EMBEDDED DUAL BAND RFID BASED BLOOD GLUCOSE MONITORING SYSTEM FOR INTERNET OF MEDICAL THINGS

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EMBEDDED DUAL BAND RFID BASED BLOOD GLUCOSE MONITORING SYSTEM FOR INTERNET OF MEDICAL THINGS

by

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LIST OF ABBREVIATIONS

ACK	acknowledgement
ADAPT	ADaptive Access Parameters Tuning
ANOVA	Analysis of variance
AODV	Ad hoc On-demand Distance Vector
AP	antenna polarization
API	Application Programming Interface
APL	Application
APS	Application Support
ASK	Amplitude-shift keying
AT	Transparent
BE	Backoff Exponent
BEn	Beacon-enabled
BI	Beacon Interval
BG	Blood glucose
BGM	Blood glucose monitoring
BGMD	Blood glucose monitoring device
BGMS	Blood glucose monitoring system
BO	Beacon Order
CAP	contention access period
CCA	Clear Channel Assessment
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CV	Coefficient of variation
DM	Diabetes mellitus
DOE	Design of experiment
DR	Delivery ratio
DRBGM	Dual band RFID Based Blood Glucose Monitoring
DUT	Device under test
ECC	Event Chains Computation
EEPROM	Electrically Erasable Programmable Read-Only Memory
ECG	electrocardiogram

EN-CSMA/CA	Enhancement Unslotted CSMA/CA
EPC	Electronic Product Code
FDA	Food and Drug Administration
FFD	Full-Function Devices
GND	Ground
GPIO	General-Purpose Input/Output
GSM	Global System for Mobile communications
GUI	Graphical User Interface
HTTP	Hyper Text Transfer Protocol
ID	Identification
IEEE	Institute of Electrical and Electronics Engineers
I-MAC	Hybrid MAC protocol using interrupt mechanism
IoT	Internet of Things
IoMT	Internet of Medical Things
IPH	Institute of Public Health
I2C	Inter-Integrated Circuit
ISO	International Organization for Standardization
ISM	Industrial, Scientific, and Medical
ISP	Internet Service Provider
IVGTT	Intravenous Glucose Tolerance Test
LCD	Liquid Crystal Display
LIFO	Last-In-First-Out
LoS	Line of Sight
M2M	Machine-to-machine
MAC	Medium Access Control
MAUDE	Manufacturer and User Facility Device Experience
MBDOE	Model-based design of experiment
MCMC	Malaysian Communications and Multimedia Commission
MOH	Ministry of Health
NB	Number of Backoffs
NBE	on-beacon-enabled
NHMS	National Health Morbidity Survey
NoEN	Number of end nodes
NoH	Number of hops

NLoS	Non Line of Sight
NHSLA	National Health Service Litigation Authority
NWK	Network
P2P	Point-to-point
PAN	Personal Area Network
PAR	Passive and Active RFID
PC	Personal Computer
PCB	Printed Circuit Board
PCD	Portable communication device
PD	Power Divider
PDA	Personal Digital Assistant
PDR	packet delivery ratio
PHP	Hypertex Preprocessor
PHY	Physical layer
PID	Patient identification
PLO	Path loss
PL	Power level
PLR	Packet Loss Rate
PoC	Proof of Concept
PWM	Pulse width modulation
QoS	Quality of Service
REQ	Request
RF	Radio Frequency
RFD	Reduced-Function Devices
RFID	Radio Frequency Identification
RSSI	Received Signal Strength Indicator
RTC	Real-time clock
RTF	Reader-Talk-Fist
RX	Data Receive
SA	Spectrum Analyser
SDEV	Standard deviation
SD	Superframe Duration
SIM	Subscriber Identification Module
SG	Signal generator

SN	Number of Sleep Periods
SO	Superframe Order
SP	Sleep Period
TCP	Transmission Control Protocol
THIS	Total Hospital Information System
TTF	Tag-Talk-First
TUT	tag under test
TX	Data Transmit
UART	Universal Asynchronous Receiver/Transmitter
UCSMA	Unslotted CSMA/CA probabilistic polling
UDP	User Datagram Protocol
UHF	Ultra High Frequency
UiTMPP	UiTM Pulau Pinang
USB	Universal Serial Bus
USSD	Unstructured Supplementary Service Data
USP	User Services Platform
VB	Visual Basic
WBAN	Wireless Body Area Network
WHO	World Health Organization
Wi-Fi	Wireless fidelity
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network
ZC	ZigBee Coordinator
ZDO	Zigbee Device Object
ZED	Zigbee End Device
ZR	Zigbee Router

SISTEM PEMANTAUAN GLUKOSA DARAH BERASASKAN RFID DWI JALUR TERBENAM UNTUK INTERNET KEBENDAAN PERUBATAN

ABSTRAK

Maklumat kesihatan yang direkodkan secara manual boleh menyebabkan kesilapan seperti pengenalpasti pesakit dengan tidak tepat dan salah memadankan data pesakit yang boleh menjejaskan keselamatan pesakit dengan serius. Untuk mengurangkan risiko kesilapan kepada pesakit diabetes, satu reka bentuk sistem pemantauan glukosa darah tanpa wayar dengan pembenamam RFID dwi jalur untuk Internet Kebendaan Perubatan telah dibangunkan. Dengan menggunakan kaedah ini, RFID pasif membolehkan komunikasi jarak dekat untuk membaca nombor pengenalan pesakit dan RFID aktif memanjangkan komunikasi jarak jauh untuk merekod dan memantau data glukosa darah wayar melalui rangkaian berbilang hop. Kerja yang dibentangkan dalam tesis ini menyumbang terutamanya kepada sistem terbenam dan aplikasinya dalam penjagaan kesihatan untuk mengurangkan beban merekod, mengesan dan memantau data pesakit dengan membenamkan sensor glukosa darah, RFID pasif, RFID aktif, WSN, M2M dan IoMT ke dalam satu platform. Konsep reka bentuk baru diwujudkan untuk mekanisme pengecaman pesakit, di mana mekanisme itu dibenamkan ke dalam peranti sumber untuk meningkatkan keupayaan sistem menetapkan nombor pengenalan secara automatik kepada setiap pengukuran glukosa darah (mmol/L) semasa pemantauan berbilang pesakit. Selain itu, keputusan dari eksperimen yang dijalankan menunjukkan bahawa sistem yang dibangunkan menghasilkan prestasi keseluruhan yang lebih baik berbanding dengan system BGM Bluetooth dan sistem BGM konvensional dari segi masa rakaman terpendek dan keupayaan penghantaran semula data. Dalam analisis

