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ANALYSIS OF CURRENT STATE OF THE ART OF RFID IC CHIPS

Master of Science Thesis

Examiner: Prof. Leena Ukkonen
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ABSTRACT

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Radio Frequency Identification (RFID) is a constantly developing technology particularly in the ultra-high-frequency (UHF) band for its long operating range, power efficiency, and maintenance-free characteristics. It has been successfully developed for many applications already, that includes identification, sensing, tracking, monitoring, etc.

In terms of tag, the integrated circuit (IC) or chip play an essential part in the functionality of the tag, where logical information is programmed into. Nowadays, the chips come in a variety of memory options, sensitivity, supported protocols, with an optional battery-assisted mode, additional commands, and features.

There are various methods that are followed to fabricate RFID tags, i.e. inkjet-printing, painting, 3D printing, etching, etc. On the way of completion of these procedures, some of the methods involve the use of chemicals, producing waste, which is unfavorable in respect of the cost, and as well as the environment.

In addition, the substrate impacts tag's performance. If the tag is going to be attached for instance, on a metal surface the radiation properties of the tag antenna would experience changes, as the electromagnetic waves will reflect on the metal surface, which will basically degrade tag's performance.

Maintaining multiple applications on a single chip has become common to a certain extent. It requires additional power than usual, which is an issue for passive tags. In order to overcome this hurdle, energy harvesting system is required, which is going to suffice the need for a power source.

In this paper, the functionalities and applications of the RFID chips have been reviewed and some suggestions have been proposed on how RFID can be commercially manufactured, in terms of fabrication methods, supplying enough power for applications, and ensuring security of the tagged object.

PREFACE

This thesis, “Analysis of Current State of The Art of RFID IC chips” was done in partial fulfillment of the requirements for the Master of Science degree in Information Technology, in the Department of Electronics and Communication Engineering at Tampere University of Technology.

I would like to thank Professor Leena Ukkonen for supervising my work. I am profoundly grateful for her immense guidance and support throughout the work. This work has increased my interest and helped to learn intensively about RFID technology.

Finally, I would like to acknowledge my parents, siblings and friends for their unconditional love and support.

Tampere, 21.05.2018

Mohammed Ashraful Islam Munna

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LIST OF SYSMBOLS AND ABBREVIATIONS

AC	Alternating Current
AES	Advanced Encryption Standard
ASIC	Application Specific Integrated Circuit
BAP	Battery Assisted Passive
CAD	Computer-Aided Design
CAGR	Compound Annual Growth Rate
CW	Continuous Wave
DC	Direct Current
DOD	Drop on Demand
EAS	Electronic Article Surveillance
EPC	Electronic Product Code
HF	High Frequency
HFSS	High Frequency Structure Simulator
IC	Integrated Circuit
IEC	International Electrotechnical Commission
IFF	Identification Friend or Foe
I^2C	Inter-Integrated Circuit
IoT	Internet of Things
I/O	Input/Output
ISO	International Organization for Standardization
ITU	International Telecommunication Union
LF	Low Frequency
LIG	Laser-Induced Graphene
LOS	Line of Sight
NFC	Near Field Communication
OTP	One-Time Programmable
PCB	Printed Circuit Board
PSF	Product Status Flag
rGo	Reduced Graphene Oxide
RFID	Radio Frequency Identification
RTC	Real Time Clock
RTLS	Real Time Locating Systems
SKU	Stock Keeping Unit
SPI	Serial Peripheral Interface
TID	Tag Identifier
TUT	Tampere University of Technology
UHF	Ultra High Frequency
UID	Unique Identifier
UTC	Universal Time Clock
WBAN	Wireless Body Area Network
c	Speed of light in vacuum
cm	centimeter
dB	Decibel
dBm	Decibel-milliwatts
F	Farad
GHz	Gigahertz
H	Henry

kcycle	Kilocycle
kbit	Kilobit
kHz	Kilohertz
MHz	Megahertz
m	Meter
s	Second
π	Pi
μW	Microwatt

1. INTRODUCTION

In recent years, the emergence of internet-of-things (IoT) in different fields has driven the development of radio frequency identification (RFID) technology significantly. This technology was first introduced by the German air force, Luftwaffe, during Second World War to differentiate their aircraft from opponents by Identification Friend or Foe (IFF) system [1]. Today we see RFID practically in a lot of our day-to-day activities, such as bus card, train card, bank card, traveling documents, ID card, shopping card, the smart key of the apartment for all doors, car key, etc.

