whole supply chain in a simple and economical way(Taoukis and Labuza, 1989). Since now, there were different kinds of TTI based on chemical(Galagan and Su, 2008, Lee and Shin, 2012, Nga et al., 2011, Kreyenschmidt et al., 2010), microbiological(Vaikousi et al., 2008, Kim et al., 2012a, Wanihsuksombat et al., 2010, Kim et al., 2012c, Ellouze and Augustin, 2010), mechanical(Mehauden et al., 2008) and enzymatic(Smolander et al., 2004, Giannakourou et al., 2005, Yan et al., 2008, Kim et al., 2012b) principles had been developed and tested in perishable food supply chain.

WSN is a cost-effective sensor and communications technology that allows the distributed acquisitions and transmission of different parameters from anywhere to end users, in locations without a previous telecommunication infrastructure(Garcia-Sanchez et al., 2011). In a 'from farm to fork' style food supply chain, the WSN has been applied in many phases include the precision agriculture(Damas et al., 2001, Morais et al., 2005, Chiti et al., 2005), precision viticulture(Matese et al., 2009, Peres et al., 2011), precision harvest(Yu et al., 2011a, Yu et al., 2011b), greenhouse control(Kolokotsa et al., 2010), grain storage monitoring(Zhao et al., 2010), animal behavior monitoring(Nadimi et al., 2011, Butler et al., 2004, Ma et al., 2011), fish farm(Qi et al., 2011b, Lloret et al., 2011), cold chain management(Yuan et al., 2009, Wang et al., 2010, Lakshmil and Vijayakumar, 2012, Kacimi et al., 2009, Jedermann et al., 2006, Chenwei et al., 2011) and entire supply chain management and its traceability(Yang et al., 2011, Chen et al., 2009, Catarinucci et al., 2011).

The characteristics of the two technologies are complementary as Table 1 figures out each strength and weakness. It is critical to notice that even if the TTI is an effective tool in CCM and can be easily applied in the perishable food supply chain's retailer to customer phase, its limitation is obvious that the shelf-life information and temperature history can't be recognized by computer or send back to the cold chain monitoring system by telecommunication so it fails to meet the cold chain stakeholders' demands in real time monitoring and LSFO stock strategy. However, WSN is an IT relevant technology but it cannot provide instant shelf life information to cold chain in field workers.

Table 1

Technical characteristics comparison of TTI and WSN.

Technology	Strength	Weakness	Cost
TTI	Instant shelf life visibility	Computer readable	Low
		Remote real time monitoring	
WSN	Computer readable	Instant shelf life visibility	High
	Real time temperature monitoring		
	Position service		

In order to improve the current cold chain management, the temperature monitoring, shelf-life visibility, position visibility and LSFO decision support are required by both cold chain managers in the remote and cold chain in field workers. Hence the combination of WSN and TTI's advantages is important. This potential WSN-TTI integration provides the advantages of the real time cold chain monitoring system and the time–temperature indicator so it achieves the bilateral information transparent during the whole perishable food cold chain logistics.

This paper intends to demonstrate user's requirement for the WSN based integrated Cold Chain Shelf Life Decision Support System (C^2SLDS), the hardware design, the software design and the system test and evaluation. The system is cost-effective and enables to be rapid adopted in different kinds of perishable food cold chain include aquatics, vegetables, fruits and meat.

A brief research back ground introduction is presented in this section. System analysis and design which includes the survey design, users' requirement analysis and system architecture design are demonstrated in section 2. The 3rd section discusses about the WSN-based TTI nodes (WTTI), ARM-based Gateway System (AGS) design and implementation. Section 4 illustrates the PC-based LSFO Decision Support System (LDSS) design and its shelf-life prediction process. Section 5 tests and evaluates the whole system. The discussion and conclusion about this research are listed last.

2. C^2SLDS system analysis and architecture design

2.1. The survey design and analysis

The research target enterprise is in Beijing, China. The methods adopted to get the user's requirement of the C^2SLDS are observation and interviews.

The observation was taken in a tilapia cold chain from Hainan province to Beijing. The whole supply chain of the tilapias' harvest, transportation, process, storage and distribute were included in the observation. The observation continued for 7 days in order to fully get the routine management means of the target enterprise.

Interviews were conducted to find out the system requirements which consisted of the functional requirement and the system module division. An interviewee list which includes cold chain managers and infield cold chain workers was formed in Beijing with the support of the target enterprise. People on the list were asked to describe the work routine, how did they record temperature information during the supply chain, how did they get the shelf-life information of their product, whether they have known LSFO strategy or whether they have used it and so forth. In particular, the cold chain managers and cold chain workers were asked about their most concerned functions of the C^2SLDS respectively. The interview continued for 5 days and totally 7 managers and 23 workers were invited to participate in the survey. The basic version of system requirements structure was formed based on the interviews.

2.2 Users' requirement of the C^2SLDS

Users' requirement based on the survey and the system analysis are concluded and demonstrated via the following tables. Table 2 shows the cold chain managers' requirement while Table 3 provides the infield cold chain workers'.

Table 2

Cold chain managers' requirements for C^2SLDS.

Requirement ID	Requirement Type	The C^2SLDS should:
Req1	Functional	● Be a system that enables the cold chain managers to get the perishable food products' real time temperature in the remote monitoring center.
Req2	Functional	● Be a system that enables the cold chain managers to get the perishable food products' shelf-life information in the remote monitoring centers.
Req3	Functional	● Be a system that enables the cold chain managers to get the perishable food products' real time position in the remote monitoring center.
Req4	Functional	● Achieve a whole process cold chain monitoring which can help managers to ignore the information gap between different phrases.
Req5	Functional	● Be a system that enables the cold chain managers to make smart decision to reduce the perishable food products quality losses during cold chain logistic based on the shelf-life.
Req6	Non-Functional	● Be a system that its user interface is friendly, easy to operate.

Table 3

Cold chain workers' requirements for C^2SLDS.

Requirement ID	Requirement Type	The C^2SLDS system should:
Req7	Functional	● Be a time temperature indicator which shows the perishable food products shelf-life information to the infield workers in the cold chain operation sites.
Req8	Functional	● Be a flexible time temperature indicator which can be easily adopted into different kinds of perishable food products via simple system configuration.
Req9	Functional	● Be an indicator which guides the infield workers to identify the cold chain pallets fast.
Req10	Non-Functional	● Performs like a traditional time temperature indicator which means low cost, low power consumption and easy to use.

2.3. System architecture

In order to transmit message between the cold chain operation sites and Internet and reduce the expense of the wireless network, this research developed 3-layer architecture which consists of WSN-based TTI nodes (WTTI), ARM-based Gateway System (AGS) and PC-based LSFO Decision Support System (LDSS). The following sections describe the structure and purpose of each layer respectively.

2.3.1. WTTI

There are two device types in a traditional ZigBee application: full-function device (FFD) and reduced-function device (RFD). An FFD is able to perform all the duties described in the ZigBee protocol and can communicate with all ZigBee devices. An RFD has limited capabilities and can communicate with only FFD (Farahani, 2008).

A WTTI is a RFD which can sense temperature data and display shelf-life information to the cold chain infield workers. This part refers to the operation sites of the cold chain logistics such as in the storage and transportation equipment. It is the tip construction of this C^2SLDS system since the temperature data sensor and the shelf-life display take place in the distributed positions. A certain WTTI establishes 'binding relationship' with a batch of perishable food which it attached to and then starts to record the temperature history and then send it to the coordinator via ZigBee network. The WTTI also receives the shelf-life information of the batch via ZigBee network and displays it to the infield workers.

