



**DESIGN AND DEVELOPMENT OF A FLEXIBLE MICROSTRIP
MULTI-RESONATOR FOR WEARABLE CHIPLESS RFID TAG
APPLICATIONS**



MASTER OF SCIENCE IN ELECTRONICS ENGINEERING

2025



**Faculty of Electronics and Computer Technology and
Engineering**

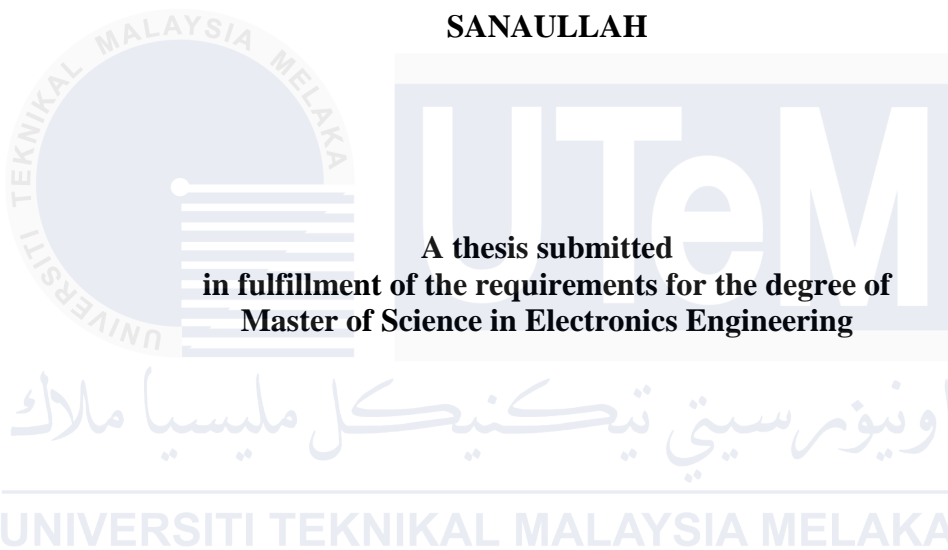
**Design and Development of a Flexible Microstrip multi-resonator for
Wearable Chipless RFID Tag Applications**

اونيورسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA
Sanaullah

Master of Science in electronics engineering

**DESIGN AND DEVELOPMENT OF A FLEXIBLE MICROSTRIP MULTI-
RESONATOR FOR WEARABLE CHIPLESS RFID TAG APPLICATIONS**

SANAULLAH



Faculty of Electronics and Computer Technology and Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2025

DECLARATION

I declare that this thesis entitled “Design and Development of a Flexible Microstrip multi-resonator for Wearable Chipless RFID Tag Applications “ is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



Signature :



Name : Sanaullah

Date : 26/02/2025

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in electronics engineering.



Signature :

Supervisor Name : Dr. A. K. M. Zakir Hossain

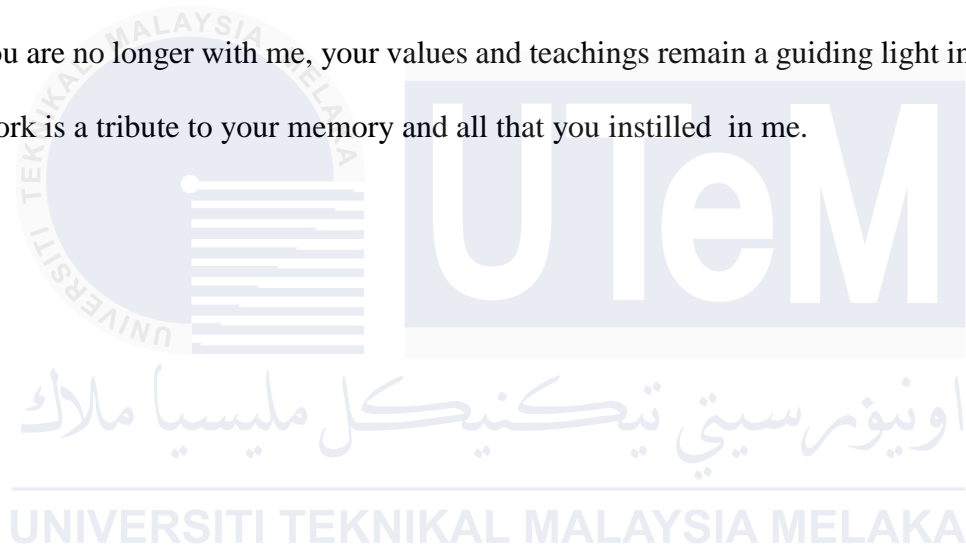
Date : 26/02/2025

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DEDICATION

To my beloved mother, whose unwavering love, prayers, and sacrifices have been my greatest strength and motivation. Your endless support and encouragement have guided me through every challenge.

