DESIGN AND OPTIMIZATION OF RFID-ENABLED WIRELESS SENSOR NETWORK (WSN) MONITORING SYSTEM FOR BIOLOGICAL AND PHARMACEUTICAL PRODUCTS STORAGE

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Design and Optimization of RFID-enabled Wireless Sensor Network (WSN) Monitoring System for Biological and Pharmaceutical Products Storage

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NG Chun Kit (Name of Student)

Abstract

Biological and Pharmaceutical (B&P) products play a critical role in many different areas in modern life, such as medicine, health-care, pharmacies and biotechnology. These products are highly susceptible to variations of environmental factors, such as temperature, humidity, vibration, tilt, light and atmospheric substance. Therefore, an effective and relatively low-cost product monitoring and tracking system with real-time and continuous monitoring capability is needed for B&P product supply chains. A Wireless Sensor Network (WSN) is a network consisting of a number of sensor nodes with wireless communication capability. Due to the characteristics of a WSN such as wireless communication, small size, easy installation and flexible detection area, this research leverages WSN and Radio Frequency Identification (RFID) to design a B&P product monitoring system, which aims to prevent faults and to enhance the supply chain visibility. The proposed conceptual architecture consists four layers, namely Information Acquisition Layer (IAL), Network Layer (NL), Logic and Processing Layer (LPL) and Service Output Layer (SOL). In IAL, the product state information and the environmental parameters (i.e. temperature, humidity and vibration) are collected by wireless sensor nodes which are widely spread over a large area like a container, warehouse and distribution centre. The collected data are then routed to the data gathering and exchanging module (i.e. the sink of WSN). After that, the data are passed to Data Integration and Analysis Core (DIAC) in LPL through the Internet via Wi-Fi, 3G, Long-Term Evolution (LTE) or other wireless technologies. The NL is used to manage the data routing and aggregation, network construction and configuration of deployed WSNs, and the SOL will deliver service outputs based on the decisions made in the LPL, including visualizing the data, prompting alerts when abnormal conditions occur, triggering the operation of actuators and storing the collected and processed data in the database for querying and further analysis in the future.

To design a WSN, deployment of sensor nodes is an irreplaceable and critical stage. However, designing of a WSN deployment strategy with a high level of performance is a challenging task, since many design factors should be considered, and many of these design factors are interrelated and there are trade-offs between them. In this thesis, two approaches are proposed to deal with the WSN deployment problem. The first approach is a three-stage framework based on statistical methods. The three stages include placing the sensor and relay nodes in the first stage, selecting a sink position in the second stage and placing additional relay nodes in the last stage. This approach uses a heuristic and statistical method to determine the placements of sensor and relay nodes, and the additional relay nodes needed in a target area. In the second approach, two deployment conditions are examined. The first one is the deployment of homogeneous sensor nodes in a 2-D region-of-interest studied. Four objectives were identified: the sensing coverage and network connectivity of the sensor nodes are required to be maximized, simultaneously, the production cost should be minimized while a certain level of fault tolerance should be maintained. To fulfil these objectives, a mathematical model is established by using the weighted sum approach. Then, a meta-heuristics algorithm, named Smart Bat Algorithm (SBA) is proposed to solve the model. SBA is designed based on the Bat Algorithm (BA) and integrated Fuzzy Inference model with decision-theoretical rules in order to determine the direction, velocity and frequency of artificial bats. To evaluate the performance of SBA, several optimization approaches including Greedy Algorithm, Genetic Algorithm (GA), an Ant Colony Optimization (ACO) based metaheuristics optimization method, called the *MAX–MIN* Ant System (*MM*AS) and Discrete Bat Algorithm (DBA), are used to solve the model. The simulation result shows that the SBA provides a better WSN deployment plan when considering the four objectives. The second condition studied a more realistic situation of WSN deployment, which is placing sensor nodes and relay nodes in a 3-D environment with obstacles. The proposed solution adopts two-stage deployment approaches. In the first stage, sensor nodes are deployed to satisfy two objectives of cost and coverage. According to the deployment of sensor nodes, a set of relay nodes is deployed in the second stage afterward to satisfy three objectives of cost, network connectivity and fault tolerance. The simulation result shows that SBA provides more robust and high quality results.

In summary, the contribution of this thesis includes:

Firstly, this thesis presents a relatively objective, quantitative and systematic approach, called semantic similarity analysis for examination of the intellectual structure of IoT. Secondly, a four-layer system architecture is proposed as a flexible and scalable base for a B&P product monitoring system as well as other related information technology systems. Thirdly, a BA-based meta-heuristics algorithm, named Smart Bat Algorithm (SBA), is proposed, whereby SBA delivers high-quality and robust solutions for both homogenous node deployment in 2-D environments and heterogeneous node deployment in 3-D environments of WSN.

Publications Arising from the Thesis

Refereed Journal Papers:

1. Ng, C.K., Wu, C.H., Ip, W.H. and Yung, K.L., 2018. A Smart Bat Algorithm for Wireless Sensor Network Deployment in 3-D Environment. *IEEE Communications Letters*, 22(10), 2120-2123, DOI: 10.1109/LCOMM.2018. 2861766.
2. Ng, C.K., Wu, C.H., Yung, K.L., Ip, W.H. and Cheung, T., 2018. A Semantic Similarity Analysis of Internet of Things. *Enterprise Information Systems*, 12(7), 820-855, DOI: 10.1080/17517575.2018.1464666.
3. Wu, C.H., Tseng, K.-K., Ng, C.K., Ho, G.T.S., Zeng, F.-F. and Tse, Y.K., 2017. An Improved Huffman Coding with Encryption for Radio Data System (RDS) for Smart Transportation. *Enterprise Information Systems*, 12(2), 137-154, DOI: 10.1080/17517575.2016.1278461.
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9. Ng, C.K., Wu, C.H., Ip, W.H., Chan, C.Y. and Ho, G.T.S., 2011. A Real Time Quality Monitoring System for the Lighting Industry: A Practical and Rapid Approach Using Computer Vision and Image Processing (CVIP) Tools. *International Journal of Engineering Business Management*, 3(4), 14-21, DOI: 10.5772/45670.

Refereed Conference Papers:

1. Ng, C.K., Wu, C.H., Ip, W.H., Zhang, J., Ho, G.T.S. and Chan, C.Y., 2016. Network Topology Management Optimization of Wireless Sensor Network (WSN), In: Huang DS., Jo KH. (eds), *Intelligent Computing Theories and Application. ICIC 2016. Lecture Notes in Computer Science,* Lanzhou, China, 2-5 August 2016, 9772, 850-859, DOI: 10.1007/978-3-319-42294-7_75.
2. Wu, C.H., Ng, C.K., Leung, P.P.L., Lau, W.Y., Ho, G.T.S. and Ip, W.H., 2014. Design of a EHS Module for an Intelligent Automobile Parking Platform. In: *2014 Enterprise Systems Conference*, Shanghai, China, 2-3 August 2014, 184-189, DOI: 10.1109/ES.2014.39.
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List of Abbreviations

ABC	Artificial Bee Colony
ACO	Ant Colony Optimization
API	Application Programming Interface
B&P	Biological and Pharmaceutical
BA	Bat Algorithm
BFS	Breadth-First Search
DBA	Discrete Bat Algorithm
DE	Differential Evolution
DFS	Depth-First Search
DIAC	Data Integration and Analysis Core
EPC	Electronic Product Code
FL	Fuzzy Logic
GA	Genetic Algorithm
GPRS	General Packet Radio Service
HCA	Hierarchical Cluster Analysis
IAL	Information Acquisition Layer
IoT	Internet of Things
LPL	Logic and Processing Layer
LTE	Long-Term Evolution
MDS	Multidimensional Scaling
***MM*AS**	*MAX-MIN* Ant System
NL	Network Layer
PSO	Particle Swarm Optimization
QAP	Quadratic Assignment Problem
QoS	Quality of Service
RFID	Radio Frequency Identification
RN	Relay Node
SA	Simulated Annealing
SBA	Smart Bat Algorithm
SN	Sensor Node
SOL	Service Output Layer
TS	Tabu Search

TSP	Travelling Salesman Problem
WiMAX	Worldwide Interoperability for Microwave Access
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
WSNMM	Wireless Sensor Network Management Module

Chapter 1

Introduction

1.1 Background

Biological products refer to natural substances obtained from living organisms (U.S. Food and Drug Administration, 2008), which include blood, blood products, tissue, tissue products, organs, vaccines, microbial samples, cellular specimens, etc. Pharmaceutical products are drugs or medicines of traditional and modern medicine (World Health Organization, 2010). The supply chain of both products is a critical and essential part of many different areas, such as medicine, health-care, pharmacy and biotechnology. However, managing biological and pharmaceutical (B&P) product supply chains is a challenging task, since these products are highly susceptible to variations of environmental factors such as temperature, humidity, vibration, tilt, light and composition of the atmosphere. For example, whole blood is required to be stored at 1°C to 6°C and transported at 1°C to 10°C (Hillyer et al., 2006); otherwise, the whole blood will deteriorate and expire within a few days. Therefore, extra attention and measures are required when handling B&P products; otherwise, serious consequences may result in various aspects.

Mishandling B&P products in one part or parts of the supply chain will cause microbial or chemical contaminations, an increase of product decomposition rate (Wigent, 2005) and leakage. The deteriorated products will jeopardize the health and even life of end users (Benitez and Lam, 2008; Ng, 2010). Eventually, manufacturers will face serious consequences including loss of money and reputation due to products being discarded, recalled and withdrawn, heavy penalties and prosecutions. Therefore, comprehensive measures are required to properly manage B&P products. One of the most effective solutions is to set up a real-time and comprehensive monitoring system to keep track of the state pedigree of the B&P products in a supply chain, in which the system should be able to be adopted in raw material collection, manufacturing, transportation, storage distribution and retail. Assisted by the monitoring system, the relevant parties (i.e. manufacturers, suppliers, distributors) in the supply chain can take timely proper action to cope with mishandling and unpredictable incidents before an accident happens.

However, in the current decade, the general practice of handling B&P products applied in supply chains is straightforward and primitive. In the core locations of the supply chain including factory, warehouse and distribution centre, there is various equipment including refrigerators, heaters, air conditioners and sterilizers for the creation and maintenance of a suitable environment for storing and processing B&P products. When transportation between core locations is required, B&P products are packed into insulated containers like adiabatic boxes and cooler chests, which can isolate the external environment from the products, with a few of them embedded with a thermometer or a temperature data logger (Medu-scientific Ltd., 2010). However, the product demand and strictness of international regulations nowadays continue growing and the requirement of B&P product quality and integrity becomes higher and higher, so the current practice no longer meets the requirements, which several aspects reflecting this consequence. Firstly, the scalability of current monitoring systems is too low to accommodate the rapid increase of the throughput of B&P products. In the core locations of the supply chain, the equipment is large and installed at fixed locations. When the layout or storage level is changed, it is difficult and costly to reinstall, extend or contract such equipment. Secondly, the measurement accuracy of most equipment is of ambient level, which means that the current system cannot provide the precise product status at a specific position of the monitoring area. This attribute makes the system unable to detect some hidden incidents and finally lead to some unexpected accidents. For example, a box of medicines is placed near a small heat source in a big warehouse. The temperature inside the box then rises above the safe level after a period of time and the medicine inside the box deteriorates, but the system cannot detect this small change since the ambient temperature is still within a safe level. Thirdly, the flexibility of the current system is low because of the size and power supply of the equipment. Consequently, the transportation process becomes an uncertainty, especially during loading and unloading operations. Although a thermometer or a temperature data logger has been installed in some transport containers and vehicles in some applications, the thermal status of the products cannot be reported in real-time, and most of the equipment just focuses on monitoring the temperature of the products and omits other environmental factors. Thus, problems such as damage, leakage and tainting are usually found during or after the receiving procedure. In addition, equipment used in the core locations rarely provides real-time reporting of product status. Hence, changes of product state cannot be reported and recorded immediately. Further, the equipment highly relies on the main power source to operate, so record failure will occur during power cuts. In order to prevent the aforementioned faults, to enhance visibility and more importantly, fulfil the emerging need in the B&P product supply chain, the current monitoring practice is urged to evolve as a real-time and comprehensive monitoring system.

1.2 Problem Formulation

In the recent decades, Wireless Sensor Network (WSN) has received significant attention among researchers and practitioners. Plenty of applications from different areas have successively emerged. It shows a high potential to be a highlighted technology in the next five to ten years (Gubbi et al., 2013). Similar to many new technologies, a WSN has a relatively high threshold to be adopted. One of the most critical concerns is the energy efficiency which highly relates to the system life time. As a WSN is usually deployed in outdoor or large areas such as forests, deserts and highways, using battery is almost the only choice for the power supply due to its portability and relatively low cost compared to a wired power supply system. Because of the usage of a limited power source (i.e. a battery), energy efficiency becomes the first consideration when designing a WSN. Another critical concern is the number of sensor nodes. Although sensor nodes are of relatively low cost, the amount of total production cost can be unexpectedly high, especially for large-scale WSNs. Therefore, optimizing the number of sensor nodes is an essential objective to be fulfilled. At the same time, the WSN should maintain a certain level of quality of service (QoS) which usually is required by the user or application. The QoS involves a series of quality metrics such as data reporting rate, coverage degree and level of network connectivity. To reach the required level of QoS, more power should be consumed and more sensor nodes should be used correspondingly. Therefore, trade-offs exist between prolonging system life-time, optimizing the number of sensor nodes and maintaining QoS. Figure 1.1 shows a hierarchical trade-off model that illustrates the relationship between parameters and quality metrics at node level and task level (i.e. service level). How to manage these trade-offs becomes an essential topic to be considered when designing a robust user- or application-oriented WSN.

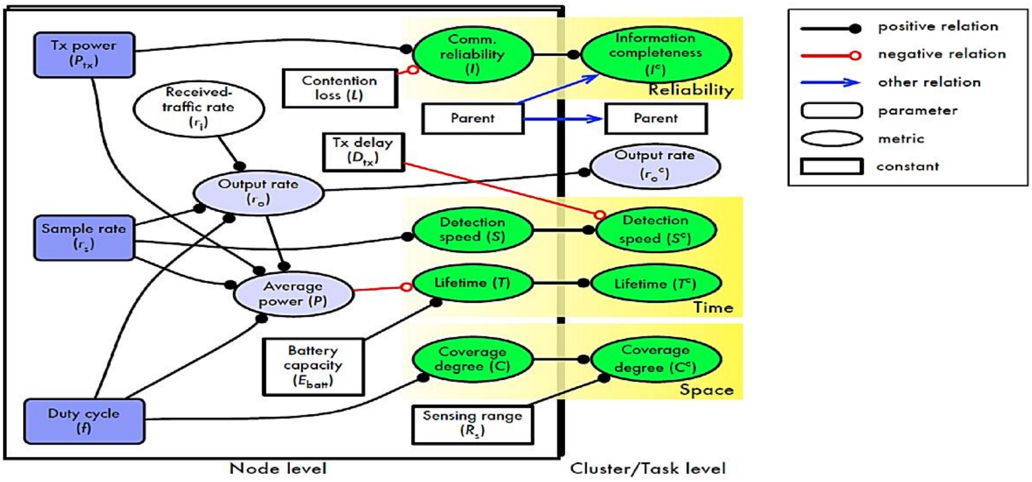


Figure 1.1 Hierarchical trade-off model for parameters and quality metrics at node level and task level (Hoes et al., 2009)

Fault tolerance is a relatively new factor of QoS to be considered. It refers to the ability of a WSN to tolerate a number of node failures and remain functional. This ability is vital to prolonging the lifetime of a WSN, since node failures can lead to network function disorder, network partition and failure, and finally terminate the

WSN much earlier than expected. In the ordinary course of events, deployment of a number of redundant sensor nodes to maintain the network connectivity is a common practice to achieve fault tolerance. However, cost will be relatively increased, so how to determine the appropriate number of redundant nodes becomes an essential factor to be considered. To sum up, this research proposed to design a WSN-based system in which the total production cost is minimal, while simultaneously, a series of basic design factors including energy efficiency, topology, sensing coverage, network connectivity and fault tolerance are well balanced.

1.3 Research Objectives

Focusing on the formulated problem, which indicates how to balance the trade-offs between the basic design factors in order to maximize the system performance, and simultaneously minimize the total production cost, this research aimed to design and model a monitoring system based on RFID and WSN technologies. The objectives included:

(i) To design a model of a WSN which balances trade-offs between basic design factors and the total production cost.

(ii) To design a flexible and scalable architecture for performing hardware communication, data processing and analysis, and decision-making for industrial applications.

(iii) To optimize the proposed deployment strategy by using meta-heuristic approaches.

(iv) To evaluate the system performance by comparing different approaches.

1.4 Thesis Outline

The structure of the dissertation is organized as follows. Chapter 2 presents a literature review of IoT, WSN and methods of managing some basic design factors when designing a WSN. In the next chapter, a conceptual system architecture of the proposed system and the conceptual framework of the WSN management module are described. Chapter 4 presents a statistical approach for WSN deployment. In Chapter 5, a modified Bat Algorithm (BA) named Smart Bat Algorithm (SBA) is proposed to solve the model of 2-D homogenous WSN deployment. Three other meta-heuristic approaches including Genetic Algorithm (GA), Ant Colony Optimization (ACO), and Discrete Bat Algorithm (DBA) are used for comparison with the proposed SBA. In the next chapter, the problem of 3-D heterogeneous WSN deployment with obstacles is studied and modelled. The four meta-heuristics methods (i.e. SBA, GA, ACO and DBA) are also used to solve the model and compare the performance of each other. After that, a discussion is presented in Chapter 7. Finally, a conclusion is drawn in Chapter 8 and some suggestions for further research are summarized in Chapter 9.

Chapter 2

Literature Review

Compared to other cargo in the field of supply chain management, such as garments and household products, the requirements of a monitoring system for biological and pharmaceutical (B&P) products required a higher standard. For example, firstly, the monitoring range of the system should be large enough to cover all the B&P products. Secondly, the system should possess the ability to report the product statuses in a real-time manner. Thirdly, the system should be able to provide a high degree of fault tolerance. To fulfil these requirements, this research adopted the Radio-Frequency IDentification (RFID) and Wireless Sensor Network (WSN) technologies to construct the core of the proposed system. In the proposed system, RFID is used to standardize the unique ID of each device in the system, and thereby allow better integration of the proposed system and the current Electronic Product Code (EPC) system of the supply chain industry and better mapping of the B&P products and monitoring devices. A WSN is adopted to provide an easy-to-install, flexible-to-install and low-cost approach for B&P product monitoring, since no infrastructure is needed to be built or reconstructed, and the cost of sensor nodes is relatively low.

In the current era, RFID and WSN are integrated with other popular information technologies such cloud computing and Machine to Machine (M2M) communication to form a higher-level paradigm, named Internet of Things (IoT). IoT is a current hot research topic. According to Google Scholar, over 9,000 articles and books related to IoT research were published in 2014. This literature covers different dimensions of IoT, but the main intellectual components of IoT are scattered across different journals, which causes the intellectual structure of IoT still to not be clearly identified. Therefore, examination and identification of the intellectual core of IoT provides significant contributions in both scientific and application aspects of IoT. More importantly, this also can be a scientific and comprehensive approach to further expound on and justify the rationale and the appropriateness of the adoption of RFID and WSN for the proposed system in this research. For this purpose, semantic similarity analysis of IoT was conducted to examine the intellectual core of IoT (Ng et al., 2018b).

Semantic similarity analysis is a relatively objective, quantitative and systematic approach for the examination of the intellectual structure of IoT. The analysis includes a series analyses. Firstly, IoT-related papers with a high citation rate are extracted from online scientific databases based on the results of citation and co-citation analysis. These two analyses are well-known statistical bibliometric analysis approaches for the identification of the intellectual structure in a specific academic field (Pilkington and Meredith, 2009). The extracted papers are considered as high-value papers in the field of IoT. Next, the high-value papers are further analysed by factor analysis, Hierarchical Cluster Analysis (HCA) and MultiDimensional Scaling (MDS). These three analyses are used to address the dimensionalities of IoT. Through analyses of the dimensionalities of IoT, the comprehensive intellectual structure of IoT can be clearly revealed.

2.1 Overview of Internet of Things (IoT)

In 1999, the cofounder of the Auto-ID Labs at Massachusetts Institute of Technology (MIT), Kevin Ashton, first raised the concept of leveraging RFID and sensor technologies to connect the cyber world (i.e. the Internet) and the physical world and introduced the term “Internet of Things (IoT)” (Ashton, 2009). Six years later, the International Telecommunication Union (ITU) firstly expounded on the concrete vision of IoT in its official report of 2005. This vision expressed that IoT is proposed to connect everyday "things" to communication networks at "anytime, anywhere, by anyone and anything" (ITU, 2005). Later on, the union issued the concrete definition of IoT, which is "A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" (ITU-T, 2012). Under this definition, the visions of IoT are further categorized into three perspectives. The first perspective includes "Things oriented" visions, which focus on "things" identification and integration. RFID, Wireless Sensor and Actuator Networks (WSAN), Unique/Universal/Ubiquitous IDentifier (UID) (Sakamura, 2006) and Smart Objects/Items come under this vison. The second perspective, "Internet oriented" visions, focus on device networking, connection efficiency and IP simplification for devices with limited capacity. These visions include IP for Smart Objects (IPSO) (Dunkels and Vasseur, 2008), e.g. 6LoWPAN (Hui, Culler and Chakrabarti, 2009), Internet 0 (Gershenfeld, Krikorian and Cohen 2004) and Web of Things (Guinard and Vlad, 2009). The last perspective is called "Semantic oriented", and is about managing the numerous IoT devices and their tremendous amount of information. These visions include semantic technologies, reasoning over data, and semantic execution environments (Atzori, Iera and Morabito, 2010).

Another concrete definition of IoT is "a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual “things” have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network", published by the Cluster of European Research projects on the Internet of Things (CERP-IoT). The vision of IoT states that "people and things to be connected Anytime, Anyplace, with Anything and Anyone, ideally using Any path/network and Any service" (Sundmaeker et al., 2010). This vision covers Pervasive Computing, Ubiquitous Computing and Ambient Intelligence, and it is further extended to cover Web 2.0, "Internet Protocol (IP), communication technology, embedded devices, its applications, the Internet of People or the Intranet/Extranet of Things." (Uckelmann, Harrison and Michahelles, 2011).

Towards the visions of IoT, the design of IoT architecture should fulfil a series of high-level and specific requirements, which include interoperability, flexibility, scalability, efficiency of real-time interaction and event-driven handling capability. The architecture is also required to interconnect heterogeneous and scattering "things" in both the physical and virtual world. Under these requirements, a feasible approach for IoT raised among the literature is multi-layer Service Oriented Architecture (SOA). A generic SOA of IoT consists of four major layers:

sensing/perception/device layer, network/networking layer, service layer and interface/application layer (Li, Xu and Zhao, 2015). In some literature, the service layer and interface/application layer are combined into one layer (Domingo, 2012). In the sensing/perception/device layer, numerous "things" with unique identities are capable of providing their internal (i.e. the status of the smart objects) and external (i.e. the condition of the surrounding environment) sensor data, and capable of exchanging data with each other through wired or wireless communication. In the network/networking layer, specific data of IoT-related services, controls, applications, network connectivity management and Quality of Service (QoS) management transport are transported. In the service layer, there are some common components including service discovery, service composition, service repository and trustworthiness management for the operations of all service-oriented activities. Based on these components, various sets of application requirements, service Application Programming Interfaces (APIs) and protocols require applications and services for performing various service requests and responses. For example, the service requests and responses include information exchange, data management, "things" monitoring and communication. In this layer, IoT middleware is also integrated to provide efficient and flexible interfacing functionalities between IoT-related hardware and software. Lastly, the interface/application layer contains various interaction methods to allow different users and applications to effectively interact with IoT-related services.

From the rise of the IoT concept to nowadays, realising IoT becomes more concrete and possible than before, since many new technologies have emerged and many existing technologies are maturing. Some of these technologies are key enabling technologies, integration of which is driving the visions of IoT. These key enabling technologies can be divided into several categories:

(1) Identification technologies (but not limited to): RFID, Near Field Communication (NFC) and barcode system;

(2) Sensing technology (but not limited to): WSN and WSAN;

(3) Communication technologies (but not limited to): Ethernet, Wi-Fi, Zigbee, Bluetooth, UWB, WiMax and Cellular Networks;

(4) Addressing scheme (but not limited to): IPv6 and 6LoWPAN;

(5) Cloud computing;

(6) Big Data analytics.

By integrating these key technologies, IoT possesses considerable potential for developing various innovative and intelligent applications in many different fields. Table 2.1 lists some IoT applications in various fields.

Table 2.1 Examples of IoT applications in various fields

Fields	Applications	Authors (year)
Health care	Remote human gait tracking	Luo et al. (2010)
	IoT-based information system for emergency medical services	Xu et al. (2014)
Food supply chain	Value-centric food supply chain management	Pang et al. (2015)
Environmental monitoring	Tailings dam monitoring	Sun, Zhang and Li (2012)
	Regional environmental monitoring	Fang et al. (2014)
Transportation and logistics	Urban Intelligent Transportation System	Zhou, Liu and Wang (2012)
Smart home	Daily activities recognition and tracking	Rashidi et al. (2011)
	Smart thermostat	Lu et al. (2010)
Smart industry	Automated assembly modelling system	Wang, Bi and Xu (2014)
	Real-time information of manufacturing resources capturing and integration	Zhang et al. (2015b)
Smart city	Smart parking system	Polycarpou, Lambrinos and Protopapadakis (2013)
Smart grid	Smoothing household electrical loads	Ancillotti, Bruno and Conti (2014)
	Load balancing and monitoring and control of distributed energy systems	Kleineidam, Krasser and Reischböck (2016)
Agriculture and breeding	Crop Monitoring System	Zhao et al. (2011)
	Livestock tracking	Voulodimos et al. (2010)
Product lifecycle management	Configurable information service platform for product lifecycle management	Cai et al. (2014)

2.2 Methodology of Semantic Similarity Analysis

Semantic similarity analysis was performed to examine the intellectual structure of IoT studies by conducting a series of bibliographic and statistical analyses. Figure 2.1 illustrates the workflow of semantic similarity analysis. Firstly, a set of source articles was collected from Web of Science/Web of Knowledge databases in order to guarantee the quality of raw data. Next, Citation analysis was used for the identification of high-value articles and the record of citation growth throughout the collected articles. After screening out irrelevant articles, a co-citation method was used to compile a co-citation matrix, which is an input for further statistical analyses, i.e. Factor analysis, HCA and MDS. These analyses were conducted to analyse and determine the intellectual structure of IoT studies.

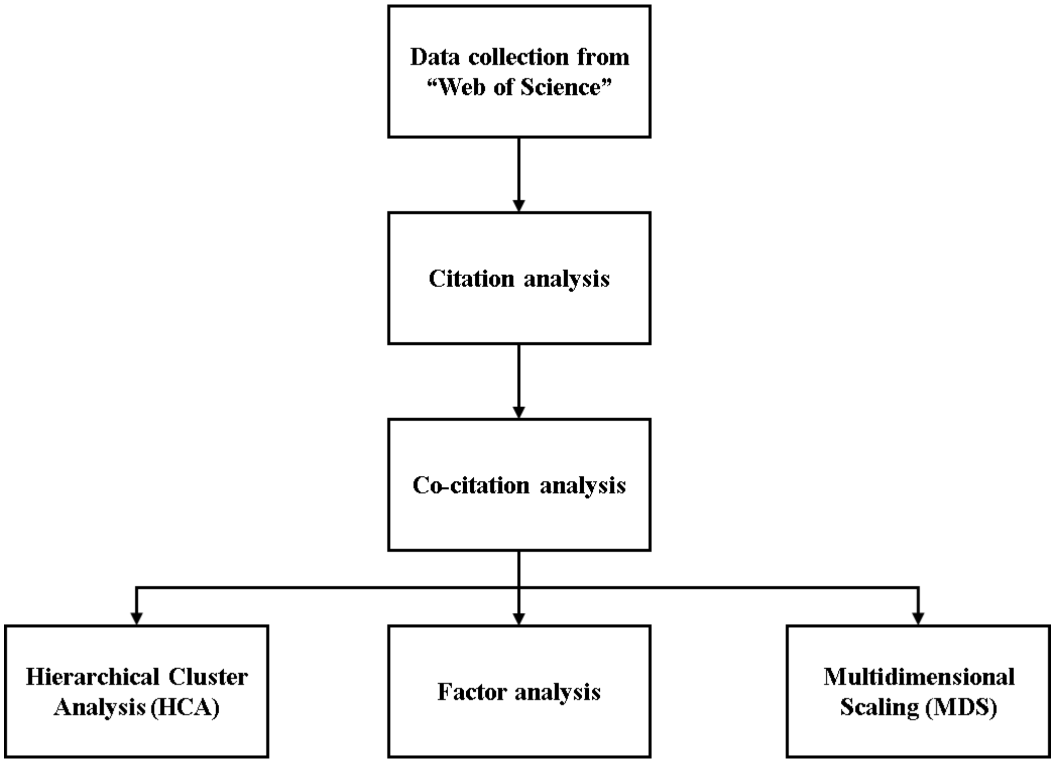


Figure 2.1 The workflow of semantic similarity analysis

2.2.1 Data Collection

In this research, the representative research papers related to IoT were retrieved from Web of Science. Web of Science is a world-leading online platform connecting many high-reputation scientific databases to provide scientific paper search and discovery, and a scientific citation indexing service. This platform covers over 12,500 high-quality journals, 170,000 conference proceedings and 70,000 scholarly books from more than 250 disciplines (Thomson Reuters, 2016). It is trusted by approximately 7,000 worldwide scholarly institutions. More importantly, it provides a useful function to list the searching result sequentially based on citation counts. Such function enables users to sort out the high-value articles efficiently. In the next step, a set of search keywords was defined. The main keywords to search IoT-related studies were "internet of things" and "IoT". However, some papers without these two main keywords may include IoT-related content. For instance, before the raising of IoT paradigm, RFID- and M2M-related studies shaped the concept of IoT. When IoT emerged, cloud and NFC were two of the main components mentioned together with IoT in many studies. Consequently, the set of keywords was defined as:-

KEYWORDS = {"internet of things", "IoT", "machine-to-machine", "M2M", "cloud", "radio frequent identification", "RFID", "near field communication", "NFC"}

By using these keywords, 1,457 results and 7,029 citations for all the results could be yielded from 2004 to 1st November 2015 in Web of Science.

2.2.2 Data Analysis

2.2.2.1 Citation Analysis

A citation refers to a reference to a published or unpublished source document. Its importance has been stated by the father of citation indexing of academic literature, Eugene Garfield, where citation is the explicit linkage between articles which contain similar specific contents (Jacso, 2010). Citation analysis can be used sort out citation sources of studies and show up their continuous citation growth in a literature field. A citation index is created to represent such linkages and indicate the sources of citations. By using the citation index, we can find out how many and what documents have cited an article (Garfield and Merton, 1979). A citation index can be used to determine high-value papers as a citation index will increase quickly if a study is frequently cited. Thus, researchers can identify valuable articles by screening out articles with a high citation index. However, citation analysis cannot reveal the linkages among topics and journals; thus, it cannot be solely used to reveal the intellectual structure of a specific academic area. For this reason, citation analysis was only conducted to screen out less influential articles for the next stage of analysis.

2.2.2.2 Co-citation Analysis

Co-citation analysis counts the frequency of two articles that are cited together by other articles (Small, 1973) and it has been an illustrious structuring measure in bibliometrics (Borgman, 1989). When performing co-citation analysis, two sets of documents should be collected to form a co-citation frequency matrix. One set contains papers with a high citation index which are representable in a research area, while another set contains papers citing highly cited papers (Hsiao and Yang, 2011).