2.3.2. AGS

An AGS is consisted of a Zigbee coordinator and an ARM-based smart device (ARM). A Zigbee coordinator is a FFD which can fulfill the network management, route and data relay. It receives the temperature information and 16 bit ZigBee network address from the WTTI and then turns the 16 bit address into 64 bit physical address (Address Mapping). When in needed, it sends the temperature information and the physical address to the ARM using RS-232 serial port. It receives the shelf-life information from ARM and sends it to a certain WTTI according to the 64 bit address.

An ARM hosts a real time binding relationship table between WTTI and foods' batch numbers. It gets temperature information and WTTI address from the coordinator via RS-232 port then turns the address into food's batch number. It calculates the longitude and latitude information from the GPS module. When GPRS or PPPoE network availables, it sends the temperature, position and batch number to the LDSS. The ARM also sends food's shelf-life information to coordinator using RS-232 port.

2.3.3. LDSS

A LDSS is conducted by the application servers, the data warehouse servers, the model base, the knowledge base, the routers and the firewalls. All the hosts are connected in a local area network. The data warehouse works as the holder of the temperature, position and shelf-life and batch information. The model base contains different decision models that used to calculate shelf-life for different food spoilage dynamics. The knowledge base maintains the expert knowledge include model selection, model parameter matching and model threshold selection for different perishable food product. The application drives the calculation of shelf-life for the perishable food products using temperature data in data warehouse, shelf-life prediction model in model base and parameters in knowledge base.

This layer has the graphic user interface of the whole C^2SLDS. It provides the monitor users not only the real-time temperature, position and shelf-life information of the batches which are on their way of logistics but also the smart LSFO stock decision to minimize quality lost. Figure 1 demonstrates the C^2SLDS system's topology and architecture while Figure 2 shows the operation sequence of the whole C^2SLDS.

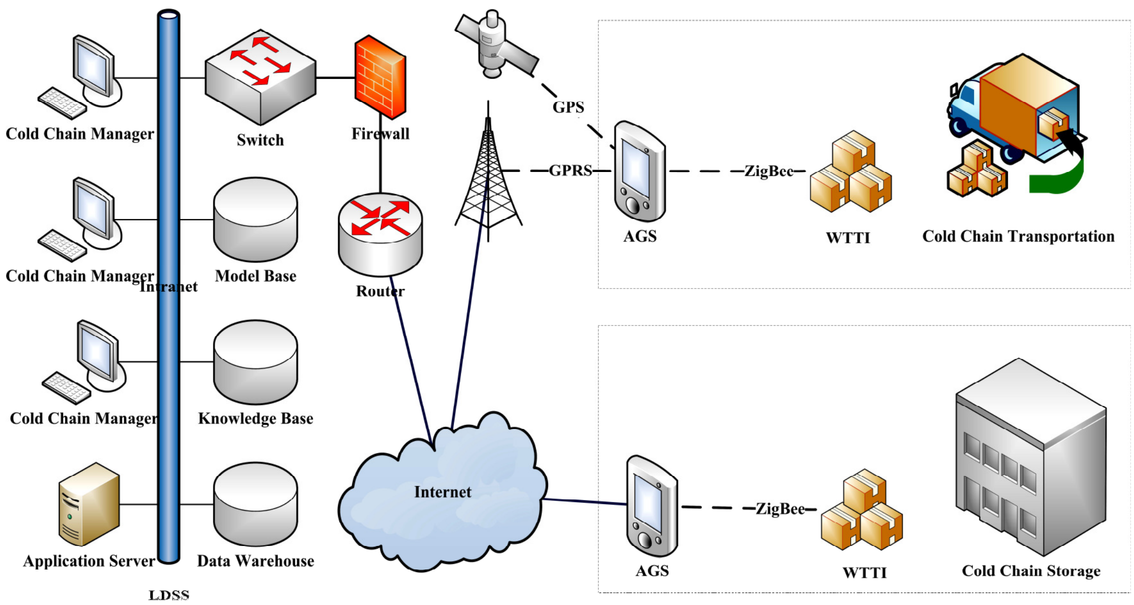


Fig.1. The C[2]SLDS system's topology and architecture.

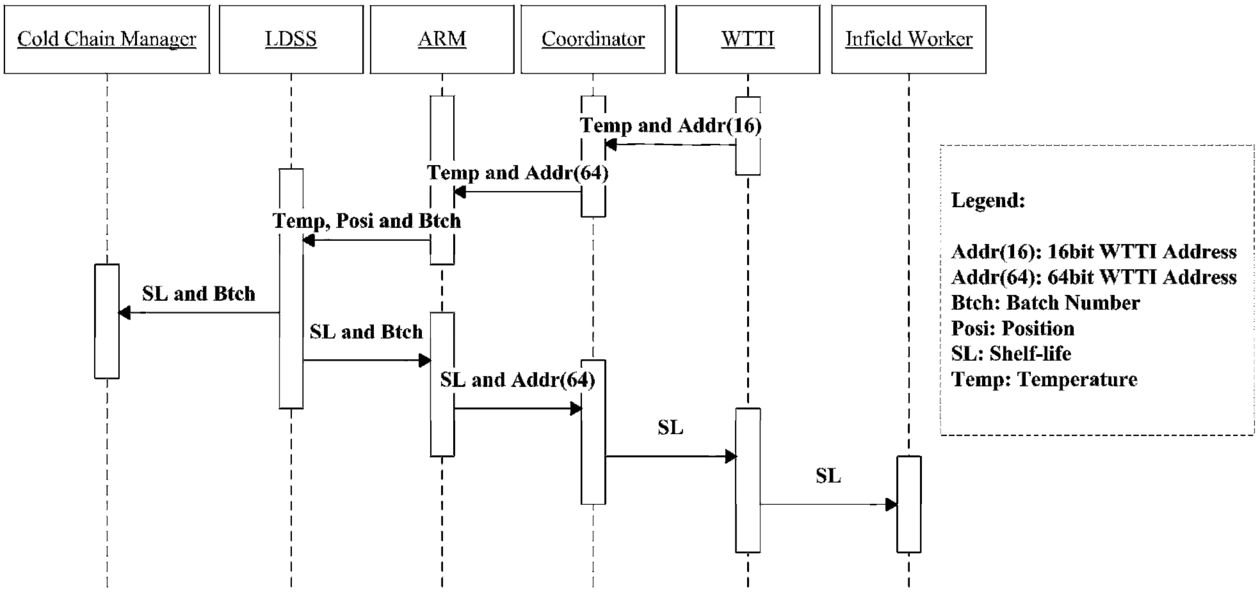


Fig.2. Sequence diagram of the C[2]SLDS system.

3. WTTI, AGS design and implementation

3.1. WTTI design

3.1.1. WTTI hardware design

The WTTI is designed as a ZigBee End-Device. It has the capability of collecting temperature data, sending them to the AGS using ZigBee network, receiving and displaying shelf-life information to the infield workers. Thus the micro processer, the radio frequency module, the temperature sensor, the energy supply module and the display unit are the indispensable compositions.