And to my late father, whose wisdom, kindness, and dreams continue to inspire me. Though you are no longer with me, your values and teachings remain a guiding light in my life. This work is a tribute to your memory and all that you instilled in me.



ABSTRACT

Chipless Radio Frequency Identification (CRFID) is gaining attention as a low-cost and flexible alternative to traditional RFID, particularly for applications in wearable electronics and smart textiles. Unlike conventional RFID, which relies on integrated circuits, CRFID utilizes passive resonators for data encoding. However, existing flexible and fabric-based CRFID implementations often suffer from low bit capacity, poor spectral efficiency, and poor-quality factor (Q-factor), limiting their practical application. This research introduces a Parallel L-shape Multi-Resonator (PLMR) design aimed at enhancing bit encoding capacity, spectral density, and overall performance. The study begins with a detailed review of microstrip resonators, textile-integrated CRFID designs, and high-Q resonator structures. A theoretical model of the PLMR-based CRFID tag is developed and refined through electromagnetic simulations using CST Microwave Studio 2022 and Advanced Design System 2023. To validate the proposed design, Prototypes were fabricated on two different types of substrates: rigid (Rogers 4003C) and flexible (AN10 Kapton). Textile-based materials such as pile, denim, felt, silk, and fleece were evaluated solely through thorough simulations. The performance of the design have been evaluated using key metrics such as coding capacity, spectral density, spatial density, and Q-factor. The fabricated prototypes have bit capacities of 15 on Rogers 4003C and 9 on AN10 Kapton. In contrast, fabric-based designs achieved a simulated bit capacity of 13 for all evaluated textile types. The design achieves high-Q value of 237.3 on Roger 4003C, 51.5 on AN10 Kapton and 278 on fleece fabric substrate. Due to high Q-value, resonator structure improves frequency selectivity, minimizes interference, and enhances detection accuracy, thereby extending the tag's operational range. Performance validation through S-parameter analysis, frequency response measurement, and Bending analysis examination confirms its reliability for practical applications. The results demonstrate that the PLMR-based CRFID tag provides superior flexibility, increased data encoding capacity, and robust signal performance, positioning it as a viable solution for next-generation chipless RFID technologies. This work contributes to the advancement of wearable and textile-integrated RFID systems, opening new possibilities for automated tracking, identification, and sensing in smart environments.