The details of citation and co-citation analysis processes are described in the following. Firstly, a set of papers $\boldsymbol{P}$ related to a specific field or topic is collected from online scientific databases. Among $\boldsymbol{P}$, the set of high value papers $\boldsymbol{P_h}$ is identified, where $\boldsymbol{P_h} \subseteq \boldsymbol{P}$. Every paper in $\boldsymbol{P_h}$ has a citation index larger than a specific threshold. In the next step, the co-citation indexes for the papers are found out by checking the frequency of every pair of papers in $\boldsymbol{P_h}$ cited by the papers in $\boldsymbol{P}$. Finally, an $\boldsymbol{N}$ x $\boldsymbol{N}$ co-citation matrix is formed, where $\boldsymbol{N}$ is the cardinality of $\boldsymbol{P_h}$. The co-citation matrix is a raw input for the next analyses (i.e. factor analysis, HCA and MDS).

2.2.2.3 Factor Analysis

Factor analysis is a well-known statistical measure to examine interrelationships between an enormous set of variables, and for semantic similarity analysis, the variables may include authors, journals or articles. This measure divides a large set of variables into smaller groups of factors and explains the maximum amount of observations with the minimum number of explanatory factors (Field, 2013). In this study, "factor" is the labelling of interrelated groups of variables performing data reduction and summarization among similar articles. Every factor is comprised of influential papers which are highly co-cited by other papers within a particular field (McCain, 1990) and a factor can also be treated as a subfield in an academic area. Different factors provide the foundation of the subfields and they portray the intellectual core of an academic area. Therefore, it is commonly used in document analysis (Leydesdorff and Vaughan, 2006).

2.2.2.4 Hierarchical Cluster Analysis (HCA)

Hierarchical Cluster Analysis (HCA) is a statistical method to cluster a group of data into different sub-groups based on their unique characteristics. In the same sub-group, elements are more similar than those in other sub-groups. There are two strategies for HCA, namely agglomerative and divisive strategies (Rokach and Maimon, 2005). Agglomerative HCA is a "bottom-up" approach, where each observation is considered as a separate cluster and these clusters are combined while moving up the hierarchy until all clusters are merged into one cluster. Divisive HCA is a "top-down" approach, where all observations are considered as one large cluster and this cluster is divided into many sub-groups recursively while moving down the hierarchy. In this research, agglomerative HCA was adopted, where documents sharing similar attributes are grouped in the clustering procedure. Thus, each group can represent a subfield in an academic area (McCain, 1990).

2.2.2.5 Multidimensional Scaling (MDS)

Multidimensional Scaling (MDS) is usually adopted with HCA for perceptual mapping to explore the similarities within objects in a set of data (McCain, 1990). MDS transforms the similarity of the objects into relative positions in a multidimensional space. In the document analysis, the interrelated distance, i.e. the closeness between papers of a specific field, implies document similarity (Hsiao and Yang, 2011). Thus, MDS can be used to reveal the intellectual structure of a specific academic field. In this research, a proximity scaling approach was adopted to perform MDS.

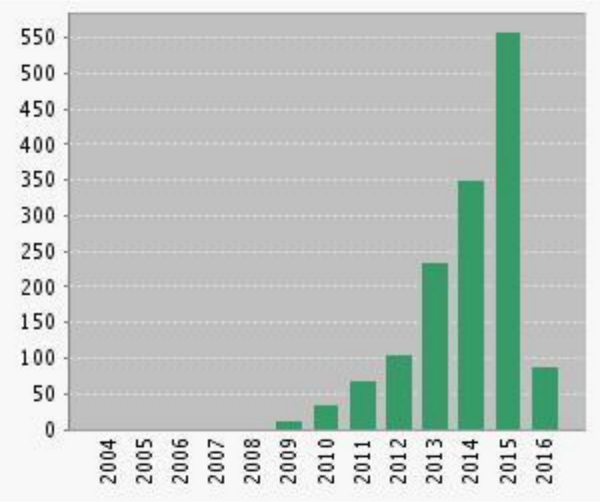
2.3 Results and Discussion of Semantic Similarity Analysis

After performing a series of analyses including citation analysis, co-citation analysis, factor analysis, HCA and MDS, a total of 1,457 IoT-related papers from 2004 to 1st November 2015 and 7,029 total citations for all the results were obtained in Web of Science. As shown in Figure 2.2, the year analysis reveals that the number of published IoT-related articles has gradually increased since 2004.

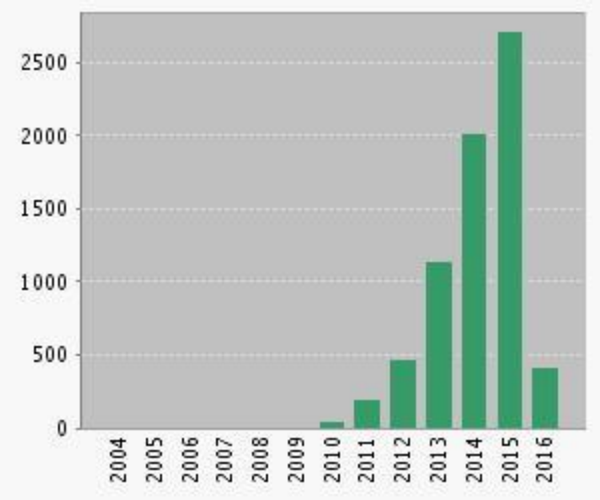
In order to ensure that influential papers, especially newly added papers, were included, the citation threshold was set as 16 citations (Shiau and Dwivedi, 2013; Shiau, 2016). As a result, a total of 84 articles within the 1,457 IoT-related papers were retrieved. To further ensure that the 84 papers were highly related to IoT, these papers were then reviewed manually one by one based on three criteria which were established for the screening of irrelevant paper: -

(a) Limited counts of keywords "Internet of things", "IoT" or equivalent;
(b) No paragraph related to IoT;
(c) Gist is relevant to IoT, but to a small extent.

Finally, 68 papers, which are listed in Table 2.2, were obtained and these papers were used as source documents for the co-citation analysis. Next, a 68 x 68 co-citation matrix was formed by these source documents. This co-citation matrix was then transformed into a Pearson's R correlation matrix for further statistical analyses. The diagonal value of the correlation matrix was set as 1, because each observation should correlate with itself perfectly (Field, 2013).



(a) Published articles of searching results



(b) Total number of cited references to all items in the searching result

Figure 2.2 Citation report from Web of Science

Table 2.2 The 68 most frequently cited IoT-related papers

ID	Authors (Year)	Source	Times cited
1	Atzori, Iera and Morabito (2010)	Computer networks	849
2	Gubbi, et al. (2013)	Future Generation Computer Systems	177

3	Miorandi, et al. (2012)	Ad Hoc Networks	170
4	Kortuem, et al. (2010)	IEEE Internet Computing	153
5	Gershenfelo, Krikorian and Cohen (2004)	Scientific American	132
6	Guinard, et al. (2010)	IEEE Transactions on Services Computing	117
7	Welbourne, et al. (2009)	IEEE Internet Computing	116
8	Ganti, Ye and Lei (2011)	IEEE Communications Magazine	107
9	Bobadilla, et al. (2013)	Knowledge-Based Systems	105
10	Xu (2011)	International Journal of Production Research	98
11	Zorzi, et al. (2010)	IEEE Wireless Communications	71
12	Bandyopadhyay and Sen (2011)	Wireless Personal Communications	63
13	Shelby (2010)	IEEE Wireless Communications	57
14	Li, Xu and Wang (2013)	IEEE Transactions on Industrial Informatics	56
15	Kiritsis (2011)	Computer-Aided Design	54
16	Zhou and Chao (2011)	IEEE Network	54
17	Roman, Najera and Lopez (2011)	Computer	53
18	Jara, Zamora and Skarmeta (2011)	Personal and Ubiquitous Computing	50
19	Perera, et al. (2014a)	IEEE Communications Surveys & Tutorials	48
20	Domingo (2012)	Journal of Network and Computer Applications	46
21	Oliveira, De Sousa and Rodrigues (2011)	International Journal of Communication Systems	45

22	He and Xu (2014)	IEEE Transactions on Industrial Informatics	44
23	Atzori, et al. (2012)	Computer Networks	42
24	Kranz, Holleis and Schmidt (2010)	IEEE Internet Computing	40
25	Broll, et al. (2009)	IEEE Internet Computing	40
26	Roman, et al. (2011)	Computers & Electrical Engineering	39
27	Atzori, Iera and Morabito (2011)	IEEE Communications Letters	37
28	Gluhak, et al. (2011)	IEEE Communications Magazine	37
29	Zuehlke (2010)	Annual Reviews in Control	37
30	Chen, Mao and Liu (2014)	Mobile Networks and Applications	36
31	Hong, et al. (2010)	IEEE Wireless Communications	36
32	Zhang, et al. (2014)	Enterprise Information Systems	35
33	Ning and Wang (2011)	IEEE Communications Letters	35
34	Sarma and Girão (2009)	Wireless personal communications	34
35	Li, et al. (2011)	IEEE Communications Magazine	33
36	Xu, He and Li (2014)	IEEE Transactions on Industrial Informatics	32
37	Zhong, et al. (2013)	The Journal of Supercomputing	32
38	Bormann, Castellani and Shelby (2012)	IEEE Internet Computing	32
39	Watteyne, et al. (2012)	Transactions on Emerging Telecommunications Technologies	31
40	Tozlu, et al. (2012)	IEEE Communications Magazine	29
41	López, et al. (2012)	Personal and Ubiquitous Computing	28

42	Sheng, et al. (2013)	IEEE Wireless Communications	27
43	Hancke, Silva and Hancke (2013)	Sensors	27
44	Estrin (2010)	IEEE Internet Computing	26
45	Perera, et al. (2014b)	Transactions on Emerging Telecommunications Technologies	25
46	Barnaghi, et al. (2012)	International Journal on Semantic Web and Information Systems	25
47	Roman, Zhou and Lopez (2013)	Computer Networks	24
48	Kelly, Suryadevara and Mukhopadhyay (2013)	IEEE Sensors Journal	23
49	Vlacheas, et al. (2013)	IEEE Communications Magazine	23
50	Palattella, et al. (2013)	IEEE Communications Surveys & Tutorials	22
51	Heer, et al. (2011)	Wireless Personal Communications	22
52	Främling, et al. (2007)	International Journal of Computer Integrated Manufacturing	21
53	Chen, Wan and Li (2012)	KSII Transactions on Internet & Information Systems	20
54	Jara, Zamora and Skarmeta (2012)	Mobile Information Systems	20
55	Gama, et al. (2012)	Computer Communications	19
56	Ma (2011)	Journal of Computer science and Technology	19
57	Yan, Zhang and Vasilakos (2014)	Journal of Network and Computer applications	18
58	Bi, Xu and Wang (2014)	IEEE Transactions on Industrial Informatics	18

59	He, Yan and Xu (2014)	IEEE Transactions on Industrial Informatics	18
60	Huang, et al. (2013)	The International Journal of Advanced Manufacturing Technology	18
61	Iera, et al. (2010)	IEEE Wireless Communications	18
62	Giner, et al. (2010)	IEEE Pervasive Computing	18
63	Guo, et al. (2013)	Journal of Network and Computer Applications	17
64	Feki, et al. (2013)	Computer	17
65	Yu, et al. (2013)	IEEE Network	16
66	Zhang, et al. (2012)	Computers & Mathematics with Applications	16
67	Chen, et al. (2011)	Computer Science and Information Systems	16
68	Cooper and James (2009)	IETE Technical Review	16

2.3.1 Factor Analysis

The factor analysis was conducted by using SPSS software with the input of the Pearson's R correlation matrix. When factors were extracted, papers were assigned to different factors by calculating their degree of variables load (or loading) on each factor. In general, most observations have high loadings on the most important factors but small loadings on the remaining factors. In order to improve the interpretation of factor analysis, the varimax rotation method was adopted, because varimax rotation maximizes the loadings dispersion within factors. Thus, the interpretation of factor analysis result can be more acceptable (Andrews, 2003; Zhao and Strotmann, 2008; Shiau, 2016). To further reduce the number of factors, the eigenvalue was set to be greater than 1. This setting retains all qualified factors and excludes less influential factors (Kaiser, 1960).

To examine the appropriateness for conducting factor analysis in this research, the Kaiser–Meyer–Olkin (KMO) test and Bartlett's test were applied. Since the input correlation matrix was not positive definite (PD), the test result could not be obtained in SPSS. Therefore, the input correlation matrix was transformed into the nearest PD correlation matrix by using the eigenvalue method (Rousseeuw and Molenberghs, 1993). As shown in Table 2.3, the test results support conducting factor analysis, since the KMO measure is 0.700 which is larger than the minimum acceptable value of 0.5 (Kaiser, 1974), and the significant level of Bartlett's test is $p = 0.000 < 0.001$, which is smaller than the value of 0.05 for rejection of the null hypothesis (Bartlett, 1950).

Table 2.3 The results of Kaiser-Meyer-Olkin (KMO) and Bartlett's test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.700
Bartlett's Test of Sphericity	Approx. Chi-Square	5593.566
	df	2278
	Sig.	0.000

Consequently, a total of 10 factors were extracted, which explain nearly 80% of articles. Table 2.4 shows the summary of each factor and it summarizes the factor analysis result.

(i) Factor 1 captures nearly half of the source documents and explains 25.737% of the calculated variance. This factor represents the frameworks and challenges of IoT, which include: IoT frameworks (Atzori, Iera and Morabito, 2011; Bandyopadhyay and Sen 2011; Atzori et al., 2012; Gubbi et al., 2013); IoT application frameworks for diabetes therapy management (Jara, Zamora and Skarmeta, 2011), people with disabilities (Domingo, 2012), and home environment monitoring (Kelly, Suryadevara and Mukhopadhyay, 2013); IoT elements including smart objects (Kortuem et al., 2010; López et al., 2012; Tozlu et al., 2012), testbeds (Zuehlke, 2010; Gluhak et al., 2011), mobile crowdsensing (Ganti, Ye and Lei, 2011), and context aware computing (Perera et al., 2014a); IoT network communication including network architecture (Gershenfelo, Krikorian and Cohen, 2004), IPv6 for IoT (Oliveira, Sousa and Rodrigues, 2011; Jara, Zamora and Skarmeta, 2012) and communication protocol (Bormann, Castellani and Shelby, 2012; Watteyne et al., 2012; Palattella et al., 2013); service-oriented approach (Guinard et al., 2010; Shelby, 2010; Gama, Touseau and Donsez, 2012; Perera et al., 2014a); IoT data management (Welbourne et al., 2009; Barnaghi et al., 2012); research and technology challenges (Zorzi et al., 2010; Ma, 2011; Miorandi et al., 2012; Feki et al., 2013); IoT security requirements (Roman et al., 2011; Roman, Najera and Lopez, 2011).

(ii) Factor 2 represents the current situations of IoT in different applications. This factor explains 13.370% of the calculated variance, which includes: the current development status and challenges of IoT in supply chain quality management (Xu, 2011), opportunistic IoT (Guo et al., 2013), modern manufacturing (Bi, Xu and Wang, 2014; Zhang et al., 2014), a data cloud platform for the automotive industry (He, Yan and Xu, 2014), distributed systems integration (He and Xu, 2014), and various industrial applications (Xu, He and Li, 2014); a compressed sensing-based data acquisition approach for resource-restricted devices (Li, Xu and Wang, 2013); a cognitive management framework of IoT for supporting smart city development (Vlacheas et al., 2013); a topological construction approach for improving and enhancing the topology of WSNs (Zhang et al., 2012); database issues of IoT and a roadmap of technological solutions (Cooper and James, 2009).

(iii) Factor 3 represents interactions of IoT. This factor explains 11.062% of the calculated variance, which includes: Physical Mobile Interaction (PMI) and Multi-Tag Interaction (MTI) approaches with IoT for design of the physical user interface (Broll et al., 2009); smart workflows utilizing mobile and labelling technologies for reducing the gap between the cyber and physical world (Giner et al., 2010); IoT-enabled Human-Computer Interaction (HCI) approaches (Kranz Holleis and Schmidt, 2010); an IP-based WSN protocol named SNAIL for smart things' interactions in the network of IoT (Hong et al,. 2010); architectural models for interactions between IoT and the physical world (Iera et al., 2010; Li et al., 2011; Ning and Wang, 2011).

(iv) Factor 4 represents security issues of IoT and explains 6.928% of the calculated variance. This factor includes: analyses and reviews of the challenges and opportunities of the Internet Engineering Task Force (IETF) communication protocol suite for IoT (Sheng et al., 2013); security challenges in IoT with distributed architecture (Roman Zhou and Lopez, 2013) and in IoT using standard Internet protocols (IP) (Heer et al., 2011); trust management approaches for IoT (Chen et al., 2011; Yan et al., 2014).

(v) Factor 5 represents application domains of IoT and explains 4.613% of the calculated variance. This factor includes: participatory-sensing applications for aspects of safety, sustainability, personal and public health (Estrin, 2010); application domains of transportation and logistics, healthcare, smart environment, individual and society, and futuristic developments (Atzori, Iera and Morabito, 2010).

(vi) Factor 6 represents data management of IoT explains 4.567% of the calculated variance. This factor includes: data management and exchange on a cloud manufacturing service platform (Huang et al., 2013); a data cycle system constructed based on IoT for managing data from social, physical, and cyber worlds (Zhong et al., 2013); virtual identities and digital shadow approaches for data privacy issues of IoT in the coming future (Sarma and Girão, 2009); a multimedia traffic security framework for multimedia services in IoT (Zhou and Chao, 2011).

(vii) Factor 7 represents IoT in product lifecycle management and explains 3.657% of the calculated variance. This factor includes: standards of product lifecycle management for intelligent and smart products in IoT (Kiritsis, 2011), different approaches for product lifecycle information management (Främling et al., 2007).

(viii) Factor 8 represents research enabling technologies of IoT and explains 3.407% of the calculated variance. This factor includes: data generation, acquisition, storage, and analysis of big data (Chen, Mao and Liu, 2014); correlations and integrations of M2M, WSNs, CPS, and IoT (Chen, Wan and Li, 2012); cloud-based vehicular networks for resources sharing among vehicles (Yu et al., 2013).

(ix) Factor 9 represents IoT in smart cities and explains 2.623% of the calculated variance. This factor introduces the role of IoT for smart city development and the significance, and technical and non-technical challenges of IoT for smart cities (Hancke, Silva and Hancke, 2013).

(x) Factor 10 represents IoT in recommender systems and explains 2.153% of the calculated variance. This factor introduces recommender systems based on the information from IoT and other sources for providing predictions and recommendations (Bobadilla et al., 2013).

Table 2.4 The results of factor analysis

Factors	Articles (#*ID*)	Eigenvalue	Percentage of variance explained (%)	Sum of percentage of variance explained (%)
1. Frameworks and challenges of IoT **(32 results)**	● Gubbi, et al. (2013) (#2) ● Miorandi, et al. (2012) (#3) ● Kortuem, et al. (2010) (#4) ● Gershenfelo, Krikorian and Cohen (2004) (#5) ● Guinard, et al. (2010) (#6) ● Welbourne, et al. (2009) (#7) ● Ganti, Ye and Lei (2011) (#8) ● Zorzi, et al. (2010) (#11) ● Bandyopadhyay and Sen (2011) (#12) ● Shelby (2010) (#13) ● Roman, Najera and Lopez (2011) (#17) ● Jara, Zamora and Skarmeta (2011) (#18) ● Perera, et al. (2014a) (#19) ● Domingo (2012) (#20) ● Oliveira, Sousa, and Rodrigues (2011) (#21) ● Atzori, et al. (2012) (#23) ● Roman, et al. (2011) (#26)	17.501	25.737	25.737

	● Atzori, Iera and Morabito (2011) (#27) ● Gluhak, et al. (2011) (#28) ● Zuehlke (2010) (#29) ● Bormann, Castellani and Shelby (2012) (#38) ● Watteyne, et al. (2012) (#39) ● Tozlu, et al. (2012) (#40) ● López, et al. (2012) (#41) ● Perera, et al. (2014b) (#45) ● Barnaghi, et al. (2012) (#46) ● Kelly, Suryadevara and Mukhopadhyay (2013) (#48) ● Palattella, et al. (2013) (#50) ● Jara, Zamora and Skarmeta (2012) (#54) ● Gama, Touseau and Donsez (2012) (#55) ● Ma (2011) (#56) ● Feki, et al. (2013) (#64)			
2. Current situation of IoT in different applications (11 results)	● Xu (2011) (#10) ● Li, Xu and Wang (2013) (#14) ● He and Xu (2014) (#22) ● Zhang, et al. (2014) (#32) ● Xu, He and Li (2014) (#36) ● Vlacheas, et al. (2013) (#49) ● Bi, Xu and Wang (2014)	9.092	13.370	39.107

	(#58) ● He, Yan and Xu (2014) (#59) ● Guo, et al. (2013) (#63) ● Zhang, et al. (2012) (#66) ● Cooper and James (2009) (#68)			
3. Interactions of IoT (7 results)	● Kranz, Holleis and Schmidt (2010) (#24) ● Broll, et al. (2009) (#25) ● Hong, et al. (2010) (#31) ● Ning and Wang (2011) (#33) ● Li, et al. (2011) (#35) ● Iera, et al. (2010) (#61) ● Giner, et al. (2010) (#62)	7.522	11.062	50.169
4. Security issues of IoT (5 results)	● Sheng, et al. (2013) (#42) ● Roman, Zhou and Lopez (2013) (#47) ● Heer, et al. (2011) (#51) ● Yan, Zhang and Vasilakos (2014) (#57) ● Chen et al. (2011) (#67)	4.711	6.928	57.097
5. Application domains of IoT (2 results)	● Atzori, Iera and Morabito (2010) (#1) ● Estrin (2010) (#44)	3.137	4.613	61.710
6. Data management of IoT (4 results)	● Zhou and Chao (2011) (#16) ● Sarma and Girão (2009) ((#34)) ● Zhong, et al. (2013) (#37) ● Huang, et al. (2013) (#60)	3.105	4.566	66.276
7. IoT in product lifecycle	● Kiritsis (2011) (#15) ● Främling, et al. (2007)	2.487	3.657	69.933

management (2 results)	(#52)			
8. Enabling technologies of IoT (3 results)	● Chen, Mao and Liu (2014) (#30) ● Chen, Wan and Li (2012) (#53) ● Yu, et al. (2013) (#65)	2.317	3.407	73.340
9. IoT in smart cities (1 result)	● Hancke, Silva and Hancke (2013) (#43)	1.783	2.623	75.963
10. IoT in recommender systems (1 result)	● Bobadilla, et al. (2013) (#9)	1.464	2.153	78.115

2.3.2 Hierarchical Cluster Analysis (HCA) and Multidimensional Scaling (MDS)

In this study, HCA and MDS were adopted to graphically classify the obtained papers into groups. Figure 2.3 is the Dendrogram obtained from the result of HCA with Ward's method. Figure 2.4 is the result of MDS, where the horizontal axis represents the chronological development of IoT ranging from visions and frameworks to advanced applications (from right to left along the x-axis), and the vertical axis represents domains of IoT ranging from infrastructural domain to serviceable and analytical domain (from top to bottom along the y-axis). As a result, the papers were analysed and classified into six groups. The papers in each group of the results of HCA and MDS are equivalent except the classification of paper 61, “The Internet of Things” (Iera et al., 2010). The details of the results are described in the following.

(i) Group 1 (frameworks and challenges of IoT) included an IoT generic framework (Gubbi et al., 2013), extended frameworks integrating with social networks (Atzori, Iera and Morabito, 2011; Atzori et al., 2012) and IoT application frameworks specialized for diabetes therapy management (Jara Zamora and Skarmeta, 2011), product life management (Kiritsis, 2011), people with disabilities (Domingo, 2012), home environment monitoring (Kelly, Suryadevara and Mukhopadhyay, 2013), and smart cities (Vlacheas et al., 2013). The group also comprised IoT elements including smart objects (Kortuem et al., 2010; López et al., 2012; Tozlu et al., 2012); testbeds (Gluhak et al., 2011) and context aware computing (Perera et al., 2014a); IoT network communication including network architecture (Gershenfelo, Krikorian and Cohen, 2004); IPv6 for IoT (Oliveira, Krikorian and Cohen, 2011; Jara, Zamora and Skarmeta, 2012); communication protocol (Bormann, Castellani and Shelby, 2012; Palattella et al., 2013); service-oriented approach (Guinard et al., 2010; Shelby, 2010; Gama, Touseau and Donsez, 2012; Perera et al., 2014a); IoT data management (Welbourne et al., 2009; Barnaghi et al., 2012);

research and technology challenges (Zorzi et al., 2010; Bandyopadhyay and Sen, 2011; Ma, 2011; Miorandi et al., 2012; Feki et al., 2013); IoT security requirements and challenges (Roman et al., 2011; Roman, Najera and Lopez 2011; Roman, Zhou and Lopez 2013).

(ii) Group 2 (interactions of IoT) included IoT-enabled Human-Computer Interaction (HCI) approaches (Kranz, Holleis and Schmidt 2010); physical mobile interaction (PMI) and multi-tag interaction (MTI) approaches with IoT for design of the physical user interface (Broll et al., 2009); an IP-based WSN protocol named SNAIL for smart things' interactions in the network of IoT (Hong et al., 2010); architectural models for interactions between IoT and the physical world (Ning and Wang, 2011; Li et al., 2011); smart workflows utilizing mobile and labelling technologies for reducing the gap between the cyber and physical world (Giner et al., 2010); virtual identities management for future Internet embedded with IoT (Sarma and Girão, 2009).

(iii) Group 3 (M2M communication and IoT security) included architectures, standards and application domains of M2M communication (Chen, Wan and Li, 2012; Zuehlke, 2010; Ganti, Ye and Lei, 2011); an open-source communication protocol for WSNs (Watteyne et al., 2012); security challenges in IoT using standard Internet protocols (IP) (Heer et al., 2011); a trust management approach based on fuzzy reputation for IoT (Chen et al., 2011); a multimedia traffic security framework for multimedia services in IoT (Zhou and Chao, 2011).

(iv) Group 4 (ICT development directions driven by IoT) included big data management and analytics for IoT (Chen, Mao and Liu, 2014); cloud-based vehicular networks for resources sharing among vehicles (Yu et al., 2013); the significance of IoT development for smart city development and the co-related technical and non-technical challenges (Hancke, Silva and Hancke, 2013); recommender systems based on the information from IoT and other sources for providing predictions and recommendations (Bobadilla et al., 2013).

(v) Group 5 (practical considerations for IoT implementation) included some open issues of IoT such as standardization, addressing and networking, security and privacy, scalability, heterogeneity, mobility, energy efficiency, efficiency for system integration and development (Atzori, Iera and Morabito, 2010; Iera et al., 2010); challenges and opportunities of the Internet Engineering Task Force (IETF) communication protocol suite for IoT (Sheng et al., 2013); trust management approaches for IoT (Yan, Zhang and Vasilakos, 2014); participatory-sensing applications for aspects of safety, sustainability, personal and public health (Estrin, 2010); data management and exchange on a cloud manufacturing service platform (Huang et al. 2013); a data cycle system constructed based on IoT for managing data from social, physical, and cyber worlds (Zhong et al., 2013); requirements of unique identifiers for product lifecycle information management (Främling et al., 2007).

(vi) Group 6 (current situation of IoT in different applications) included the current development status of IoT in supply chain management (Xu, 2011), distributed systems integration (He and Xu, 2014), modern manufacturing (Bi, Xu and Wang, 2014) and various industrial applications (Xu, He and Li, 2014); a compressed sensing-based data acquisition approach for resource-restricted devices of IoT (Li, Xu and Wang, 2013); a cloud manufacturing paradigm leveraging IoT for advanced manufacturing in the near future (Zhang et al., 2014); a vehicular data cloud platform integrated with IoT (He, Yan and Xu, 2014); an opportunistic IoT for connecting human and smart things (Guo et al., 2013); a topological construction approach based on weighted networks and local-world theory for improving and enhancing the topology of WSNs of IoT (Zhang et al., 2012); a summary and analysis of database issues of IoT and a roadmap of technological approaches for handling such issues (Cooper and James, 2009).

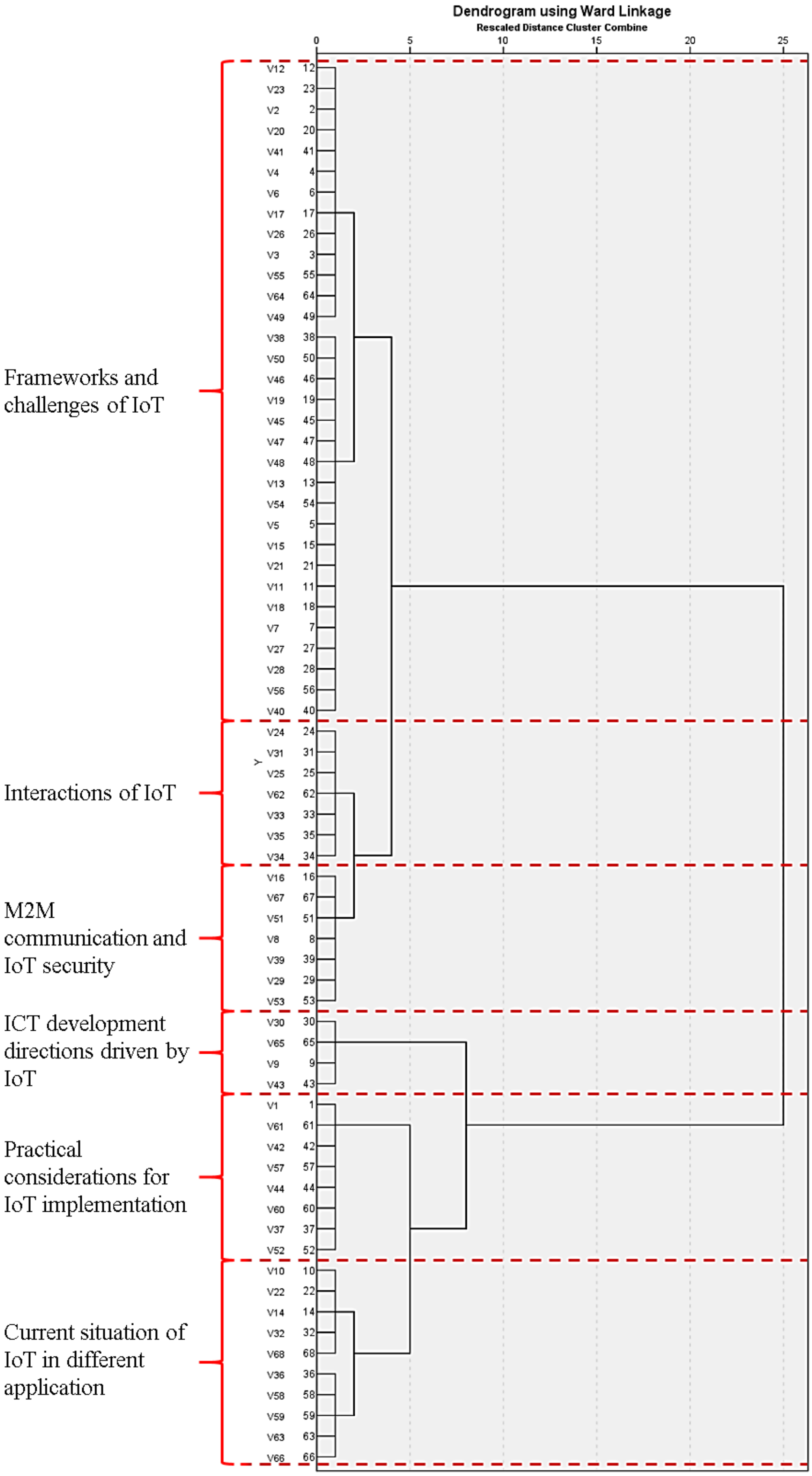


Figure 2.3 The result of hierarchical cluster analysis

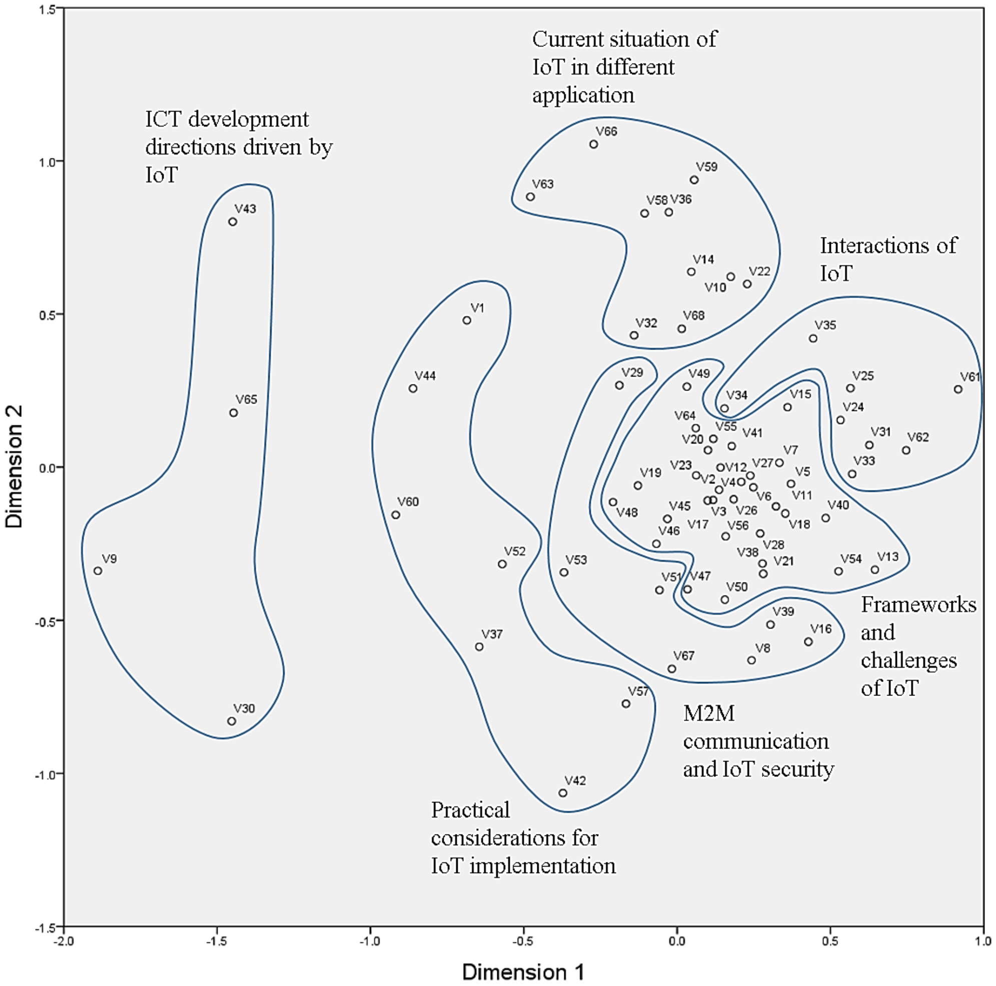


Figure 2.4 The result of multidimensional scaling analysis

2.3.3 Discussion

In this research, 68 highly cited (i.e. high-value) papers were identified from 1,457 IoT-related papers obtained from Web of Science. By using these high-value papers, ten factors were obtained from factor analysis and six groups were classified after conducting HCA and MDS. Comparing the results of HCA and MDS and the results of factor analysis, it was found that the six groups could be mapped to the ten factors. Figure 2.5 illustrates this mapping. Group 1 covers the same aspects of factor 1, and Group 2 covers the same aspects of factor 3. Group 3 covers some aspects of factor 1 about IoT communication and the aspects of factor 4 about security issues of IoT. Group 4 covers the aspects of factors 8, 9 and 10, which discussed some main development directions of ICT driven by IoT. These development directions of ICT include big data technologies, pervasive cloud computing and its derived topics such as fog computing and edge intelligence, advanced recommender systems and advanced applications in smart cities. Group 5 covers the aspects of factors 4, 5, 6 and 7, which concern practical considerations such as security and trust management, communication protocols and data management for implementing IoT in different application domains such as product lifecycle information management, transportation and logistics, health-care and environmental monitoring. Lastly, Group 6 covers the same aspects of factor 2. This mapping indicates that the two sets of results from section 2.31 and 2.32 identify the same intellectual components of IoT.