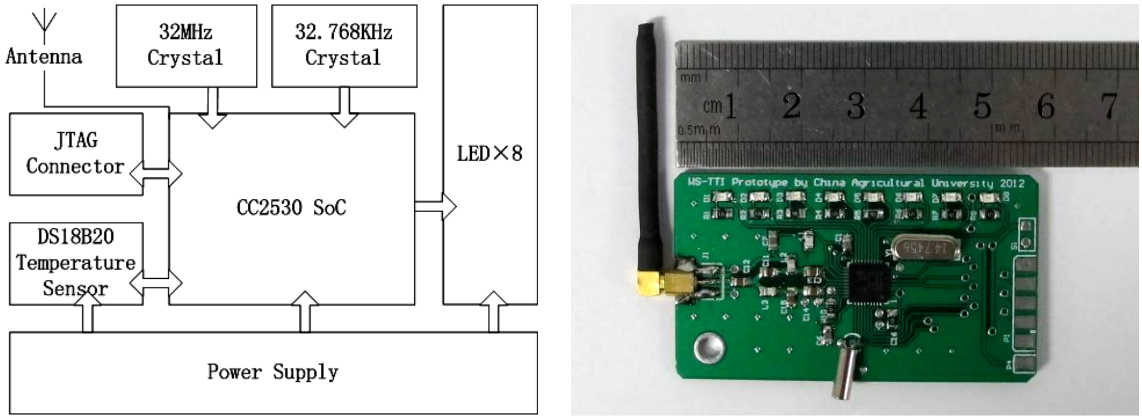
In order to improve the integration in the WTTI and optimize the hardware design, this research adopts the CC2530 wireless sensor System on Chips (SoC) which produced by the Texas Instruments (TI) company as the processor and the radio frequency module solution. This SoC embedded an enhanced 8051 SCM which includes a 256kb EEPROM. The RF front-end supports IEEE 802.15.4 protocol data transmission at 2.4GHz, it also provide a hardware solution for CSMA/CA algorithm.

The Dallas DS18B20 digital temperature sensor with its low economic and hardware costs becomes the temperature sensor module of the WTTI. This sensor provides 9-bit to 12-bit Celsius temperature data and has an operating temperature range of -55°C to +125°C and is accurate to ±0.5°C over the range of -10°C to +85°C.

The display module consisted with 8 LEDs which arrange in a row so that the light of the LED can consists as a progress bar and show the shelf-life information.

The energy supply module is a 3.6V Lithium-ion polymer battery with its 1550mAh capacity.

The WTTI block diagram and its prototype is illustrated in Figure 3 (a) and (b).



(a) (b)

Fig.3. The WTTI block diagram (a) and prototype (b).

3.1.2. WTTI software design

The WTTI embedded software finishes the system initialization which initials the clock, the stack, the network and so forth in case the node is powered. After the WTTI initialization, it starts a timeout timer which used for trigger the temperature data sampling and information exchange. In the interrupt service routine, the WTTI first establishes the communication with the DS18B20 and check if the sensor is in normal condition. If the temperature sensor works well, the data sampling starts; otherwise, the WTTI restarts the sensor. After the data sampling, the WTTI calls the Application Support Sub-layer Data Entity Service Access Point (APSDE-SAP) in the ZigBee protocol to send the data to the coordinator of the AGS. Besides upload the temperature data, the WTTI also checks if there are shelf-life data for itself which stored in the AGS. If exist, it downloads the latest one and send it to the LEDs so that the shelf-life display updated.

Figure 4 is a work flow of the temperature data acquisition and transmission process on the WTTI.

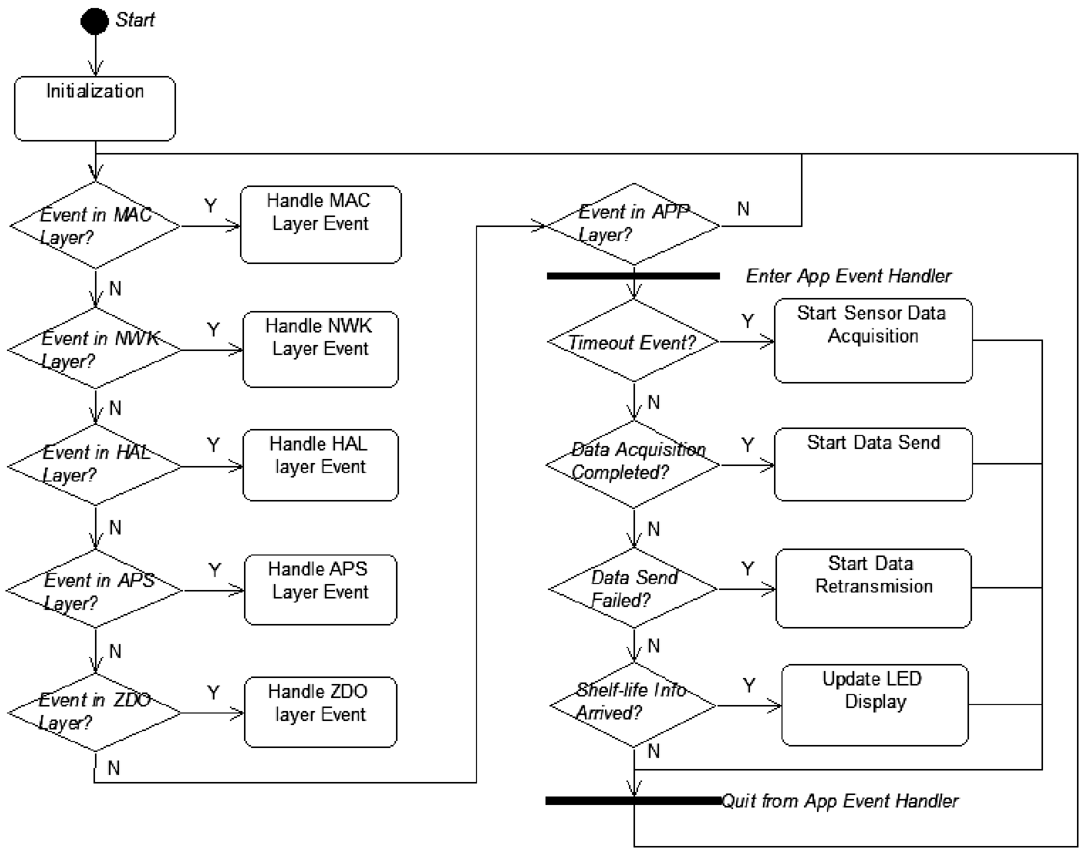


Fig.4. Flow chart of the temperature data acquisition and transmission process on the TTI node.

3.2. AGS design and implementation

3.2.1. AGS hardware design

The AGS plays an important role in the C^2SLDS since it not only relays the data between the WTTIs and the LDSS, but also establishes and terminates the binding relationship between the WTTIs and a certain batch of perishable food products. In order to achieve the above functions, the AGS is designed as a combination of an ARM and a ZigBee coordinator.

The coordinator functions as the establisher and the maintainer of the ZigBee network in which the WTTIs exist. It receives the ZigBee frames from the WTTIs and sends network configure commands to them. So the micro-processor, the ZigBee radio frequency module, the data communication interface with the ARM and a power supply module are in needed.

In order to form a seamless communication with WTTIs, the coordinator also uses the CC2530 SoC serves as the processor and the radio frequency module solution. The RS-232 serial port is chosen as the data communication interface between the coordinator and the ARM. A MAX3232 IC is introduced into the coordinator to achieve the voltage conversion between the CC2530 pins and the RS-232 standard.

The ARM is a commercial ARM smart device development board by Zhiyuan Electronics Co., Ltd. An EB-3531 GPS module by Huantian Co., Ltd is added to provide the real time position information of the AGS so as to represent the food product batches position. A barcode scanner is connected via RS-232 port used to scan the barcode on the WTTIs and perishable food batches in order to establish binding relationship between a certain WTTI and perishable food product batch. An SIM300 GSM communication module and an external antenna is added to the development board so that the ARM can exchange temperature data, position data, batch information, binding information and shelf-life information with the LDSS servers via GPRS network.

The block diagram of the AGS is shown in Figure5 and its hardware prototype is illustrated in Figure 6.