REKA BENTUK DAN PEMBANGUNAN MIKROSTRIP BERBILANG RESONATOR FLEKSIBEL UNTUK APLIKASI TAG RFID TANPA CIP BOLEH DIPAKAI

ABSTRAK

Pengenalpastian Frekuensi Radio Tanpa Cip (Chipless Radio Frequency Identification, CRFID) semakin mendapat perhatian sebagai alternatif kos rendah dan fleksibel kepada RFID konvensional, terutamanya untuk aplikasi dalam elektronik boleh pakai dan tekstil pintar. Tidak seperti RFID konvensional yang bergantung kepada litar bersepadu, CRFID menggunakan resonator pasif untuk pengekodan data. Namun begitu, pelaksanaan CRFID fleksibel dan berasaskan fabrik yang sedia ada sering mengalami kekangan dari segi kapasiti bit yang rendah, kecekapan spektrum yang lemah, serta faktor kualiti (Q -factor) yang rendah, sekali gus menghadkan aplikasi praktikalnya. Kajian ini memperkenalkan reka bentuk Resonator Berbilang Bentuk-L Selari (Parallel L-shape Multi-Resonator, PLMR) yang bertujuan untuk meningkatkan kapasiti pengekodan bit, ketumpatan spektrum, dan prestasi keseluruhan sistem. Kajian dimulakan dengan ulasan terperinci mengenai resonator mikrostrip, reka bentuk CRFID bersepadu tekstil, dan struktur resonator berkualiti tinggi (high- Q). Seterusnya, satu model teori bagi tag CRFID berasaskan PLMR dibangunkan dan diperhalusi melalui simulasi elektromagnetik menggunakan CST Microwave Studio 2022 dan Advanced Design System 2023. Bagi mengesahkan reka bentuk yang dicadangkan, prototaip telah dibina pada dua jenis substrat berbeza: substrat tegar (Rogers 4003C) dan substrat fleksibel (AN10 Kapton). Bahan berasaskan tekstil seperti kain berbulu (pile), denim, felt, sutera, dan fleece pula dinilai secara eksklusif melalui simulasi terperinci. Prestasi reka bentuk dinilai berdasarkan metrik utama seperti kapasiti pengekodan, ketumpatan spektrum, ketumpatan ruang, dan faktor- Q . Prototaip yang dibina mencatatkan kapasiti bit sebanyak 15 pada Rogers 4003C dan 9 pada AN10 Kapton. Sebaliknya, reka bentuk berasaskan fabrik mencapai kapasiti bit simulasi sebanyak 13 bagi semua jenis tekstil yang dinilai. Reka bentuk ini juga mencapai nilai Q yang tinggi, iaitu 237.3 pada Rogers 4003C, 51.5 pada AN10 Kapton, dan 278 pada substrat fabrik fleece. Dengan nilai Q yang tinggi ini, struktur resonator memperbaiki selektiviti frekuensi, meminimumkan gangguan, dan meningkatkan ketepatan pengesanan, sekali gus memperluas julat operasi tag tersebut. Pengesahan prestasi melalui analisis parameter- S , pengukuran tindak balas frekuensi, dan analisis lenturan membuktikan kebolehpercayaannya untuk aplikasi dunia sebenar. Hasil kajian menunjukkan bahawa tag CRFID berasaskan PLMR menawarkan fleksibiliti unggul, peningkatan kapasiti pengekodan data, dan prestasi isyarat yang kukuh, menjadikannya satu penyelesaian yang berdaya maju bagi teknologi RFID tanpa cip generasi akan datang. Kajian ini menyumbang kepada kemajuan sistem RFID boleh pakai dan bersepadu tekstil, sekali gus membuka peluang baharu dalam penjejakan automatik, pengecaman, dan penderiaan dalam persekitaran pintar.

ACKNOWLEDGEMENT

In the Name of Allah, the Most Gracious, the Most Merciful. First and foremost, I would like to express my sincere gratitude to my supervisor, Dr A. K. M. Zakir Hossain for their invaluable guidance, continuous support, and insightful advice throughout this research journey. Their expertise and encouragement have played a vital role in shaping this work, and I am deeply appreciative of their mentorship.

I am also profoundly grateful to my father and brothers for their unwavering support, sacrifices, and motivation. Their belief in my abilities has been a driving force, inspiring me to stay dedicated and give my best throughout this journey. Without their encouragement, this accomplishment would not have been possible.

A heartfelt thanks to my friends for their constant support, engaging discussions, and for making this experience more enjoyable. Their encouragement and companionship have helped me stay focused and motivated every step of the way.

Finally, I extend my appreciation to everyone who has directly or indirectly contributed to this research. Their guidance and support have been truly invaluable, and I am sincerely thankful for their role in this achievement.