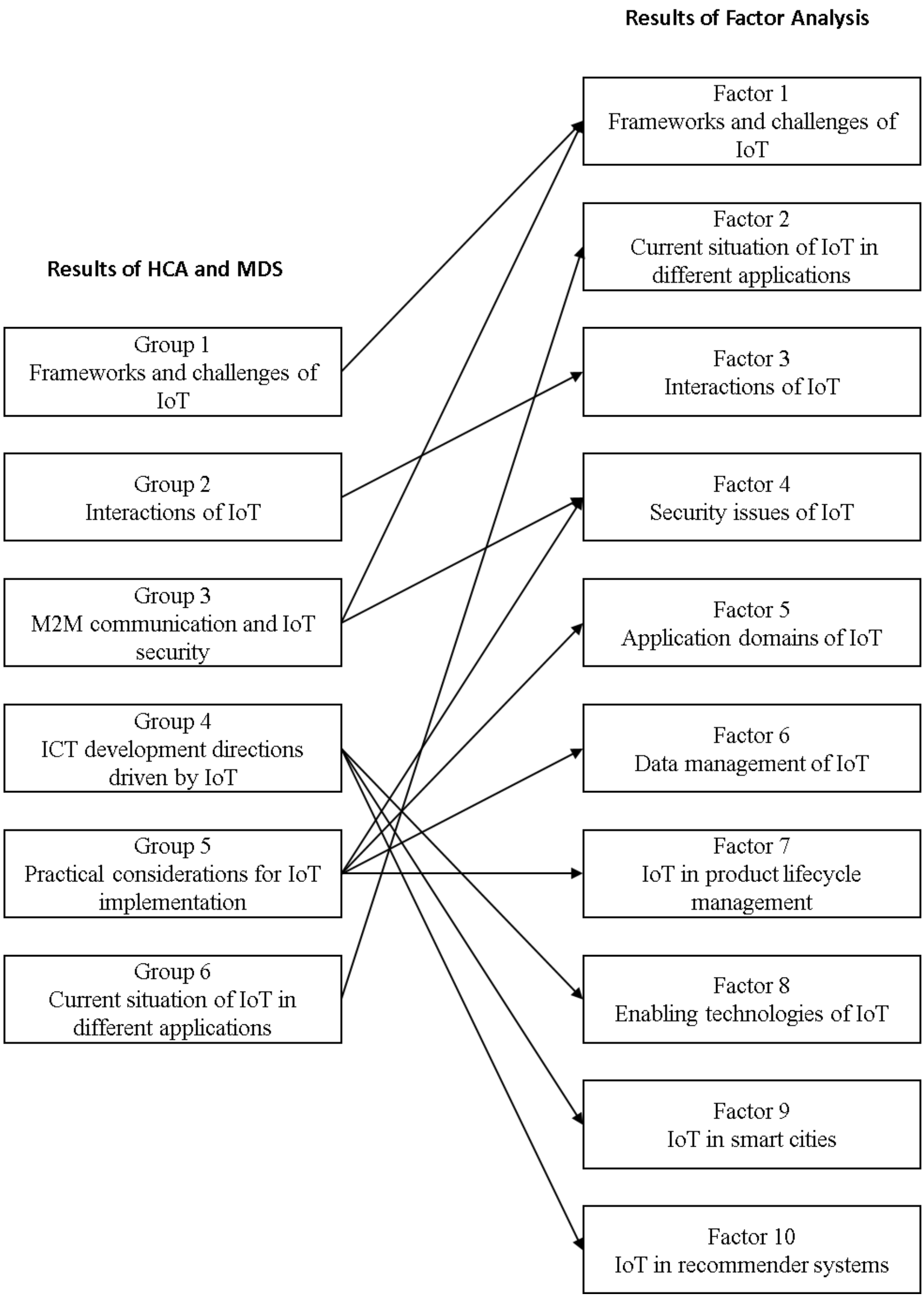


Figure 2.5 Mapping between results of HCA and MDS and results of factor analysis

In the results of sematic similarity analysis, RFID and WSN were identified as two key fundamental enabling technologies of IoT. Leveraging these two technologies, IoT is acknowledged as having great potentialities to be applied in different application domains. In the domains related to this research, there are many suggested applications proposed in the literature. For example, in transportation and logistics domains, applications include real-time monitoring and information collection in every link of the supply chain, environmental monitoring for perishable products, assisted driving, augmented maps and mobile ticketing reaction. In the healthcare domain, applications include real-time human position and motion tracking, real-time asset and materials tracking, identification and authentication of human and asset usage, real-time sensing in both in-patient and out-patient care, and automatic data collection and transfer. In the smart environment domain, applications include smart home, smart industry, smart museum and smart gym (Atzori, Iera and Morabito 2010). Among these applications, some have a smaller scale, some have a similar scale and some have a larger scale when compared with this research, but RFID and WSN undoubtedly function as two necessary and important components throughout all these applications. This provides a strong justification for the rationale and appropriateness of the adoption of RFID and WSN in this research. More specifically, designing the WSN was the core part of this research as the major functionalities of the proposed monitoring system for B&P products mostly rely on the sensor technologies. Thus, a review of designing WSNs will be presented in the following sections.

2.4 Overview of Wireless Sensor Network (WSN)

WSN refers to a collection of sensor nodes with the capability of wireless communication. These sensor nodes are generally small in size and low in price, have limited computational power and memory, and are equipped with a restricted power source, the most common form of which is a battery. In typical usage, sensor nodes are distributed over a target region and form a WSN. Each sensor node collects the physical or environmental information of the surroundings, such as temperature, humidity, light intensity and vibration, etc. The information is sent to a base station (BS), also called a sink, which is a central information aggregation node. Through the BS, a backend system stores the gathered information and performs further analysis and processing. Figure 2.6 shows an example of a WSN with two sensor fields.

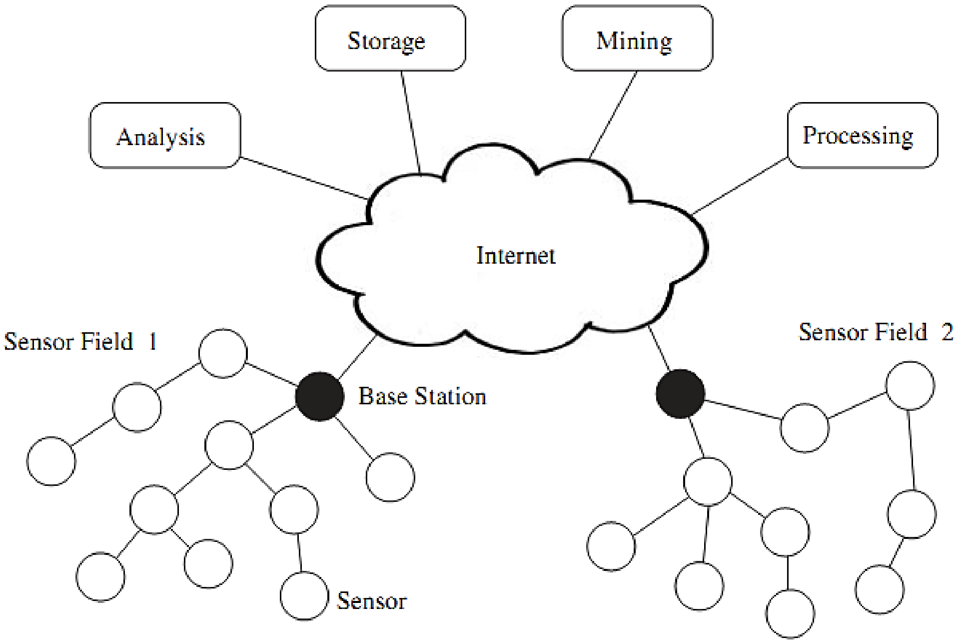


Figure 2.6 A WSN with two sensor fields (Dargie and Poellabauer, 2010)

A sensor node consists of an individual processing unit and memory, the sensor node is capable of performing self-organization and configuration, data fusion, storage, preliminary analysis and in-network correlation. The term of self-configuration means a node is able to configure the operation parameters, e.g. report rate, role, sleep time and address, by itself automatically, which avoid manual configuration one by one. Self-organization means the nodes in WSN can form a network automatically, instead of manually. As the processing power of the sensor node is limited, the data analysis is simple and at a low level; examples include filtering signal noise and invalid readings. The embedded processing power and memory also allow the sensor to be connected to a sensor node in the same WSN; it is not only limited to a single type, but also different types, and even multiple types. Moreover, the number of sensor nodes in a WSN is not restricted. When the monitoring area is large, hundreds, thousands and even more sensor nodes can be deployed on the site and form the WSN. As a result, the characteristics of WSN help to develop a wide range of applications in different areas. The applications can be classified into five main categories, which include military, environment, health, home, and industry (Akyildiz and Vuran, 2010). Table 2.5 summarizes some applications in these categories.

Table 2.5 Examples of WSN application

Category	Application
Military	Battlefield monitoring Sniper detection Object protection
Environment	Volcano monitoring Flood detection Wild-life monitoring
Health	Patient monitoring Artificial retina Emergency response
Home	Smart home Water monitoring
Industry	Preventive maintenance Structural health monitoring Automatic meter reading

While WSN have the capability to be applied in many different areas, the design of a WSN is always a challenging task. Apart from the requirement of substantial knowledge of different research areas, which include microelectronicmechanical systems (MEMS), wireless communication and networking, signal processing and software engineering, various design factors need to be considered when starting to design a WSN. Some factors are application-specific, which vary from application to application. Some factors are crucial, which influence the design of a WSN significantly and are common in most of the applications. In this chapter, several important factors are discussed including production cost, energy efficiency, topology and QoS.

2.5 Production Cost

As mentioned above, a WSN may contain hundreds, thousands and even more sensor nodes and other function nodes such as relay nodes, so the changing of the unit cost of a node will significantly affect the total production cost of a WSN. When considering minimizing the total production cost, the objective can be changed to minimizing the number of nodes deployed in the monitoring area. Being one of the basic objectives when designing a WSN and closely related to almost all the factors mentioned in this chapter, considering the number of nodes in a WSN becomes a constant criterion when dealing with various WSN problems.

2.6 Energy Efficiency

The sensor nodes in a WSN are mainly powered by batteries with limited capacity. The exhausted batteries of some sensor nodes not only cause information loss of some parts of the monitoring area, but also cause operation disorder of the whole network and can even cause network collapse. Generally, a battery-powered sensor node cannot survive for more than one week if the node always remains active. Moreover, it is difficult or impossible to recharge or replace the batteries in most of the situations because of the harsh physical environment and the high maintenance cost (Anastasi, Conti and Francesco, 2009). However, in many applications, the life-time of a WSN is required to be months and even years. All of these cause researchers and practitioners to take energy efficiency into account as the primary consideration when designing a WSN.

The power consumption sources of a sensor node come from three main parts, where sensors consume energy for sensing, the processing unit consumes energy for data processing and the radio communication module consumes energy for communication. In a WSN application, the used sensors and the tasks required to be processed are normally predetermined and the energy consumption is approximately constant. In contrast, the radio communication module consumes the largest amount of energy of the three parts. It consumes almost the same power during transmitting data, receiving data and even remaining idle (Akyildiz and Vuran, 2010). Consequently, minimizing the energy consumption for communication becomes the focus of energy efficiency optimization in a WSN.

In the last decade, researchers developed plenty of approaches to improve the energy efficiency of WSNs. The approaches can be classified into three types, which are duty cycling, data-driven approaches and mobility (Anastasi et al., 2009).

(i) Duty cycling

Duty cycling refers to switching the sensor node between active and sleep mode to conserve energy. Since the power consumption of the sensor node in sleep mode is significantly less than in active mode, the duty cycling approaches, in which the sensor nodes wake up when transmitting and receiving data and sleep in idle periods, are believed to be the most effective way to conserve energy in WSN (Anastasi, Conti and Francesco, 2009; Anastasi et al., 2009; Pantazis et al., 2009). Duty cycling approaches can be sub-divided into several groups and sub-groups. Figure 2.7 shows the taxonomy of duty cycling approaches. Topology control is the method to determine the role of each node, where a number of nodes are set to active mode to maintain the necessary network connectivity and the remainder are set to sleep mode. On the other hand, power management involves the design of sleep/wakeup scheduling directly on the media access control (MAC) layer or on the higher layers such as network and application layer.

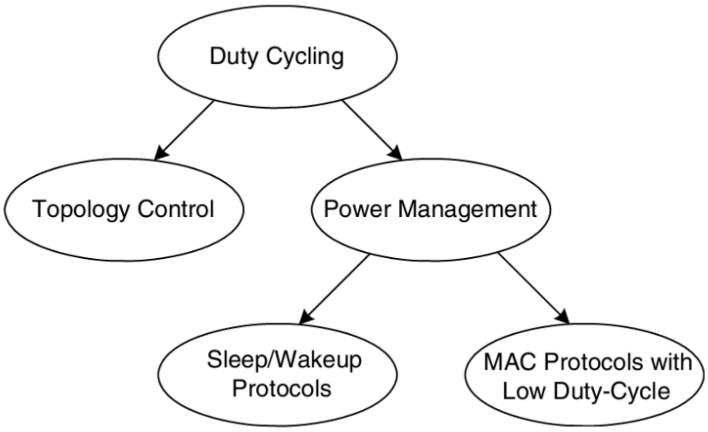


Figure 2.7 Taxonomy of duty cycling approaches (Anastasi et al., 2009)

(ii) Data-driven approaches

The main ideas of data-driven approaches can be classified into two main groups as Figure 2.8 shows, namely data reduction and energy-efficient data acquisition. While energy-efficient data acquisition approaches focus on reducing the power consumption of the sensor, data reduction approaches focus on reducing the unnecessary data samples and thereby ease the communication load of the sensor node. To achieve this purpose, three approaches arise. First, the sensor nodes are set to perform in-network processing such as data aggregation and preliminary calculations, and send the processed data instead of raw data to the sink. Second, the sensor nodes compress the raw data by using low-weight data compression techniques. Lastly, data prediction techniques are used to reduce the frequency of data reporting from the sensor nodes to the sink.

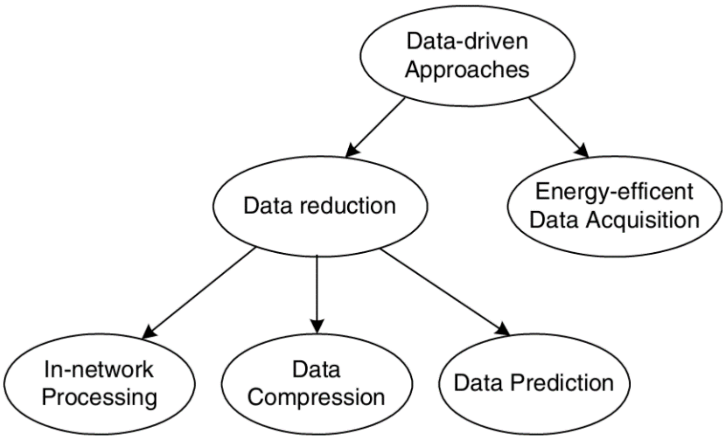


Figure 2.8 Taxonomy of data-driven approaches (Anastasi et al., 2009)

(iii) Mobility

The mobility approaches normally involve adding mobility to the sink or relay to shorten the distance between the transmitter and receiver since the power consumption of communication is proportional to the distance as Figure 2.9 shows. Furthermore, based on the topology design, some paths from the data source to the sink may bear a heavier load. Changing the position of the sink may change the selection of heavy-load path, and consequently help to consume power in a WSN uniformly. However, mobility approaches have some drawbacks. Apart from the additional cost of mobile elements, the WSN designer should pay more attention to estimating the motion behaviours of the mobile sink or relay. It also implies that the designer should handle dynamic topology change.

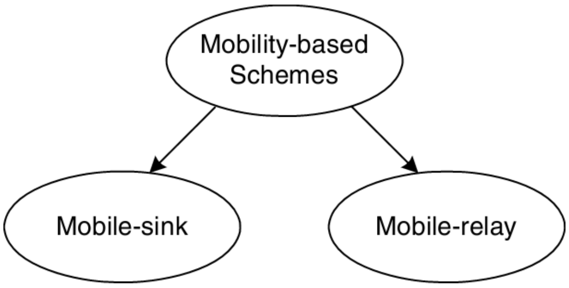


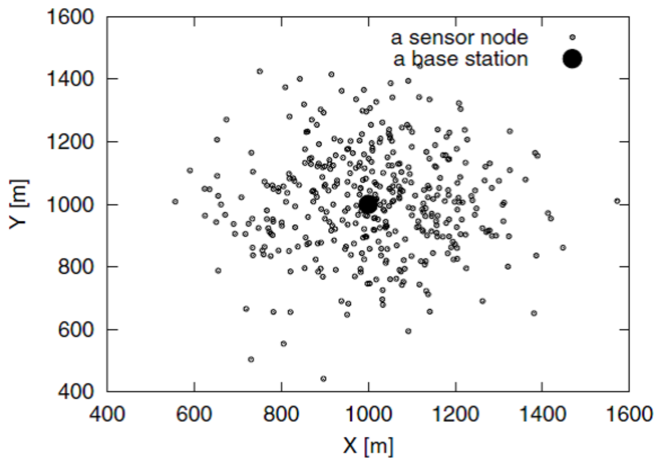
Figure 2.9 Taxonomy of mobility-based approaches (Anastasi et al., 2009)

2.7 Topology

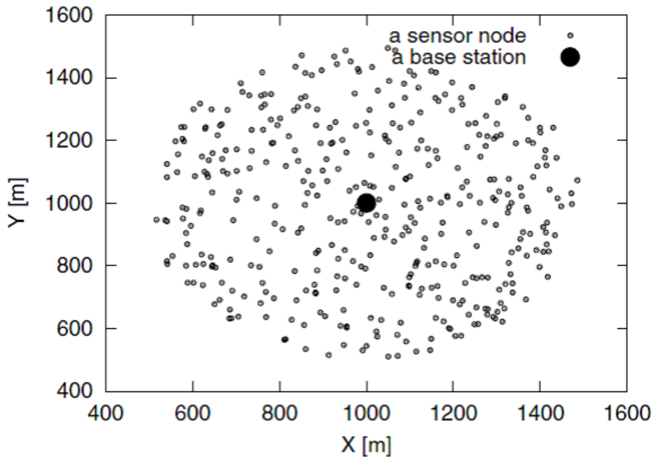
Topology in a network plays an important role to determine the location of nodes in the network and the links between the nodes which allow direct communications. In a WSN, topology also determines the active states of nodes to fulfil certain requirements, for example, conversing network energy, avoiding collisions and increasing network capacity (Labrador et al., 2009). Among the topology management solutions, node placement is always the first consideration since it is crucial to determine the nodes' locations and states.

2.7.1 Node Placement

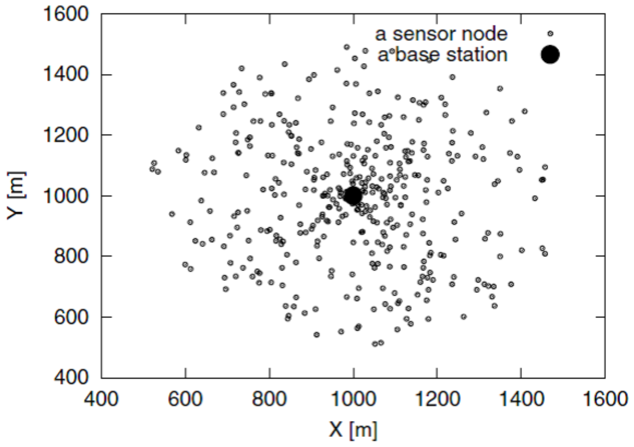
Node placement not only affects the network topology of a WSN, but also affects network performance metrics such as energy efficiency, coverage, delay and throughput. Node placement strategies can be classified into two categories based on the node deployment methodology. Deterministic node placement is used when the nodes are expensive, monitoring in specific locations is required, the nodes' performance is highly affected by the deployment location and some specific requirements such as sensing coverage and fault tolerance need to be fulfilled. However, in some situations such as where the deployment environment is hazardous and the deployment area is enormous, deterministic node placement becomes risky, costly and even infeasible and random node placement is the only option for the deployment (Younis and Akkaya, 2008). In Figure 2.10, three typical random node placement methods are introduced. Simple diffusion is the simplest method which just spreads the sensor nodes from air to the monitoring area. Constant placement and R-random placement are uniform distribution methods for sensor node placement. R-random placement will also consider the radius and the angular direction from the base station (Ishizuka and Aida, 2004).



a) Simple diffusion



(b) Constant placement



(c) R-random placement

Figure 2.10 Examples of random node placement (Ishizuka and Aida, 2004)

2.7.2 Relay Node Placement

In large-scale WSNs such as the WSN for forest monitoring, the distances between some sensor nodes and the sink are large. It is costly or infeasible to transmit data in a single hop. This results in the placement of relay nodes to route the data from remote sensor nodes to the sink. Besides data routing, relay nodes make contributions to many aspects of a WSN such as data aggregation, efficient transmission, network expansion, energy conservation and fault tolerance (Vallimayil et al., 2011). Relay nodes in a WSN can be some existing or additional sensor nodes with the same capabilities as the existing nodes and this type of WSN is called a homogenous WSN. The relay nodes can also be some additional nodes with or without sensing ability and have a larger communication and/or sensing range and larger power source. This type of WSN is called a heterogeneous WSN (Zheng and Jamalipour, 2009). As relay nodes will form the communication backbone of a WSN, relay node placement is a critical factor to be considered. In relay node placement strategies, some strategies work on the flat network architecture where every node in the network performs the same tasks. When communication is required, the sink sends requests to the target sensor node through the flooding forward method, and the target node responds through a multi-hop manner where the transmitting node find its neighbouring nodes as relays to route the message. In some other strategies, two-tiered network architecture is applied. Sensor nodes are divided into clusters and a cluster head is elected in each cluster to gather data from its cluster members and route the data to the sink as a relay. The cluster head will be reassigned in a fixed period to balance the power consumption of each node. In other approaches using two-tiered architecture, additional relay nodes work with the sink to composite the upper tier while the lower tier is composited by sensor nodes (Hou et al., 2005). As Figure 2.11 shows, sensor nodes are clustered into groups and each group attaches to a relay node to form the network.

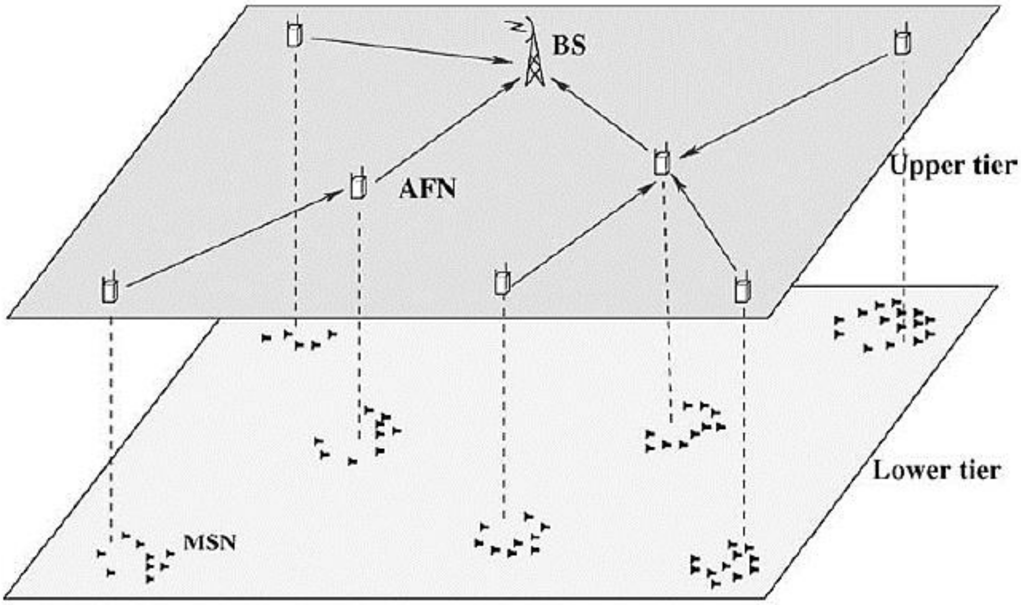


Figure 2.11 Hierarchical view of a two-tiered WSN (Hou et al., 2005)

2.8 Quality of Service (QoS)

QoS refers to a measure of service quality based on the requirements of users or applications. In a WSN, QoS is important to deal with and it may be a series of performance metrics such as coverage, connectivity, reliability, fault tolerance, data delay and data accuracy. However, QoS requirements vary from application to application. It is difficult to apply one pattern of QoS requirements to all WSN applications (Chen and Varshney, 2004). In this section, some key QoS requirements which can be applied to most WSN applications are discussed.

2.8.1 Sensing Coverage and Network Connectivity

Sensing coverage and network connectivity are two factors always considered together when designing a WSN since coverage ensures the data collection from the region of interest while connectivity ensures the path of data reporting from sensor nodes to the sink (Ammari, 2009; Lin et al., 2012). If one of them is ignored, the WSN cannot be considered as a satisfactory solution. Some research works reveal the relationship between these two factors, where a WSN is connected and provides certain coverage if the communication radius of sensor nodes is double their sensing radius (Ammari and Das, 2010). Currently, sensing coverage models are used to measure the coverage quality. In most of the common models, the

Euclidean distances and the angles between a point in the monitoring area and sensor nodes will be the inputs, while the output will be a nonnegative real number which is called the coverage measure. For example, if there are a point ***z*** and a set of sensor nodes $\boldsymbol{S} = \{\boldsymbol{s_1}, \boldsymbol{s_2}, \ldots, \boldsymbol{s_n}\}$, then the Euclidean distance $\boldsymbol{d}(\boldsymbol{s}, \boldsymbol{z})$ will be:

$$d(s,z) = \sqrt{(s_x - z_x)^2 + (s_y - z_y)^2} \tag{2.1}$$

where $(\boldsymbol{s_x}, \boldsymbol{s_y})$ and $(\boldsymbol{z_x}, \boldsymbol{z_y})$ are the Cartesian coordinates of the point ***z*** and a sensor node ***s*** and $\boldsymbol{d}(\boldsymbol{s}, \boldsymbol{z}) >= \boldsymbol{0}$. The angle $\boldsymbol{\Phi}(\boldsymbol{s}, \boldsymbol{z})$ will be the anticlockwise angle from the horizontal line where $\boldsymbol{0 <= \Phi(s, z) < 2\pi}$. Finally, a sensor coverage model can be formulated as:

$$f\colon (d_n, \Phi_n) \longrightarrow R^+ \tag{2.2}$$

where $\boldsymbol{d_n = (d(s_1, z), d(s_2, z), \ldots, d(s_n, z)), \Phi_n = (\Phi(s_1, z), \Phi(s_2, z), \ldots, \Phi(s_n, z))}$, $\boldsymbol{f(d_n, \Phi_n)}$ is a coverage function mapping $(\boldsymbol{d_n, \Phi_n})$ to a nonnegative real number and $\boldsymbol{R^+}$ is the set of nonnegative real numbers (Wang, 2010). When working on the sensing coverage, two concepts about coverage and connectivity are introduced. *k*-coverage is defined as each point in the monitoring area which is covered by at least *k* sensor nodes where $k \geq 1$, and *k*-connectivity is defined as every pair of sensor nodes connected by at least *k* disjoint paths. These two concepts are not only applied in coverage and connectivity problems, but are also applied in providing fault tolerance for a WSN.