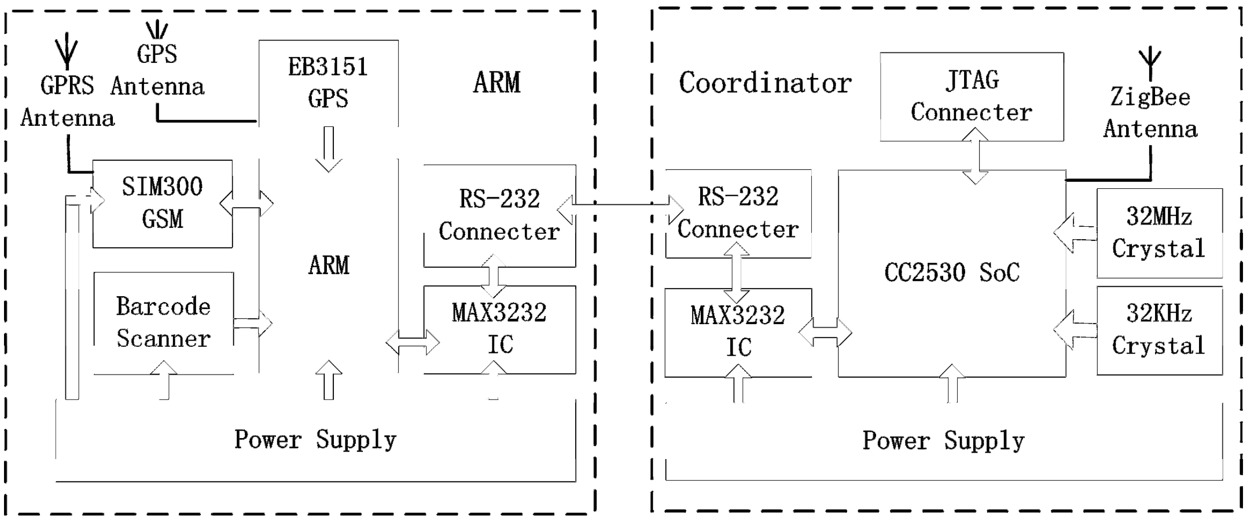


Fig.5. The AGS block diagram (an ARM with a ZigBee coordinator).

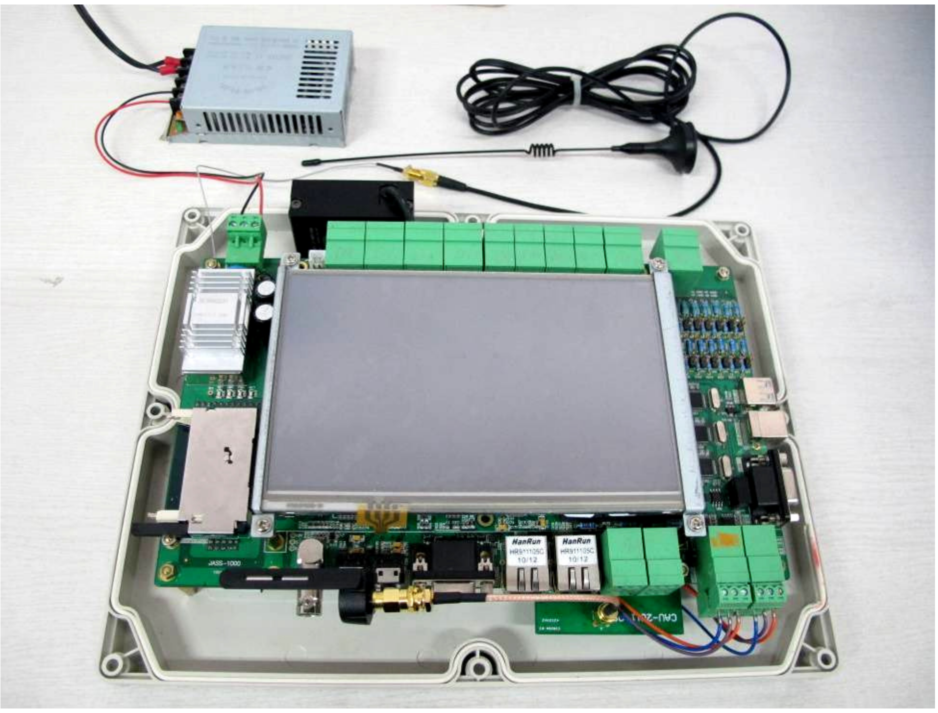


Fig.6. The AGS hardware prototype.

3.2.2. AGS software design

(1) Coordinator software design

Similar with the WTTI, the coordinator initials the hardware and configures the RS-232 interface first. When finished the above configuration it starts a ZigBee network and waits for network join requests from WTTIs. The coordinator holds a binding table which maintains the relationship between the WTTIs' 16 bit network address and their 64 bit physical addresses. When a temperature data from a WTTI comes it replaces its 16 bit network address with the 64 bit physical address after the temperature data and relays it to the ARM via RS-232 interface. It also sends the shelf-life information to the WTTI according to the physical address.

(2) ARM software design

The ARM scans the barcode on the WTTI to get its physical address and scans the barcode on the pallet to get the batch number of the perishable food products so that to maintain the binding relationship between the perishable food products batch number and a certain WTTI. When it receives the temperature and the 64 bit physical address data frame from the coordinator it replaces the physical address with the batch number, adds position data and then transmits them to the LDSS to get shelf-life information. It also replaces the batch number in the shelf-life information from the LDSS into physical address of the target WTTI and sends it to the coordinator. The ARM communicates with the LDSS by GPRS network during the cold chain transportation phase and PPPoE network during the cold chain storage phase.

3.2.3. AGS implementation

The AGS software system is implemented by C# language in Microsoft Visual Studio 2005 while its database is running on SQLite 3.0.

There are mainly four functions in the system: 1) WTTI control, 2) binding relationship management, 3) data relay and 4) system communication management. Since the ARM touching screen resolution is only 640×480 pixels, there is no main menu set in the top of the window in order to prevent misuse. A tab control which has four tab pages is introduced into the window to achieve the function selection.

Fig.7 illustrates the binding management interface of the system. The window is divided into 3 parts: left, middle and right. The left part and the right part are control buttons while the middle of the screen is the information display zone. On the left part of the screen, users can start a scan of the foods batch number and WTTI 64bit address by click the first and second buttons which control the barcode scanner. The batch number or WTTI 64bit address can be shown in the textboxes in the middle of the window. After get the above information, users can establish a binding relationship between a batch of food and a WTTI by click the third button on the left. The forth button is used for clear the information in the textboxes in case an input error occurs. All binding relationship is listed in the data list in the middle bottom, user can select one data row and click the last button on the left to terminals this binding relationship. However, the blue buttons on the right side is used for jump selection between different functions in the system so that the users don't have to click the small tab page index on the window top.

Fig.7. AGS software prototype graphic user interface.

4. LDSS design and implementation

4.1. LDSS architecture design

In order to provide high cohesion and low coupling system fabric, the LDSS system adopts 3-tier architecture which includes the UI tier, Functional logic tier and Database tier, as shown in Figure 8.

(1) User Interface tier

The User Interface (UI) tier provides a user interface function which is responsible for passing data between the user and a decision support functional logic. It completes the integrity check of the input data and displays the results of the real time temperature, position and shelf-life information for the current logistics perishable food product. It also provides the decision result based on LSFO strategy.

(2) Business Logic tier

The business logic layer is the intermediate structure of the 3-tier architecture which is responsible for a variety of processing logic calls. Management logic and decision support logic are the main component of this tier.