Passive ultra-high frequency (UHF) RFID tag has drawn the attention with their power efficiency and long operating range. A passive tag consists of two main parts, i.e. antenna and application specific integrated circuit (ASIC) [1]. Though RFID is a prominent term for identification, nowadays, there are numerous applications that are explicitly entitled to RFID, such as, sensing, monitoring, tracking, access controlling, etc.

The fast progression of RFID tags in industries, advance garment sectors, health organizations, and other commercial premises is clearly visible. In order to enable commercialization of RFID tags, there are several hindrances that need to be addressed, for instance, cost efficiency, optimization of fabrication methods, utilization of eco-friendly materials etc. The material selection for antenna fabrication has a significant consequence on the environment, and the cost as well. The fabrication process is one more influential part of RFID tags, e.g. some of the fabrication processes involve multiple phases, usage of chemicals, and lengthy heat sintering period.

As running multiple applications on a single chip with additional circuitry is on the rise, providing power for these additional applications is a concerning issue. At the same time, paying attention to the chip size, so that it does not become bulky, is of foremost importance.

Ensuring safety of the tagged object is another key concern of RFID. If the security system of the tag can be easily hacked, an individual with bad intention can do harm to the attached object. To avoid misuse of the tag and make it more convenient in terms of security, the RFID chips should be able to provide assurance of the tagged object.

According to the market prediction of www.marketsandmarkets.com, the RFID market is apparently going to grow at a compound annual growth rate (CAGR) of 7.7% in the coming years between 2017 and 2023. By 2023 the market value is about to reach USD

31.42 Billion as a result of increased usage of RFID technology in industries, surveillance, and access control applications [2].

In this paper, the provided features by the available RFID chips have been studied and the various application of RFID chips have been analyzed. Finally, some suggestions have been proposed on fabrication methods.

2. RADIO FREQUENCY IDENTIFICATION (RFID)

A Radio Frequency Identification (RFID) system is composed of a reader or interrogator, tag, and antennas, as Figure 2.1 depicts. An RFID reader acts as a transceiver, which communicates with the tags in the form of electromagnetic waves through antennas. The tags also have antennas which are entitled to receive signal and respond to queries from RFID reader. In addition, tag integrated circuit (IC) contains Electronic Product Code (EPC) in their internal memory which makes them unique from one another [1].

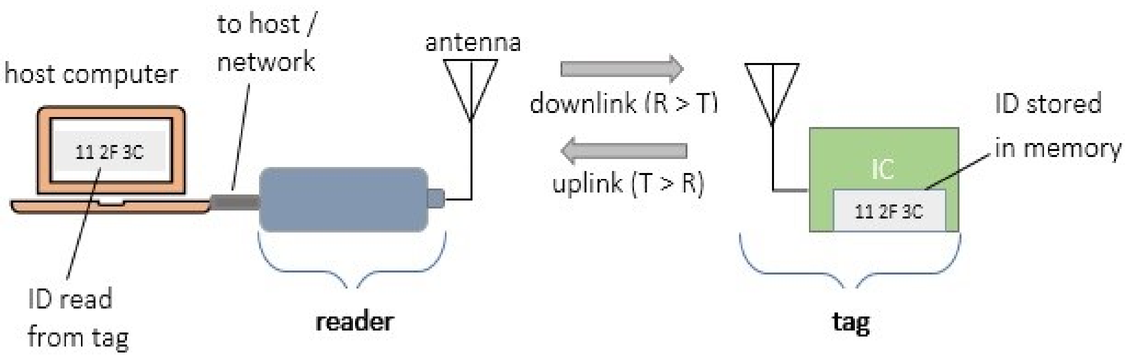

Figure 2.1: *Archetypical representation of an RFID System* [1]

The basic requirements of an RFID system include [1],

- Identifying object using radio waves with no requirement of visual contact or direct line-of-sight (LOS).
- Enough ID space for enabling unique identification of the object.
- Connection to a sensor that provides information about the condition of the identified object.
- Transmitting relevant information from the reader to the tag.