2.8.2 Fault Tolerance

Fault tolerance is another important QoS of a WSN. Since many WSNs are deployed in outdoor areas, some of them are even in harsh environments such as volcanos, underground and under-water, so node failures like energy drain, node damage and connection break are inevitable. The node failures usually cause serious consequences for a WSN such as function disorder, network partition and network collapse. In general, two strategies are commonly used for fault tolerance of a WSN. The first one is to place additional sensor nodes in a WSN at the beginning of deployment. These additional nodes are normally set to sleep mode. When a node failure is detected, one of the additional neighbouring nodes will wake up and take over the sensing area of the failed node. However, this strategy is costly, especially for large-scale WSNs (Vaidya and Younis, 2010). Considering this issue, some research works proposed *k*-connectivity approaches to optimize the number of additional sensor nodes, where a *k*-connected WSN is able to tolerate *k*-1 fail nodes. For example, an approach called full fault-tolerant relay node placement (FFRP) is proposed to maintain *k* vertex-disjoint paths between every pair of sensor nodes and/or relay nodes through deploying a minimum of relay nodes (Bredin et al., 2005). Another approach called partial fault-tolerant relay node placement (PFRP) only ensures *k* edge or vertex-disjoint paths between every pair of sensor nodes (Kashyap, Khuller and Shayman, 2006). The second strategy for fault tolerance of a WSN is to reconfigure the network connectivity and recover any lost coverage due to node failures. This approach requires no additional sensor nodes or relay nodes, but the process may be very complex and arduous since relocation of a series and even all the sensor nodes in the WSN is usually required (Vaidya and Younis, 2010).

2.9 Optimization of Trade-offs between Basic Design Factors

After reviewing the nature of some basic design factors, the optimization method for these design factors in the literature will be presented in this section. As mentioned before, keeping a good balance of the trade-offs of basic design factors is critical when designing a WSN system, so researchers have utilized different approaches to deal with these factors. Heinzelman, Chandrakasan and Balakrishnan (2000) proposed a clustering-based routing protocol called Low-Energy Adaptive Clustering Hierarchy (LEACH) to minimize energy consumption in the network. This protocol utilizes random rotating cluster head assignment among all the nodes to distribute the load to all the nodes at different points in time, and consequently extend the network life. In this approach, only energy efficiency is considered. By considering cost and sensing coverage, Chakrabarty et al. (2002) utilized Integer Linear Programming (ILP) and alternative divide-and-conquer approaches to obtain the minimum cost of sensor nodes for a complete covered region. Similarly considering a fully covered region, some researchers have revealed the relationship between the sensing coverage and the network connectivity when the communication range is at least twice the sensing range, and complete coverage of a convex area implies connectivity among the nodes (Wang et al., 2003; Zhang and Hou, 2005). On top of this finding, Ammari and Das (2006) prove that the network connectivity of a k-covered area is higher than k by using the proposed Augmented Equilateral Triangle (AET) model. Apart from considering sensing coverage and network connectivity, other researchers, Huang, Tseng and Wu (2007), proposed a distributed protocol which is able to determine the levels of coverage and connectivity, and also has the capability to reduce power consumption via putting some sensors into sleep mode and reducing some sensors' transmission power. Regarding the method of putting some sensors into sleep mode, Jia et al. (2009) proposed a coverage control scheme based on the multi-objective genetic algorithm (GA) to select the minimum number of sensor nodes from a WSN that can preserve full coverage being activated, and put other sensor nodes into sleep mode. For the same purpose, Zeng et al. (2010) proposed a framework that takes dynamically periodic reconstruction strategies to select a subset of nodes for communication and sensing tasks only when the residual energy of the network drops to a threshold. Another design factor the researcher wished to consider was fault tolerance. Both Pu, Xiong and Lu (2009) and Bredin et al. (2010) proposed algorithms to add additional nodes into an existing WSN to improve the *k*-connectivity, where Pu, Xiong and Lu's (2009) algorithm results in a *k*-connected or partially *k*-connected network while Bredin et al.'s (2010) algorithm results in a *k*-connected network, for any desired *k*.

When the optimization takes more design factors into account, the multi-objective optimization approach is introduced. Ferentinos and Tsiligiridis (2007) proposed an algorithm for the optimal design of WSNs in precision agriculture based on the Genetic Algorithm (GA). In this approach, energy efficiency, sensing coverage, network connectivity and an application-specific design factor (i.e. deployment uniformity) are the objectives needed to be optimized while considering grid deployment and different node operating modes. Likewise, Chaudhry et al. (2011) proposed an algorithm called flexible algorithm for sensor placement (FLEX) to optimize the placement of sensor nodes by using the multi-objective GA. This algorithm aims to maximize coverage and the desired *k*-connectivity and minimize energy cost simultaneously. Table 2.6 summarizes the addressed design factors in the literature mentioned in this section.

Table 2.6 Summary of addressed design factors in the literature

Journal Papers	Addressed Factors	Approach
Heinzelman, Chandrakasan and Balakrishnan (2000)	● Energy Efficiency	Low-Energy Adaptive Clustering Hierarchy (LEACH)
Chakrabarty et al. (2002)	● Cost ● Sensing Coverage	Integer Linear Programming (ILP)
Wang et al. (2003)	● Sensing Coverage ● Network Connectivity	Coverage Configuration Protocol (CCP)
Zhang and Hou (2005)	● Sensing Coverage ● Network Connectivity	Optimal Geographical Density Control (OGDC)
Ammari and Das (2006)	Sensing Coverage Network Connectivity	Augmented Equilateral Triangle (AET) model
Ferentinos and Tsiligiridis (2007)	● Energy Efficiency ● Sensing Coverage ● Network Connectivity ● Deployment Uniformity (application-specific)	GA
Huang, Tseng and Wu (2007)	● Energy Efficiency ● Sensing Coverage ● Network Connectivity	Distributed coverage and connectivity protocols

Jia et al. (2009)	● Energy Efficiency ● Sensing Coverage	Multi-objective GA
Pu, Xiong and Lu (2009)	● Network Connectivity ● Fault Tolerance	Generic partial k-connectivity repair algorithm
Bredin et al. (2010)	● Network Connectivity ● Fault Tolerance	Distributed *k*-connectivity repair algorithm
Zeng et al. (2010)	● Energy Efficiency ● Sensing Coverage ● Network Connectivity	Efficient distributed approximation algorithm (ECDS), Energy conservation node self-scheduling algorithm (ECSS)
Chaudhry et al. (2011)	● Energy Efficiency ● Sensing Coverage ● Network Connectivity ● Fault Tolerance	Multi-objective GA

2.10 Meta-heuristic approaches for WSN Deployment

As mentioned before, designing a WSN for deployment in a region of interest can be complex, since the trade-offs between various design factors should be considered. Therefore, most of the WSN deployment problems cannot be solved within a reasonable computing time by using limited computation resources, in which these problems are NP-Hard problems. Traditional deployment approaches, such as polygon deployment algorithms, random deployment algorithms and greedy deployment algorithms, cannot provide better solutions than meta-heuristic methods. The reasons behind this include: (1) Most of these algorithms only consider a single design factor or equal weighting design factors; (2) Most of these algorithms are easily trapped in local optima at a very early stage; and (3) Most of these algorithms are computationally expensive because of the NP-hard deployment problems. Considering these dilemmas of traditional approaches, many studies started applying metaheuristic approaches as alternative solutions for deployment problems, especially for large-scale problems, because of the higher performance of the metaheuristic approaches. This has become one of the research trends of WSNs in recent years (Tsai et al., 2015). Table 2.7 summarizes some meta-heuristic approaches for WSN deployment. These approaches include: Tabu Search (TS), Simulated Annealing (SA), GA, Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) and Artificial Bee Colony (ABC).

Table 2.7 Summary of some meta-heuristics for WSN deployment

Journal Papers	Approach	Space
Wang and Ma (2007)	PSO	2-D
Aitsaadi et al. (2008)	TS	2-D
Kalayci and Uğur (2011)	GA	2-D
Ozturk et al. (2011)	ABC	2-D
Xhafa et al. (2011)	SA	2-D
Liu and He (2014)	ACO	2-D

2.11 Summary

In this chapter, the intellectual components of IoT were examined by using semantic similarity analysis. These components include: (1) frameworks and challenges of IoT; (2) current situation of IoT in different applications; (3) interactions of IoT; (4) security issues of IoT; (5) application domains of IoT; (6) data management of IoT; (7) IoT in product lifecycle management; (8) enabling technologies of IoT; (9) IoT in smart cities; and (10) IoT in recommender systems. These 10 factors provide good justifications for the rationale and appropriateness of the adoption of RFID and WSN in the proposed system. In the proposed system, WSN plays a crucial role for monitoring the status of B&P products. Therefore, the design and optimization of WSNs is the core part of the system development.

When designing a WSN, various factors should be considered and many of them are application-specific. In this literature review, some common and important design factors include production cost, energy efficiency, topology and quality of service (QoS), which are highly related to the life-time and service quality of a WSN and are discussed. These factors not only affect the performance of a WSN, but also affect each other. When considering the energy efficiency of a WSN, sleep/wakeup switching of sensor nodes will be the most effective method and it also results in the placement of some active relay nodes to route the data to the sink. The relay nodes are either the existing sensor nodes or additional nodes with a larger communication range and larger battery capacity. During the placement, the sensor nodes in the WSN should be divided into groups and each group of sensor nodes will be associated with a relay. Moreover, the node placement should fulfil a certain sensing coverage and network connectivity. Recently, more and more WSN researchers also take fault tolerance of the WSN into account when designing a WSN. It is a relatively new factor attracting the attention of researchers. There are two methodologies to implement the fault tolerance measure, where one is inserting additional sensor/relay nodes into the WSN and another is relocating sensor nodes to recover the original functionality. The former methodology is considered as less complex than the latter one since the later one involves changing the structure of the WSN and mobility of some sensor nodes in some situations such as in dangerous and hostile environments.

In the literature, sensing coverage is usually considered together with network connectivity. Some researchers have proven that nodes in a fully covered convex area are connected if the communication range is at least twice the sensing range. For the optimization of design factors, many of the studies reviewed in this research propose algorithms to optimize only one or two basic design factors, and the most common design factors optimized in the literature are: (a) Energy Efficiency, (b) Sensing Coverage and (c) Network Connectivity. When more design factors (e.g. three or four) are considered together, the WSN deployment problems become complicated, and most of them are NP-Hard problems. Considering these difficulties, meta-heuristic optimization techniques are suggested to be applied in regard to such WSN optimization problems. One point to be noted here is that individual consideration of the cost factor and the fault tolerance can be found in the literature, but few studies consider these two factors together. Therefore, this can be a research direction since the cost factor and fault tolerance are both critical in practical WSN design and development.

Chapter 3

RFID-enabled Wireless Sensor Network (WSN) Monitoring System

In this chapter, the conceptual system architecture will be presented and the assumptions for the WSN deployment optimization model of the proposed system will be described.

3.1 Conceptual System Architecture

The conceptual architecture of the proposed system is shown in Figure 3.1, which consists of four layers, namely Information Acquisition Layer (IAL), Network Layer (NL), Logic and Processing Layer (LPL) and Service Output Layer (SOL). In the IAL, the product state information and environmental parameters (i.e. temperature, humidity and vibration) are collected by the wireless sensor nodes which are widely spread over a large area like container, warehouse and distribution centres. The collected data are then routed to the data gathering and exchanging module (i.e. the sink of WSN) through the Wireless Personal Area Network (WPAN). After that, the data are passed to the Data Integration and Analysis Core (DIAC) in the LPL through the Internet via General Packet Radio

Service (GPRS), Wi-Fi, Worldwide Interoperability for Microwave Access (WiMAX) or other wireless technologies.

Before setting up the WSN, the user configuration such as data reporting rate and technical specification will be injected into the LPL for configuring and fine-tuning the performance of the DIAC and Wireless Sensor Network Management Module (WSNMM). In the DIAC, the data from the NL are integrated with the RFID data and further analysed for decision-making. In addition, the WSNMM is used to configure and manage the wireless sensor nodes and optimize their performance. The commands of configuration and management are passed back to the WSN control module in the NL and all wireless sensor nodes are updated.

As the WSN is deployed, the SOL is based on the decision made in the LPL to deliver service outputs including visualising the data and delivering them to users, prompting alerts when abnormal conditions occur, triggering operation of actuators and storing the collected and possessed data in the database for querying and further analysis in the future.

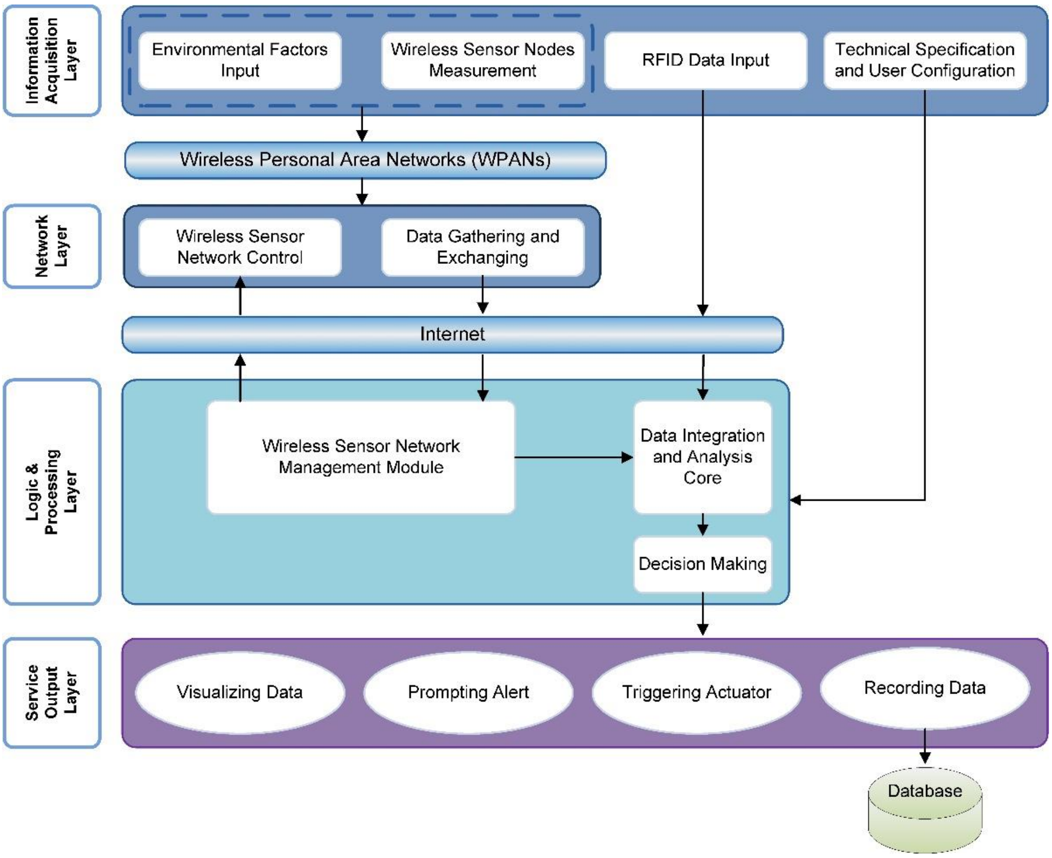


Figure 3.1 The conceptual system architecture of the proposed system

3.2 Wireless Sensor Network Deployment Optimization

In the Wireless Sensor Network Management Module, wireless sensor nodes are configured and managed. A wireless sensor network deployment optimization model is proposed to perform the tasks. The proposed model is designed under some assumptions which are listed below:

(a) The sensing model is defined as the Boolean sensing disk model:

$$c_{xy}(s_i) = \begin{cases} 1, & \text{if } d(s_i, P) < r \\ 0, & \text{otherwise} \end{cases} \tag{3.1}$$

where s_i is a sensor node, P is a point in the monitoring area, r is the sensing range of a sensor node, $d(s_i, P)$ is the Euclidean distance between the sensor node s_i and a point P, and $c_{xy}(s_i)$ is the Boolean sensing function.

(b) The communication model is defined as the Boolean communication disk model:

$$c(s_i, s_j) = \begin{cases} 1, & \text{if } d(s_i, s_j) < R \\ 0, & \text{otherwise} \end{cases} \tag{3.2}$$

where s_i, s_j are two sensor nodes, R is the communication range of a sensor node, $d(s_i, s_j)$ is the Euclidean distance between the sensor node s_i and s_j, and $c(s_i, s_j)$ is the Boolean communication function.

(c) The optimization model works under an ideal network, which is no data loss during communication.

Based on these assumptions, the preliminary settings of the proposed optimization model can be defined. The node deployment method is proposed to be grid deployment since the position of each node can be determined simply and the node density may require less than other deployment strategies such as random deployment strategies (Zhang and Hou, 2006). Figure 3.2 shows the preliminary settings of the grid deployment strategy in a 2-D region. The sensing range r is equal to the unit grid size and the communication range ***R*** is twice the sensing range, which is ***R*** = ***2r***.

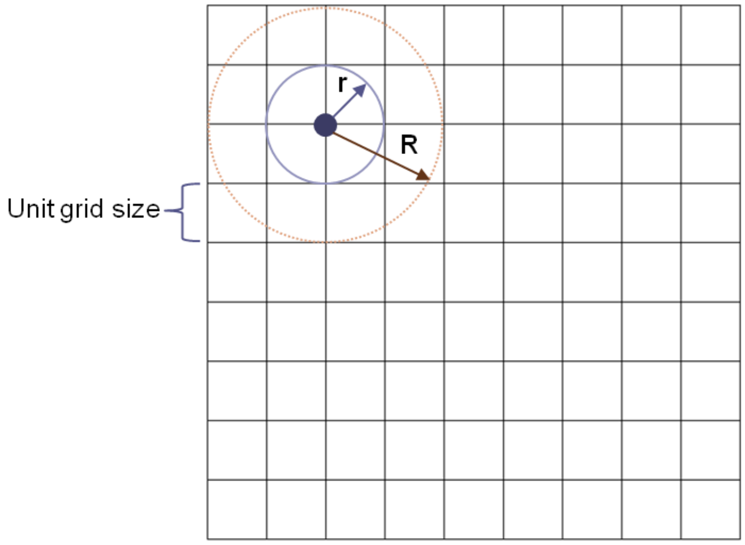


Figure 3.2 The preliminary settings of grid deployment strategy in a 2-D region

Chapter 4

Statistical approach for WSN Deployment in Biological and Pharmaceutical Product Warehouse

4.1 Introduction

Biological and pharmaceutical (B&P) products are essential in modern life. The demand and requirements of these products keep growing; product quality and integrity then become crucial. To ensure quality and integrity, establishment of a product status monitoring system is one of the most effective approaches. In this chapter, the design of a Wireless Sensor Network (WSN) monitoring system in an indoor environment for B&P product storage is studied. Based on the practices of storing B&P products, a statistical approach for the deployment of a WSN monitoring system is proposed (Wu et al., 2015a). This approach consists of three stages of the deployment process. The first-stage process is to generate a WSN for full coverage of the monitoring area in the warehouse. The second stage is to determine the optimal position of the sink, during which the overall energy consumption for the communications between relay nodes and the sink is minimized. The last process is to add additional relay nodes to provide fault tolerance to the WSN. For evaluation of the feasibility and performance of the proposed approach, a feasibility test in regard to B&P product storage in a hospital was conducted.

The contributions of this approach can be summarized as follows:

This approach provides a generic system architecture for designing a WSN-based monitoring system. The generic system refers to an adaptive system, which can be applied in different application domains. It is different from a general system, where a general system is built based on common practice and is different in nature from application to application. The proposed system not only can be used for B&P products, but also is a reference for other applications. Considering the WSN deployment strategy, a relatively simple and systematic three-stage node deployment scheme was developed for the deployment of sensor nodes and relay nodes in a practical indoor environment. It also provides a relatively simple method for industries in general to follow and implement when designing a WSN system. In the experiment of comparison with two general sensor node deployment strategies, which are even deployment with grid and random deployment using the Poisson process method, the WSN constructed by using the proposed deployment scheme has a longer network life than the other two.

4.2 Related Works

The applications of WSN-based monitoring systems can be classified into two categories: outdoor and indoor applications. Outdoor applications generally involve deploying a large number of sensor nodes in a large space. The application examples include precision agriculture monitoring (Jibe, Harroud and Karmouch, 2011), coal mine monitoring (Li, 2011) and environmental monitoring (Arrenetxea et al., 2008). The deployment of these monitoring systems is challenging due to the harsh outdoor environment. Thus, sensor node deployment, communication protocol design and experiments for outdoor applications are difficult, costly and time-consuming (Lazarescu, 2013). For indoor applications, such as data centre monitoring (Vuppala et al., 2012), patient monitoring (Megalingam et al., 2012) and industrial storage monitoring (Mikhaylov et al., 2012), the deployment challenge is relatively lower and many deployment strategies only consider the coverage and network connectivity. However, these strategies may not satisfy the fault tolerance requirements of certain applications for long-term and reliable service. To address this issue, researchers have proposed solutions for some applications. A backup sensor placement algorithm for Structure Health Monitoring (SHM) application was proposed by Bhuiyan et al. (2015). Backup sensors are placed beside potential failure sensor nodes. Once a sensor node fails, a backup sensor beside it will take over its role in the WSN. The potential failure nodes are determined by performing network analysis after the WSN is formed. Some other research works proposed *k*-connectivity approaches to optimize the number of redundant sensor nodes, in which a *k*-connected WSN is able to tolerate *k*-1 fail nodes. For example, an approach called full fault-tolerant relay node placement (FFRP) was proposed to maintain *k* vertex-disjoint paths between every pair of sensor nodes and/or relay nodes through deploying minimum relay nodes (Bredin et al., 2010). Another approach called partial fault-tolerant relay node placement (PFRP), has been proposed which is used to ensure *k* edge or vertex-disjoint paths between every pair of sensor nodes (Kashya, Khuller and Shayman, 2006). These approaches successfully provide a certain level of fault tolerance to a WSN, but the implementation of these approaches involves complex calculations and procedures, which may be difficult and impractical for most industries to employ.

4.3 Statistical Approach for Wireless Sensor Network (WSN) Deployment

In this chapter, the proposed statistical approach focuses on dealing with heterogeneous WSNs, where the WSN consists of both sensor and relay nodes.

The sensor nodes are set to switch between sleep and wakeup mode in order to conserve energy. When a sensor node wakes up after sleeping for a period of time, it sends the monitoring data to the relay node for data forwarding to the sink. Then, the sensor enters sleep mode again. The relay nodes are set to be always active for routing of the message from sensor nodes to the sink. For the deployment of both sensor and relay nodes, a three-stage process for WSN management is proposed.

In the first stage, a WSN model is formulated by considering the sensing coverage and network connectivity. The sensor nodes are defined as a set ***S = {s1, s2... sn}*** and each sensor has the same sensing range r_s and communication range r_t. The sensing range and communication range are defined based on the unit disc graph model (Akyildiz and Vuran, 2010), in which there is no significant RF attenuation between the centre and the circumference of the disc. Similarly, the relay nodes are defined as a set ***T = {t1, t2... tn}*** with the same communication range R_t, which is larger than r_t. The monitoring area is defined as a set of space points ***P = {p1, p2... pn}***. For a space point p*i* in the monitoring area, it is covered by at least one sensor node. This coverage constraint can be represented as:

$$\sqrt{(si_x - pi_x)^2 + (si_y - pi_y)^2} \le r_s \tag{4.1}$$

where (si_x, si_y) and (pi_x, pi_y) are the Cartesian coordinates of a sensor node ***si*** and a space point ***pi***. Each sensor node in the WSN is also covered by at least one relay node. This constraint can be represented as:

$$\sqrt{(si_x - ti_x)^2 + (si_y - ti_y)^2} \leq r_t \tag{4.2}$$

where (si_x, si_y) and (ti_x, ti_y) are the Cartesian coordinates of a sensor node ***si*** and a relay node ***ti***. Moreover, between each pair of relay nodes, there should be a path shorter than the communication range of relay node R_t, and this constraint can be represented as:

$$\sqrt{(ti_x - tj_x)^2 + (ti_y - tj_y)^2} \leq R_t \tag{4.3}$$

As the relationships between the nodes in the WSN are built up, the next step is to calculate the required number of sensor nodes. The objective of the first stage is to obtain the minimum number of sensor nodes so that the total sensing range covers all the space points in the monitoring area.

In the second stage, the position of the sink is determined. The sink is suggested to be located at an optimal place where the total power consumption of data transmission between all the relay nodes and the sink is a minimum (Vincze, Vida and Vidacs, 2007). In other words, the total distance between each relay node and the sink should be minimized, because the power consumption of wireless communication is proportional to the distance between the transmitter and the receiver. This constraint can be represented as:

$$(x_0, y_0) = \arg\min_{x,y} \sum_{i=1}^{N} \sqrt{(ti_x - b)^2 + (ti_y - b_y)^2} \qquad (4.4)$$

where ***(b_x, b_y)***, ***(ti_x, ti_y)*** and ***(x_0, y_0)*** are the Cartesian coordinates of a sink ***b*** at an initial position, a relay node ***ti*** and the optimal position of sink ***b***. ***N*** is the total number of relay nodes in the WSN.

After going through the first two stages, a WSN is constructed and it is ready to operate. However, the WSN is still weak in regard to tolerating node failure, especially relay node failure. As mentioned before, the relay nodes continue in an active state for the routing of data, and the failure rate due to energy exhaustion and hardware/firmware malfunction can be significantly high. Since the relay nodes form the communication backbone of a WSN, failure of any of them may cause data loss and even network collapse. Therefore, the last stage of the deployment process is to insert additional relay nodes into the WSN to prevent relay node failure. The additional relay nodes should be deployed around the existing relay nodes and stay in sleep mode at the beginning. They will wake up periodically and communicate with the existing relay nodes following the Ping-

Ack protocol. The Ping-Ack protocol refers to a ping and acknowledge mechanism. For example, node A pings the address of node B, and node B replies with an acknowledgement message. Then, node A knows that node B is online. When a relay node fails, an additional node nearby will not receive any acknowledgement when it wakes up and polls the relay node. Then, the additional node will wait for a random time such as from one to five seconds, and retry to poll the relay node. If the additional node cannot receive acknowledgement after five successive retries, the additional node will substitute the functionality of the failed relay node.

To determine the number of additional relay nodes, a statistical approach with a series of procedures is proposed. Firstly, the monitoring area is divided into ***n*** regions based on the coverage areas of the relay nodes. Then, the number of days in terms of different area usage rate is counted in a period from the date of new batteries installation to the date that the batteries are expected to be recharged or replaced. The area usage rate refers to how many regions are used for B&P product storage. For example, the days in period 1 in which the area usage rate stays above ***0, 1/n, 2/n … n-1/n*** are counted respectively, where *n* is the total number of relay nodes. The results are represented as D_{11}, D_{12}... D_{1n}. Since one sample is inadequate, the day counts are recorded in the successive periods until the sample size is statistically reasonable. In the next step, the mean and standard deviation of a region ***k*** can be calculated as:

$$\overline{D}_k = \frac{D_{1k}+D_{2k}+\cdots D_{mk}}{m} \tag{4.5}$$

$$\sigma_k{}^2 = \frac{m-1}{m}\sum_{i=1}^{m}(D_{ik} - \overline{D}_k)^2 \tag{4.6}$$

where ***m*** is the number of periods counted. The collected data are then inputted into a distribution fitting software program, called Stat::fit for statistical analysis, and the distribution of $\boldsymbol{D_k}$ can be obtained. For example, the normal distribution is obtained from the data of the feasibility study, which is described in the next section.

$$f(D_k, \overline{D}_k, \sigma_k{}^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{(-\frac{(D_k-\overline{D}_k)^2}{2\sigma^2})} \tag{4.7}$$

The reliability level should be guaranteed to be larger than a specific threshold ***r***.

$$F(D_k, \overline{D}_k, \sigma_k{}^2) \geq r \tag{4.8}$$

Then, the number of relay nodes in space ***k*** can be represented as:

$$N = \left\lfloor \frac{D_k}{E} \right\rfloor - 1 \tag{4.9}$$

where ***N*** represents the additional number of relay nodes, and ***E*** represents the days that a relay node can survive when it is in maximum throughput.

4.4 A Feasibility Study of the Proposed System

In this section, a case study is reported to show the feasibility, and describes the operation procedures of the proposed system.

As shown in Figure 4.1, there is a storage room for B&P products in the studied hospital. There are four zones in the storage room. Zone D is a refrigerated area, which is for products with different storage temperature needs, with existing monitoring devices. Therefore, we only discuss the WSN designed and installed for Zone A, Zone B and Zone C.

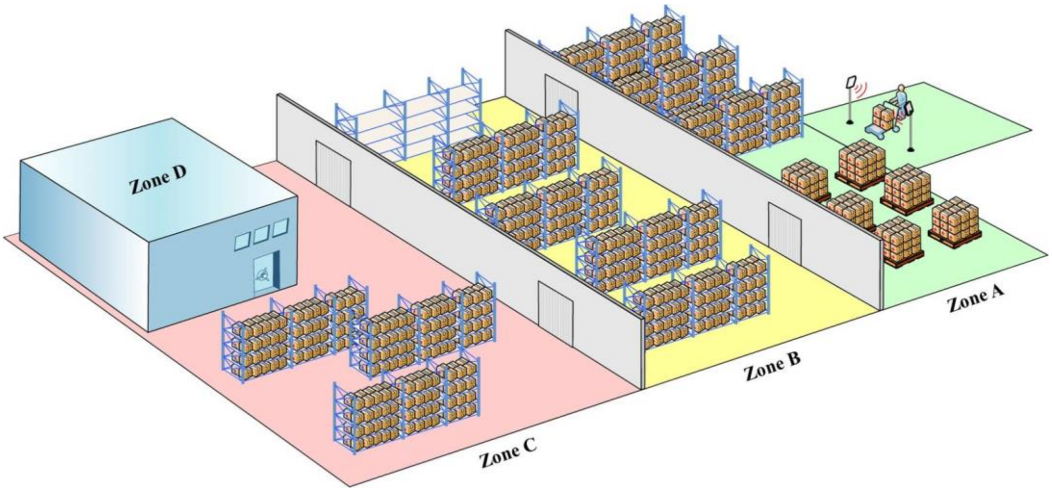
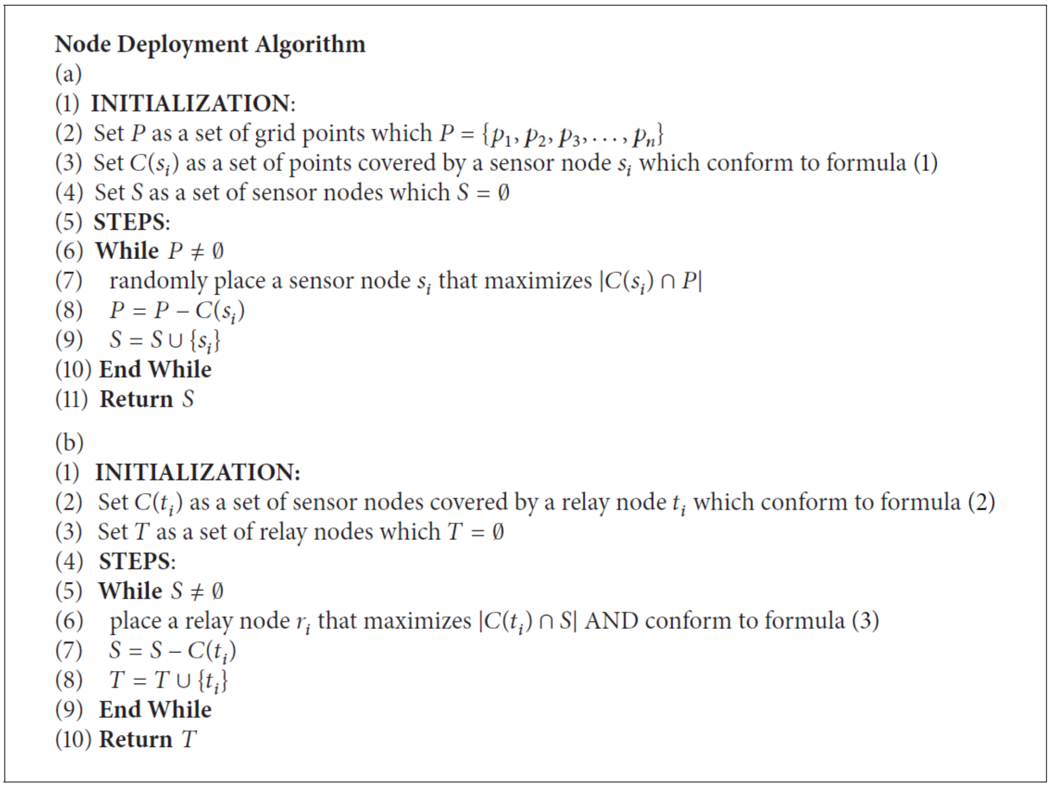


Figure 4.1 The storage zones for B&P products

The wireless sensor nodes and relay nodes were deployed in the storage room to monitor the environmental conditions surrounding the B&P products. According to the previous section, the first stage deployment can be divided into two steps. In the first step, the sensor nodes were deployed to cover all the area in the storage room by applying Equation (4.1). The sensor node deployment strategy is based on a greedy algorithm. Figure 4.2(a) shows the pseudo code of the sensor node deployment. In the initialization stage, ***P*** is defined as a set of small grid points representing the space points in the monitoring area. ***C***(s_i) is defined as a set of points covered by a sensor node s_i, in which the covered points conform to Equation (4.1). ***S*** is defined to store the position of the deployed sensor nodes, which is set as empty at the beginning. When the algorithm starts to execute, a sensor node s_i is placed in a position, where the intersection of the area covered by s_i and the uncovered monitoring area is a maximum. If there are many options in placing the sensor node, the algorithm will randomly choose one of the options. As the sensor node is placed, the covered points are subtracted from ***P*** and the position of the sensor node is stored in ***S***. The placement process runs continuously until ***P*** becomes an empty set, which means that all the grid points are covered.