The management logic component consisted with authorization management, communication management, data management, model management and knowledge management modules. The authorization management and communication management modules exchange data with system database in the database tier. The data management, model management and knowledge management module exchanges data with data warehouse, model base and knowledge base representatively.

The decision support logic component derived from the management logic. It consisted with cold chain real time monitoring, shelf-life prediction and LSFO decision making modules. This component exchange basic perishable food batch information, real time temperature and position information from data management module in the management component. It makes the selection of the best shelf-life prediction model and parameters based on the knowledge management module and gets model functions from the model management module. When data, model and parameter are all prepared, it provides the user interface tire the real time cold chain monitor information, shelf-life prediction result and LSFO decision result based on the model calculation.

(3)Database tier

The Database tier includes the data warehouse, the knowledge base, the model base and the database. Bases are independent of each other and can communicate with each other since they are driven by representative base management module in the Functional Logic tier. SQL Server 2005 database management system is used to manage all the bases' operation.

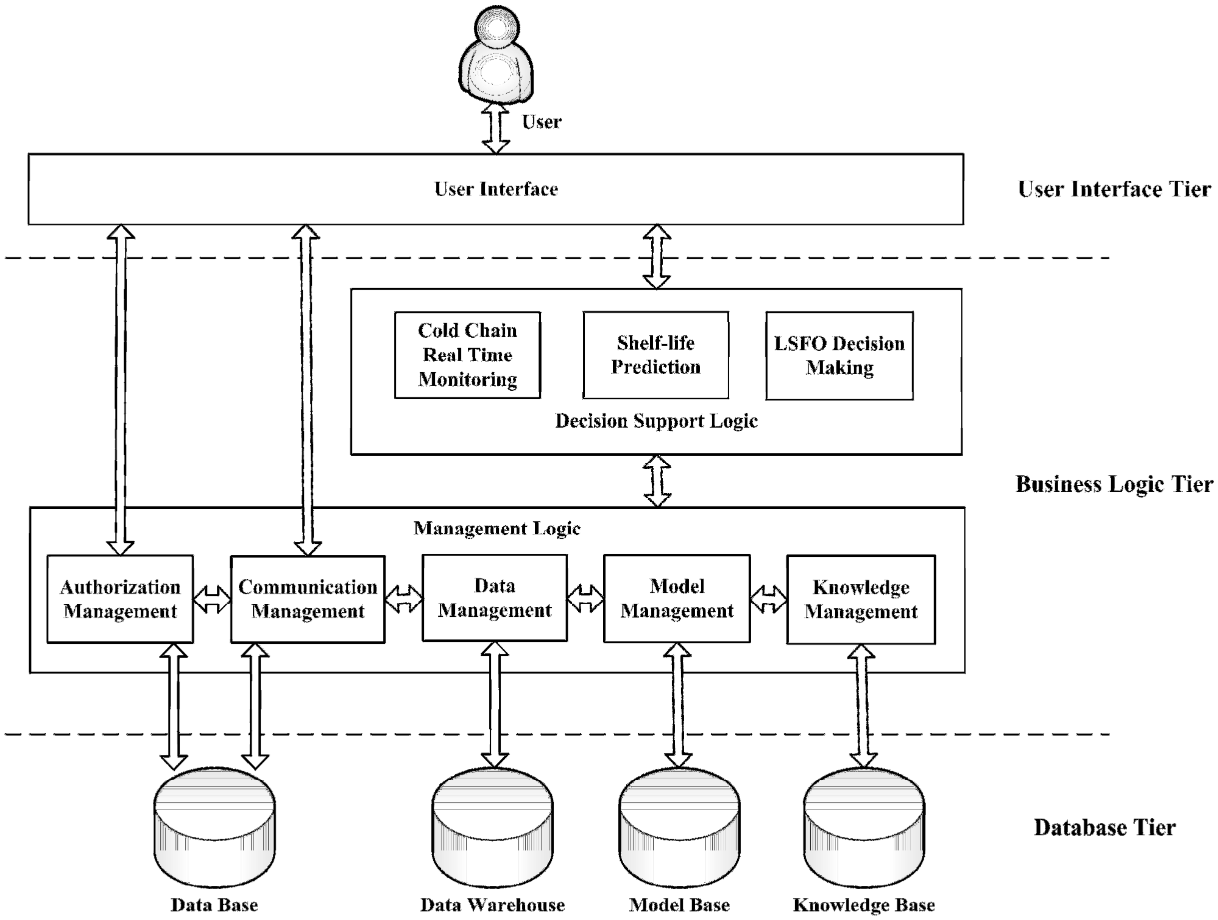


Fig.8. LDSS system architecture.

4.2. LDSS shelf-life prediction process

Shelf-life prediction is the basic of the LSFO strategy decision support. In this research, the critical to achieve the precise shelf-life prediction for different kinds of perishable food products is the correct selection of shelf-life prediction model as well as parameters according to certain quality decay mechanism and temperature distribution.

Different perishable food products have difference on quality decay mechanisms and then different quality decay evaluation indexes. Thus the LDSS knowledge base is used to help automatically pre-select the best matched quality decay models and parameters according to perishable food category and its quality decay mechanism.

According to Liu (2010) and Xing et al. (2010), different quality decay model have different performance in constant or fluctuate temperature status. In order to better simulate the quality decay progress, the most suitable model should be matched to the temperature segmentation which means to cut the whole temperature history into segments based on the intensity of the temperature fluctuations using a certain segment model such as a Statistic Process Control (SPC) based model (Qi et al., 2011a).

After the temperature segmentation and their prediction model matching, segment level perishable food product quality decay can be calculated. When the quality decay in each of segments is calculated, the total quality decay in the whole supply chain under the temperature history can be summed up and shelf-life predicted.

Figure 9 shows the LDSS shelf-life prediction process.