kebolehpercayaan dengan menggunakan kaedah statistik ANOVA dan DOE, mengesahkan bahawa bilangan hop dan bilangan nod akhir memberikan kesan ketara kepada prestasi PDR CSMA/CA konvensional. Kedua-dua parameter ini kemudiannya diambil kira dalam persediaan eksperimen untuk menilai prestasi algoritma CSMA/CA yang dipertingkatkan (EN-CSMA/CA), yang menggunakan mekanisme interupsi luaran dan pendekatan berasaskan lapisan silang. PDR meningkat daripada 94% (CSMA/CA konvensional) kepada 99.33% (EN-CSMA/CA), iaitu peningkatan 5.33%. Model PDR menganggarkan bahawa untuk senario terbaik dan paling teruk, peratusan PDR adalah 100.0% dan 51.67%, masing-masing. Untuk mengoptimumkan penyusunan penghala bagi perlaksanaan sebenar sistem DRBGM di kemudahan kesihatan, model kehilangan laluan yang dibangunkan menganggarkan bahawa penghala harus diletakkan pada jarak 30 m antara satu sama lain, yang disepakati dengan hasil ujian yang menunjukkan kedudukan penghala harus ≤ 40 m untuk mencapai prestasi terbaik PDR. PDR meningkat daripada 94% (CSMA/CA konvensional) kepada 99.33% (EN-CSMA/CA), peningkatan 5.33%. Model PDR menganggarkan bahawa untuk senario terbaik dan paling teruk, peratusan PDR adalah 100.0% dan 51.67%, masing-masing. Untuk mengoptimumkan penyusunan penghala bagi perlaksanaan sebenar sistem yang dibangunkan di kemudahan kesihatan, model kehilangan laluan yang dibangunkan menganggarkan bahawa penghala harus diletakkan pada jarak 30 m antara satu sama lain, yang disepakati dengan hasil ujian yang menunjukkan kedudukan penghala harus ≤ 40 m untuk mencapai prestasi terbaik PDR.

EMBEDDED DUAL BAND RFID BASED BLOOD GLUCOSE MONITORING SYSTEM FOR INTERNET OF MEDICAL THINGS

ABSTRACT

Manually recorded health information could lead to errors such as inaccurate patient identification and mismatch patient data that could seriously affect patient safety. In order to reduce the risks of error for patients with diabetes, a new design of wireless blood glucose monitoring system with the embedment of dual band RFID for Internet of Medical Things is being developed. Using this method, passive RFID allows short-range communication to read automatically the patient identification number and active RFID extends long-range communication for recording and monitoring blood glucose data through multi-hop WSN. The work presented in this thesis contributes mainly to the embedded system and its application in healthcare to reduce the burden of recording, tracing and monitoring the patient's data by embedding blood glucose sensor, passive RFID, active RFID, WSN, M2M and IoMT into a single platform. A new design concept is established for the patient identification mechanism, where the mechanism is embedded in the source device to enhance the ability of the system to automatically assign the identification number to each blood glucose measurement (mmol/L) during multiple patients monitoring. Additionally, the results from the experiments conducted showed that the developed system produced better overall performance compared to the Bluetooth BGM and conventional BGM system in terms of the shortest recording time and the ability to retransmit data. In the reliability analysis using ANOVA and DOE statistical methods, the result validates that the number of hop and number of end node significantly affects the PDR performance of conventional CSMA/CA. These two

parameters are then taken into account in experimental setup for performance evaluation of the enhanced CSMA/CA (EN-CSMA/CA) algorithm that uses an external interrupt mechanism and a cross layer approach. The PDR increased from 94% (conventional CSMA/CA) to 99.33% (EN-CSMA/CA), an improvement of 5.33%. The PDR model estimates that for the best and worst scenario, the percentage of PDR is 100.0% and 51.67%, respectively. To optimize the arrangement of routers for real implementation of the developed system in health facilities, the developed path loss model estimates that the router should be positioned at a distance of 30 m from each other, which agrees with the test results which indicate that the router should be positioned ≤ 40 m in order to achieve the best PDR performance.

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Diabetes mellitus (DM) is a significant public health problem that is recognised globally. The World Health Organisation (WHO) estimates that by the year 2030, Malaysia will have around 2.48 million people with DM (IPH, 2011). Figure 1.1 illustrates the trends and projections of diabetes by the year 2020, showing that the prevalence of diabetes even in 2011, based on the National Health Morbidity Survey (NHMS), was higher compared to the projected prevalence of diabetes in NHMS 2006 (Ngah et al., 2017).

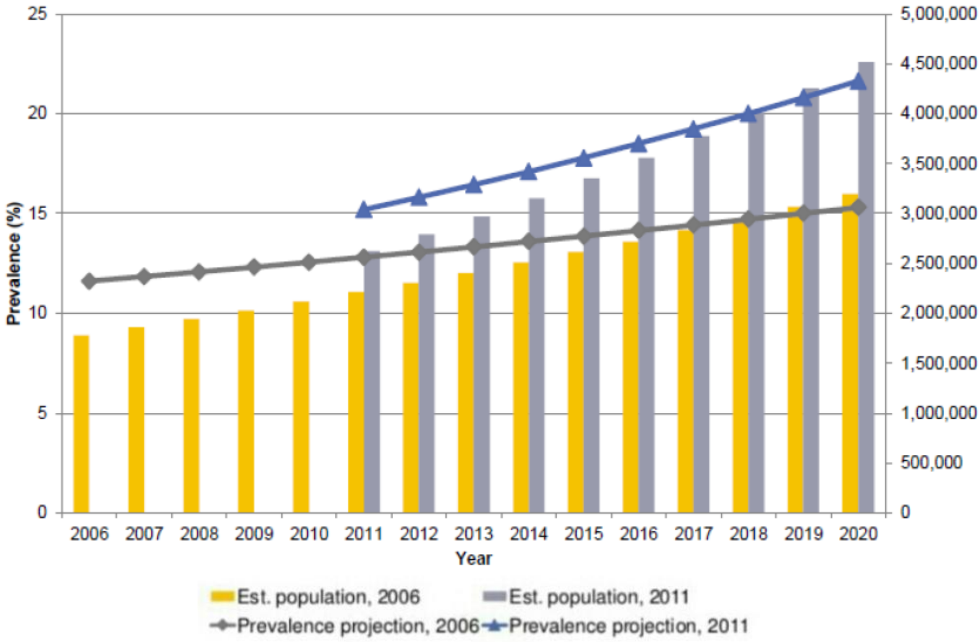

Figure 1.1 Diabetes trends and projections by 2020 in Malaysia (Ngah et al., 2017)

NHMS 2015 revealed that most people with diabetes sought medical treatment at Ministry of Health (MOH) health clinics (59.3%), followed by MOH hospitals (20.0%), private clinics (15.1%) and private hospitals (3.6%) as illustrated in Figure 1.2 (IPH, 2015). NHMS 2015 also estimated that the high population growth in Malaysia, if continued, will undoubtedly overload the nation's healthcare systems. Currently, the ratio of doctors to the population is 1:633 and the ratio of nurses to the population is 1:333 (Mei Kei, 2017).