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Node Deployment Algorithm
(a)
INITIALIZATION:
Set $P$ as a set of grid points which $P = \{p_1, p_2, p_3, \ldots, p_n\}$
Set $C(s_i)$ as a set of points covered by a sensor node $s_i$ which conform to formula (1)
Set $S$ as a set of sensor nodes which $S = \emptyset$
STEPS:
While $P \neq \emptyset$
    randomly place a sensor node $s_i$ that maximizes $|C(s_i) \cap P|$
    $P = P - C(s_i)$
    $S = S \cup \{s_i\}$
End While
Return $S$

(b)
INITIALIZATION:
Set $C(t_i)$ as a set of sensor nodes covered by a relay node $t_i$ which conform to formula (2)
Set $T$ as a set of relay nodes which $T = \emptyset$
STEPS:
While $S \neq \emptyset$
    place a relay node $r_i$ that maximizes $|C(t_i) \cap S|$ AND conform to formula (3)
    $S = S - C(t_i)$
    $T = T \cup \{t_i\}$
End While
Return $T$
```

Figure 4.2 Pseudo code of node deployment algorithm: (a) Sensor node deployment algorithm. (b) Relay node deployment algorithm

The in-house developed sensor node used in the case study is shown in Figure 4.3. It consists of a digital humidity and temperature sensor, an ultrasonic sensor and a Zigbee communication module.

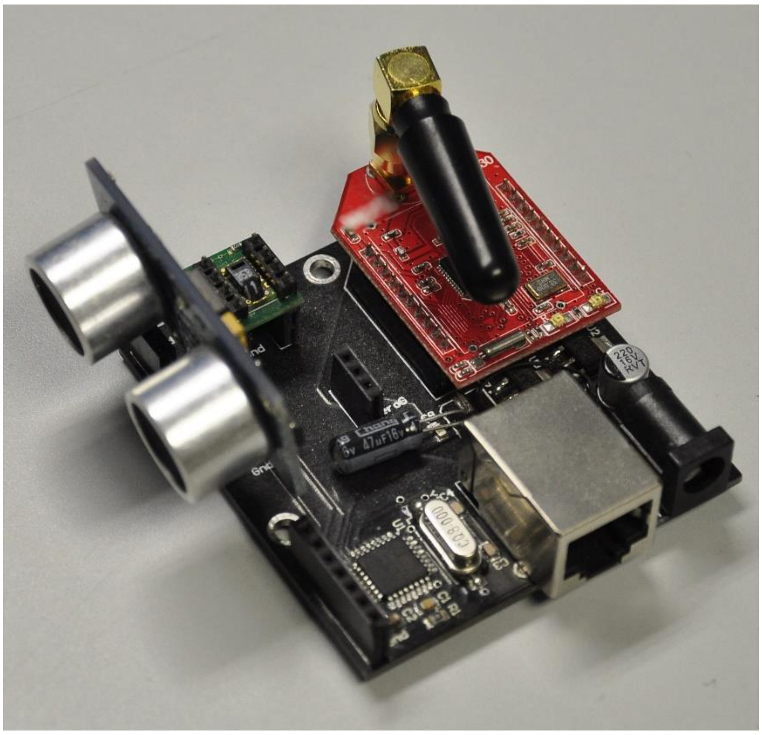


Figure 4.3 The sensor node used in the case study

The relay node was developed using the same hardware architecture as the sensor nodes, but the wireless communication module was set as a Zigbee router instead of a Zigbee end device, and a higher grade of microcontroller was used. Table 4.1 shows the specifications of the sensor and relay nodes. The sensor node deployment results are shown in Figure 4.4. After calculation, it was found that 42 sensor nodes were needed to cover the monitoring area.

Table 4.1 Specification of the sensor and relay nodes

Parameter	**Value**
Frequency band	2.4 GHz
Receive current consumption (RX)	24 mA
Transmit current consumption (TX with 1 dBm output)	29 mA
Transmit current consumption (TX with 4.5 dBm output)	33.5 mA

Sleep current consumption	1 μA
Radio baud rate	250 Kbps
Flash memory	128 KB
RAM	8 KB
Packet size	45 bytes

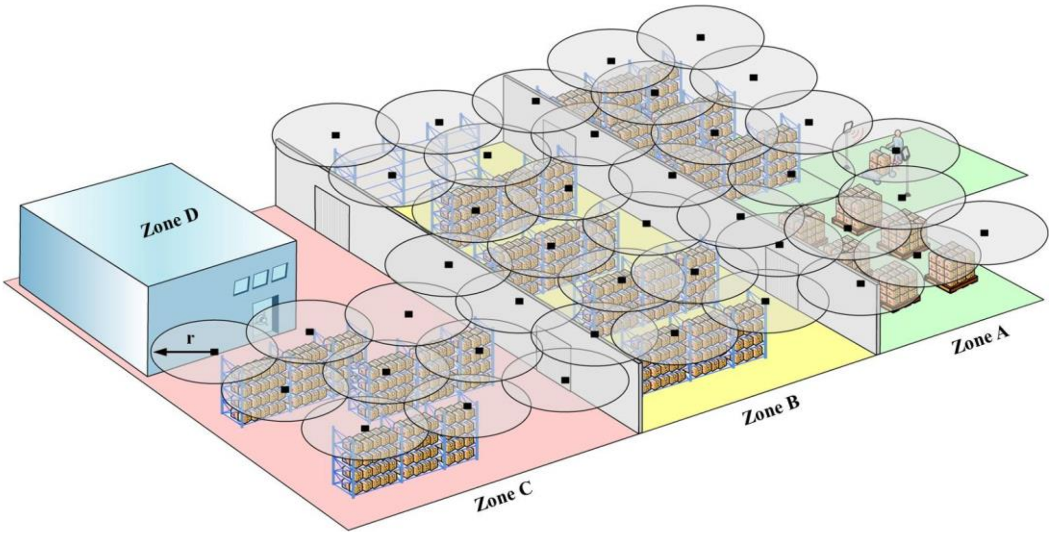


Figure 4.4 Deployment of sensor nodes

In the second step, Equations (4.2) and (4.3) are applied to calculate the number of relay nodes to cover all the sensor nodes in the deployment area for the routing of all the information. The pseudo code of the relay node deployment algorithm is shown in Figure 4.2(b). It is also based on a greedy algorithm, which is similar to the sensor node deployment strategy. In this feasibility study, 14 relay nodes were deployed in the monitoring area. The second stage of deployment is to determine the optimal location of the sink by using Equation (4.4). Figure 4.5 shows the positions of the sink and the relay nodes. At this point, the initial instalment of the node deployment is finished.

In the third stage of deployment, an investigation is carried out to find how many additional relay nodes should be added for fault tolerance of the deployed WSN. As 14 replay nodes were deployed, the room could be divided into 14 regions. Thus, the days that the inventory level stayed above 0%, 7.1%, 14.2%… 92.3% were counted. In this case study, the historical inventory information was used for the statistics, and a normal distribution was obtained from the distribution fitting software, Stat::fit. Concerning the goodness of fit, the Kolmogorov Smirnov (KS) test was used and the result showed an acceptance of "Do not reject" with a significance value of 0.05. Batteries of the nodes were replaced regularly each month (30/31 days). The average active working days for the battery of a relay node was 6 days. The reliability was set as 99.5%. After calculation by Equations (4.5) - (4.9), the additional relay nodes in each region were determined. Table 4.2 shows the results.

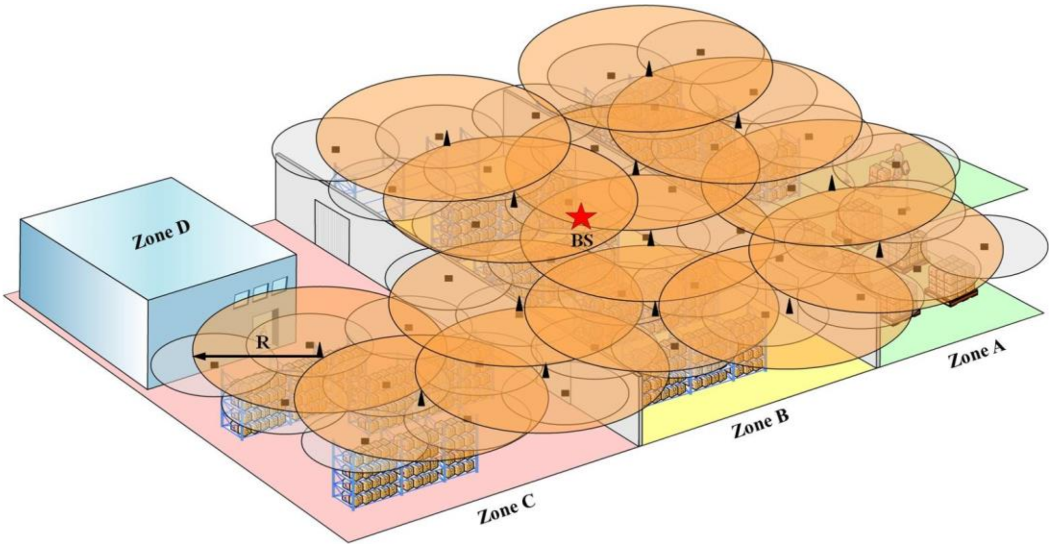


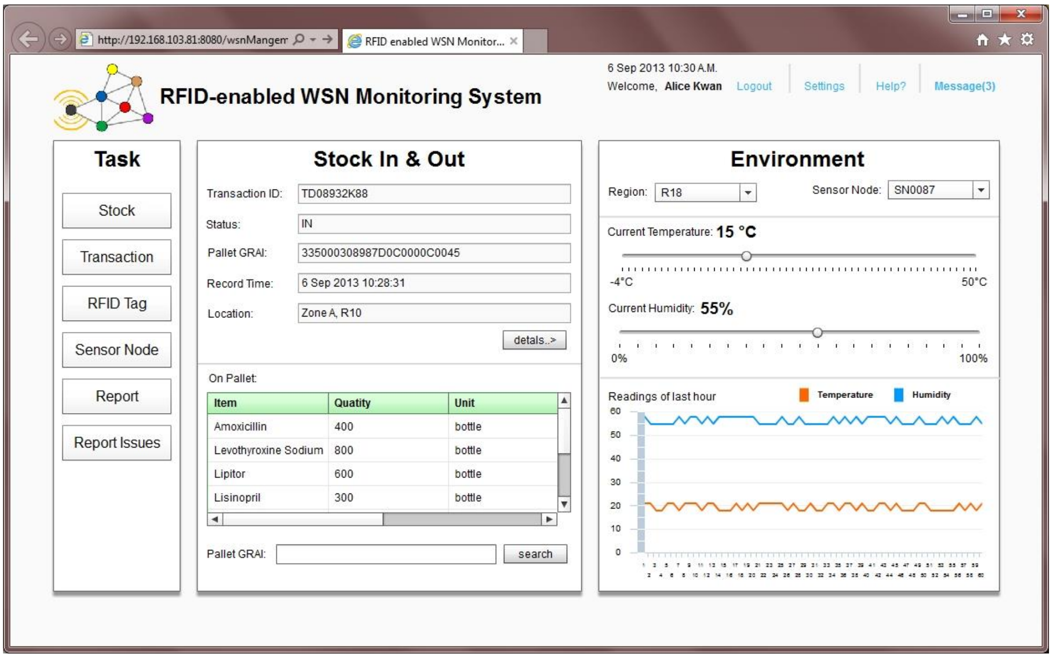
Figure 4.5 Deployment of relay nodes and the sink

Table 4.2 Estimation of additional relay nodes

Zone	Region (*k*)	D_k	*N*
A	1	31	5
A	2	31	5
A	3	28	4
A	4	29	4
B	5	27	4
B	6	27	4
B	7	25	4
B	8	26	4
B	9	10	1
B	10	6	0
C	11	17	2
C	12	19	3
C	13	12	1
C	14	4	0

As the result shows, Zone A had the highest priority for deploying more additional nodes. Four to five additional nodes for each relay node in this zone were needed. Zone B had less priority and Zone C had the lowest priority. After the additional relay nodes were deployed, all the additional nodes were set to sleep mode. If the warehouse was not full, the idle relay node in the region was also set to sleep mode.

After the deployment of a WSN, the system works to collect data. Figure 4.6 illustrates the main interface of the web-based system. In this case, the main function of the system is to monitor the stock in and out, and, more importantly, the environmental factors (i.e. temperature and humidity) in the storage room. When there are products stored in a particular region, the corresponding relay node is set to active status. It activates sensor nodes in the region to monitor temperature and humidity. Once an abnormal temperature reading is recorded, the system will send an alert to the users. Thus, the hospital can take immediate action to cope with any accidental events. RFID tags are recommended to be installed on B&P products or pallets of B&P products. The functions of the system can be therefore extended with the application of RFID. The arrival and leaving time can also be recorded automatically, making it useful for the management of B&P products. Table 4.3 summarizes the information collected by the system.



RFID-enabled WSN Monitoring System

6 Sep 2013 10:30 A.M.
Welcome, **Alice Kwan**

Stock In & Out

Transaction ID: TD08932K88
Status: IN
Pallet GRAI: 335000308987D0C0000C0045
Record Time: 6 Sep 2013 10:28:31
Location: Zone A, R10

On Pallet:

Item	Quatity	Unit
Amoxicillin	400	bottle
Levothyroxine Sodium	800	bottle
Lipitor	600	bottle
Lisinopril	300	bottle

Pallet GRAI:

Environment

Region: R18
Sensor Node: SN0087
Current Temperature: **15 °C**
Current Humidity: **55%**

Figure 4.6 The web-based interface of the proposed system used in the case study

Table 4.3 Types of collected environmental and product information

Global Data	Date & Time Number of Zones Zone ID(s) Number of Regions Region Number(s) Number of Nodes Nodes Number(s)
Relay Node Data	Battery Capacity Serial Number Node Number Region Number Status
Sensor Node Data	Temperature Humidity Battery Capacity Serial Number Model Number Node Number Status
Product Data	Zone ID

	Region Number
	Product Serial Number
	Transaction ID
	Tag ID / Pallet ID
	Arrival Date & Time
	Storage Date & Time
	Leaving Date & Time
	Quality Guarantee Date
	Temperature Record (during the storage)
	Humidity Record (during the storage)

4.5 Experimental Analysis

For evaluation of the performance of the proposed system, two types of general sensor node deployment strategies were used for comparison in this experiment. The objective of these two deployment strategies is to achieve full coverage (i.e. the coverage metric $k = 1$) of the region of interest. One of the deployment strategies is controlled deployment, where the nodes are deployed in the region of interest evenly following a grid, with size $r/2$. Another one is random deployment, in which the nodes are deployed randomly following a Poisson point process with the density λ equal to 0.044 in order to fulfil the coverage requirement (Philips, Panwar and Tantawi, 1989). The sink position of both strategies was set to the middle of the region of interest.

To perform the comparison more comprehensively, a new performance metric called network health was introduced, and an experiment was conducted to test the network health of the three approaches. The network health was measured as a percentage, where 100% network health means that the data from all the sensor nodes can be received by the backend system under the assumption that the Internet can always be connected. If there are ***S*** nodes in total in a WSN, the connection loss of one node results in a ***1/S*** decrease in network health.

To conduct the experiment, each sensor node in the WSN was set to send measurement data periodically every 5 seconds to the backend server through the sink when products are stored in its sensing coverage zone. If there is no product detected, a node will send a message of no product present to the backend system and switch to sleep mode, and it will wake up every 10 seconds to check whether there are products in its sensing zone. The backend system will collect the data from each node. If the data of a node are not received continuously for over 1 minute (60 seconds), the node is treated as a dead node and the overall network health will decrease in proportion accordingly.

Table 4.4 shows the preliminary comparison results of these two general node deployment strategies (approaches A and B) and the proposed approach (approach C). In approach A, 58 sensor nodes were deployed in the targeted monitoring zone with a 100% coverage rate and the LEACH clustering algorithm was used as the energy efficiency measure. Similarly, in approach B, 129 sensor nodes were deployed with a 100% coverage rate and the LEACH clustering algorithm was used. In approach C, 42 sensor nodes were deployed with a 100% coverage rate. Since the two-tiered clustering method was applied, 14 relay nodes were deployed for the routing of the data from the sensor nodes to the backend system, and also 41 additional relay nodes for fault tolerance. For the cost in terms of the number of sensor nodes, approach A was 58, approach B was 129 and approach C was 108, where the cost of a relay node used in approach C was equal to 1.2 times that of a sensor node. Figure 4.7 illustrates the experimental results of these three approaches. As the results show, the network health remained 100% at the beginning. On around the 14th day, the network using approach A started losing nodes. This node loss occurred in the network using approach B on around the 16th day, which was later than in approach A. For approach C, the network health drop occurred on around the 18th day.

Table 4.4 The deployment results of the three deployment approaches

	A (Even Deployment with Grid)	**B (Poisson Process Deployment)**	**C (Proposed Approach)**
No. of Sensor Nodes	58	129	42
No. of Relay Nodes	0	0	14
Energy Efficiency measure	LEACH clustering	LEACH clustering	Two-tiered clustering

Additional Relay Nodes	0	0	41
Coverage Rate (%)	100	100	100
Total Nodes	58	129	97
Cost	58	129	108

As the results show, the three approaches can achieve a 100% coverage rate. Approach A had poorer performance in terms of network health than the other two approaches, although its cost was the lowest. For approach B, the occurrence of node loss was later than in approach A. This may be because of more nodes sharing the routing load in approach B, but its cost was the highest. Approach C contained fewer nodes than approach B, but it had better performance in the experiment. The reason is that the relay nodes take over the routing work and they are fault-tolerated by the additional relay nodes. Another reason is that there is no guaranteed number of redundant nodes to share the routing load in some critical regions (e.g. the region connecting two large portions of the network) in the WSN. When the energy of the nodes in these critical regions runs out, a large number of sensor nodes will become dead nodes and the network health may drop significantly.

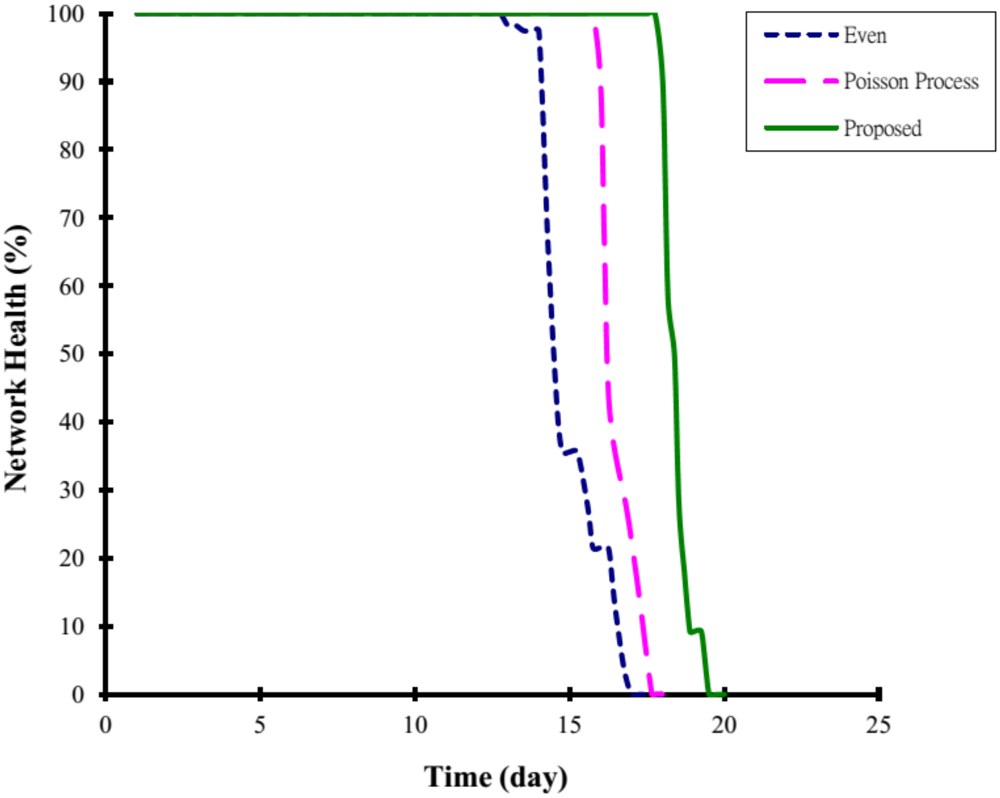


Figure 4.7 The experiment results of the three deployment approaches

4.6 Summary

Adopting WSN technology requires consideration of a series of design factors, including energy efficiency, sensor node placement, sensing coverage and network connectivity. To manage these factors effectively, a three-stage framework for WSN deployment is proposed. In the first stage, a minimum number of sensor nodes and relay nodes are placed to fully cover the monitoring area. Next, the sink is put in an optimal place so that the total transmission power of all the relay nodes can be minimized. Lastly, the proposed approach uses statistics to calculate the number of additional relay nodes needed in a target area. The additional relay nodes are used to provide fault tolerance to the relay nodes in a WSN. Furthermore, a feasibility test was conducted to show the deployment procedure and functions of the system. In the experiment, the proposed system exhibited its superiority over the common control and random sensor node deployment strategies, in which the WSN using the proposed approach can provide longer monitoring services. To conclude, the proposed system provides a systematic manner for the deployment of sensor nodes and relay nodes, which also provides a relatively simple and rapid method for industries, in general, to follow and implement when designing a WSN system. However, the proposed deployment algorithm is mainly based on a greedy algorithm. An optimal result in terms of the number of deployed nodes may not be guaranteed, which implies the total implementation cost of a WSN system using the proposed approach may not be well justified. Therefore, alternative approaches are required to optimize both the aforementioned basic design factors and the number of deployed nodes simultaneously.

Chapter 5

Meta-heuristic Approaches for 2-D Homogenous WSN Deployment

5.1 Introduction

As discussed in the Literature Review chapter, designing a WSN can be complex, since the trade-offs between various design factors need to be considered and balanced. As revealed from the literature, six design factors are considered as basic design factors. These basic factors include energy efficiency, node placement, sensing coverage, network connectivity, fault tolerance and production cost. However, when considering more design factors, the WSN deployment problem will become more complex. Thus, many deployment problems are NP-Hard problems. Among these basic design factors, energy efficiency is highly related to the network life-time, especially for outdoor and large-scale applications. To deal with this factor, many approaches based on communication protocol, clustering method, duty cycle management, relay node deployment and mobile agent deployment have been proposed in the literature. Since this factor can be independently optimized by various methods, the WSN deployment optimization model studied in this research may not consider the energy efficiency as one of the optimization objectives. Moreover, as stated in Chapter 3, the grid-based deterministic node placement approach will be applied for all the proposed approaches in this study. Therefore, four basic design factors including sensing coverage, network connectivity, fault tolerance and production cost were finally taken into account as the main optimization objectives of this research. According to the finding of the literature review, adoption of meta-heuristic approaches will be an effective solution for complicated WSN deployment problems. Thus, when also considering the shortage of the statistical approach presented in the previous chapter, the remaining parts of this thesis will focus on the investigation of applying meta-heuristic approaches to solve WSN deployment problems. To test the performance of meta-heuristic approaches, the investigation scope was firstly set as a relatively simpler WSN deployment problem, that is, the deployment of homogeneous sensor nodes in a 2-D environment.

In this chapter, a mathematical model is proposed to optimize the deployment of a WSN, to balance the trade-offs of total production cost, sensing coverage, network connectivity and fault tolerance. The model focuses on dealing with homogenous WSNs. To solve the proposed model, a Bat Algorithm (BA) based approach named Smart Bat Algorithm (SBA) is proposed in this chapter. BA is an emerging meta-heuristic algorithm recently proposed by Yang (2010). It has been applied to many optimization problems with promising results. SBA is an enhanced version of BA for solving WSN deployment problems studied in this research. It leverages decision theory and fuzzy logic techniques to calculate more sensible searching direction, velocity and frequency for artificial bats. To evaluate the performance of SBA, three meta-heuristic approaches are also used for solving the proposed model. These approaches include: (1) Genetic Algorithm (GA), (2) Ant Colony Optimization (ACO) based meta-heuristic method, called the *MAX–MIN* Ant System (*MM*AS) (), and (3) Discrete Bat Algorithm (DBA), which is a version of BA for dealing with discrete problems. For better comparison of the results of the four approaches, a benchmark is set up by using a heuristic method called Greedy algorithm (Greedy) to solve the model. Due to the limitation of Greedy, the algorithm only considers two design factors, which are sensing coverage and network connectivity.

5.2 Related Works

As mentioned before, keeping a good balance of the trade-offs between the basic design factors is critical for a WSN system. Thus, researchers have utilized different approaches to deal with these trade-offs. By considering the cost and sensing coverage, Chakrabarty et al. (2002) utilized Integer Linear Programming (ILP) and alternative divide-and-conquer approaches to obtain the minimum cost of sensor nodes for a completely covered region. Jia et al. (2009) proposed a coverage control scheme based on a multi-objective genetic algorithm to select the minimum number of sensor nodes from a WSN that can preserve full coverage to be activated, and put other sensor nodes into sleep mode. For the same purpose, Zeng et al. (2010) proposed a framework that uses dynamically periodic reconstruction strategies to select a subset of nodes for communication and sensing tasks only when the residual energy of a network drops to a threshold. Considering the factor of fault tolerance, both Pu, Xiong and Lu (2009) and Bredin et al. (2010) proposed algorithms to add additional nodes into an existing WSN to improve the *k*-connectivity, which Pu, Xiong and Lu's (2009) algorithm results in a *k*-connected or partially *k*-connected network while Bredin et al.'s (2010) algorithm results in a *k*-connected network, for any desired *k*.

When the optimization takes more design factors into account, the multi-objective optimization approach is introduced. Ferentinos and Tsiligiridis (2007) proposed an algorithm for the optimal design of WSNs in precision agriculture based on the GA. In this approach, energy efficiency, sensing coverage, network connectivity and an application specific design factor (i.e. deployment uniformity) are the objectives that need to be optimized while considering grid deployment and different node operating modes. Likewise, Chaudhry et al. (2011) proposed an algorithm called flexible algorithm for sensor placement (FLEX) to optimize the placement of sensor nodes by using a multi-objective GA. This algorithm aims to maximize coverage and the desired *k*-connectivity and minimize energy consumption simultaneously.

5.3 Problem Formulation

The aim of this chapter is to present an approximately optimized approach for homogeneous WSN deployment in a 2-D region of interest such that the sensing coverage and network connectivity are maximized, while a certain level of fault tolerance is maintained. Simultaneously, minimum production cost is achieved. Before applying the optimization approach, a mathematical model is established to formulate the homogeneous WSN deployment problem in a 2-D environment. In the proposed model, the node deployment strategy is selected to be grid deployment and the assumptions of the model are the same as listed in section 3.2. The formulated model addresses four basic factors which dominate the design and performance of a WSN. These factors are total production cost, sensing coverage, network connectivity and fault tolerance. The energy efficiency may not be considered in the proposed model since this factor can be optimized independently after the WSN is formed.

As four basic design factors are considered in the optimization model, a multi-objective (i.e. four objectives) WSN deployment problem is formulated. To perform the multi-objective optimization, the weighted sum approach is used to combine the four optimization objectives into one single objective function. This approach attaches a weighting coefficient to each optimization objective to adjust its importance in the optimization model. The weighted sum approach is a fundamental form of multi-objective optimization. It is easy to implement and requires less complex computation (i.e. less computational resources). More importantly, the weight of each objective can be adjusted independently; thus, this feature provides a flexibility to the model for different applications. This is because different applications have different requirements regarding the optimization objectives. For example, in this research, B&P product monitoring requires higher rates of these four objectives while other applications may require higher rates of the cost factor only. After applying the weighted sum method, the objective function of the proposed optimization model will be formed as a maximization objective function:

$$f = \alpha_1 \frac{p_{cov}}{p_{tot}} + \alpha_2 \frac{n_{conn}}{n_{dep}} + \alpha_3 \frac{n_{ft}}{n_{dep}} + \alpha_4 \frac{1}{c \cdot n_{dep}} \tag{5.1}$$

where $\boldsymbol{\alpha_x}$ is the weighting coefficient and $\boldsymbol{\alpha_x \geq 0}$. Each part with the weighting coefficient attached represents one optimization objective. The detail of each objective will be described in the following sections.

5.3.1 Coverage Ratio

The coverage ratio can be represented as the number of grid points covered by the largest connected cover of the WSN ($\boldsymbol{p_{cov}}$) divided by the total number of intersection points in the grid ($\boldsymbol{p_{tot}}$). The total number of points in the grid can be obtained by multiplying the number of row lines in the grid ($\boldsymbol{m}$) and the number of column lines in the grid ($\boldsymbol{n}$).

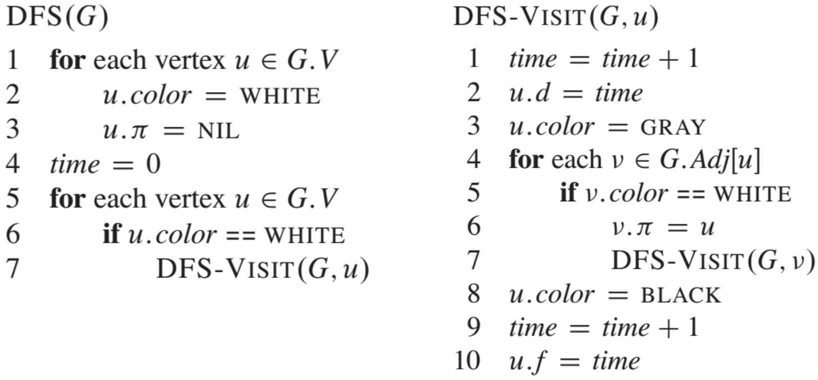
$$\frac{p_{cov}}{p_{tot}}, \quad p_{tot} = m \cdot n \tag{5.2}$$

5.3.2 Connectivity Ratio

The connectivity ratio can be represented as the number of sensor nodes in the largest connected cover ($\boldsymbol{n_{conn}}$) divided by the total number of wireless sensor nodes deployed in the grid ($\boldsymbol{n_{dep}}$).

$$\frac{n_{conn}}{n_{dep}} \tag{5.3}$$

The same as the previous optimization metric, the largest connected cover should be obtained first before calculating these two ratios. Breadth-first search (BFS) and depth-first search (DFS) are two graph algorithms for searching in a graph, which can be applied to find out the largest connected cover. In this case, the DFS is selected because it is more efficient in search-connected components. When searching starts at a source, the algorithm tries to search as deep as possible along a branch path. Once the end of the branch path is reached, the algorithm backtracks to another connect branch path to perform the search. This process continues until all the connected nodes have been visited. Figure 5.1 shows the pseudo code of the DFS algorithm.