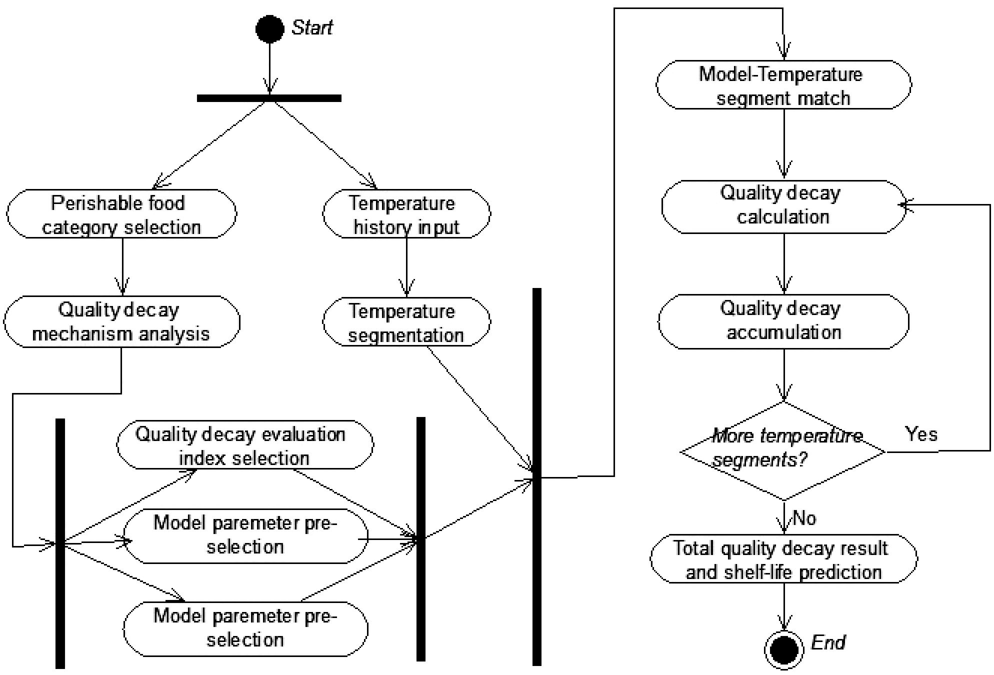
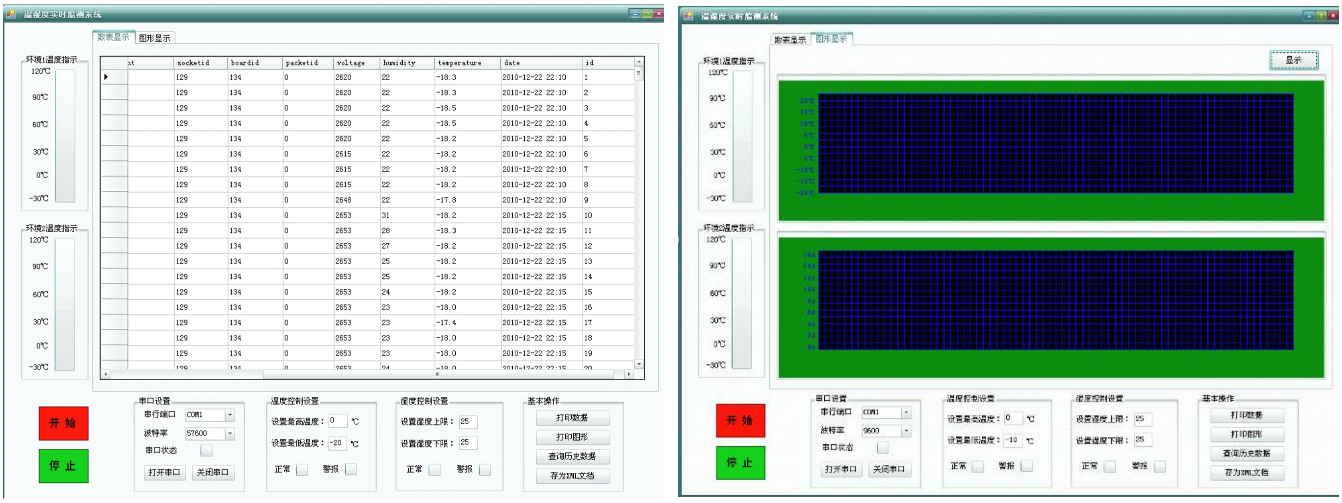


Fig.9. LDSS system shelf-life prediction process.

4.3. LDSS implementation

The LDSS is developed by C# language in Microsoft Visual Studio 2008 and the shelf-life prediction model is fulfilled by Matlab dynamic link library. The database of this system is running on Microsoft SQL Server 2005.

Fig. 10 shows the shelf-life prediction interface of this LDSS prototype. The interface provides two kinds of data monitoring methods, the data grid and the data chart. Fig.10 (a) shows the data grid in the LDSS which enables the managers to get the detailed information of the perishable food product that the WTTI uploaded such as the temperature and batch number as well as the WTTI information. Fig.10 (b) gives the data chart interface of the LDSS. The blue data chart on the top of the window shows the real time temperature information of the perishable food product as well as its historical temperature. The shelf-life prediction model calculates the shelf-life using those temperature data and then the shelf-life information can be showed on in the second data chart.



(a) (b)

Fig.10. LDSS prototype graphic user interface.

5. C^{2}SLDS System test and evaluation

5.1. WTTI radio performance test

WTTI radio performance test is implemented on the square of College of Engineering, China Agricultural University. The test indicators are Received Signal Strength Indicator (RSSI) and packet loss rate in ZigBee communication.

Set the radio frequency at 2475MHz, implement 99 groups' tests which crossed by 9 different distances and 11 different radio power. In each group, 500 MAC frame with 30 bytes each are sent from the coordinator to the WTTI in order to statistic the RSSI and packet loss rate.

An original RSSI that can be read from the received MAC frame need a conversion so that it can indicate the received signal strength, the conversion equation as follows(Farahani, 2008):

$$RSSI = RSSI\_VAL + RSSI\_OFFSET \quad (5)$$

where $RSSI\_VAL$ is the original RSSI from the MAC frame (dBm); $RSSI\_OFFSET$ is the offset (dBm).

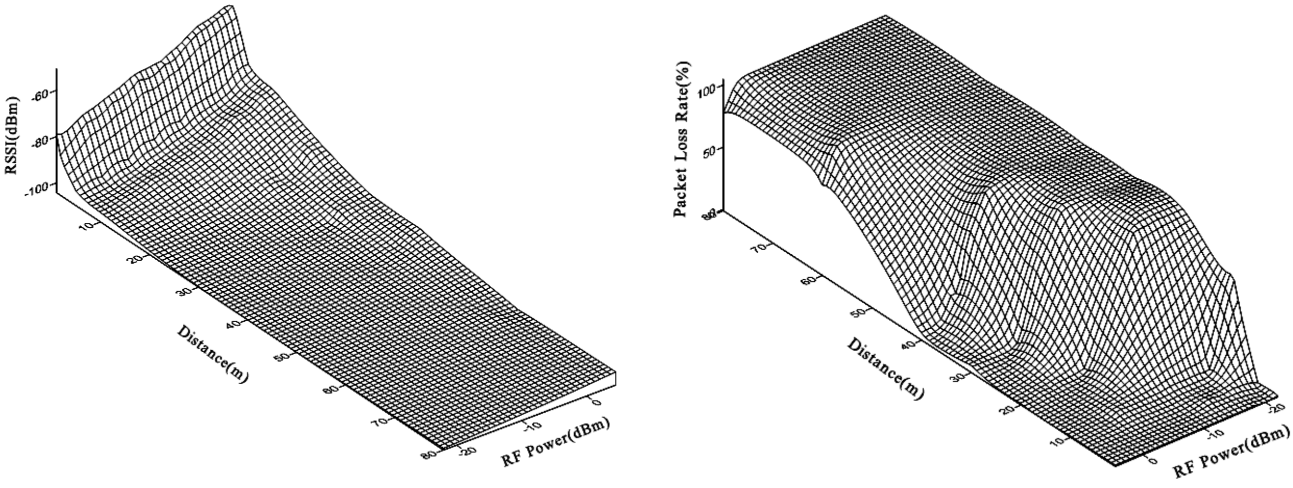
In order to reduce the error that occurs in each frame send, the statistical average is adopted to adjust the test results as the follow equation describes:

$$\mu_{\mathrm{rssi}} = \frac{1}{k}\sum_{i=1}^{k} RSSI_i \quad (6)$$

where k is the amount of MAC frames in each group (k =500 in this research); $RSSI_i$ is the $RSSI$ value of the MAC frame i (dBm).

Figure 11 (a) illustrate the RSSI variation in response to radio power difference and communication distance variation while Figure 11 (b) shows the packet loss rate variation under the same testing condition.

Radio performance test shows that the RSSI endured attenuation with the RF power reduction and communication distance increment. The packet loss rate increases obviously when RSSI nears -97dBm or even lower. Within a 30m distance, a -3dBm or higher RF power is able to ensure a packet loss rate of lower than 8.5% which means a reliable ZigBee data transmission with data retransmission mechanism.



(a) (b)

Fig.11. RSSI (a) and packet loss rate (b) variation with radio power difference and communication distance variation.

5.2. C²SLDS System evaluation

System evaluation measures the improvements of cold chain management on technological capacity, performance and system utilization which brought by the C²SLDS as well as the defects of this system prototype.