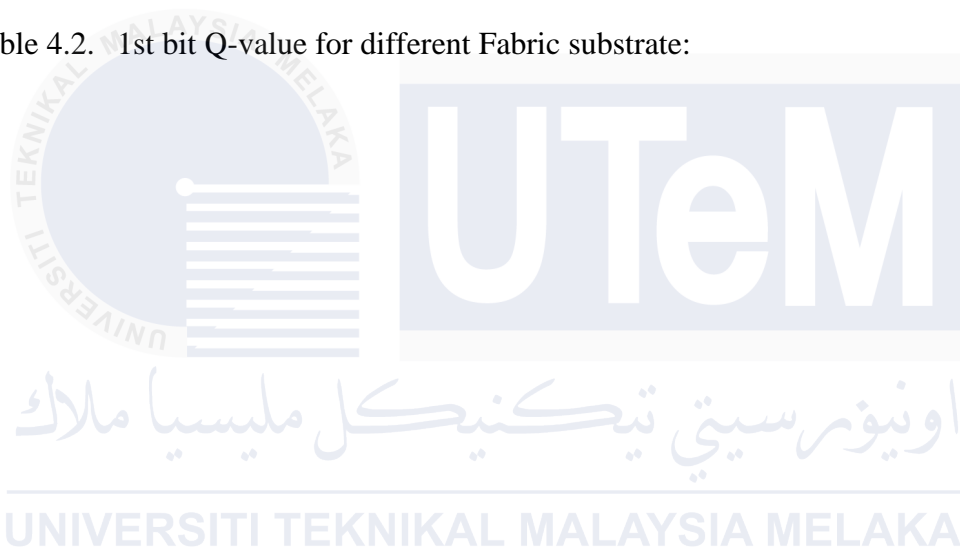
TABLE OF CONTENTS

	PAGES
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENT	iii
LIST OF TABLES	vi
LIST OF FIGURES	vii
LIST OF ABBREVIATIONS	xi
LIST OF SYMBOLS	xiii
LIST OF PUBLICATIONS	xiv
 CHAPTER	 1
1. INTRODUCTION	1
1.1 Background	1
1.1.1 Radio-Frequency Identification	2
1.1.2 Classification of RFID tags	4
1.2 Chipless RFID Tag	5
1.3 Problem Statement	7
1.4 Objectives	9
1.5 Scope of the Research	9
1.6 Hypothesis	10
1.7 Research Questions	11
1.8 Thesis Structure	11
 2. LITERATURE REVIEW	 13
2.1 Introduction	13
2.2 Coding Mechanism for IDing	15
2.3 Retransmission based CRFID tags	17
2.4 RCS based CRFID tags	23
2.5 Summary	37
 3. RESEARCH METHODOLOGY	 39
3.1 Introduction	39
3.2 Performance Assesment parameters of CRFID Tag	42
3.2.1 Coding Capacity	42
3.2.2 Spectral density	42
3.2.3 Spatial density	43
3.2.4 Q value	43

3.3	Tag Design	44
3.3.1	Tag on Rogers4003C Substrate:	44
3.3.2	Tag on Flexible Substrate:	51
3.3.3	Tag on Fabric Substrate:	59
3.4	Experimental Setup of PLMR Tag	63
3.4.1	Steps for Calibration (Using SOLT Method)	64
3.5	Summary	65
4.	RESULT AND DISCUSSION	67
4.1	Introduction	67
4.2	Performance Assessment and Comparison	67
4.3	S-parameter	67
4.3.1	Simulated and measured Results	68
4.4	Factor affecting the Response of Fabricated design	78
4.5	Summary	79
5.	CONCLUSION AND FUTURE WORK	81
5.1	Conclusion	81
5.2	Future work	83
REFERENCES		85

LIST OF TABLES

TABLE	TITLE	PAGE
Table 2.1.	A Comprehensive Survey of Various Flexible and Wearable Chipless RFID Tags	33
Table 3.1.	Charasteristics of different types of substrate.	64
Table 4.1.	1st bit Q-value for different substrates:	73
Table 4.2.	1st bit Q-value for different Fabric substrate:	77



LIST OF FIGURES

FIGURE	TITLE	PAGE
Figure 1.1.	Block diagram of Conventional RFID System	3
Figure 1.2.	Application of RFID	3
Figure 1.3.	Classification of CRFID Tags	4
Figure 1.4.	A re-transmission based CRFID system.	6
Figure 1. 5.	Chapters distribution and structure of the thesis.	12
Figure 2.1.	OOK coding mechanism of IDing section.	16
Figure 2.2.	(a) Simulation setup and dimension of the TCMR tag (b) S21 response for different substrates	18
Figure 2.3.	(a) Geometry of the proposed multi-stopband structure (b) S21 calculated from full-wave simulations for amplitude	19
Figure 2.4.	(a) DDRR antenna line drawing and prototype (b) S11 response of the DDRR antenna in flat and Max bend condition	19
Figure 2.5.	(a) Layout of metamaterial split ring resonator structure a) Front, b) backside (b) S21 response of circular and rectangular (SMCSRR)	20
Figure 2.6.	(a) Design of the multi-stopband structure (b)S21 simulation results for four coding configurations	21
Figure 2.7.	(a) Geometry of the proposed fully-textile chipless tag (b) Experimental results achieved for a 3-bit chipless tag.	22
Figure 2.8.	(a) three-finger prototype structure (b) Schematic representation of the three-finger prototype	23
Figure 2.9.	(a) Proposed tag (b) Simulated cross-polar RCS responses	24