```
DFS($G$)
for each vertex $u \in G.V$
    $u.color = $ WHITE
    $u.\pi = $ NIL
$time = 0$
for each vertex $u \in G.V$
    if $u.color ==$ WHITE
        DFS-VISIT($G, u$)

DFS-VISIT($G, u$)
$time = time + 1$
$u.d = time$
$u.color = $ GRAY
for each $v \in G.Adj[u]$
    if $v.color ==$ WHITE
        $v.\pi = u$
        DFS-VISIT($G, v$)
$u.color = $ BLACK
$time = time + 1$
$u.f = time$
```

Figure 5.1 The pseudo code of the DFS algorithm (Cormen et al., 2009)

5.3.3 Fault Tolerance Ratio

The fault tolerance ratio can be represented as the number of sensor nodes with the desired degree of fault tolerance ($\boldsymbol{n_{ft}}$) divided by the total number of wireless sensor nodes deployed in the grid ($\boldsymbol{n_{dep}}$).

$$\frac{n_{ft}}{n_{dep}} \tag{5.4}$$

The degree of fault tolerance is measured by the number of vertex-disjoint (node-disjoint) paths between a sensor node and the sink. To find out the number of vertex-disjoint paths of the connected nodes, maximum flow or minimum method can be used. Firstly, the problem should be transformed into a max-flow min-cut problem based on Menger’s theorem (Oellermann, 2013).

Menger's theorem is as below:

Menger's Theorem *If v and w are non-adjacent vertices in a graph G, then the maximum number of internally disjoint v-w paths equals the minimum number of vertices in a v-w separating set.* (Oellermann, 2013)

Then, the maximum flow or minimum cut between a source node and a sink in a graph can be found by using the Ford-Fulkerson algorithm according to the max-flow min-cut theorem (Even, 2011). The max-flow min-cut theorem is as below.

Max-flow Min-cut Theorem *Every finite network has a maximum flow and a minimum cut, and their values are equal.* (Even, 2011)

However, this approach requires large computing power and time to solve the problem. It will become a drawback when the number of deployed nodes is large. Therefore, a fault tolerance objective is represented as a ratio between the number of sensor nodes which have k adjacent nodes (k is the degree of fault tolerance) and the total number of sensor nodes. The value of k can be found out through constructing an adjacency matrix of the WSN

5.3.4 Cost

The cost can be represented as the unit cost of a sensor node ($\boldsymbol{c}$) multiplied by the total number of wireless sensor nodes deployed in the grid ($\boldsymbol{n_{dep}}$).

$$c \cdot n_{dep} \tag{5.5}$$

As the objective of this metric is to minimize the cost, this metric is reciprocal in the objective function as shown below.

$$\frac{1}{c \cdot n_{dep}} \tag{5.6}$$

In addition, the total number of wireless sensor nodes deployed in the grid ($\boldsymbol{n_{dep}}$) can be obtained through the equation shown below.

$$n_{dep} = \sum_{i=1}^{m} \sum_{j=1}^{n} p_{ij} \tag{5.7}$$

where

$$p_{ij} = \begin{cases} 1, & \text{if } a\ sensor\ node\ is\ deployed \\ 0, & \text{otherwise} \end{cases}$$

In the proposed optimization model, the four optimization objectives including the coverage ratio, the connectivity ratio, the fault tolerance ratio and the cost factor are addressed. These four objectives will be connected by using the weighted sum method. In general, the weighting coefficients are set with equal importance for each metric and they can also be determined based on the experience of specialists according to different applications.

5.4 Optimization Approaches

To solve the proposed optimization model, four meta-heuristic algorithms are utilized. These algorithms include the GA, ACO-based algorithm –*MAX-MIN* Ant System (*MM*AS), BA-based algorithm – DBA and the newly proposed BA-based algorithm – SBA.

5.4.1 Genetic Algorithm (GA)

The Genetic Algorithm (GA) is the first selected meta-heuristic algorithm to solve the proposed model, because the GA is the most well-known meta-heuristic algorithm and it has been applied in various problems with promising results. The working mechanism of the GA is similar to the evolution of biological genes, in which the genes of human being change slowly and are transferred generation to generation (Holland, 1992). The GA operates a set of chromosomes with three processes, which are selection, crossover, and mutation. The detail of these three processes are described as follows:

(a) Selection: in this process, better chromosomes which record better solutions for a problem, are selected for further processes to produce next-generation chromosomes. The selection method adopted in this research is a common selection method named roulette wheel selection. Through this method, the chromosome with a higher fitness value will have higher probability of being selected.

(b) Crossover: this is a process to improve the fitness values of the selected chromosomes. This operator executes with a predefined probability named crossover probability. Generally, when the execution probability is larger than crossover probability, two selected parent chromosomes will exchange some parts of themselves with each other in order to create new chromosomes, which are called offspring. In this research, single-point crossover is used.

(c) Mutation: this is a process to add diversity to the chromosomes. Similar to the crossover operator, the mutation operator executes with the mutation probability. During the execution, a randomly selected bit of the chromosome will be inverted.

Moreover, an elitism strategy is adopted to keep the best chromosome from being changed in the crossover and mutation processes. Following the GA operation processes generation after generation, more and more chromosomes with high fitness values are conserved in the population. Thus, after a certain number of generations, a close-to-optimal solution will be obtained.

Before experimenting, a chromosome was designed for the WSN deployment problem. The monitoring area is covered by an **n** by **n** grid. Sensor nodes are placed on the intersection points of the grid, and the presentation of a sensor node on a grid point is denoted by ‘1’ or ‘0’. Therefore, a chromosome of the GA represents the sequence of 1/0 of the grid.

5.4.2 Ant Colony Optimization (ACO)

Ant Colony Optimization (ACO) is a meta-heuristic optimization algorithm developed based on the food searching behaviour of ants. ACO algorithms make use of artificial ants to construct candidate solutions every iteration, and each solution will be associated with a pheromone trail. The candidate solutions will then be evaluated according to their fitness value. Based on the result, the pheromone trail with better fitness value will have more pheromone deposited, and the pheromone in all the trails evaporates after every iteration. Following this mechanism, an approximately optimized solution will be obtained when the ACO algorithm is converged. ACO is commonly used for solving NP-hard combinatorial optimization problems such as Traveling Salesman Problem (TSP) and Quadratic Assignment Problem (QAP). Because of the step-by-step solution construction characteristic, ACO typically can find better solutions to graph-related problems such as path searching and path construction problems. As the grid-based WSN deployment problem studied in this research can be considered as a graph-related problem, ACO is therefore selected as the second meta-heuristic algorithm to solve the proposed model. Among most ACO-based algorithms, the *MAX-MIN* Ant System (*MM*AS), a modified ACO algorithm, exhibits the best performance for many different combinatorial optimization problems, especially for the TSP and QAP (Stutzle and Hoos, 2000). This is because the *MM*AS better utilizes the search results of every iteration, and more effectively avoids premature convergence. As a result, the *MM*AS is adopted to solve the proposed optimization model.

When applying the *MM*AS to solve the proposed model, the area for WSN deployment is represented as a grid, $\boldsymbol{G = (V, E)}$, with $\boldsymbol{V}$ being the set of vertexes (i.e. the grid points) and $\boldsymbol{E}$ being the set of edges of the grid. The base station is placed at the lower left corner of the grid. To start constructing the solution, an ant is moved from its initial position, which is a random node around the base station.

The path selection of the ant is based on the probability assigned to each path, which is calculated by:

$$P_{i,j} = \frac{{\tau_{i,j}}^{\alpha} \cdot {\eta_{i,j}}^{\beta}}{\sum {\tau_{i,j}}^{\alpha} \cdot {\eta_{i,j}}^{\beta}} \tag{5.8}$$

where $\boldsymbol{\tau_{i,j}}$ is the amount of pheromone between vertex $\boldsymbol{i}$ and $\boldsymbol{j}$, $\boldsymbol{\eta_{i,j}}$ is the local sensor coverage heuristic information, and $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are the parameters to determine the degree of affection of the pheromone. $\boldsymbol{\eta_{i,j}}$ can be calculated following the equation proposed in Fidanova and Marinov (2011) :

$$\eta_{i,j} = S_{i,j} \cdot l_{i,j}\left(1 - b_{i,j}\right) \tag{5.9}$$

where $\boldsymbol{S_{i,j}}$ is the available area in the grid covered by the new sensor node at the position where an ant will move to. $\boldsymbol{l_{i,j}}$ is a binary coefficient, where its value is either 1 or 0, and is determined based on whether there is a connection existing between the edge $\boldsymbol{E(i, j)}$ and the constructed path. $\boldsymbol{b_{i,j}}$ is used to check the availability for the new sensor node placement. If the position is already occupied, $\boldsymbol{b_{i,j} = 1}$; otherwise, $\boldsymbol{b_{i,j} = 0}$.

In every iteration of the *MM*AS algorithm, every ant constructs a path in the grid for a solution. All the solutions are then examined using the proposed objective function. After the solution examination, the pheromone trails are updated. The evaporation process is first performed on the trails. In the next step, only the ant with the best iteration solution is allowed to deposit pheromone on its constructed path. Particularly, the pheromone update process is represented as:

$$\tau_{i,j} = \rho \cdot \tau_{i-1,j-1} + \Delta\tau_{i,j} \tag{5.10}$$

$$\Delta\tau_{i,j} = 1/C(V) \tag{5.11}$$

where $\boldsymbol{\rho}$ denotes the pheromone residual factor and ***C(V)*** represents the fitness value of either the iteration best solution or the global best solution. The limits of pheromone are set as [$\boldsymbol{\tau_{min}}$, $\boldsymbol{\tau_{max}}$] with the relationship given by:

$$\tau_{min} = 0.087 \cdot \tau_{max} \tag{5.12}$$

$$\tau_{max} = 1/[(1-r) \cdot C(V)] \tag{5.13}$$

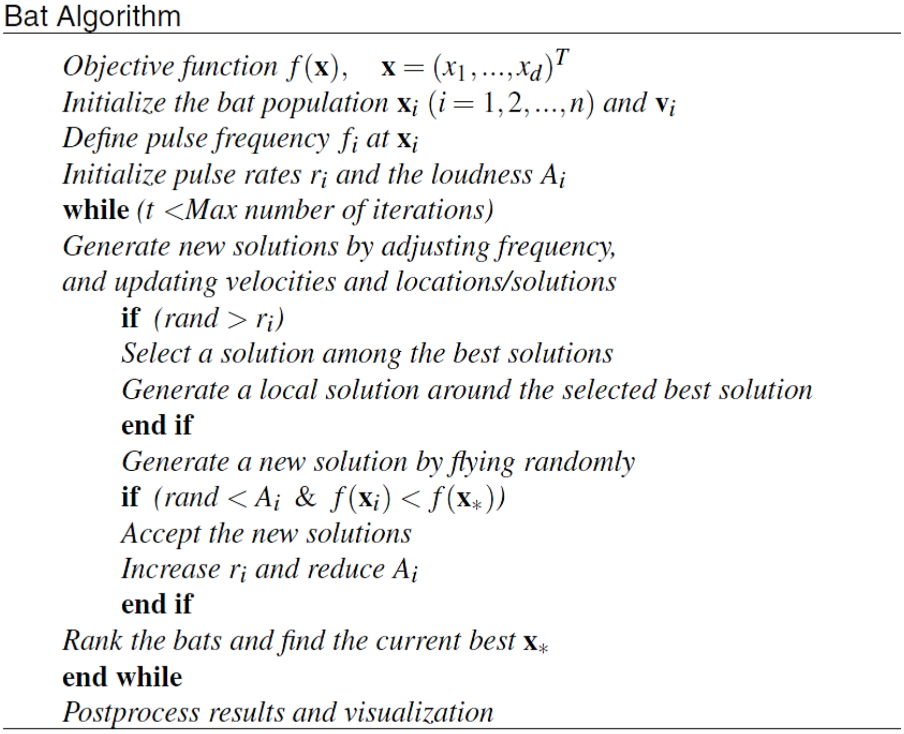
To avoid ants being trapped in local optimal solutions, the roulette wheel selection method is used for an ant to select the next node to construct its path when the probabilities assigned to all the available points are calculated. This approach allows the point with lower probability to be chosen which is significant for global search of ACO.

When ants start searching, there are three conditions for stopping the path searching process: 1) no more available points for searching; 2) the remaining available points have been covered; 3) it is impossible to reach other available points. At the end of each iteration, the best path with the highest fitness value is chosen to update the pheromone of all the points, and the new pheromone information will be passed to the next iteration.

5.4.3 Discrete Bat Algorithm (DBA)

The Bat Algorithm (BA) is a bioinspired metaheuristic algorithm. It was developed based on the simulation of echolocation systems of microbats, which use ultrasonic pulses to identify obstacles and prey. The BA is a newly emerging metaheuristic algorithm and it has been successfully applied for solving different optimization problems. Considering these characteristics, the BA is applied to solve the proposed optimization model in this research.

When the BA starts to execute, artificial bats search for prey position $\boldsymbol{x_i}$ with velocity $\boldsymbol{v_i}$, and the ultrasonic pulses are emitted with a frequency $\boldsymbol{f_i}$, a wavelength $\boldsymbol{\lambda_i}$ and a loudness $\boldsymbol{A_i}$. When a bat is close to prey, it will adjust the frequency (or the wavelength) and the pulse rate $\boldsymbol{r_i} \in [0, 1]$ of the ultrasonic pulses. Figure 5.2 shows the pseudocode of the BA. The objective function and the initial bat population are set up at the beginning. Then, the four main parameters including the velocity $\boldsymbol{v_i}$, frequency $\boldsymbol{f_i}$, pulse rate $\boldsymbol{r_i}$, and loudness $\boldsymbol{A_i}$, are initialized. In every iteration, each bat keeps updating its position and velocity for searching for prey, i.e. a better solution (Yang, 2010).



```
Bat Algorithm
Objective function $f(\mathbf{x})$,    $\mathbf{x} = (x_1, ..., x_d)^T$
Initialize the bat population $\mathbf{x}_i$ $(i = 1, 2, ..., n)$ and $\mathbf{v}_i$
Define pulse frequency $f_i$ at $\mathbf{x}_i$
Initialize pulse rates $r_i$ and the loudness $A_i$
while (t <Max number of iterations)
Generate new solutions by adjusting frequency,
and updating velocities and locations/solutions
    if $(rand > r_i)$
    Select a solution among the best solutions
    Generate a local solution around the selected best solution
    end if
    Generate a new solution by flying randomly
    if $(rand < A_i \ \& \ f(\mathbf{x}_i) < f(\mathbf{x}_*))$
    Accept the new solutions
    Increase $r_i$ and reduce $A_i$
    end if
Rank the bats and find the current best $\mathbf{x}_*$
end while
Postprocess results and visualization
```

Figure 5.2 The pseudocode of the bat algorithm (Yang, 2010)

For updating the position of a bat $\boldsymbol{i}$, the frequency $\boldsymbol{f_i}$ and velocity $\boldsymbol{v_i}$ are required to be adjusted. The frequency is adjusted by the following equation:

$$f_i = f_{min} + (f_{max} - f_{min})\beta \tag{5.14}$$

where $\boldsymbol{f} \in [\boldsymbol{f_{min}}, \boldsymbol{f_{max}}]$ and $\boldsymbol{\beta}$ is a uniform distribution random number of [0, 1]. At iteration $\boldsymbol{t}$, the velocity $\boldsymbol{v_i}$ is given by:

$$v_i{}^t = v_i{}^{t-1} + (x_i{}^{t-1} - x^*)f_i \tag{5.15}$$

where $\boldsymbol{x_i}$ represents the position of the $\boldsymbol{i}$ th bat, and $\boldsymbol{x^*}$ is the position of bats with the best fitness value. The position $\boldsymbol{x_i}$ is updated by:

$$x_i{}^t = x_i{}^{t-1} + v_i{}^t \tag{5.16}$$

For local searches, a new solution is generated by the following equation:

$$x_{new} = x_{old} + \varepsilon\bar{A} \tag{5.17}$$

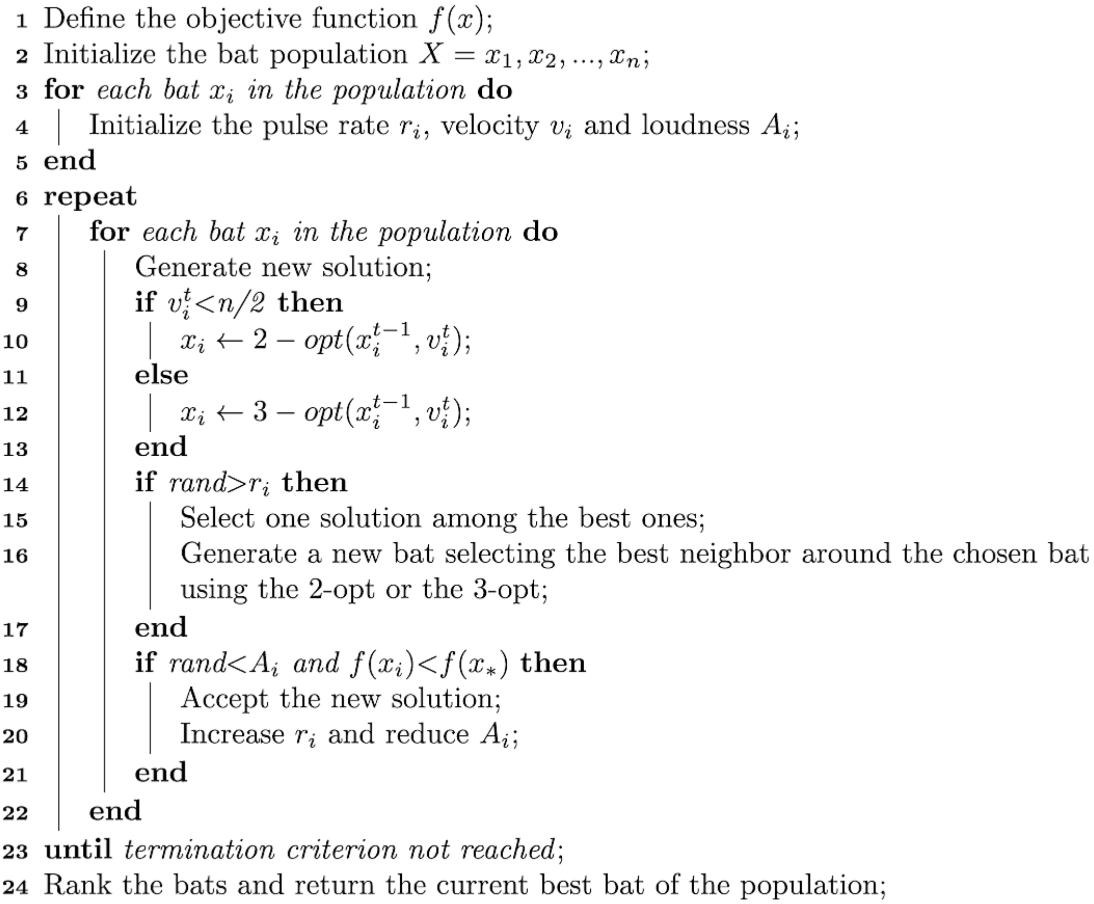
where $\boldsymbol{\varepsilon}$ is a random value between [-1, 1], and $\boldsymbol{\bar{A}}$ is the average value of loudness $\boldsymbol{A}$ of all the bats at the same time step. The loudness $\boldsymbol{A_i}$ and pulse rate $\boldsymbol{r_i}$ have to be updated in the prey searching process. Their updated method is given by:

$$A_i{}^{t+1} = aA_i{}^t \tag{5.18}$$

$$r_i{}^{t+1} = r_i{}^0(1 - e^{-\gamma t}) \tag{5.19}$$

where $\boldsymbol{A} \in [\boldsymbol{A_0}, \boldsymbol{A_{min}}]$, $\boldsymbol{r_i^0} \in [0, 1]$, $0 < \boldsymbol{\alpha} < 1$, and $\boldsymbol{\gamma} > 0$. To simplify the implementation of BA, $\boldsymbol{\alpha} = \boldsymbol{\gamma}$ is suggested by many studies in the literature.

The standard BA was originally designed for continuous optimization problems. Thus, a modified version of the BA, named Discrete Bat Algorithm (DBA), is applied to solve the proposed WSN deployment optimization model (Osaba et al., 2016). Figure 5.3 shows the pseudo code of the DBA.



```
Define the objective function $f(x)$;
Initialize the bat population $X = x_1, x_2, ..., x_n$;
for each bat $x_i$ in the population do
    Initialize the pulse rate $r_i$, velocity $v_i$ and loudness $A_i$;
end
repeat
    for each bat $x_i$ in the population do
        Generate new solution;
        if $v_i^t < n/2$ then
            $x_i \leftarrow 2 - opt(x_i^{t-1}, v_i^t)$;
        else
            $x_i \leftarrow 3 - opt(x_i^{t-1}, v_i^t)$;
        end
        if $rand > r_i$ then
            Select one solution among the best ones;
            Generate a new bat selecting the best neighbor around the chosen bat
            using the 2-opt or the 3-opt;
        end
        if $rand < A_i$ and $f(x_i) < f(x_*)$ then
            Accept the new solution;
            Increase $r_i$ and reduce $A_i$;
        end
    end
until termination criterion not reached;
Rank the bats and return the current best bat of the population;
```

Figure 5.3 The pseudocode of the discrete bat algorithm (Osaba et al., 2016)

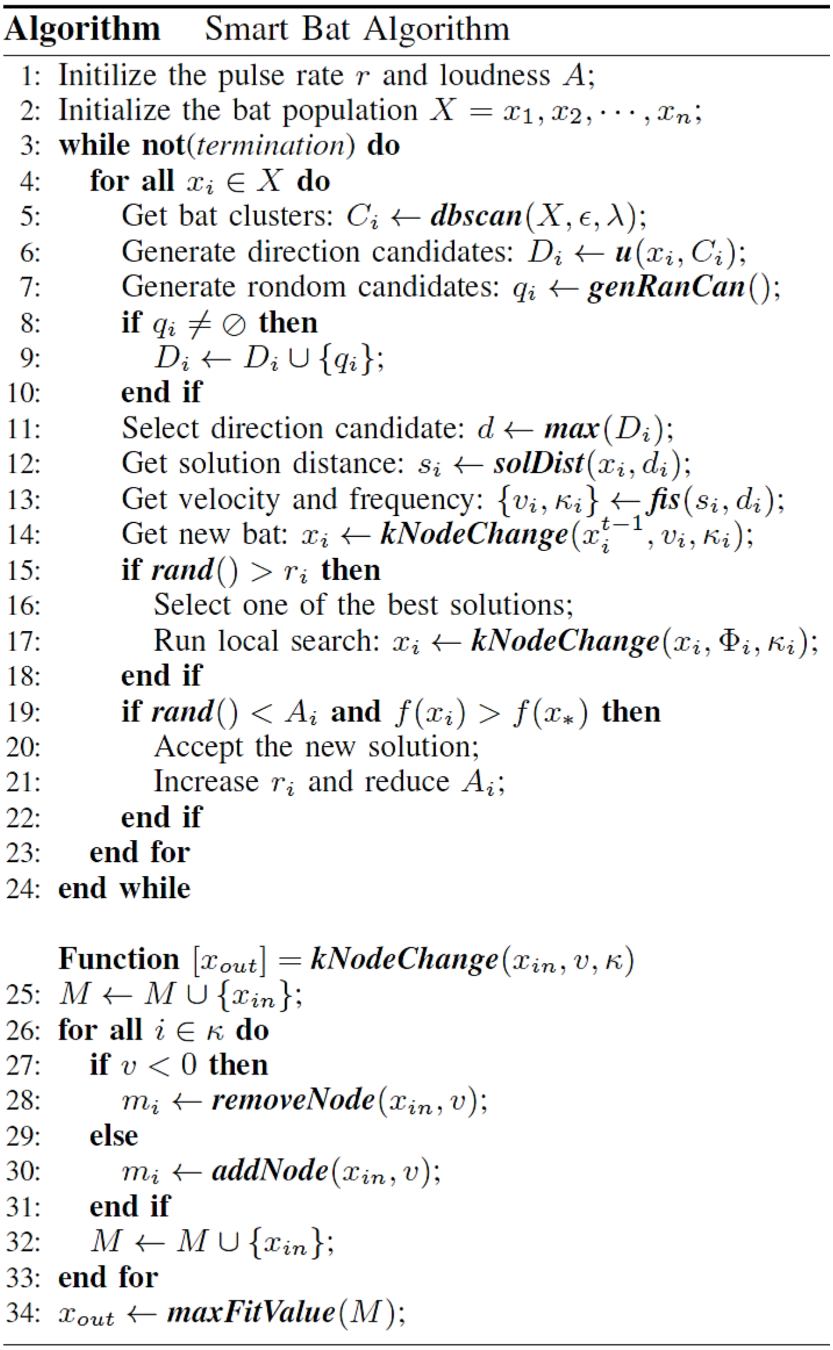
In the DBA, the forms of pulse rate r_i, and loudness A_i remain the same as the BA, but the frequency f_i is not considered in the algorithm and velocity v_i has been modified. The modified v_i can be represented as:

$$v_i{}^t = Random[1,\ HammingDistance(x_i{}^t, x^*)] \qquad (5.20)$$

where the ***HammingDistance***() returns the difference of elements in sequence between two bats. Moreover, the position update method of position $\boldsymbol{x_i}$ is changed to be the well-known 2-opt and 3-opt algorithms.

5.4.4 Smart Bat Algorithm (BA)

According to the literature, the BA exhibits good efficiency in solving continuous optimization problems, and many modified versions are proposed for addressing different discrete problems. For example, the DBA introduced in section 5.4.3 is designed to solve symmetric and asymmetric TSPs. However, the modified version of the BA specifically for the problem of WSN deployment is rare. To examine the performance of the BA in solving the proposed optimization model, a modified BA, named Smart Bat Algorithm (SBA) is proposed. Besides redefining the calculation of the solution distance between two bats, the main idea of the SBA is to make the artificial bats be smart by regulating their behaviour in the solution searching process through utilizing decision theory and Fuzzy Logic (FL) techniques (Ng et al., 2018a). Figure 5.4 shows the pseudo code of SBA.



```
Algorithm Smart Bat Algorithm
Initilize the pulse rate $r$ and loudness $A$;
Initialize the bat population $X = x_1, x_2, \cdots, x_n$;
while not(termination) do
    for all $x_i \in X$ do
        Get bat clusters: $C_i \leftarrow$ dbscan$(X, \epsilon, \lambda)$;
        Generate direction candidates: $D_i \leftarrow$ u$(x_i, C_i)$;
        Generate rondom candidates: $q_i \leftarrow$ genRanCan$()$;
        if $q_i \neq \oslash$ then
            $D_i \leftarrow D_i \cup \{q_i\}$;
        end if
        Select direction candidate: $d \leftarrow$ max$(D_i)$;
        Get solution distance: $s_i \leftarrow$ solDist$(x_i, d_i)$;
        Get velocity and frequency: $\{v_i, \kappa_i\} \leftarrow$ fis$(s_i, d_i)$;
        Get new bat: $x_i \leftarrow$ kNodeChange$(x_i^{t-1}, v_i, \kappa_i)$;
        if rand$() > r_i$ then
            Select one of the best solutions;
            Run local search: $x_i \leftarrow$ kNodeChange$(x_i, \Phi_i, \kappa_i)$;
        end if
        if rand$() < A_i$ and $f(x_i) > f(x_*)$ then
            Accept the new solution;
            Increase $r_i$ and reduce $A_i$;
        end if
    end for
end while

Function $[x_{out}] =$ kNodeChange$(x_{in}, v, \kappa)$
$M \leftarrow M \cup \{x_{in}\}$;
for all $i \in \kappa$ do
    if $v < 0$ then
        $m_i \leftarrow$ removeNode$(x_{in}, v)$;
    else
        $m_i \leftarrow$ addNode$(x_{in}, v)$;
    end if
    $M \leftarrow M \cup \{x_{in}\}$;
end for
$x_{out} \leftarrow$ maxFitValue$(M)$;
```

Figure 5.4 The pseudocode of the smart bat algorithm

At the beginning of the algorithm, a 2-D environment is simulated by a 2-D grid model using the Cartesian coordinate system. Then, in the bat population initialization process, each bat represents a solution which is generated by placing a set of nodes on grid points randomly. Next, the objective and utility functions will be defined. The definitions of objective functions have been presented previously and the utility function is shown below:

$$u(x_i, C_i) = \left(f(x_j) - f(x_i)\right) \cdot \frac{\Gamma}{|C_i|}, \quad f(x_j) > f(x_i) \;\&\; j = [1, n] \tag{5.21}$$

The utility function is constructed according to the decision theory for governing a search direction of each artificial bat. The utility function consists of two basic parts. The first part calculates the differences of fitness value between an artificial bat ($\boldsymbol{x_i}$) and its peer bats ($\boldsymbol{x_j}$, $\boldsymbol{j}$ = [1, $\boldsymbol{n}$]), which have larger fitness values (i.e. $\boldsymbol{f(x_j)}$ > $\boldsymbol{f(x_i)}$). The second part is the ratio of the bat number threshold of a bat cluster ($\boldsymbol{\Gamma}$) and the number of bats in the cluster ($|\boldsymbol{C_i}|$) that bat $\boldsymbol{x_i}$ belongs to. This ratio is a part of a designed mechanism to prevent bats stagnating in a local optimum. The stagnation prevention mechanism starts from clustering the bats using the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm (Ester et al., 1996). Figure 5.4 shows the detail of the DBSCAN algorithm. Compared to other clustering algorithms such as *k*-means-type algorithms, the DBSCAN algorithm is a more efficient clustering algorithm and requires no predefined cluster number.

Pseudocode of DBSCAN based Algorithm for Smart Bat Clustering