People from the China Agricultural University (CAU) and target enterprise were invited to take part in the system evaluation to have a discussion on the system performance and form a consistent view on how should this system to be completed to help cold chain management and its information transparent.

Effectiveness analysis before and after C²SLDS deployment is shown in Table 6 and the system improvement suggestions in Table 7.

Table 6

Effectiveness analysis before and after C²SLDS system deployment.

ID	Content	Before deployment	After deployment
1	Cold chain remote temperature monitoring	Null	Real time
2	Shelf-life prediction for different kinds of perishable food products	Null	Yes
3	Shelf-life monitoring for cold chain managers	Null	Real time
4	Shelf-life monitoring for cold chain workers	Null	Real time
5	Decision support for perishable food product storage and stock	Null	Yes
6	Perishable food product storage and stock strategy	FIFO	LSFO
7	Information gap existed between different cold chain phrases	Yes	No
8	Cold chain logistics traceability	Manual	Automatic

Table 7

C²SLDS System improvement suggestions.

ID	Suggestion	Suggestion type
1	Introduce GIS and map into LDSS to provide intuitive perishable food product location information	Functional
2	Extend different kinds of sensors so as to cope with the requirements of Controlled Atmosphere Packaging (CAP) or Modified Atmosphere Packaging (MAP) supply chain	Functional
3	Reduce the size and weight of AGS module	Non-functional
4	Reduce the economic costs of WTTI	Non-functional
5	Certain operation flow improvement to make the use of C²SLDS in cold chain management more natural and easy	Non-functional

6. Discussion and conclusion

Temperature monitoring, shelf-life visibility and LSFO stock strategy are important contents in perishable food cold chain logistics for both cold chain managers and workers in order to reduce quality and economic losses. This paper illustrates the C^2SLDS system designed for perishable food product's cold chain management. The system is implemented based on the wireless sensor networks and time temperature indicator features and enables perishable food's cold chain temperature monitoring and shelf-life visibility both in remote and in field. As a decision support system it achieves the perishable food LSFO stock strategy decision support.

The temperature information can be acquisitioned by WTTI and send back to the LDSS system in cold chain monitoring center by the GPRS or PPPoE via AGS to calculate the shelf-life for the batch of perishable food product it attached to. The cold chain managers can read the shelf-life information from the UI tier of the LDSS while the cold chain infield workers from the LED display on WTTI.

Based on the shelf-life information, a more accurate Least Shelf-life First Out storage and transportation strategy decision is made to help cold chain managers to minimize the perishable food product's quality loss as well as the spoilage brought by First In First Out strategy currently.

System test and evaluation shows that the infield WTTI radio transmission is reliable and the whole system meets most of the users' requirements raised in system analysis.

Compared with the traditional information record methods that used by perishable food product's cold chain logistics before, the C^2SLDS not only bridges the information gap which existed between different cold chain phase for a long period but also provide a method of automatically information acquisition during cold chain logistics to help reduce the economics cost of traceability.

This work can be extend by introducing different kind of sensors into the WTTI to achieve real time shelf-life prediction and decision making in CAP and MAP supply chain or by introducing GIS technology into LDSS to provide intuitive perishable food product location information. Meanwhile, the size and weight of AGS module and the economic costs of WTTI should also be reduced in order to meet the demands of scaled application.

Acknowledgement

This research is founded by the National Nature Science Foundation of China (71072153), the China-Romania governmental cooperation research project (40-14) and Qi Lin holds a China Scholarship Council Studentship (20123013) with Portsmouth Business School, University of Portsmouth. The authors would also wish to thank the anonymous reviewers for their constructive comments.

References

BUTLER, Z., CORKE, P., PETERSON, R. & RUS, D. Virtual fences for controlling cows. Robotics and Automation, 2004. Proceedings. ICRA'04. 2004 IEEE International Conference on, 2004. IEEE, 4429-4436.

CATARINUCCI, L., CUI AS, I., EXPOSITO, I., COLELLA, R., FERN NDEZ, J. A. G. & TARRICONE, L. RFID and WSNs for traceability of agricultural goods from Farm to Fork: Electromagnetic and deployment aspects on wine test-cases. Software, Telecommunications and Computer Networks (SoftCOM), 2011 19th International Conference on, 2011. IEEE, 1-4.

CHEN, J., PANG, Z., ZHANG, Z., GAO, J., CHEN, Q. & ZHENG, L. A novel acceleration data compression scheme for wireless sensor network application in fresh food tracking system. Electronic Measurement & Instruments, 2009. ICEMI'09. 9th International Conference on, 2009. IEEE, 3-1-3-5.

CHENWEI, Y., DAO, L., DUNPING, Y., SHENGXING, Y. & ZULING, L. Design of monitor-and-control system for Supermarket fresh area based on ZigBee. Electric Information and Control Engineering (ICEICE), 2011 International Conference on, 2011. IEEE, 1302-1305.

CHITI, F., DE CRISTOFARO, A., FANTACCI, R., TARCHI, D., COLLODO, G., GIORGETTI, G. & MANES, A. Energy efficient routing algorithms for application to agro-food wireless sensor networks. Communications, 2005. ICC 2005. 2005 IEEE International Conference on, 2005. IEEE, 3063-3067.

DAMAS, M., PRADOS, A., G MEZ, F. & OLIVARES, G. 2001. HidroBus system: fieldbus for integrated management of extensive areas of irrigated land. *Microprocessors and Microsystems,* 25**,** 177-184.

ELLOUZE, M. & AUGUSTIN, J. C. 2010. Applicability of biological time temperature integrators as quality and safety indicators for meat products. *International Journal Of Food Microbiology,* 138**,** 119-129.

FARAHANI, S. 2008. *ZigBee wireless networks and transceivers,* Burlington, Newnes.

GALAGAN, Y. & SU, W. F. 2008. Fadable ink for time–temperature control of food freshness: Novel new time–temperature indicator. *Food Research International,* 41**,** 653-657.

GARCIA-SANCHEZ, A. J., GARCIA-SANCHEZ, F. & GARCIA-HARO, J. 2011. Wireless sensor network deployment for integrating video-surveillance and data-monitoring in precision agriculture over distributed crops. *Computers and Electronics in Agriculture,* 75**,** 288-303.

GIANNAKOUROU, M., KOUTSOUMANIS, K., NYCHAS, G. & TAOUKIS, P. 2005. Field evaluation of the application of time temperature integrators for monitoring fish quality in the chill chain. *International journal of food microbiology,* 102**,** 323-336.

HOLLEY, R. A. & PATEL, D. 2005. Improvement in shelf-life and safety of perishable foods by plant essential oils and smoke antimicrobials. *Food Microbiology,* 22**,** 273-292.

IFST 1993. *Shelf-life of foods: Guidelines for its determination and prediction,* London, Institute of Food Science and Technology.

JEDERMANN, R., BEHRENS, C., WESTPHAL, D. & LANG, W. 2006. Applying autonomous sensor systems in logistics—Combining sensor networks, RFIDs and software agents. *Sensors and Actuators A: Physical,* 132**,** 370-375.

KACIMI, R., DHAOU, R. & BEYLOT, A. L. Using energy-efficient wireless sensor network for cold chain monitoring. Consumer Communications and Networking Conference, 2009. CCNC 2009. 6th IEEE, 2009. IEEE, 1-5.

KIM, M. J., JUNG, S. W., PARK, H. R. & LEE, S. J. 2012a. Selection of an optimum pH-indicator for developing lactic acid bacteria-based time–temperature integrators (TTI). *Journal of Food Engineering,* 113**,** 471-478.

KIM, W., CHOE, W. Y. & HONG, K. W. 2012b. Development of a Lipase-based Time Temperature Indicator System for Monitoring Ground Beef Quality. *Journal Of the Korean Society for Applied Biological Chemistry,* 55**,** 535-540.