Figure 2.10. (a) Representation of Dual L-shape tag (b) RCS response of the tag with 3 different bending conditions	24
Figure 2.11. Octagonal Chipless RFID tag on (a) Embroidered Chipless RFID Tags (i) HC12-Tag (ii) LIB40-Tag (b)RCS response on HC12 (c) RCS response on LIB40	25
Figure 2.12. (a) A 6-bit SRR-based CRFID Tag design (b) simulated RCS magnitude response	26
Figure 2.13. (a) 6 Slots RFID tag antenna on the jeans fabric (b) S11 Response of RFID tag Antenna	27
Figure 2.14. (a) Chipless RFID tag geometry (b) RCS response of the dipole shape RFID tag	27
Figure 2.15. (a) Chipless RFID Octagonal Tag Geometry (b) RCS simulated and measured response of the tag	28
Figure 2.16. (a) Fabricated chipless RFID tag (i) three and (ii) four slotted ring. (b) S11 response of the tag Simulated and measured.	29
Figure 2.17. (a) Structural diagram of Bow-Tie chip-less RFID system (b) RCS response of the tag in different bending conditions	30
Figure 2.18. (a) Dual rhombic loop scatterer (b) RCS response of the Dual rhombic tag	30
Figure 2.19. (a) Fully printed fabricated tags i.e. single and dual layer configuration (b) The cross-polar RCS response of DSSRR-based tags.	31
Figure 2.20. (a) Bow-Tie Chipless RFID design and dimensions (b) Octagonal Chipless RFID design and dimensions (c) Simulated and measured RCS responses of Octagonal and Bow-Tie Chipless RFID tags.	32

Figure 3.1. Design Procedure for Flexible Substrate CRFID Tag	40
Figure 3.2. Flow diagram of the proposed Tag design and development.	41
Figure 3.3. Quality factor estimation in CRFID.	44
Figure 3.4. Geometry of a single PLR ($L_1=22.25\text{mm}$, $L_2=21.45\text{mm}$, $L=28\text{mm}$, $W=21.65\text{mm}$, $WTL=1.55\text{mm}$)	46
Figure 3.5. Surface current (a) at 1GHz (b) at 3GHz (c) at 2.297GHz	48
Figure 3.6. Stages of the proposed PLMR tag design.	49
Figure 3.7. 15-bit design in (a) Simulated (b) Fabricated	49
Figure 3.8. Layout of different bit coding (a) 1's bit (b) even bit (c) Odd bit	50
Figure 3.9. Stages of the proposed PLMR tag design.	51
Figure 3.10. 9-bit PLMR layout (a) front view (b) back view.	52
Figure 3.11. Different layers of parallel L-shape RFID tag.	53
Figure 3.12. Fabrication steps of RFID tag.	55
Figure 3.13. 9-bit PLMR layout Simulated vs Fabricated for (a) all 1's bit (b) even bits (c) Odd bits (d) Random bits on AN10 kapton Substrate.	57
Figure 3.14. Different radius bending conditions; (a) no bending; (b) 15 mm bending; (c) 20 mm bending and (d) 30mm bending	58
Figure 3.15. Layout of 13-bits parallel L-shape RFID tag on (a) Fleece (b) Felt (c) Silk (d) Denim and (e) Pile Substrates	60
Figure 3.16. Different radius bending conditions; (a) no bending; (b) 15 mm bending; (c) 20 mm bending and (d) 30mm bending	61
Figure 3.17. Investigation setup for W-CRFID System in real world environment.	65

Figure 4.1. S21 response for different stages of the PLMR tag design (a) single TL;	
(b) pair of TLs; (c) 16 TL without filling; (d) 16 TL with filling.	69
Figure 4.2. S21 response of different coding bits (a) 1's bit; (b) odd bit; (c) even bit;	
(d) random bit.	70
Figure 4.3. Comparison of simulated and measured S21 responses using Rogers 4003C	
substrate.	70
Figure 4.4. S21 response for different stages of the PLMR tag design with 9 bits (a)	
single TL (b) pair of TLs (c) 10 TL without filling (d) 10 TL with filling.	71
Figure 4.5. Comparison of simulated and measured S21 response of different coding	
bits (a) 1's bit; (b) odd bit; (c) even bit; (d) random bit.	72
Figure 4.6. S21 response of different radius bending conditions; (a) no bending;	
(b) 30 mm bending; (c) 20 mm bending; (d) 15 mm bending.	75
Figure 4.7. S21 response of different substrates (a) Pile; (b) Denim; (c) Silk; (d) Felt;	
(e) fleece.	76
Figure 4.8. S21 response of different radius bending conditions; (a) no bending;	
(b) 30 mm bending; (c) 20 mm bending; (d) 15 mm bending.	78