```
DBSCAN (solution set of $n$ Smart Bats: $B = b_1, b_2, ..., b_n$,
minimum elements required for a cluster: $m_p$,
neighbourhood radius: $r$)
Class number $C := 0$;
FOR EACH $b_i$ in $B$ DO
    IF $class(b_i) = Undefined$
        Neighbor set $N := expandCluster(B, b_i, r)$;
        IF $size(N) < m_p$
            $class(b_i) := Noise$;
        ELSE
            Class number $C := C + 1$;
            $class(b_i) := C$;
            Seed set $S := N \setminus \{b_i\}$;
            FOR EACH $s_i$ in $S$ DO
                IF $class(s_i) =$ Noise
                    $class(s_i) := C$;
                END IF
                IF $class(s_i) = Undefined$
                    $class(s_i) := C$;
                    $N := expandCluster(B, s_i, r)$
                    IF $size(N) \geq m_p$
                        $S := S \cup N$;
                    END IF
                END IF
            END FOR
        END IF
END FOR

expandCluster($S, p, r$): $N$
Neighbor set $N := \emptyset$;
FOR EACH $s_i$ in $S$ DO
    IF $solDist(p, s_i) \leq r$
        $N := N \cup \{s_i\}$;
    END IF
END FOR
```

Figure 5.5 The pseudocode of the DBSCAN algorithm

There are two parameters that need to be set in DBSCAN. One is the neighbour distance (ε) and the other is the minimum number of bats required to form a cluster

(λ). The distance between two bats is determined by the function ***solDist***() and it is constructed based on the equation as follows:

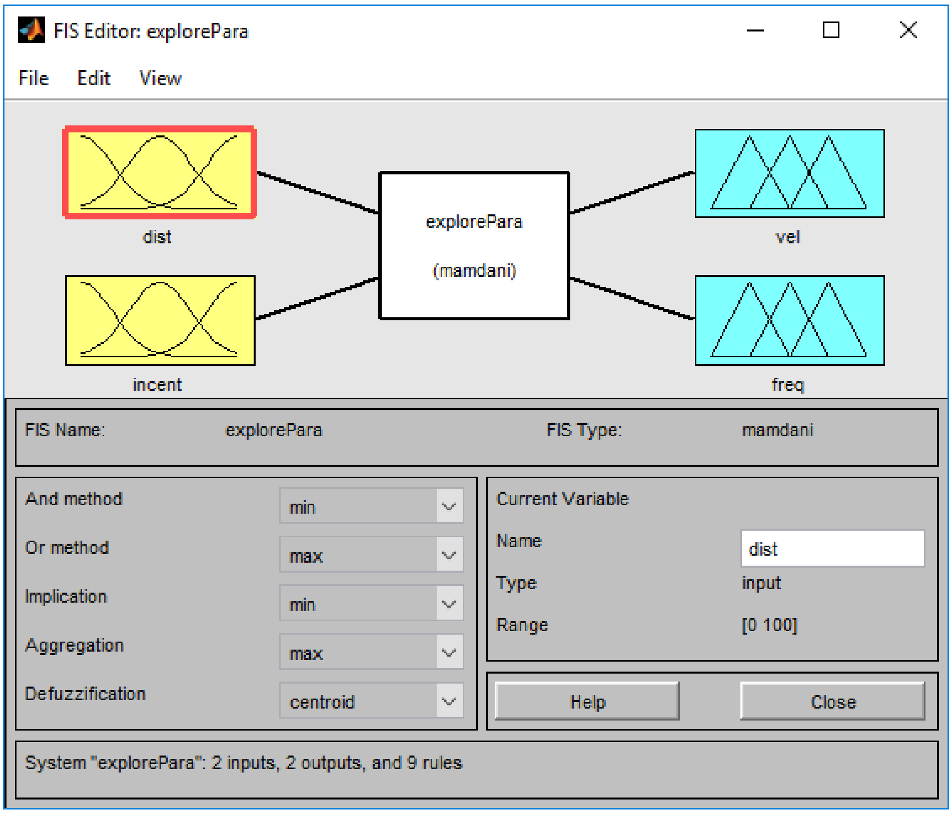
$$\eta_{sn}(x_i, x_j) = n_{hole}(x_i) + n_{sn}(x_i) - n_{hole}(x_j) - n_{sn}(x_j) \tag{5.22}$$

As shown in the equation, the distance between the two bats, x_i and x_j, is equal to the difference of the sum of the number of holes ($n_{hole}(x)$) and the number of deployed SNs ($n_{sn}(x)$) between the two bats. After the clustering process, a set of utility values (D_i) can be obtained for the bat (x_i). Meanwhile, an artificial utility value (q_i) is generated by the function ***genRanCan()*** and will be inserted into the set D_i, if q_i is larger than $f(x_i)$. The artificial value q_i is obtained through a random-based formula which is shown as:

$$q_i = \left((f_{gmax} - f_{gmin}) \cdot \zeta + f_{gmin} - f(x_i)\right) \cdot \frac{|C_i|}{\Gamma},\ \zeta = [0,1] \tag{5.23}$$

where f_{gmax} is the global maximum fitness value and f_{gmin} is the global minimum fitness value. The symbol ζ is a random number between 0 and 1. In the next step, the largest value in D_i will be selected and its associated bat (i.e. the direction reference candidate) will be used to generate the next-iteration bat (x_i^{t+1}). In addition, if q_i is selected, its associated solution will be a random-generated feasible solution. In the case of cluster saturation, the artificial value q_i is more likely to be selected, which means that bats may try searching for a solution in other solution spaces rather than keep searching around the local optima. This mechanism helps bats escape from a local optima trap.

When the direction reference candidate is selected, the bat x_i updates its position via using the function ***kNodeChange***() based on two parameters, the velocity v_i and the frequency κ_i. The velocity v_i is the number of node changes in a feasible solution x_i. If v_i is a positive number, ***kNodeChange***() will add v_i nodes on the holes of x_i; otherwise, v_i nodes will be removed from the deployed nodes in x_i. The frequency κ_i is the number of tries of adding/removing v_i nodes in x_i. The function ***kNodeChange***() will return a solution with the largest fitness value within the set M, which contains tried results and the original input solution. To determine the velocity v_i and the frequency κ_i, the fuzzy logic inference technique is adopted based on the solution distance and the direction utility value, in which fuzzy logic is capable to provide reasonable outputs with a good balance between all inputs (Lee, Cheng and Ng, 2015). A fuzzy inference system ***fis***() with two inputs and two outputs is established by using the Fuzzy Logic Toolbox in MATLAB. The two inputs include the solution distance with the range [0, p_{tot}] and the direction utility value with the range [0, $((f_{gmax}-f_{gmin})\cdot\Gamma)$]. The two outputs include the velocity v_i and the frequency κ_i with the range [0, s_i]. Figure 5.6 presents the detailed settings of the fuzzy inference system, in which a triangular-shaped membership function is chosen for the membership functions of both inputs and outputs, and centroid defuzzification is chosen as the defuzzification method. Table 5.1 shows the nine fuzzy rules of the fuzzy inference system.



FIS Name: explorePara

FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Defuzzification: centroid

Current Variable

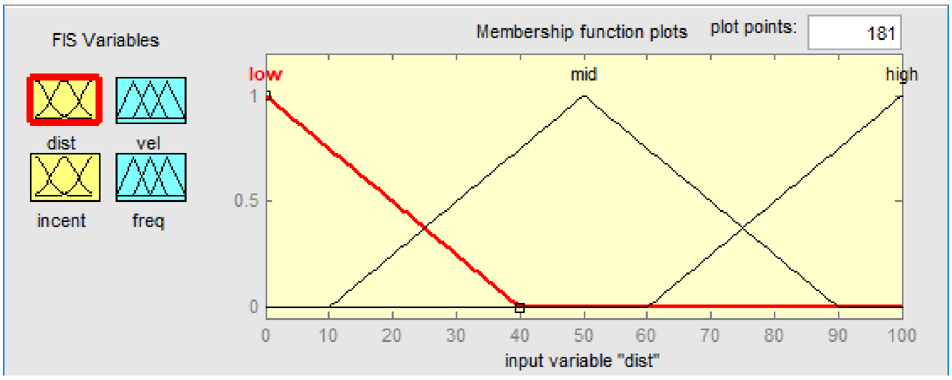
Name: dist

Type: input

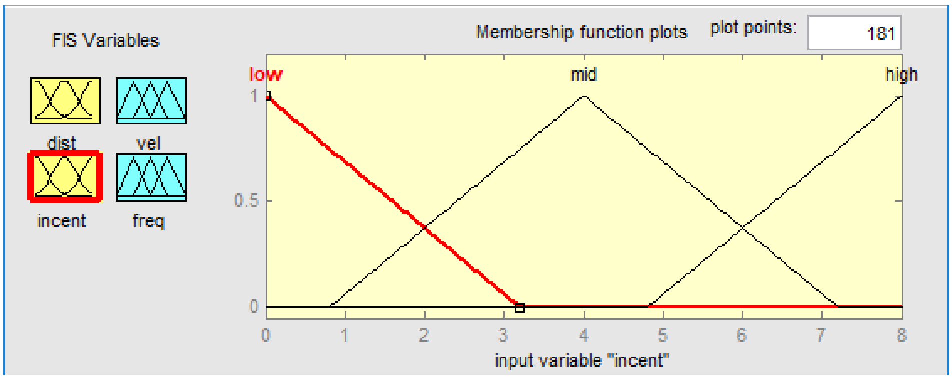
Range: [0 100]

System "explorePara": 2 inputs, 2 outputs, and 9 rules

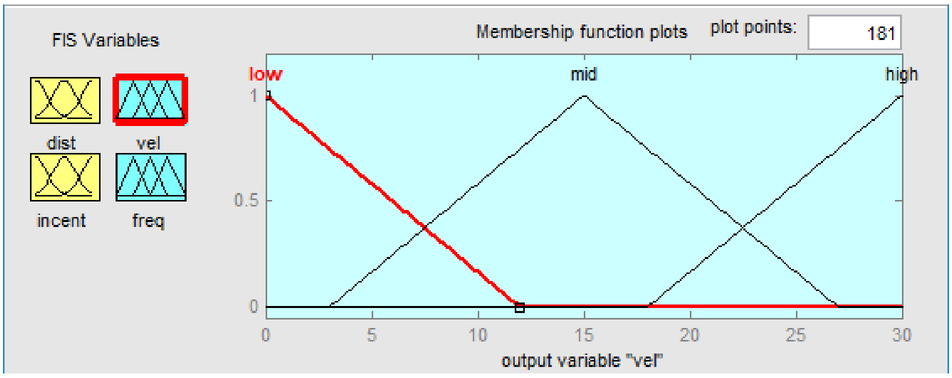
(a)



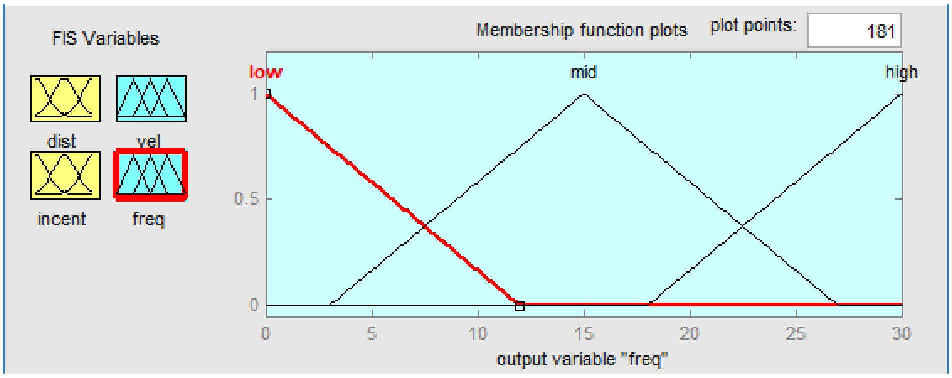
(b)



(c)



(d)



(e)

Figure 5.6 Fuzzy Inference System

Table 5.1 Fuzzy rule set

		Direction Incentive		
		H	M	L
Solution Distance	H	(H)[H]	(H)[M]	(L)[H]
	M	(M)[H]	(M)[M]	(L)[M]
	L	(L)[H]	(L)[M]	(L)[L]

Remark: H = High, M = Middle, L = Low, (*) = Output of search velocity,

[*] = Output of search frequency

When bat $\boldsymbol{x_i}$ updates its position, which means a new solution is generated, the local search process will be performed if the pulse rate $\boldsymbol{r_i}$ is less than a random number with the range [0, 1].

Inspired by the flight pattern of a falcon when it is approaching its prey, where the flight trajectory is a golden spiral (Livio, 2003), a new local search approach is proposed. Firstly, a set of velocity values ($\boldsymbol{\Phi_i}$) is generated based on the Cartesian equations of a golden spiral, which is shown as:

$$x = a \cdot cos\theta \cdot e^{b\theta},\ y = a \cdot sin\theta \cdot e^{b\theta} \tag{5.24}$$

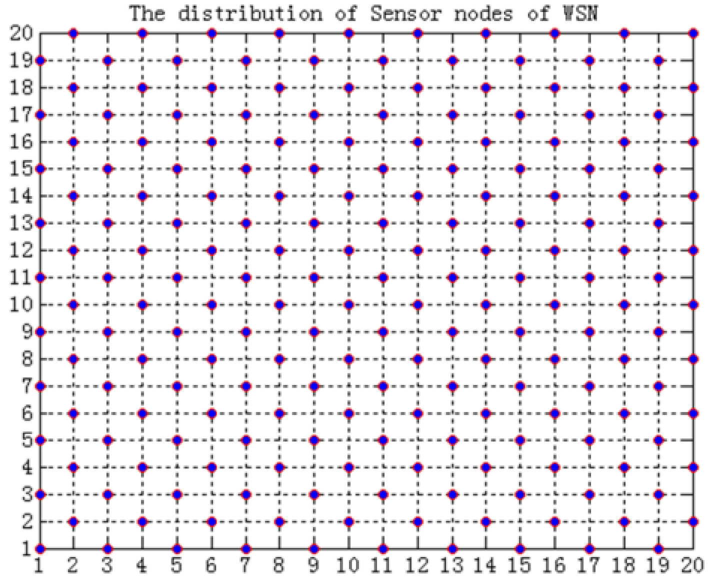
where $\boldsymbol{a}$ is an arbitrary constant, $\boldsymbol{\theta}$ is the angle in radians from the x-axis and **b** is a constant equal to 0.3063489, which is derived from the golden ratio. Next, the local search will be performed by using the function ***kNodeChange***() with the velocity set $\boldsymbol{\Phi_i}$ in a fixed frequency $\boldsymbol{\kappa_l}$.

5.5 Experiment

In this section, the experiment for the proposed model and the results are described. Initially, the region for WSN deployment was set as a 20 by 20 grid with a 1-unit cell size. The base station was placed at the lower left corner. All sensors were homogeneous, with the sensing range $\boldsymbol{r}$ of a sensor node equal to the cell size of the grid and the communication range $\boldsymbol{R}$ twice the sensing range, that is, $\boldsymbol{R} = 2\boldsymbol{r}$. The weight of the four objectives were equal, which $\boldsymbol{\alpha_1} = \boldsymbol{\alpha_2} = \boldsymbol{\alpha_3} = \boldsymbol{\alpha_4} = 1$. Apart from applying the four meta-heuristic approaches (i.e. the GA, *MM*AS, DBA and SBA), the Greedy algorithm was also used in the experiment as a bench-mark in order to compare the performances of the four meta-heuristic approaches. All the tests were developed using MATLAB R2016b and conducted in Windows 7 on a desktop PC with an Intel Core i7-4790 CPU @ 3.6GHz and 16GB of RAM.

Figure 5.7 summarizes the experimental results. In the result for Greedy as shown in Figure 5.7 (a), the required number of sensor nodes was 200 and the fitness value was 3.4875. In the GA approach, the algorithm was run for 100 generations with the crossover rate of 0.75 and mutation rate of 0.1. The population size was set to 300. Figure 5.7 (b) shows the sensor deployment result, in which the number of used sensor nodes was 182 and the fitness value was 3.4473. For the *MM*AS, the parameter settings are listed as follows: $\alpha = 1$, $\beta = 4$, $\rho = 0.5$ and the number of ants placed in the grid was 20. As Figure 5.7 (c) shows, the number of used sensor nodes was 146 and the fitness value was 3.45. For the DBA and SBA, some parameter settings were the same, including $\boldsymbol{\alpha} = \boldsymbol{\gamma} = 0.9$, $\boldsymbol{r_i^0} = [0, 1]$, $\boldsymbol{A_i^0} = [1, 2]$ and the number of artificial bat was 20. The specific settings of the SBA were $\boldsymbol{\varepsilon} = 20$, $\boldsymbol{\lambda} = 5$ and $\boldsymbol{\Gamma} = 6$. For the local search of the SBA, $\boldsymbol{a} = -1$, $\boldsymbol{\theta} = [\pi, 2\pi, 3\pi, 4\pi, 5\pi, 6\pi]$ and $\boldsymbol{\kappa\eta} = 30$. Figure 5.7 (d) shows the sensor deployment result for the DBA, in which the number of used sensor nodes was 185 and the fitness value was 3.459595. Figure 5.7 (e) shows the sensor deployment result for the SBA, in which the number of used sensor nodes was 183 and the fitness value was 3.4875.

Greedy:
Sensor number = 200;
Fitness value = 3.4875;
Coverage rate = 0.9975;
Connective rate = 0.995;
Fault tolerance rate = 0.995;
Cost rate = 0.5.



(a)

GA:

Sensor number =

182;

Fitness value =

3.448022;

Coverage rate =

0.925;

Connective rate =

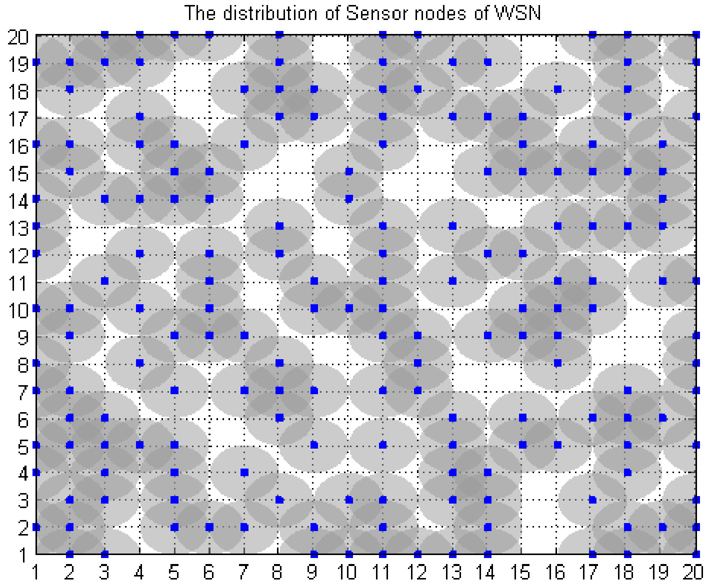
1;

Fault tolerance rate =

0.978022;

Cost rate =

0.545.



(b)

***MM*AS:**

Sensor number =

146;

Fitness value =

3.45;

Coverage rate =

0.815;

Connective rate =

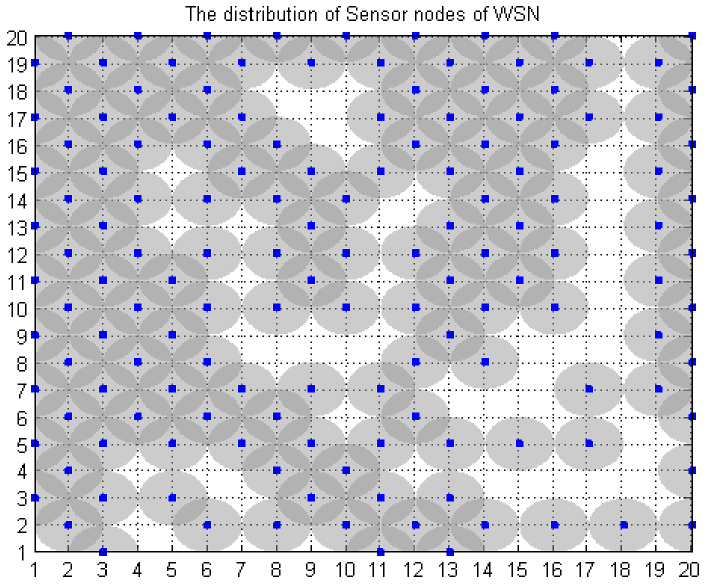
1;

Fault tolerance rate =

1;

Cost rate =

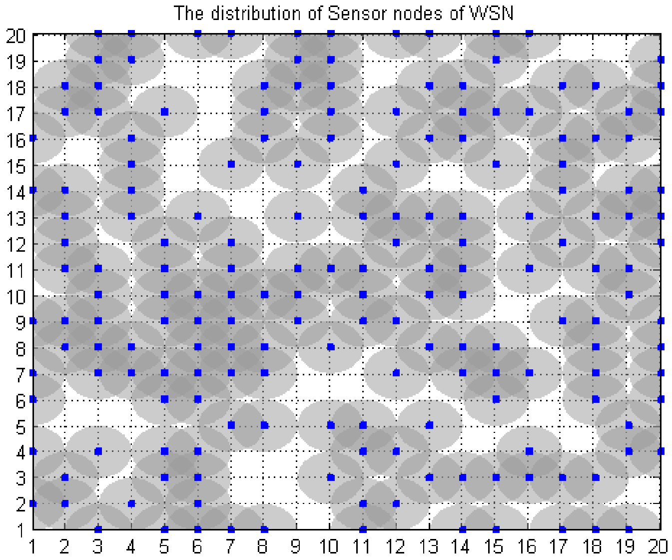
0.635.



(c)

DBA:

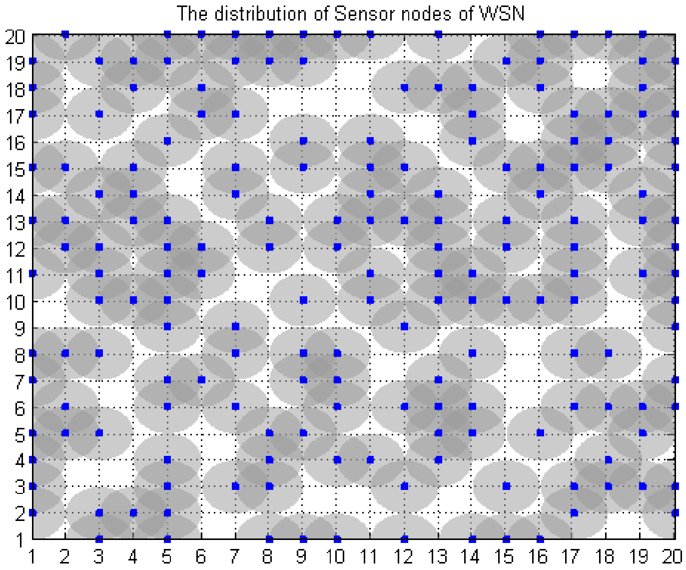
Sensor number =
185;
Fitness value =
3.459595;
Coverage rate =
0.9275;
Connective rate =
1;
Fault tolerance rate =
0.994595;
Cost rate =
0.5375.



(d)

SBA:

Sensor number =
183;
Fitness value =
3.4875;
Coverage rate =
0.945;
Connective rate =
1;
Fault tolerance rate =
1;
Cost rate =
0.5425.



(e)

Figure 5.7 The distribution of sensor nodes by using (a) Greedy, (b) GA, (c) *MM*AS, (d) DBA and (e) SBA

As compared with all the results shown in Figure 5.7, the result of data analysis indicates that the result for Greedy includes the best fitness value, but requires the largest number of sensor nodes. In contrast, the result for the GA requires less sensor nodes, but had a lower fitness value than the result for Greedy. The result for the *MM*AS shows that the least number of sensor nodes is required, and shows a better fitness value than the result for the GA. But the result for the *MM*AS also has the lowest coverage rate. The DBA requires a similar number of sensor nodes to the GA, but a better fitness value than the GA and *MM*AS. The SBA had the highest fitness value as Greedy and less sensor number than Greedy. To sum up, among the four meta-heuristic approaches, the *MM*AS provides a solution with the least number of sensor nodes (i.e. lowest cost), while the SBA provides a solution with the highest fitness value.

5.6 Summary

When designing a WSN, one of the most critical concerns is the energy efficiency which is highly related to the network life time, while another critical concern is the design of the WSN deployment strategy. To effectively design a WSN, a series of factors should be considered. In this chapter, four basic design factors including the total production cost, sensing coverage, network connectivity and fault tolerance are considered. Based on these four factors, a mathematical model is proposed to optimize four corresponding optimization objectives. In the proposed model, these four optimization objectives are combined into one single objective function by using the weighted sum approach. This approach attaches a weighting coefficient to each optimization objective to adjust their importance in the optimization model. To solve the proposed model, four meta-heuristic approaches including the Genetic Algorithm (GA), an Ant Colony Optimization (ACO) based metaheuristics method, called the *MAX–MIN* Ant System (*MM*AS), Discrete Bat Algorithm (DBA) and the proposed Smart Bat Algorithm (SBA) were adopted in the experiment. For better comparison of these four approaches, the Greedy algorithm (Greedy) was also adopted as a benchmark. The results indicated that the *MM*AS and SBA exhibited a satisfactory performance in regard to solving the proposed model, where *MM*AS exhibited an improvement in the number of sensor nodes compared to the result for Greedy, and the proposed SBA delivered the highest fitness value as Greedy. However, the proposed model mainly focuses on homogenous WSNs in 2-D environments, whereas heterogeneous WSNs and 3-D environments, which are more practical situations, may not be considered. Therefore, the next chapter will focus on enhancing the proposed model to cover heterogeneous WSNs and 3-D space.

Chapter 6

Meta-heuristic Approaches for Heterogeneous WSN Deployment in 3-D Environments

6.1 Introduction

With the rapid development of Internet of Things (IoT) in recent years, studies of Wireless Sensor Network (WSN) in academic and industrial fields have increased dramatically over the last decade. Sensor deployment strategy is one of the most significant topics for designing a WSN to be studied. When adopting sensor node deployment strategies, a series of design factors including system lifetime, cost, coverage, connectivity and fault tolerance, should be considered. As revealed in the literature, the deployment of Relay Nodes (RNs) is one of the most effective approaches. RNs usually have much more power, memory and computing capacity, as well as larger communication range than Sensor Nodes (SNs). However, in many cases, determination of the optimal positions of SNs and RNs with consideration of the aforementioned factors is an NP-hard problem. Although many models and strategies have been proposed for SN/RN deployment problems in the literature, many of them only take 2-D environment applications into account. Nowadays, there are increasing numbers of practical applications in 3-D environments such as patient and asset monitoring in hospitals and underwater monitoring, so SN/RN deployment strategies in 3-D environments have drawn much more attention. However, WSN deployment in 3-D environments is challenging and deployment with RNs is even more complicated. In this chapter, a two-stage WSN deployment strategy for SN/RN deployment in 3D environments is proposed by considering five design factors including system lifetime, cost, coverage, connectivity and fault tolerance. For sink node placement, a relay node can be selected to be a sink node by using Equation (4.4) in Chapter 4. To solve this deployment problem, the proposed Smart Bat Algorithm (SBA) is adopted. Furthermore, a Body Centered Cubic (BCC) lattice-based approach and three other meta-heuristic approaches including the Genetic Algorithm (GA), *MAX–MIN* Ant System (*MM*AS) and Discrete Bat Algorithm (DBA) are also adopted for evaluation of the performance of the SBA (Ng et al., 2018a).

6.2 Related Works

In Al-Turjman, Hassanein and Ibnkahla (2013b), the researchers specifically proposed a genetic approach for evaluating the connectivity of 3-D grid-based WSN deployment under realistic aspects (Al-Turjman, Hassanein and Ibnkahla, 2013b). They also formulated 3-D grid-based deployment for SNs, RNs and mobile RNs as a Mixed Integer Linear Program (MILP) optimization problem. In their work, four design factors including lifetime, cost, connectivity and fault tolerance were considered and a two-phase deployment strategy was proposed. The first phase is used to minimize the total energy consumption of a WSN and the second phase is used to fix connectivity and load balancing problems. Near-optimal solutions are obtained by using MATLAB lp-slover with a 15-minute timeout (Al-Turjman et al, 2015). To deal with such deployment problem, adopting meta-heuristic algorithms is also considered as another suitable approach. For example, in Unaldi and Temel (2014), the researchers utilized a multi-objective genetic algorithm (GA) integrated with wavelet transform (WT) and a minimum spanning tree (MST) to solve the problem of maximizing sensor coverage and network connectivity for WSN deployment in 3-D environments (Unaldi and Temel, 2014). The researchers in Al-Turjman , Hassanein and Ibnkahla (2013a) introduced an efficient RN deployment approach called Optimized 3D deployment with Lifetime Constraint (O3DwLC) to optimize the connectivity, lifetime and cost by using a MST and semi-definite programming (Al-Turjman, Hassanein and Ibnkahla, 2013a). To further extend the network lifetime, Ayinde and Barnawi (2014) employed Differential Evolution (DE) to improve O3DwLC. In these research works, only some of the design factors were considered (Ayinde and Barnawi, 2014). To the best of our knowledge, no research work has considered all the five aforementioned factors while adopting meta-heuristic algorithms, specifically, using the Bat Algorithm (BA) based algorithm. Motivated by this observation, we propose a two-stage WSN deployment strategy in 3D environments considering the five aforementioned factors and implementation of the strategy by using the proposed SBA approach.

6.3 The Two-stage Deployment Strategy

In this chapter, a two-stage deployment strategy is proposed, which considers five design factors including system lifetime, cost, coverage, connectivity and fault tolerance. To extend the system lifetime, the approach of addition of RNs is adopted. Therefore, the first-stage strategy is proposed for SN deployment and the second-stage strategy is proposed for RN deployment. Throughout the deployment strategy, a 3-D grid model is used to simulate the region of interest, and Boolean sensing and communication models based on Euclidean distance in 3-D space are applied:

$$d(i,j) = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \tag{6.1}$$

where $(\boldsymbol{x_i}, \boldsymbol{y_i}, \boldsymbol{z_i})$ and $(\boldsymbol{x_j}, \boldsymbol{y_j}, \boldsymbol{z_j})$ are the coordinates of nodes $\boldsymbol{i}, \boldsymbol{j}$.

6.3.1 First stage: Sensor Node (SN) Deployment

In the first stage, the SN deployment is determined by a mathematical model which optimizes two objectives, including the area coverage quality and the cost of deployment. The coverage objective is represented as the ratio of the number of grid points covered by the deployed SNs ($\boldsymbol{p_{cov}}$) and the total number of accessible grid points ($\boldsymbol{p_{tot}}$). The cost objective can be simply defined as 1 minus the ratio of the number of deployed SNs ($\boldsymbol{n_{sdep}}$) and $\boldsymbol{p_{tot}}$. These two objectives are combined by the weighted sum approach, in which a weighting coefficient ($\boldsymbol{\alpha_x}$, $\boldsymbol{\alpha_x} \geq 0$) is attached to each objective to adjust their importance in the objective function. A maximization objective function of the SN deployment is formulated as follows:

$$f_1 = \alpha_1 \left(\frac{p_{cov}}{p_{tot}}\right) + \alpha_2 \left(1 - \frac{p_{sdep}}{p_{tot}}\right) \tag{6.2}$$

6.3.2 Second stage: Relay Node (RN) Deployment

The second stage is designed for the RN deployment. Initially, a condition to ensure that each SN is covered by at least one RN and at most *k* RNs is specified. *k* is the degree of fault tolerance. This condition is a basic requirement for a RN-adopted WSN. Under this condition, the RN deployment model is set up to optimize three objectives, including the connectivity quality, the fault-tolerance quality and the number of deployed RNs. The connectivity objective is represented as the ratio of the number of RNs in the largest connected cover ($\boldsymbol{n_{conn}}$) to the total number of deployed RNs ($\boldsymbol{n_{rdep}}$). The fault-tolerance objective can be represented as the ratio of the number of RNs with a desired degree of fault tolerance ($\boldsymbol{n_{ft}}$) to the total number of deployed RNs ($\boldsymbol{n_{rdep}}$). The degree of fault tolerance refers to the number of node-disjoint paths between each pair of RNs (*k*-connected RNs). The last objective is the minimization of cost which is 1 minus the ratio of the number of deployed RNs ($\boldsymbol{n_{rdep}}$) to the total number of possible RN positions ($\boldsymbol{n_{rpos}}$). These objectives are combined by attaching a weighting coefficient ($\boldsymbol{\alpha_x}$, $\boldsymbol{\alpha_x} \geq 0$) to each objective in the maximization objective function which is defined as follows:

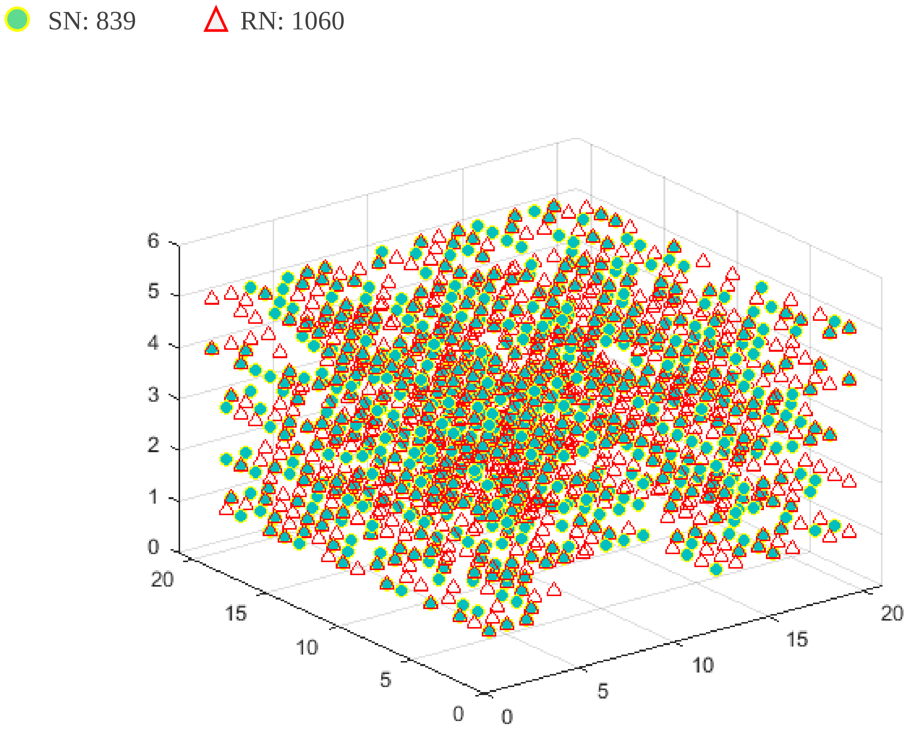
$$f_2 = \alpha_3\left(\frac{n_{conn}}{n_{rdep}}\right) + \alpha_4\left(1 - \frac{n_{ft}}{n_{rdep}}\right) + \alpha_5\left(1 - \frac{n_{rdep}}{n_{rpos}}\right) \tag{6.3}$$

6.4 Experiment

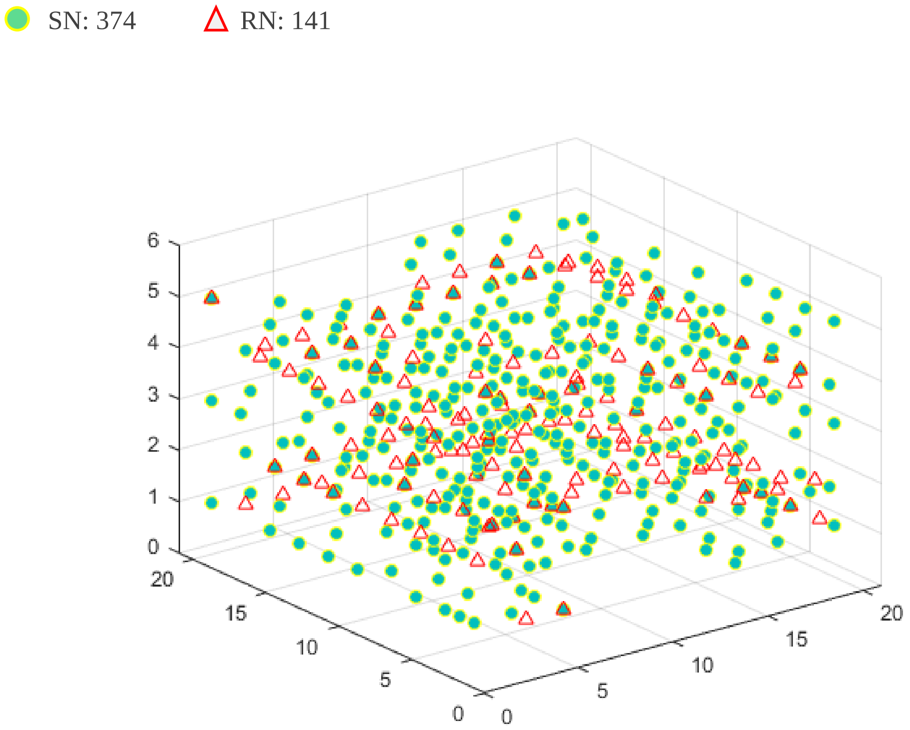
In this section, simulation tests for the proposed deployment strategy and SBA approach are explained. All the tests were developed using MATLAB R2016b and conducted in Windows 7 on a desktop PC with an Intel Core i7-4790 CPU @ 3.6GHz and 16GB of RAM. In these tests, three meta-heuristic methods including the GA, *MM*AS, and DBA were utilized for comparison with the SBA. For a better evaluation of these four algorithms, a benchmark was set up by using a Body Centered Cubic (BCC) lattice-based approach. The BCC-based approach can provide the best sphere covering result in a 3-D space (Commuri and Watfa, 2006). In this simulation, the BCC-based approach only considers the coverage and connectivity. Thus, when the required degree of fault tolerance increases, this approach cannot provide satisfactory results. This effect is reflected in Table 6.4. The performance of these algorithms was examined in three aspects: different grid sizes, different sensing and communication (S:C) ratio, and different degrees of fault tolerance (*k*). Throughout the tests, the weighting coefficients used in the first stage of deployment were: $\alpha_1 = \alpha_2 = 0.5$, and the coefficients used in the second stage of deployment were: $\alpha_3 = 0.3$, $\alpha_4 = 0.3$ and $\alpha_5 = 0.4$. All tests were executed using 100 iterations except the test for identical execution time. This identical time was set as the time for the SBA to run 100 iterations. Except the test with the grid size of 10x10x5, all the tests had an obstacle with the size of 5x5x5 in the grid model.

The chromosome encoding and parameter settings of the GA were referenced from related work of Ferentinos and Tsiligiridis (2007). Each gene in the first stage of deployment represents the state of the sensor placement of a grid point, and each gene in the second stage of deployment represents positions of RNs covered by a sensor node. The other settings of the GA included: population size = 200, one-point crossover with probability = 0.75 and classical mutation with probability = 0.1. The settings of the *MM*AS included $\boldsymbol{\rho} = 0.5$, $\boldsymbol{\alpha} = 1$, $\boldsymbol{\beta} = 4$ and the number of artificial ants = 20. For the DBA and SBA, some settings were shared, including $\boldsymbol{\alpha} = \gamma = 0.9$, $\boldsymbol{r_i^0} = [0, 1]$, $\boldsymbol{A_i^0} = [1, 2]$ and the number of artificial bats was 20. There were some specific settings of the SBA, which were $\boldsymbol{\varepsilon} = 20$, $\boldsymbol{\lambda} = 5$ and $\boldsymbol{\Gamma} = 6$. In the local search of the SBA, $\boldsymbol{\Phi}$ is generated by using the $\boldsymbol{x}$ values in the golden spiral equation with $\boldsymbol{a} = -1$, $\boldsymbol{\theta} = [\pi, 2\pi, 3\pi, 4\pi, 5\pi, 6\pi]$ and $\boldsymbol{\kappa_l} = 30$. The reason for only using the $\boldsymbol{x}$ values is that the solution space actually has no axis and the SBA only considers the solution distance; therefore, the approximate $\boldsymbol{x}$ value can be taken as the distance when the $\boldsymbol{y}$ value is close to 0.