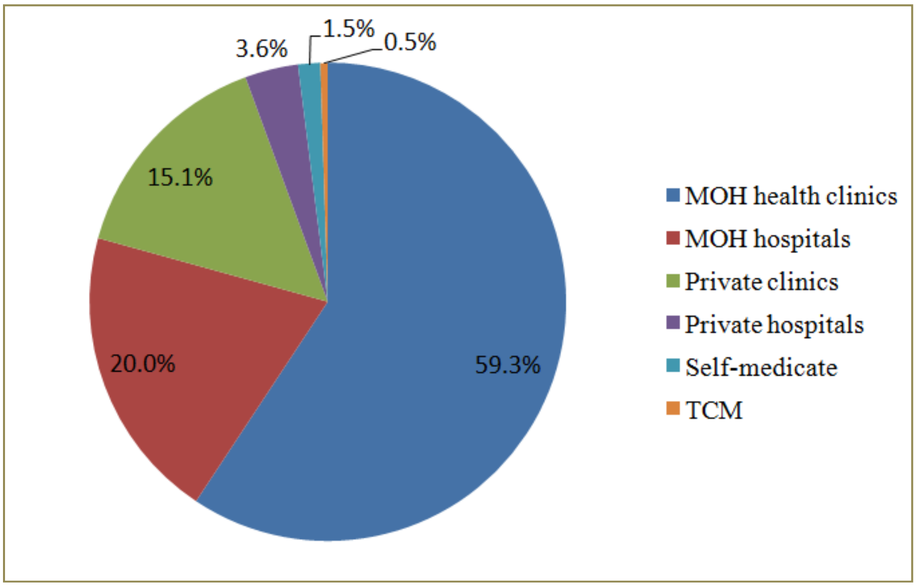

Figure 1.2 Common place of treatment for diabetic patients (IPH, 2015)

The MOH has implemented a Total Hospital Information System (THIS) in order to improve the scheduling and day-to-management of surgical operations and services within the healthcare system. In utilising this system, diabetes health records should be recorded directly into the system electronically, and information and equipment tracked through using barcode identification tags and patient ID numbers. At present, nurses record blood glucose data on a piece of paper, and following the conclusion of their ward rounds, will enter the data into the hospital system at the nurses' station. In contrast, the proposed process as outlined in this study will provide a significant benefit concerning the reliability of blood glucose data compared to manually recorded information which may not be accurately entered and recorded into the system. For instance, data may become mixed up with other data during the data entry and compiling process in the hospital system. Therefore, to improve the reliability and integrity of blood glucose data, the use of a wireless blood glucose monitoring (BGM) system will assist to automatically store data into THIS, thus minimising the occurrence of errors due to human intervention.

Also important is the accurate identification of patients in the effective management of diabetes. From patient admission and throughout the range of care provided by the hospital, matching the correct patient name and personal details to the correct medication, specimen, test, and procedure are crucial to improving patient safety. In the conventional manual process to identify patients, mistakes can invariably occur which may seriously compromise the patient's safety and health condition, and preventing them from receiving proper treatment.

The emergence of smart devices, Radio Frequency Identification (RFID), Wireless Sensor Network (WSN) and other communication technologies as shown in Figure 1.3 has led to the exponential growth of online applications associated with the Internet of Things (IoT).

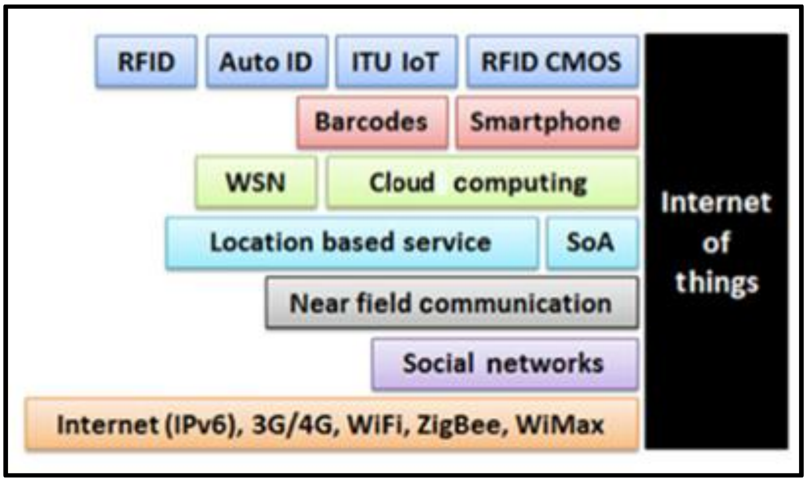

Figure 1.3 Technologies associated with the IoT (Xu et al., 2014)

In fact, it has been projected that by the year 2025, healthcare applications will dominate the IoT as shown in Figure 1.4. In the modern health care environment, the application of IoT technologies has brought with it, the convenience for both medical professionals and patients, given these applications can be applied to various medical areas and procedures including real-time monitoring, patient information management, and healthcare management. Indeed, electronically connected medical devices will help to free up much-needed resources in clinics, alleviate and reduce stress and costs for those undergoing treatment, and will ultimately improve the delivery of services in hospitals and other health care facilities.

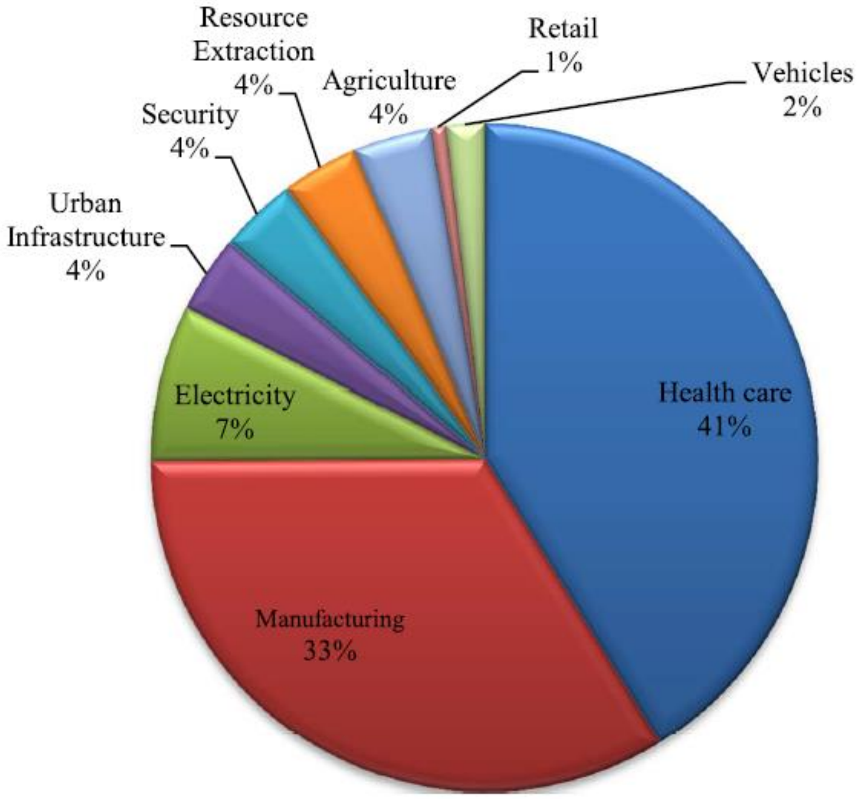

Figure 1.4 Projected market share of dominant IoT applications by 2025 (Al-Fuqaha et al., 2015)