LIST OF ABBREVIATIONS

ABBRIVATIONS

DESCRIPTION

CRFID	-	Chipless Radio Frequency Identification
WRFID	-	Wearable Radio Frequency Identification
PLMR	-	Parallel L-shape Multi-Resonator
Q-F	-	Quality Factor
TDR	-	Time Domain Reflectometry
RCS	-	Radar Cross Section
PCB	-	Printed Circuit Board
UWB	-	Ultra Wide Band
SAW	-	surface acoustic wave
CST	-	Computer Simulated Software
ADS	-	Advance Design System
UHF	-	Ultra High Frequency
CSRR	-	Complementary Split Ring Resonators
OOK	-	On-Off Keying
FSK	-	Frequency Shift Coding
PET	-	Polyethylene Terephthalate
BAN	-	Body Area Networks
FD	-	Frequency-domain
VNA	-	Vector Network Analyzer
SD	-	spectral density
SPD	-	spatial density

TLs	-	Transmission lines
RF	-	Radio Frequency



اونيورسيتي تيكنيكل مليسيا ملاك

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF SYMBOLS

SYMBOLS		DESCRIPTION
ϵ_r	-	Dielectric constant
$\tan \delta$	-	Tangent loss
f_0	-	Center frequency
Ω	-	Ohm
cm^2	-	Centimeter Square
mm^2	-	Millimeter Square
BW	-	Bandwidth
dB	-	Decibel

LIST OF PUBLICATIONS

The followings are the list of publications related to the work on this thesis:

Sanaullah Khan, A K M Zakir Hossain, S. M. Kayser Azam, Mohamadariff Othman, Nurulhalim Bin Hassim “Design Prospects of Parallel U-shaped Multi Resonator for Fabric-based Chipless RFID Tags” 4th International Conference on Innovations in Power and Advanced Computing Technologies, i-PACT-2023, Kuala Lumpur, Malaysia.

Sanaullah Khan, A. K. M. Zakir Hossain , Nurulhalim Bin Hassim and Muhammad Inam Abbasi “An RCS based Planar Parallel V-Shaped Multi Resonators for Wearable Chipless RFID Application” IEEE 22nd Student Conference on Research and Development (SCOREd), UiTM, Shah Alam, Malaysia, 2024

Sanaullah Khan, Mujeeb Abdullah, A. K. M. Zakir Hossain and Saad Hassan Kiani “Dual-band S-Shaped mmWave MIMO Antenna System for Ka-band Applications” IEEE 22nd Student Conference on Research and Development (SCOREd), UiTM, Shah Alam, Malaysia, 2024

A K M Zakir Hossain, Sanaullah, Md. Kayser Azam, Muhammad ibn Ibrahimy “Investigation on the Planar Resonator for Fabric Based Chipless RFID” 9th International Conference on Computer and Communication Engineering (ICCCE), Kuala Lumpur, Malaysia, 2023

CHAPTER 1

INTRODUCTION

1.1 Background

RFID (Radio Frequency Identification) plays a vital role in modern industries by offering a highly efficient and accurate way to automate identification, tracking, and data management processes. Its ability to function without the need for line-of-sight scanning makes it superior to traditional methods than barcodes, because barcode need line-of-sight, Risk of susceptibility to damage, and vulnerability to tampering (Finkenzeller, Klaus, 2010). RFID technology allowing for real-time tracking and management of assets, inventory, and individuals (Dobkin, David M., 2006). RFID can store significant amounts of data, ensuring that each tag carries detailed information, which is critical for complex applications such as supply chain management, healthcare, and retail (Finkenzeller, K., 2004). The technology also enhances security by enabling encrypted communication and authentication, reducing the risks of counterfeiting and unauthorized access (Mulloni, V. & Donelli, M., 2020).

Wearable RFID (WRFID) tags further advance this technology by embedding RFID capabilities into clothing, accessories, and other wearable items, unlocking a range of new possibilities. WRFID tags provide real-time monitoring in applications like healthcare, where they are used for patient tracking, medication management, and monitoring vital signs, ensuring safety and accuracy (Mulloni & Donelli, 2020). In industrial settings, WRFID tags improve worker safety by tracking movements in hazardous areas and optimizing workflows (Karmakar, Vena & Costa, 2016). In sports and fitness, these tags allow for the monitoring of performance metrics such as speed, distance, and heart rate,

helping athletes improve their training regimens. Additionally, in retail, wearable RFID tags enable personalized shopping experiences, such as interactive fitting rooms that recognize tagged items and provide suggestions (Preradovic & Balbin, 2010). Lightweight, compact, and easy to integrate, WRFID tags enhance convenience and comfort while offering seamless, contactless interactions, making them particularly valuable in a world increasingly focused on efficiency and connectivity.