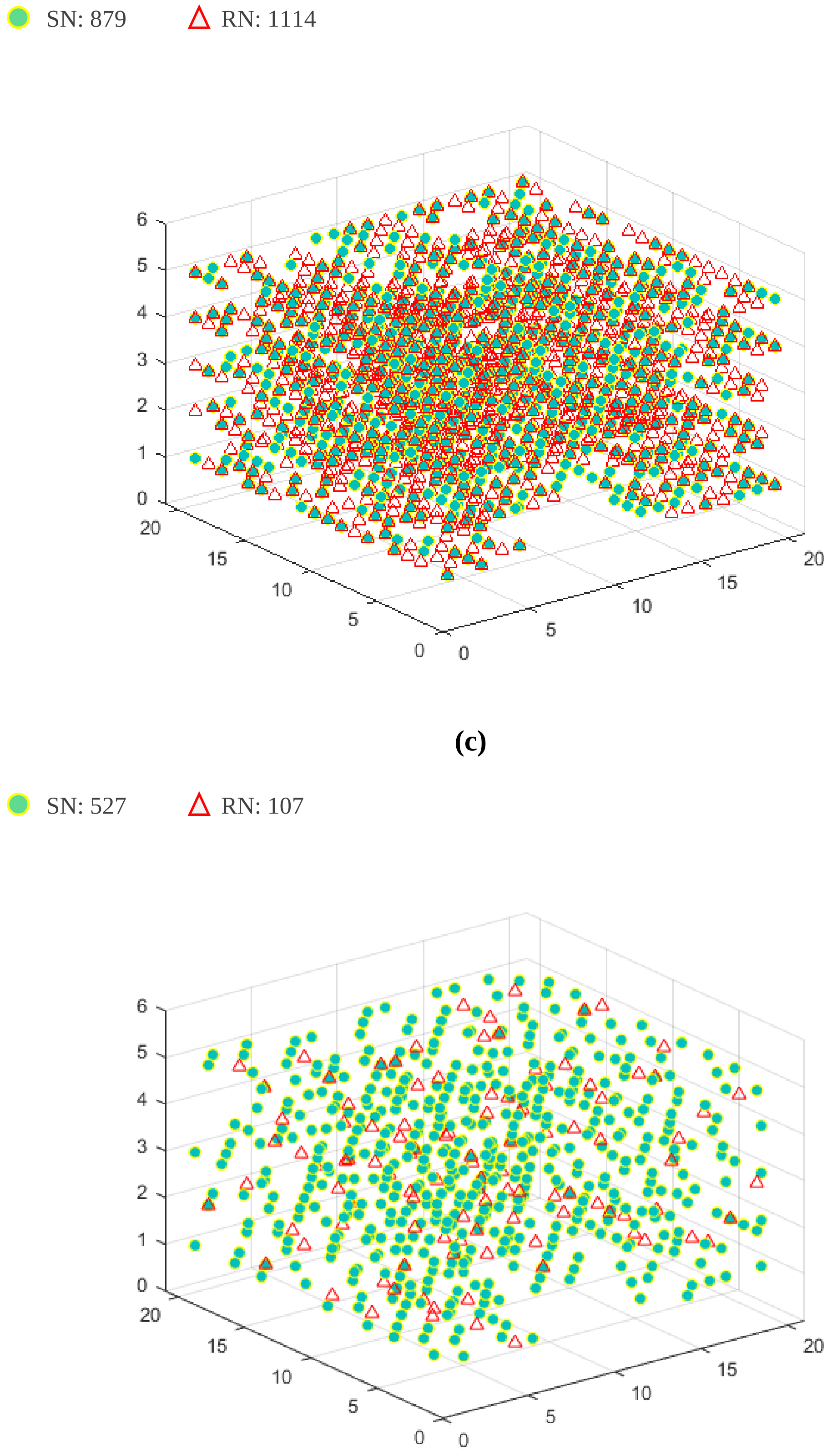
Finally, seven tests were conducted in the experiment. The results of the eight tests are summarized in Tables 6.1, 6.2, 6.3 and 6.4. In the tables, $\boldsymbol{t}$(s) refers to the average running time (in seconds) per agent and $\boldsymbol{n}$ is the iteration number. Figure 6.1 illustrates the distribution of sensor nodes and relay nodes with basic environmental settings, i.e. grid size = 20x20x5, S:C = 1:2 and $k = 2$. In the figure, both the GA and DBA provided solutions with dense SNs and RNs, and the number of RNs was even larger than the number of SNs. In contrast, the results for the *MM*AS and SBA required much less SNs and RNs, and ratio of the number of SNs to RNs (SN/RN ratio) was more reasonable, where the number of RNs was smaller than the number of SNs. The solution of the *MM*AS required the least SNs, but more RNs than the SBA. The SBA provides a solution with the least RNs and higher SN/RN ratio, where the SBA was 529 / 107 = 4.94 and the *MM*AS was 336 / 141 = 2.38. This higher SN/RN ratio indicates that SBA requires less RNs to manage all the SNs while simultaneously fulfilling the fault tolerance requirement. Moreover, although the SBA required more SNs, it provided the best coverage rate among the four approaches as shown in Table 6.1. Therefore, the result implies that the SBA provides better-quality solutions than the *MM*AS, as well as the GA and DBA.


● SN: 839
△ RN: 1060
0
1
2
3
4
5
6
20
15
10
5
0
0
5
10
15
20

(a)


● SN: 374
△ RN: 141
0
1
2
3
4
5
6
20
15
10
5
0
0
5
10
15
20

(b)



(c)

(d)

Figure 6.1 The distribution of sensor nodes by using (a) GA, (b) *MM*AS, (c) BA and (d) SBA

For the eight tests, Table 6.1 shows the results of the tests of identical iterations and identical execution time with the settings of grid size = 20x20x5, S:C = 1:2 and *k* = 2. Table 6.2 summarizes the results of the tests when the grid size is changed, i.e. grid size = [10x10x5, 40x40x10]. Table 6.3 presents the results of the tests when the S:C ratio is changed, i.e. S:C = [1:1, 2:1]. Lastly, Table 6.4 contains the results of the tests when the degree of fault tolerance is changed, i.e. *k* = [4, 6]. In all the results (i.e. Tables 6.1-6.4), all the four meta-heuristic algorithms obtained very high values for obj3 (RN connectivity) and obj4 (RN fault tolerance). This is benefited from the proposed condition in the second stage of deployment. Moreover, the results for the GA and DBA were relatively poorer, the main reason being that the values obtained for obj2 and obj5 were lower, which means that greater numbers of SNs and RNs are required. In contrast, the results for the *MM*AS and SBA were close to the results for the BCC (i.e. the benchmark). Among the four algorithms, the *MM*AS performed the best for obj2 and the SBA performed the best for obj5. But, more significantly, the SBA provided more robust and high-quality results when the execution settings (i.e. number of iterations, execution time, grid size, S:C ratio and degree of fault tolerance) were changed. The only drawback of the SBA is that its time overhead is relatively larger than for the GA and *MM*AS.

Table 6.1 Results of the tests with grid size=20x20x5, S:C=1:2, *k*=2

	Identical iterations					Identical execution time				
	BCC	GA	MMAS	DBA	SBA		GA	MMAS	DBA	SBA
obj1	1.000	0.979	0.925	0.986	0.997	obj1	0.978	0.916	0.991	0.997
obj2	0.770	0.581	0.813	0.561	0.737	obj2	0.583	0.819	0.559	0.737
f_1	0.885	0.780	0.869	0.773	0.867	f_1	0.781	0.867	0.775	0.867
obj3	1.000	1.000	1.000	1.000	1.000	obj3	1.000	1.000	1.000	1.000
obj4	1.000	1.000	1.000	1.000	1.000	obj4	1.000	1.000	1.000	1.000
obj5	0.974	0.427	0.924	0.398	0.942	obj5	0.431	0.924	0.392	0.942
f_2	0.989	0.771	0.969	0.759	0.977	f_2	0.773	0.969	0.757	0.977
t(s)	-	0.017	0.206	8.540	0.999	n	598	486	12	100

Table 6.2 Results of the tests with different grid size, S:C=1:2, *k*=2

	10x10x5 (without obstacle)					40x40x10				
	BCC	GA	MMAS	DBA	SBA	BCC	GA	MMAS	DBA	SBA
obj1	1.000	0.982	0.968	0.984	0.982	1.000	0.989	0.783	0.990	0.995
obj2	0.750	0.572	0.778	0.572	0.748	0.752	0.519	0.863	0.509	0.701
f_1	0.875	0.779	0.873	0.778	0.865	0.876	0.754	0.823	0.750	0.848
obj3	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
obj4	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
obj5	0.960	0.466	0.926	0.438	0.944	0.981	0.383	0.923	0.370	0.945
f_2	0.984	0.786	0.970	0.775	0.978	0.992	0.753	0.969	0.748	0.978
t(s)	-	0.004	0.057	0.535	0.557	-	0.948	2.328	220.4	38.49

Table 6.3 Results of the tests with grid size=20x20x5, different S:C, *k*=2

	S:C = 1:1					S:C = 2:1				
	BCC	GA	MMAS	DBA	SBA	BCC	GA	MMAS	DBA	SBA
obj1	1.000	0.979	0.917	0.993	0.997	1.000	1.000	0.999	1.000	0.999
obj2	0.770	0.582	0.815	0.558	0.739	0.907	0.579	0.949	0.576	0.924
f_1	0.885	0.780	0.866	0.775	0.868	0.954	0.789	0.974	0.788	0.962
obj3	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
obj4	1.000	1.000	1.000	1.000	1.000	0.996	1.000	0.991	1.000	0.996
obj5	0.852	0.388	0.700	0.361	0.822	0.754	0.386	0.631	0.377	0.749
f_2	0.941	0.755	0.880	0.744	0.929	0.901	0.754	0.850	0.751	0.898
t(s)	-	0.026	0.106	8.899	1.03	-	0.045	0.394	13.92	0.708

Table 6.4 Results of tests with grid size=20x20x5, S:C=1:2, different *k*

	$k = 4$					$k = 6$				
	BCC	GA	MMAS	DBA	SBA	BCC	GA	MMAS	DBA	SBA
obj1	1.000	0.983	0.902	0.988	0.993	1.000	0.983	0.903	0.988	0.999
obj2	0.770	0.580	0.826	0.570	0.745	0.770	0.573	0.822	0.563	0.739
f_1	0.885	0.782	0.864	0.779	0.869	0.885	0.778	0.863	0.775	0.869
obj3	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
obj4	0.776	1.000	1.000	1.000	1.000	0.000	1.000	1.000	1.000	1.000
obj5	0.974	0.183	0.922	0.159	0.945	0.974	0.075	0.921	0.061	0.930
f_2	0.922	0.673	0.969	0.664	0.978	0.689	0.630	0.968	0.624	0.972
t(s)	-	0.036	0.180	10.52	1.128	-	0.048	0.176	5.818	1.435

6.5 Summary

Wireless Sensor Network (WSN) deployment in 3-D environments with an optimal balance of system lifetime, cost, coverage, connectivity and fault tolerance is a challenging task. Current studies on this task are still very rare. As revealed by the literature, the approach of deployment of Relay Nodes (RNs) in a WSN is one of the most effective approaches for maintaining a long system lifetime of a WSN. Therefore, this approach was adopted in this research to deal with the factor of system lifetime. Considering four other design factors and the deployment of both Sensor Nodes (SNs) and RNs, a two-stage deployment strategy is proposed in this chapter. In the first stage of deployment, SNs are placed in the region of interest while considering the sensing coverage and the deployment cost in terms of number of SNs. In the second stage of deployment, RNs are placed in the sensor monitoring region formed in the first stage of deployment. When deploying RNs in the second stage, some objectives are taken into account. These objectives include the communication coverage of SNs, network connectivity quality of all RNs, fault tolerance quality and the deployment cost in terms of the number of RNs. To implement the strategy, the SBA is proposed to be adopted. The performance of the SBA was evaluated by comparing the implementation results for the three other meta-heuristic algorithms, the GA, MMAS, and DBA, and the benchmark results of the BCC approach. The simulation results indicate that the SBA delivers better and more robust solutions compared to the three other popular meta-heuristic algorithms. Future work will extend the tests to reducing the time overhead of the SBA and parallel computing techniques will be employed in the SBA, especially in large-scale applications

Chapter 7

Discussion

According to the review of the background of Biological and Pharmaceutical (B&P) products' storage, the monitoring system for monitoring the status of B&P products is required to be more sophisticated and comprehensive. The monitoring range of the system is required to cover all the B&P products and the product statuses should be able to be reported in real time and queried at any time. Moreover, the system should be capable of a high degree of fault tolerance in order to ensure that the monitoring system can be operated in a 24/7 manner. To fulfil these needs, Wireless Sensor Network (WSN) was adopted in this research for the establishment of a B&P product monitoring system. When designing a WSN deployment strategy, a series of design factors such as system lifetime, cost, coverage, connectivity and fault tolerance, should be considered. Responding to these requirements, this research work proposed two approaches for the optimal deployment of WSNs.

The first approach is a statistics-based deployment strategy, which is a systematic and easy-to-implement approach for the deployment of Sensor Nodes (SNs), sink and Relay Nodes (RNs). However, this approach requires a relatively large amount of historical area usage data to support the construction of an area usage distribution model, which is used for calculation of the additional number of relay nodes. If no history data are provided, a long period of time is needed for data collection. For a long running time, this approach also requires a regular data collection operation of inventory storage locations to fine-tune the deployment locations of nodes in WSNs. This may generate additional workload for the operators of the system. Moreover, the proposed deployment algorithm of both SNs and RNs is mainly based on a greedy algorithm, which only considers the sensing coverage and network connectivity. An optimal result in terms of the number of deployed nodes may not be guaranteed, which implies that the total implementation cost of a WSN system using the proposed approach may not be well justified. Therefore, the second WSN deployment approach is proposed.

The second proposed approach is a meta-heuristic algorithm, called the Smart Bat Algorithm (SBA) to balance the trade-offs between the aforementioned basic WSN design factors. In this research, both homogenous node deployment in a 2-D environment and heterogeneous node deployment in a 3-D environment of WSN were studied. For the deployment in 2-D space, the experiments showed that the

SBA provides the same fitness value as the benchmark approach, i.e. the Greedy algorithm, but required less sensor number. This result for the SBA is the best solution among the other three meta-heuristic algorithms, i.e. the Genetic Algorithm (GA), an Ant Colony Optimization (ACO) based metaheuristics method called the *MAX–MIN* Ant System (*MM*AS), and a modified Bat Algorithm (BA) named the Discrete Bat Algorithm (DBA). For the deployment in a 3-D environment, this research proposed a two-stage WSN deployment strategy and implemented this strategy by using the proposed SBA. To evaluate the performance of SBA, four implementations were developed for comparison with the SBA. Three implementations were developed by using the aforementioned three meta-heuristic algorithms respectively, and one implementation for benchmarking was developed by using the Body Centered Cubic (BCC) lattice-based approach, whereby the BCC can provide the best sphere covering result in a 3-D space. In the experiments, the results for the GA and DBA were relatively poorer because of the larger required number of SNs and RNs. More critically, the required RNs were more than the required SNs. This outcome is due to the condition defined in the second phase of deployment of the proposed deployment strategy, in which each sensor node is required to be covered by at least one relay node. The program of the GA and DBA will randomly generate a set of valid relay nodes for each sensor node in the initialization stage, which causes the solution searching space to become extremely huge. The GA and DBA may not be able to generate an acceptable solution within the predefined iterations (i.e. 100 iterations). To improve this consequence, an upper boundary of the possible relay nodes for each sensor node, equal the degree of fault tolerance (k), was set. This upper boundary further specifies the condition to ensure that each sensor node is covered by at least one relay node and at most k relay nodes. In contrast, the results for the *MM*AS and SBA were better than for the GA and DBA, which were close to the results for the BCC approach (i.e. the benchmark). Among these two algorithms, the *MM*AS required less computing time overhead for the generation of the results. This is due to the characteristics of the *MM*AS, in which each artificial ant constructs a close-to-optimal solution as its initial path from its nest and food source using a heuristic methods. However, the drawbacks can be observed obviously in the experiments. When the execution parameters such as number of iterations, execution time, grid size, sensing and communication ratio, and degrees of fault tolerance were changed, the *MM*AS failed to consistently provide as robust and high-quality results as the results provided by the SBA.

Chapter 8

Overall Conclusion

Biological and pharmaceutical (B&P) products are essential in modern life. Currently, the demand for and requirements of these products are dramatically growing; product quality and integrity then become crucial. As a key factor for ensuring quality and integrity, the current product status monitoring system needs to be enhanced in a more sophisticated and comprehensive way. This thesis describes the design of a RFID-enabled WSN monitoring system for B&P products' storage. As the major functionalities of the proposed monitoring system for B&P products mostly rely on sensor technologies, designing a WSN was the core part of this research. Wireless Sensor Network (WSN) is an emerging technology in recent years. It possesses high capacities to be applied in many applications of various areas such as military, environment, health, home, and industry. However, adopting WSN technology requires consideration of a series of basic design factors, including production cost, energy efficiency, sensing coverage, network connectivity and fault tolerance. These design factors are interrelated and there are trade-offs between them. Many researchers have proposed different approaches to properly balance the trade-offs between such significant design factors. However, few of them take all the basic design factors into account, especially considering the production cost together with the fault tolerance. To effectively deploy a WSN, two approaches are proposed to deal with this deployment problem. The first approach is a three-stage framework based on statistical methods. This approach uses a heuristic and statistical method to determine the placements of sensors, relay nodes, sink and the additional relay nodes needed in a region of interest. In the second approach, two deployment situations were examined. The first one is the deployment of homogeneous sensor nodes in a 2-D environment. In this situation, four objectives include the sensing coverage, the network connectivity, the production cost and fault tolerance need to be optimized. To fulfil these objectives, an optimization model was established by using the weighted sum approach. Then, a meta-heuristics algorithm, named the Smart Bat Algorithm (SBA) was proposed to solve the model. The SBA was designed based on the Bat Algorithm (BA) and integrated with the Fuzzy Inference model and decision-theoretical technique in order to determine a rational searching direction, velocity and frequency of artificial bats. To evaluate the performance of the SBA, several optimization approaches including the Greedy Algorithm, Genetic Algorithm (GA), an Ant Colony Optimization (ACO) based metaheuristics optimization method called the MAX–MIN Ant System (MMAS) and a modified Bat Algorithm (BA) named the

Discrete Bat Algorithm (DBA), were used to solve the model. The simulation result shows that the SBA provides a better WSN deployment plan when considering the four objectives. The second situation is a more realistic situation of WSN deployment, which is placing sensor nodes and relay nodes in a 3-D environment and considering the presence of obstacles. The proposed solution adopts two-stage deployment approaches. In the first stage, sensor nodes are deployed to satisfy two objectives of cost and sensing coverage. In the second stage, relay nodes are deployed afterward to satisfy three objectives including cost, network connectivity and fault tolerance. The simulation result shows that the SBA provides more robust and higher-quality results than the GA, *MM*AS and DBA.

The contributions of this thesis are summarized as follows. Firstly, this thesis utilized a relatively objective, quantitative and systematic approach, called semantic similarity analysis for examination of the intellectual structure of IoT in order to provide good justification for the rationale and appropriate adoption of RFID and WSN in the proposed monitoring system. Secondly, a four-layer system architecture was proposed as a flexible and scalable base for a B&P product monitoring system as well as other related information technology systems. Thirdly, a statistical additional relay node approach was proposed to achieve a certain degree of fault tolerance for a heterogeneous WSN monitoring system in a B&P products’ warehouse. Fourthly, a two-stage WSN deployment strategy was proposed for the heterogeneous WSN deployment in a 3D environment with obstacles. Lastly, a BA-based meta-heuristics algorithm, named the Smart Bat Algorithm (SBA) was proposed for solving WSN deployment optimization models, which consider multiple objectives including sensing coverage, network connectivity, fault tolerance and production cost. The experimental results indicated that the SBA delivered high-quality and robust solutions for both homogenous WSN deployment in 2-D environments and heterogeneous WSN deployment in 3-D environments.

Chapter 9

Suggestions for Further Research

As the proposed optimization model was established based on some simplified conditions, including homogeneous sensor nodes, Boolean sensing and communication models, future research is suggested to focus on considering more practical conditions in the WSN deployment optimization model. Firstly, the wireless sensor nodes in reality have different sensing ranges, communication ranges and power consumptions; thus, heterogeneous sensor nodes should be considered instead of homogenous sensor nodes in future optimization models. Secondly, the node failure prediction model is suggested to take a series of other factors, such as battery discharge rate, battery degradation rate, packet delivery success rate and hardware failure probability, into account together with the basic design factors focused on in this research. Secondly, the sensing and communication models are suggested to adopt more practical ones. For example, the probabilistic sensing model can be adopted for the sensing model, and the log-normal shadowing communication model can be adopted for the communication model. Moreover, practical case studies are suggested to be conducted for making the proposed system and proposed optimization model more applicable in various industries, and further improving the proposed system and model.

In this research, fault tolerance measure in terms of adding redundant nodes in the WSN was used for preventing system failure and ultimately extending the system’s lifetime. However, redundant nodes inevitably increase the product cost of the system. Furthermore, fault tolerance is a preventive measure based on the estimation of the potential failures, which implies it cannot deal with unexpected failures. For example, when sensor nodes, relay nodes and redundant relay nodes in part of a monitored area are damaged because of disasters such as earthquake and flooding, the monitoring system may fail since the network backbone may be damaged, which is because the damaged relay node cannot route data anymore. Therefore, another suggested research direction is to extend the proposed system to a resilient WSN monitoring system. Resilience refers to “a property of the system on how the system can still function to a desired level when the system suffers from a partial damage” (Zhang, 2007). The differences between fault tolerance and resilience are summarized in Table 9.1. To add the resilience property into the RFID-enabled WSN monitoring system, network connection reconstruction and deployment of a mobile sink or mobile relay nodes can be possible future research directions.

Table 9.1 The differences between fault tolerance and resilience

	Fault tolerance	**Resilience**
Nature	Preventive measure against faults	System property against partial damage
Component damage	May Not	Yes
Function/role change of Component	No	Yes
Redundancy	Component	Functional

Nowadays, RFID, WSN and the related technologies are developing in the direction of Internet of Things (IoT) which refers to the networks formed by objects surrounding us and it contains three paradigms which are internet-oriented (i.e. middleware), things-oriented (i.e. sensors) and semantic-oriented (i.e. knowledge) (Gubbi et al., 2013). The development of IoT is also integrated with cloud computing. Cloud computing is a computing and Internet service model for the current and coming development of Information Technologies (IT). It consists of three basic service models which are Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS) (Buyya et al., 2009). In order to integrate the proposed system with current and future backend systems and enhance the flexibility and generality, the system architecture described in Chapter 3 is proposed to be expanded based on the IoT framework. Figure 9.1 shows the new proposed system architecture. The data acquisition process of WSN and RFID technologies resides in the sensing layer and the collected data are passed to the cloud computing platform through the network layer. In the network layer, the IoT middleware acts as a translator where the data coming from the sensing layer are repackaged into a general format so that the backend system can be processed and sent to the cloud computing platform. In addition, the IoT middleware also performs low level hardware and data management such as hardware configuration, hardware interfacing, data filtering and data aggregation. The core modules (i.e. Data Integration and Analysis Core, Wireless Sensor Network Management Module and Decision-Making Module) of the proposed system are deployed on the cloud computing platform. In addition, data storage and visualization can also be performed on the platform. In the application layer, the service provided by the cloud computing platform can be used in different applications. In this research, the applications in B&P product monitoring and B&P product tracing and tracking in the supply chain may be given precedence over all others.

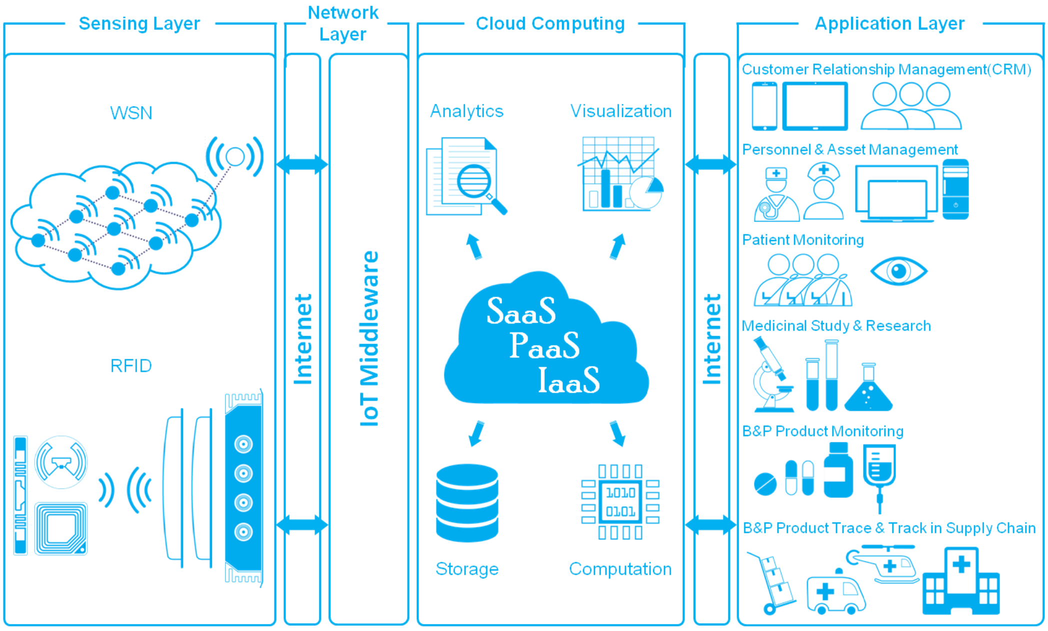


Figure 9.1 Expanded System Architecture

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