For indoor healthcare monitoring systems, several alternate technologies have been proposed including the use of Wi-Fi, RFID and Bluetooth. Mainetti et al. (2014) carried out a comparison among these technologies and concluded that RFID and Bluetooth technologies were the optimal solutions to reduce costs and providing less complexity in terms of hardware development and implementation. Blood glucose testing in hospitals and clinics involves a multitude of patients, covering a large area in monitoring patients simultaneously. The main concern in using a Bluetooth glucometer in a health facility for blood glucose monitoring is due to the limitation in transmitting data over long distances, inability to provide unique identification for multiple patients and compatibility with smartphone devices. Additionally, the pairing process of the Bluetooth glucometer requires a lengthy setup process, whereas RFID can provide an effective solution in overcoming the limitations of using Bluetooth technology.

Embedding RFID and WSN technology in forming IoT components can contribute to remote and automated blood glucose monitoring in a health facility environment. Furthermore, the deployment of a diabetes monitoring system utilising the IoT platform will enable the system to be deployed anywhere. For remote monitoring, doctors can access data via an online diabetes management system for tracking the performance of patients' blood glucose levels which can assist doctors in diagnosing and providing treatment to patients. Therefore, there is a need to improve the BGM system by utilising RFID in a WSN platform and embedding the system with a mechanism to identify patients for crowd testing and regular usage. To the best of the researcher's knowledge, such a design of a wireless BGM system is the first of its kind.

1.2 Problem Statements

In crowd blood glucose monitoring, the existing wireless BGM system does not have the ability to automatically attach a patient identification number to the blood glucose reading for each patient during the remote recording of data into an electronic health record system. To overcome the limitations, the proposed system requires wireless technology capable of managing wireless communication at both short and long ranges. The short-range is for collecting the identification number of the patient, while the long-range is for remote data recording. Nonetheless, the wireless technology cited in the literature for the existing blood glucose monitoring system operates in a single band, restricting system interoperability and functionality to manage short- and long-range application. Besides, the existing wireless BGM design is focused on self-monitoring instead of monitoring multiple patients in which a single device can be shared across multiple patients. For example, the Bluetooth BGM system invented by Simpson et al. (2010) and Ow-Wing (2015), the identification number of the patient is registered in the mobile application at the receiving device. Such design limits the BGM system in detecting the identification number of different patients, as it requires the removal of the previous patient's data by uninstalling the mobile application and reinstalling it. Moreover, data collection and data analyses are dependent on human's intervention to input the data.

The main concerns regarding communication schemes for a BGM system in the WSN platform is regarding the ability to use the system remotely in real-time and to preserve the integrity of the monitoring data. Zigbee provides solution to data collision with the use of CSMA/CA mechanism. Due to its technical uniformity, highly scalability, the efficiency of CSMA/CA mechanism of ZigBee protocol will be affected in specific environments. In fact, collision rate and back off period are still relatively high and long in star topology deployment even though the Zigbee network occupied only with fewer nodes (Singh, 2012). The development of the beacon-enabled mode (slotted CSMA/CA) protocol developed by Shu et al. (2015) and Di Francesco et al. (2011) is not feasible in accommodating the need for real-time data processing in a multi-hop network as the nodes need to synchronise with the coordinator and listen to periodic beacons in order to the transmit data. In contrast, using an unslotted CSMA/CA mechanism, the nodes have no restriction in transmitting data at any time due to no alignment to a slot boundary. However, if all nodes attempt to transmit data simultaneously, data will collide which will jeopardise the integrity of collected data and affect the analysis of data for diagnosis and treatment of diabetic patients. The majority of work on the development of the unslotted CSMA/CA protocol has only considered simulation analysis, for example, the work developed by De Guglielmo et al. (2016) and Ur Rehman et al. (2014). These works also do not provide analysis on the multi-hop network given this information is vital for prediction efficiency in implementing the system in a large area of a health facility.

1.3 Research Objectives

The objectives of the research are as follows.

i. To improve the design and functionalities of the wireless BGM system by embedding dual band RFID (passive and active RFID) into a single WSN platform by focusing on patient identification number assignment to the blood glucose reading for each patient during remote data recording into an electronic system in order for the system to be used in crowd monitoring with regular use in a large area of a health facility.

ii. To propose a new approach to enhance conventional unslotted CSMA/CA for preserving data integrity, to evaluate the performance of the proposed protocol and improve the reliability of real-time wireless blood glucose monitoring data.

iii. To develop and construct a prototype of the proposed real-time wireless BGM system as a proof of concept for the implementation of the Internet of Medical Things.

1.4 Research Scopes and Limitations

The research work in this thesis focuses on two elements. First by defining the problem precisely and proposing solutions, and secondly, by producing meaningful results in order to achieve the objectives of this research.

The first element incorporates the process of designing and developing embedded dual-band RFID (passive and active) tags and the active RFID reader starting from designing the circuit diagrams, selection of the glucometer, passive reader, microcontroller, active components, design circuit schematic, the Printed Circuit Board (PCB) layout design and fabrication as well as installation of the components.

The second element encompasses software development, which focuses on various functions for the microcontroller to communicate with the glucometer, passive reader, Zigbee module, external memory, in real-time as well as developing the GUI to interface with the RFID reader. The tag is designed not only to communicate with the glucometer and passive reader but also to achieve high data integrity of glucose information by embedding the enhancement anti-collision algorithm into the program coding. The raw data sent by the system tags contain information such as the IEEE address, patient ID, glucose reading, time stamp, meal flags and patient comment. The developed system supports M2M communication that enables the active RFID reader to exchange real-time information with the embedded active RFID tags in a two-way communication channel to update the status of delivery and validate the data with minimal human intervention through utilising the IoT environment.

All experiments are conducted in a real-world environment by assuming that the same environment is applied during blood screening of diabetic patients to ensure the research objectives are achieved. However, this work does not focus on the accuracy of the blood reading as the glucometer that is used in this research is a commercial device. Instead, the focus is towards system design, development, improvement, implementation, embedding technology and testing in order to achieve the objectives of this research from various perspectives.