1.1.1 Radio-Frequency Identification

RFID refers to a method of conveniently retrieving data and identifying an object using electromagnetic radiation. It uses electromagnetic frequency signals to communicate information from the RFID reader to the RFID tag (Want, 2006). Basic blocks of conventional RFID system as illustrated in the figure 1.1 comprises of three basic elements; the RFID tag or transponder that contains the code; an RFID reader or interrogator that sends signals to the tag to read it; and a middleware application that manages the computer windows accessible by the software for encoding the information received from the reader and decoding it into computer (Juels, 2006).

In 1948, Stockman (Roberts, 2006) first proposed RFID in his historic article, "Communication by Means of Reflected Power". According to Stockman, modulation can be achieved by varying the amount of reflected power through the tag antenna's load (a process known as "antenna load modulation"). Today, RFID is the name given to this latest generation of wireless technology. Ever since, engineers and academics have been attempting to create inexpensive RFID systems.

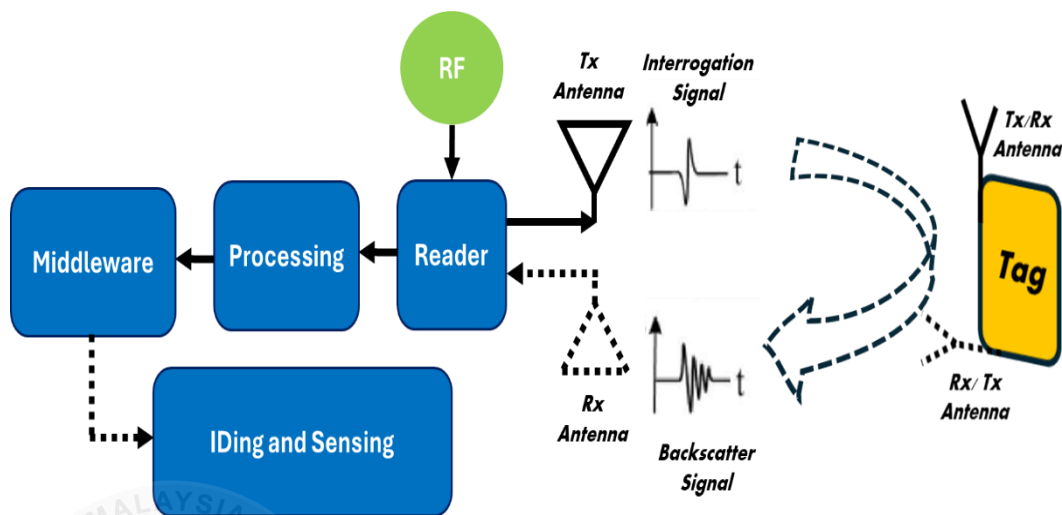


Figure 1.1. Block diagram of Conventional RFID System

RFID is One of the branches of the Auto Identification system, and currently, its application is widespread in a different industry, including inventory management, library operations, toll collection, and item identification and localization etc (Jia et al., 2012), as illustrated in figure 1.2.