KIM, Y. A., JUNG, S. W., PARK, H. R., CHUNG, K. Y. & LEE, S. J. 2012c. Application of a Prototype of Microbial Time Temperature Indicator (TTI) to the Prediction of Ground Beef Qualities during Storage. *Korean Journal for Food Science Of Animal Resources,* 32**,** 448-457.

KOLOKOTSA, D., SARIDAKIS, G., DALAMAGKIDIS, K., DOLIANITIS, S. & KALIAKATSOS, I. 2010. Development of an intelligent indoor environment and energy management system for greenhouses. *Energy Conversion and Management,* 51**,** 155-168.

KREYENSCHMIDT, J., CHRISTIANSEN, H., HUBNER, A., RAAB, V. & PETERSEN, B. 2010. A novel photochromic time-temperature indicator to support cold chain management. *International Journal Of Food Science And Technology,* 45**,** 208-215.

KUO, J. C. & CHEN, M. C. 2010. Developing an advanced multi-temperature joint distribution system for the food cold chain. *Food Control,* 21**,** 559-566.

LAKSHMIL, V. R. & VIJAYAKUMAR, S. 2012. Wireless Sensor Network based Alert System for Cold Chain Management. *Procedia Engineering,* 38**,** 537-543.

LEE, B. S. & SHIN, H. S. 2012. Polymer-based time-temperature indicator for high temperature processed food products. *Food Science And Biotechnology,* 21**,** 1483-1487.

LIU, L. 2010. *Construction of cold chian decision support systems for aquatic products.* China Agricultural University.

LLORET, J., SENDRA, S., GARCIA, M. & LLORET, G. Group-based underwater wireless sensor network for marine fish farms. GLOBECOM Workshops (GC Wkshps), 2011 IEEE, 2011. IEEE, 115-119.

MA, C., WANG, Y. & YING, G. The Pig Breeding Management System Based on RFID and WSN. Information and Computing (ICIC), 2011 Fourth International Conference on, 2011. IEEE, 30-33.

MATESE, A., DI GENNARO, S., ZALDEI, A., GENESIO, L. & VACCARI, F. 2009. A wireless sensor network for precision viticulture: The NAV system. *Computers and Electronics in Agriculture,* 69**,** 51-58.

MEHAUDEN, K., BAKALIS, S., COX, P., FRYER, P. & SIMMONS, M. 2008. Use of Time Temperature Integrators for determining process uniformity in agitated vessels. *Innovative Food Science & Emerging Technologies,* 9**,** 385-395.

MORAIS, R., VALENTE, A. & SER DIO, C. A wireless sensor network for smart irrigation and environmental monitoring: A position article. 5th European federation for information technology in agriculture, food and environement and 3rd world congress on computers in agriculture and natural resources (EFITA/WCCA), 2005. 845-850.

NADIMI, E., BLANES-VIDAL, V., J RGENSEN, R. N. & CHRISTENSEN, S. 2011. Energy generation for an ad hoc wireless sensor network-based monitoring system using animal head movement. *Computers and Electronics in Agriculture,* 75**,** 238-242.

NGA, M., AUDORFF, H., REICHSTEIN, W., HAARER, D., OLAFSDOTTIR, G., BOGASON, S. G., KREYENSCHMIDT, J. & ARASON, S. 2011. Performance of a photochromic time-temperature indicator under simulated fresh fish supply chain conditions. *International Journal Of Food Science And Technology,* 46**,** 297-304.

PERES, E., FERNANDES, M. A., MORAIS, R., CUNHA, C. R., L PEZ, J. A., MATOS, S. R., FERREIRA, P. & REIS, M. 2011. An autonomous intelligent gateway infrastructure for in-field processing in precision viticulture. *Computers and Electronics in Agriculture,* 78**,** 176-187.

QI, L., TIAN, D., ZHANG, J., ZHANG, X. & FU, Z. 2011a. Sensing Data Compression Method Based on SPC for Agri-food Cold-chain Logistics. *Transactions of the Chinese Society for Agricultural Machinery,* 42**,** 129-134.

QI, L., ZHANG, J., XU, M., FU, Z., CHEN, W. & ZHANG, X. 2011b. Developing WSN-based traceability system for recirculation aquaculture. *Mathematical and Computer Modelling,* 53**,** 2162-2172.

SMOLANDER, M., ALAKOMI, H. L., RITVANEN, T., VAINIONP , J. & AHVENAINEN, R. 2004. Monitoring of the quality of modified atmosphere packaged broiler chicken cuts stored in different temperature conditions. A. Time–temperature indicators as quality-indicating tools. *Food Control,* 15**,** 217-229.

TAOUKIS, P. & LABUZA, T. 1989. Applicability of time - temperature indicators as shelf life monitors of food products. *Journal of Food Science,* 54**,** 783-788.

VAIKOUSI, H., BILIADERIS, C. G. & KOUTSOUMANIS, K. P. 2008. Development of a microbial time/temperature indicator prototype for monitoring the microbiological quality of chilled foods. *Applied and environmental microbiology,* 74**,** 3242-3250.

WANG, X., JABBARI, A., JEDERMANN, R., LAUR, R. & LANG, W. Adaptive data sensing rate in ad-hoc sensor networks for autonomous transport application. Information Fusion (FUSION), 2010 13th Conference on, 2010. IEEE, 1-8.

WANIHSUKSOMBAT, C., HONGTRAKUL, V. & SUPPAKUL, P. 2010. Development and characterization of a prototype of a lactic acid–based time–temperature indicator for monitoring food product quality. *Journal of Food Engineering,* 100**,** 427-434.

XING, S., ZHANG, X., ZHANG, H. & FU, Z. 2010. Validation of CHAID growth model of specific spoilage organisms in chilled large yellow croaker. *Transactions of the Chinese Society for Agricultural Engineering,* 26**,** 384-387.

YAN, S., HUAWEI, C., LIMIN, Z., FAZHENG, R., LUDA, Z. & HENGTAO, Z. 2008. Development and characterization of a new amylase type time–temperature indicator. *Food control,* 19**,** 315-319.

YANG, H., YANG, L. & YANG, S. H. 2011. Hybrid Zigbee RFID sensor network for humanitarian logistics centre management.

Journal of Network and Computer Applications, 34**,** 938-948.

YU, P., LI, C., RAINS, G. & HAMRITA, T. 2011a. Development of the Berry Impact Recording Device sensing system: Hardware design and calibration. *Computers and Electronics in Agriculture,* 79**,** 103-111.

YU, P., LI, C., RAINS, G. & HAMRITA, T. 2011b. Development of the Berry Impact Recording Device sensing system: Software. *Computers and Electronics in Agriculture,* 77**,** 195-203.

YUAN, S., BECKER, M., JEDERMANN, R., GORG, C. & LANG, W. An Experimental Study of Signal Propagation and Network Performance in Monitoring of Food Transportation. Sensor, Mesh and Ad Hoc Communications and Networks Workshops, 2009. SECON Workshops' 09. 6th Annual IEEE Communications Society Conference on, 2009. IEEE, 1-3.

ZHANG, J., LIU, L., MU, W., MOGA, L. M. & ZHANG, X. 2009. Development of temperature-managed traceability system for frozen and chilled food during storage and transportation. *Journal of Food, Agriculture & Environment,* 7**,** 28-31.

ZHAO, Y., YU, Y. & YUAN, M. The grain depot temperature measurement system's research based on wireless sensor networks. Intelligent Control and Automation (WCICA), 2010 8th World Congress on, 2010. IEEE, 4112-4115.