1.5 Research Contributions

The contributions of this research are summarised as follows.

i. New design architecture comprises of embedded blood glucose sensor, passive RFID, active RFID, WSN, M2M and IoMT in a single platform for real-time wireless blood glucose monitoring for healthcare facilities. This new embedded system enables short-range communication to read patient identification number and extend long-range communication via multi-hop network for remote blood glucose data recording into an electronic system. A new design concept is established for a patient identification mechanism, where the mechanism is embedded into a source device. This enhances the capability of the proposed system to be used for multiple patients, and each blood glucose measurement is automatically assigned to their identification number during blood glucose testing. These features allow easy tracking, monitoring and analysis.

ii. Formulating new approaches and algorithm for performance enhancement unslotted CSMA/CA (EN-CSMA/CA) for preserving the integrity and improving the reliability of real-time monitoring data of the developed BGM system in large area of health facility. This is achieved by implementing a DOE approach and statistical analysis to verify the robustness of the system and performance and also considering multi-hop network factor analysis.

iii. A new prototype system is developed and implemented as proof of concept in performing M2M communication for remote blood glucose monitoring. This embedded system is in the form of a portable wireless BGM system which is relatively easy to be set up in a health facility thereby allows more extensive wireless coverage in a multi-hop network.

iv. Formulating a packet delivery ratio model for predicting the effects from the distance and interaction factors of a number of DRBGM tags * number of hops, for reliable implementation in large area of health facility.

1.6 Thesis Outline

The structure of this thesis is comprised of six chapters as described below.

Chapter Two reviews the various methodologies and problems with the current wireless BGM system based on existing literature.

Chapter Three describes the specifications and operation of the key components used in the research work in order to develop an active RFID system embedded with a glucose meter and passive reader functionality with the aid of a WSN communication platform for indoor monitoring. This chapter also describes the hardware and software design, development and configuration of a complete embedded RFID system.

In Chapter Four, the methodology used to setup the hardware, software and network design and development including the embedded mechanism between devices and WSN in the IoT is described. The schematics of the embedded RFID tag, reader and router are presented along with the communication algorithm implemented in the RFID tag and reader, respectively. All testing and results concerning the proposed embedded RFID system prototype are compared with the standalone RFID system and an RFID system embedded with sensors to evaluate and verify the capabilities of the proposed system.

Chapter Five describes the findings and discusses the process of testing the wireless BGM system as a Proof of Concept (POC) in the selected real-world indoor environment. This chapter also details the actual contributions and advantages of the entire package of the proposed embedded RFID system by summarising the findings in the form of design specifications for the RFID tag and reader together with a comparison between the proposed embedded RFID system with prior approaches found in the literature.

Chapter Six concludes the research by addressing the objectives of the research along with recommendations for future improvements.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The chapter begins with an overview of diabetes mellitus and continues by highlighting the patient identification issues in healthcare. Discussion on the important aspects of Internet of Things (IoT) applications, RFID, WSN and Zigbee are next presented along with a comparison with other wireless technologies. This chapter next examines the existing body of literature on the design of a wireless blood glucose monitoring (BGM) system and related works on patient identification technologies. Related to the event-driven application as implemented in the proposed system, the chapter examines the issue of IEEE 802.15.4 MAC by investigating the related works in addressing the issue. Design of experiment concept is discussed in the last section of this chapter. The flowchart of the literature review is summarised and illustrated in Figure 2.1.

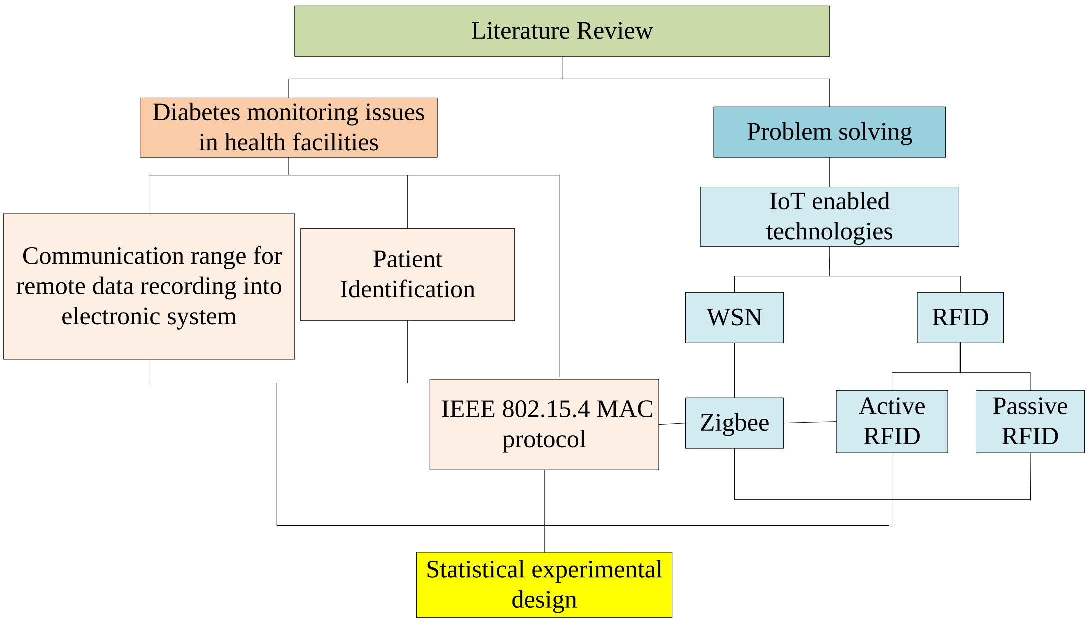

Figure 2.1 Flowchart of the literature review

2.2 Overview of Diabetes Mellitus

The Egyptians first mentioned diabetes mellitus around 1500 BCE. Diabetes mellitus (DM) is an incurable disease resulting from an insufficient amount of insulin in the human body, causing elevated blood glucose levels, known as hyperglycaemia, or reduced glucose concentrations, known as hypoglycaemia (Sabokdast et al., 2015). Insulin is a hormone made by the pancreas in the body that regulates the amount of glucose in the blood.

Diabetes is classified into type 1 diabetes, type 2 diabetes, and gestational diabetes. Type 1 diabetes occurs when no or very little insulin is released into the body due to the immune system mistakenly attacking and killing the beta cells of the pancreas. As a result, sugar builds up in the blood instead of being used as energy. Type 1 diabetes requires treatment with insulin. Whereas, type 2 diabetes occurs when the body cannot properly use the insulin that is released or does not make sufficient insulin. Similar to type 1, sugar builds up in the blood instead of being used as energy. Type 1 and type 2 diabetes have been associated with many medical complications including cardiovascular disease, neuropathy, nephropathy, retinopathy, foot damage, skin problems, hearing impairment and chronic depression. The third type of diabetes, gestational diabetes, is a temporary condition that occurs during pregnancy. Here, uncontrolled blood sugar levels in pregnancy can also cause the baby to grow too large, having a higher risk of developing obesity as well as causing death either before or shortly after birth. Additionally, the mother may also experience preeclampsia and subsequent gestational diabetes (Berger et al., 2016).