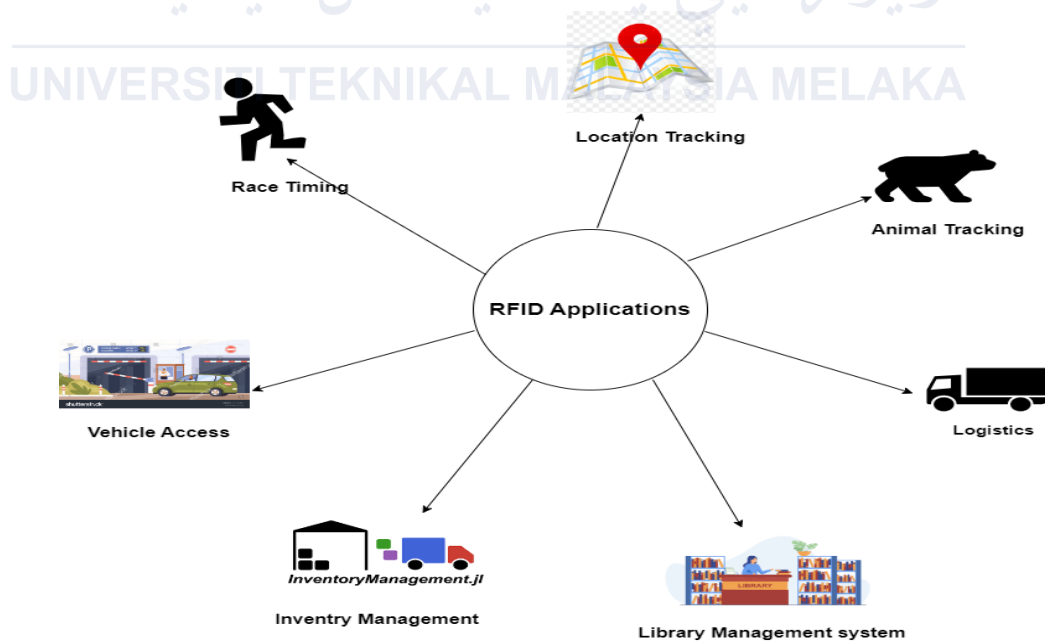


Figure 1.2. Application of RFID (Jia et al., 2012)

1.1.2 Classification of RFID tags

RFID tags can be classified in various ways, one such classification is based on tag's power source: Active tags are those which operate entirely on batteries; semi-active tags are those that operate on batteries to some extent; and passive tags do not operate on batteries. Because of their intrinsic costs, active and semi-active or semi-passive RFID classes are not appropriate barcode system replacements (Rao, Nikitin & Lam, 2005). Under the passive RFID category there are two types, Chipped and chipless RFID. RFID chips with SHF/UHF antennas are used in the majority of sensing and tracking applications, which leads to their high cost. But researchers are looking more closely into chipless RFID (CRFID) in an effort to reduce the cost of passive RFID. in CRFID technology uses Microwave multi-resonators for encoding instead of traditional chip to reduce the Cost (Chen et al., 2019; Zakir Hossain et al., 2023).

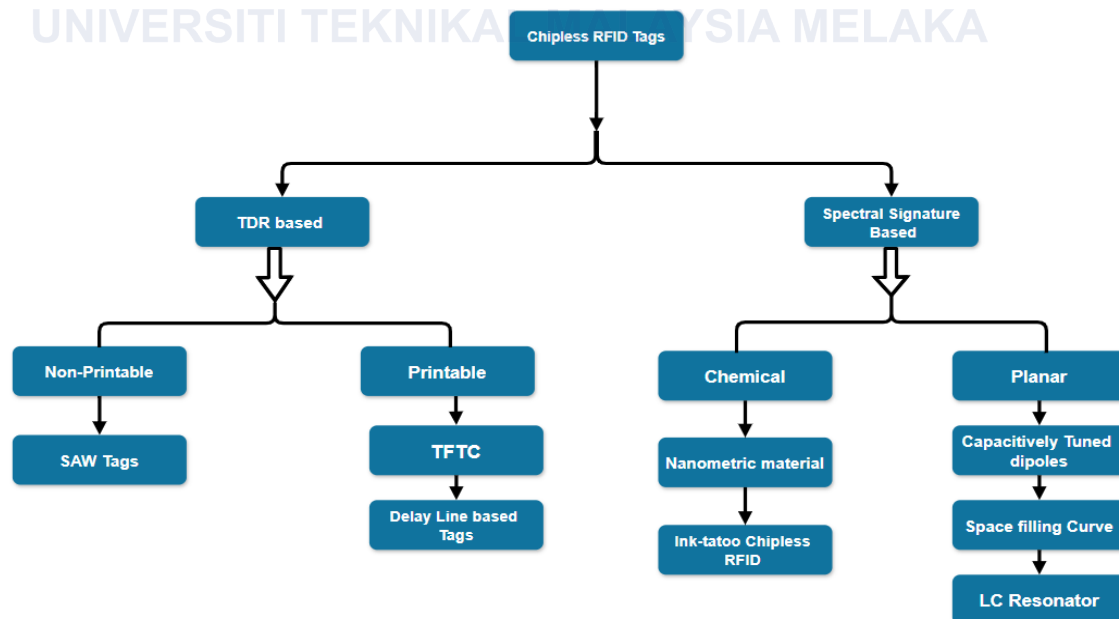


Figure 1.3. Classification of CRFID Tags