Complications from diabetes have resulted in greater expenditure and reduced productivity, becoming a socio-economic concern (Huse et al, 1989; O’Brien et al., 1998). Moreover, monitoring glucose levels in the blood has been proven to prolong life expectancy by enabling people with diabetes to manage episodes of hypo- or hyperglycaemia, therefore providing better control over their condition and by preventing some of the debilitating side effects (Makaram et al., 2014; Ferrante do Amaral & Wolf, 2008).

The key part of diabetes management is in understanding blood glucose level ranges, which are checked using a blood glucose monitoring system. The blood sugar levels in diagnosing diabetes are shown in Table 2.1.

Table 2.1 Blood glucose levels for diagnosing diabetes (Great Britain Association, 2017)

Plasma glucose test	Normal (mmol/L)	Prediabetes (mmol/L)	Diabetes (mmol/L)
Random	Below 11.1	N/A	11.1 or more
Fasting	Below 5.5	5.5 to 6.9	7.0 or more
2 hour post-prandial	Below 7.8	7.8 to 11.0	11.0 or more

According to the results from the 2011 National Health & Morbidity Survey (NHMS), an estimated 1.1 million patients with diabetes received treatment at public health care facilities in Malaysia, with 70% of patients attending primary care clinics. Whereas, the remaining patients received treatment and follow-up at public hospitals (IPH, 2012). Notably, medical officers and physicians mostly deliver public hospital-based diabetes care within general medicine outpatient clinics in the hospital (Hussein et al., 2015).

On the other hand, glycaemic control for hospitalised patients with diabetes requires accurate near-patient glucose monitoring systems. During the last decade, point-of-care blood glucose monitoring devices have become the mainstay of near-patient glucose monitoring in hospitals globally (Rajendran & Rayman, 2014), given that the blood glucose measurement result can be obtained in minutes compared to what could take hours employing laboratory tests. The Ministry of Health in

Malaysia has enforced the use of Total Hospital Information Systems (THIS) to record all health-related data, including blood glucose data into the system. However, the data entry of THIS is a manual process, which is susceptible to human errors. The technical performance of conventional blood glucose monitoring (BGM) system is tabulated in Table 2.2. Therefore enhancing the functionality and capability of the BGM system could positively affect the level of work involved and enhance patient care across the public health care facilities.

Table 2.2 Technical performance of conventional blood glucose monitoring system

System	**Conventional BGM System**
Method to record data to database system	Manual data entry
User identification mechanism	Visual check the Patent ID Card
Type of blood glucose data collection	Non-real-time
Number of patient per system setup	One patient
Diabetes Management Software	NA

2.2.1 Patient Identification Issues in Healthcare

A blood glucose reading without knowing the identification of a patient is meaningless. Patient identification refers to the process of assigning a unique identification ID to a patient. Patient identification is one of the most important elements of patient safety by identifying each patient precisely and correctly matching their data to facilitate the best possible decisions about treatment and diagnosis (Morris, 2014). The Joint Commission for Accreditation of Health Care Organizations (2016) recommends the use of at least two identifiers (e.g., the patient's name and their date of birth) to verify a patient's identity. In the health facilities in Malaysia, the inpatients are identified based on the presence of the ID band that contains information on the patient's full name, medical record number and date of birth whereas, outpatients are identified through their National ID and are confirmed with details contained in their medical record.

However, there is significant evidence that errors in the identification of patients do occur in health services. The misidentification of patients has been disclosed as the root cause for the majority of medical errors including specimen misidentification (Upreti et al., 2013), adverse drug events (Fyhr & Akselsson, 2012) and incorrect blood transfusion (Cottrell et al., 2013), which can cause the loss of a patient's life. In the root cause analyses study, Dunn and Moga (2010) found that 9.48% out of 182 patient ID errors in the medical results from the post-analytic phase were recorded into the wrong patient medical record. While, the study conducted at the Endocrinology-Diabetology-Nutrition Department at Montpellier Hospital, France revealed that patients with diabetes had more serious medication errors at the hospital compared to non-diabetic patients (Breuker et al., 2017). Medication errors can be lethal, with the estimated death of more than 7,000 patients each year from preventable errors (Walsh, 2015). In Malaysia, the figures in 2010/2011 NHSLA Annual Report and Accounts reveals that the number of clinical negligence claims reported in 2010/11 was 8655, which represents a 30% increase over 2009/10 (6652) (Hambali & Khodapanahandeh, 2014).

2.3 Internet of Things Applications and Benefits

The IoT comprises a network of electronic physical devices that are interconnected, exchange data and interacts with each other beyond machine-to-machine (M2M) communication. Multiple technologies are involved in the IoT, with one solution in managing all communications. This ingenious evolution has attracted the interest and attention of many industries to be part of the IoT such as information, transportation, agricultural, healthcare and manufacturing industries as shown in Figure 2.2. In balancing the demand and supply in healthcare services, the growth of the IoT continues to grow and proliferate. The capability of medical devices and application systems to interact and share data through online computer networks enable fast, accurate, seamless and transparent services in the healthcare system.

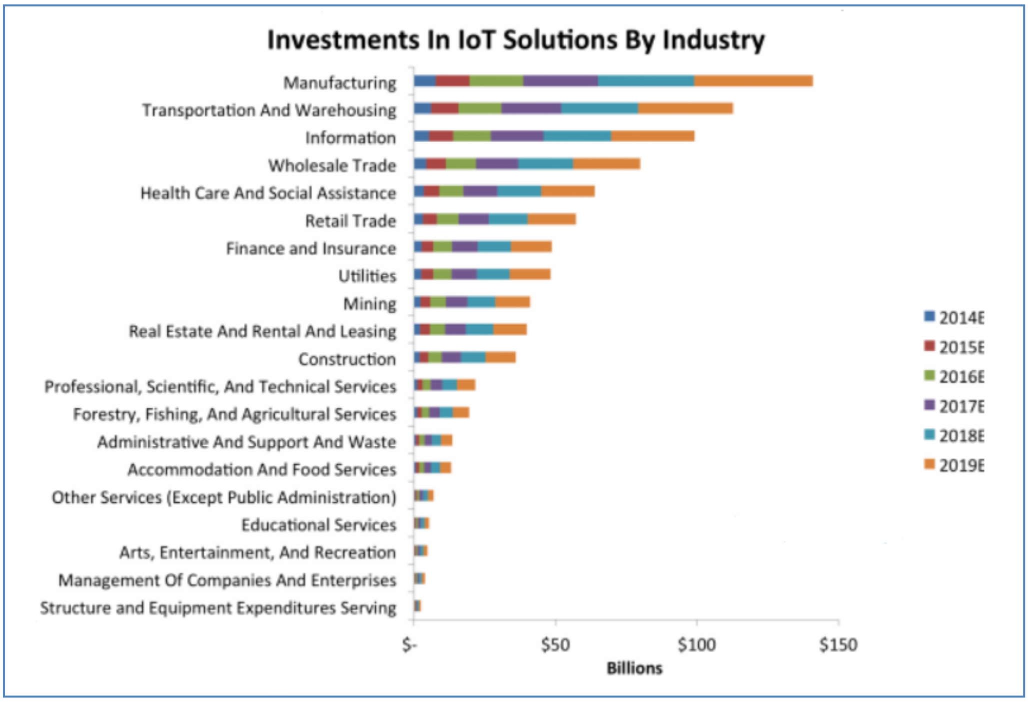

Figure 2.2 Investments in IoT solutions by industry (Newman, 2019)

In other spectrums, the industrial revolution aimed at creating intelligent factories by applying advanced technologies including the IoT and cloud computing is known as Industry 4.0 (Lee et al., 2015). In the context of the healthcare system, the term Industry 4.0 is used to represent an in-depth change in the way healthcare services are provided and how information, technology and processes integrate forming a lean healthcare system. Lean healthcare is a set of operating philosophies and methods that help to create maximum value for patients by reducing waste and waiting time (Lawal et al., 2014). Hence, integrating Industry 4.0 in the healthcare system is important given the benefits of improving access to care, reducing healthcare costs and most importantly increasing patients' quality of life. This transformation can be realised through utilising and taking advantage of the IoT.

Innovative technologies like ZigBee, WSN, RFID, smart sensors, distributed databases and energy saving technologies, associated with IoT, have huge potential in remote healthcare monitoring systems and medical services to improve patient safety, healthcare services and also to reshape the future of the healthcare industry. The interaction of the elements in IoT communication is illustrated in Figure 2.3.

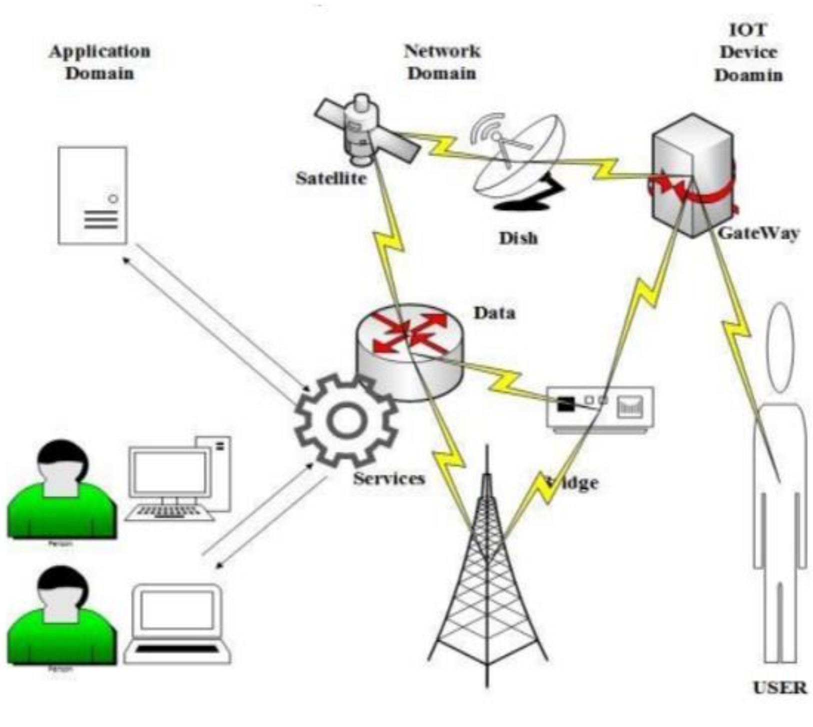

Figure 2.3 Communication of IoT (Joyia et al., 2017)

Given the benefit afforded by IoT infrastructure, many researchers have shown significant interest in adopting IoT in their applications. Table 2.3 shows some of the related work in healthcare applications that have adopted the IoT concept.

Table 2.3 Healthcare applications using IoT

Authors	Application	Benefit
Muhammad et al. (2017)	Voice pathology monitoring	High accuracy detection and easy to use
Chandel et al. (2016)	Continuous monitoring for step count, stride length, fall and calorie	Trigger an automatic alarm for the need of an urgent attention to the elderly subject, real-time feedback on step count and distance , accurate calories estimate
Puri et al. (2016)	Cardiac Arrhythmia Management	enable an inexpensive auto-triggered arrhythmia cardiac management solution catering the need of in-house, round-the-clock cardiac health monitoring

2.4 Radio Frequency Identification (RFID)

The concept of RFID was initially discovered during World War II (Landt ,2005) which has since evolved. RFID provides a feasible solution to all tracking applications using an identification mechanism via radio waves. The frequency ranges of RFID based on the international standards range from 135 kHz to 2.4 GHz. The characteristics of RFID operating frequencies are described in Table 2.4. RFID can be categorized into passive and active which are embedded for short and long range communication, respectively, in the proposed system. Details of these RFIDs are further discussed in the next section.

Table 2.4 Characteristics of RFID operating frequencies (Adhiarna & Rho, 2009)

Frequencies	**Low Frequency (LF)**	**High Frequency (HF)**	**Ultra High Frequency (UHF)**	**Microwave (MW)**
	125,134-135 kHz	13.56 MHz	902-908 MHz (US), 865 – 868 MHz (Europe)	2.4 GHz
Characteristics	1.Short-range (<1m) 2.Low data transfer rate (<1kbps) 3.Penetrate water but not metal	1.Higher range (<1.5m) 2.Reasonable data rate = 25 kbps (similar to GSM phone) 3.Penetrate water but not metal	1.Long-range (3-6m Europe, 6-8m US for passive tag and >100m for active tag) 2.High data transfer rate (=30 kbps) 3.Cannot penetrate water and metal	1.Long-range (>10m and 100m for active tag) 2.High data transfer rate (>100 kbps) 3.Cannot penetrate water or metal
Operating principles	Inductive coupling		Electromagnetic coupling (backscatter)	
Energy supply	Typically passive		Typically passive and active	
Tag size	Large	Medium	Small	Small
Typical RFID Applications	Animal tracking, Access controls, Car keys	Smart cards, Access control, Public transport, Item level identification, Apparel application	Supply chain pallet & box level identification, Electronic toll collection	Finished products tracking, Electronic toll collection
ISO Standards	14223 11784/5 18000-2	15693 14443 18000-3	10374 18000-6	10374 18000-4 18000-5
EPC Standards	-	Class 1 (Gen1) HF	Class 0 (Gen1) Class 1 (Gen1) UHF Class 2 (Gen2)	-

2.4.1 Passive RFID

A basic configuration of a passive RFID system consists of a reader, passive tag, and application computer (Tashi et al., 2011) as illustrated in Figure 2.4. The type of RFID system depends on the type of utilised tag. A passive tag does not have a battery, and vice versa for an active tag. The passive tag obtains all the energy from the generated RF field and then backscatters the signal to the RFID reader (Chawla & Ha, 2007). The backscatter signal contains data in the form of an identification string, which is pre-stored in the internal memory of the passive tag.

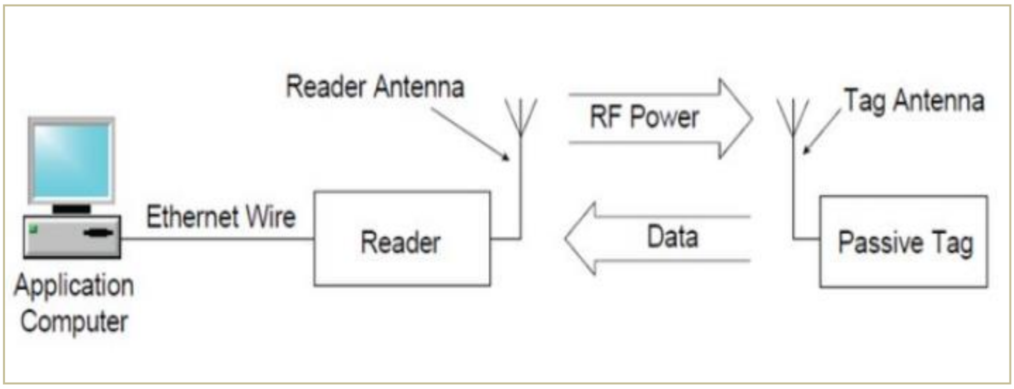

Figure 2.4 Passive RFID system (Tashi et al., 2011)

In the majority of cases, the read range of the passive RFID system is limited given the low sensitivity of the passive tag which requires a strong RF signal from the reader (Koelle et al., 1975). Conventional passive RFID tags are limited in their capability; however, the tags have an indefinite operational life and are sufficiently tiny enough to fit into a practical adhesive label (Want, 2006).

The passive RFID systems can be operated in low frequency (LF), high frequency (HF), and ultra-high frequency (UHF) bands. However, there are currently no commercially available passive RFID ICs for 2.4 GHz (Nikitin, 2019). Numerous communication protocols exist for RFID systems as shown in Table 2.5. The standards and guidelines for the interactions between the passive tags and the readers are based on the Electronic Product Code (EPC) global specifications (GS1, 2015) and International Organization for Standardization (ISO) 18000-6 (ISO, 2013), which are adopted by industry in the Ultra High Frequency (UHF) passive RFID field. The first generation of the RFID was named as Generation 1 (Gen 1) and the second generation (Gen 2) of the RFID UHF tags were then developed to establish a standard for RFID tags, operating frequency band and offer a longer operational range (Coca & Popa, 2011). Table 2.5 displays details of the improvements in Gen 2 in comparison to the Gen 1 protocol.

Table 2.5 Comparison between Gen 1 and Gen 2 (Coca & Popa, 2011)

Description	Gen 1	Gen 2
Acceptance level	Not a global standard	ISO-UHF 18000-6 standard
Arbitration	Deterministic binary tree for Class 0 and deterministic slotted for Class 1	Probabilistic slotted
Anti-collision/tag-sorting algorithm	Binary tree algorithm with persistent state/wake states	Q algorithm, which is a variant of the slotted aloha protocol
Air interface	Pulse width modulation (PWM) for Class 0 and Class 1	Pulse interval encoding (PIE−ASK), Miller, FM0
Data rate	40/80 Kbits for Class 0 and 70/140 bits for Class 1	40 to 640 Kbits
Distance	Less than 10 meters	Less than 10 meters
Frequency range	850–930 MHz	860 to 960 MHz
Security password	8 and 24−bit passwords, respectively, for Class 1 and Class 0	32 bits
Data write verification	No	Yes
Write speed (for 96−bit electronic product code)	Three tags per second	Minimum five tags per second

Gen 2 protocol provides great versatility in properties of physical layers and linking layer procedures to suit different conditions (Zhang et al., 2009). Gen 2 standard specifies the communication between the reader and the tag regardless of the particular frequency range within which the system operates, thereby providing developers with basic blueprint detailing how the system (readers and tags) should communicate. It also provides a robust mechanism, the EPC number, for unique ID which can handle the need for the trillions of unique IDs required by healthcare sector. The Gen 2 frequency range is between 860 and 960 MHz and it covers all international frequency spectrums. Factors such as interoperability of Gen 2, short reading range and small tag size fulfil the requirement that the proposed passive RFID operates within this frequency range.

2.4.2 Active RFID

Given the availability of an internal power source, the sensors can be embedded into the active tag in order to extend the capability of the RFID system for tracking and monitoring applications. For instance, the vibration sensor is embedded into an active RFID system for asset monitoring (Hamid et al., 2013) as demonstrated in the architecture design of an active tag in Figure 2.5.

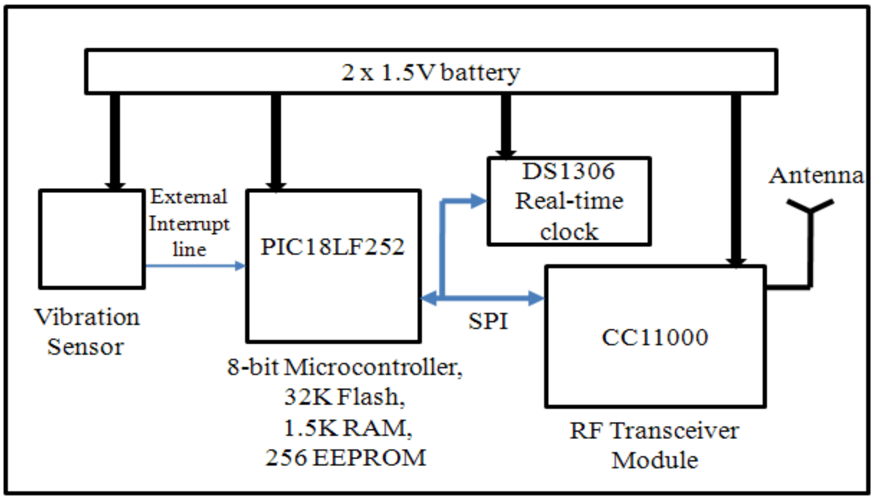

Figure 2.5 Architecture of an active RFID tag (Hamid et al., 2013)

In addition to that, the capability of the active tag to establish communication with the reader enables the RFID system to be actively deployed in real-time applications such as those that are event-driven and for periodic monitoring in the healthcare system. Table 2.6 displays the capability of an active RFID system in comparison to a passive RFID system (Cisco, 2008).

Table 2.6 Active RFID versus passive RFID (Cisco, 2008)

Characteristics	Passive RFID	Active RFID
Tag power source	Energy transferred from the reader via RF	Internal to tag
Tag battery	No	Yes
Availability of tag power	Only within field of reader	Continuous
Required signal strength from reader to tag	Very high	Very low
Communication Range	Short-range (3m or less)	Long-range, more than 100 m depends on types
Sensor capability	Read and transfer sensor data only when tag is power by reader without date/time stamp	Continuously monitor and record sensor input with date/time stamp
Data storage	Small (typically 128 bits)	Large (128kB or larger)