2.1 Classification of RFID Systems

The RFID system can be classified based on frequency bands upon which the reader and the tag interact, as well as the power requirements of tags to communicate with the reader.

2.1.1 Based on Frequency Bands

RFID tags can be categorized into three groups based on their frequency usage for exchanging data with the reader, such as low frequency (LF), high frequency (HF) and ultra-high frequency (UHF). The frequency band selection depends on the need of communication distance. Usually, lower frequency has shorter read range and slower information read rate, than higher frequency. Although, each frequency has its own strengths and weaknesses [1].

Low Frequency RFID: The low frequency (LF) RFID systems operate at 125/134 kHz. They have shorter read ranges and slower data rates compared to higher frequencies. But, they are robust to radio waves interference and perform better in terms of metallic objects and liquids. The applications of LF RFID system include vehicle identification, access control, livestock tracking, and such.

High Frequency RFID: The high frequency (HF) RFID systems mostly operate at 13.56 MHz. The read range of these systems is longer than LF systems and comparatively sensitive to metal substances and liquids. General usages are electronic ticketing, contactless payment, garment tracking, data transfer applications.

Ultra-High Frequency RFID: The ultra-high frequency (UHF) RFID systems operate between 860-960 MHz and at 2.4 GHz, both are considered as UHF RFID system. The applications include automobile tolling, asset management, container tracking, baggage tracking, work in progress tracking, pharmaceutical anti-counterfeiting, wireless device configuration.

2.1.2 Based on Power Source

RFID tags are feasible to embed onto various objects depending on their characteristics. From the functional point of view of the tags, the power source plays a vital role in terms of divergence among tags. Based on power requirements tags can be categorized into three kinds, such as passive tags, semi-passive tags, and active tags [1].

Passive tags are dependent on RFID reader for a power source, the reader transmits a signal through reader antenna in the form of electromagnetic waves, which activates the tag, as well as convey information for the tag, and in response, tag uses the backscattered signal to send information back to the reader. The exceptional assets of passive tags are circuital simplicity and reasonably low production cost. Figure 2.2 represents the operational characteristic of passive tags.

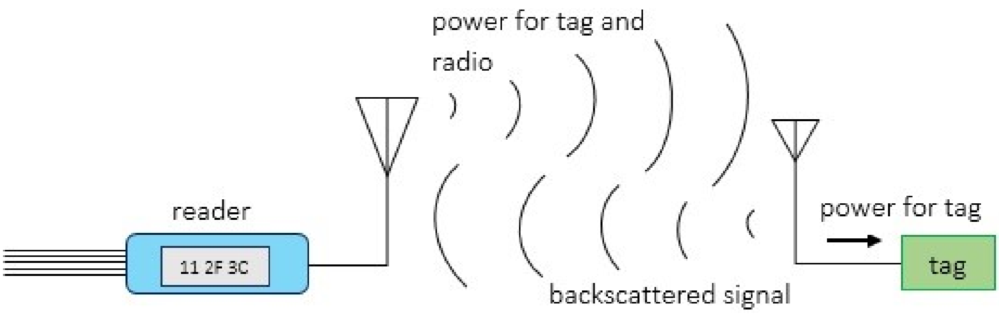

Figure 2.2: *Passive Tag* [1]

Semi-passive tags are not thoroughly dependent on the reader for a power source, these kinds of tags incorporate their own power source, which can activate the electrical circuitry of the tag (see Figure 2.3). However, they don't inherent any transmitter, yet uses the backscattered signal to communicate with the reader, which is why they also known as battery-assisted passive (BAP) tags.

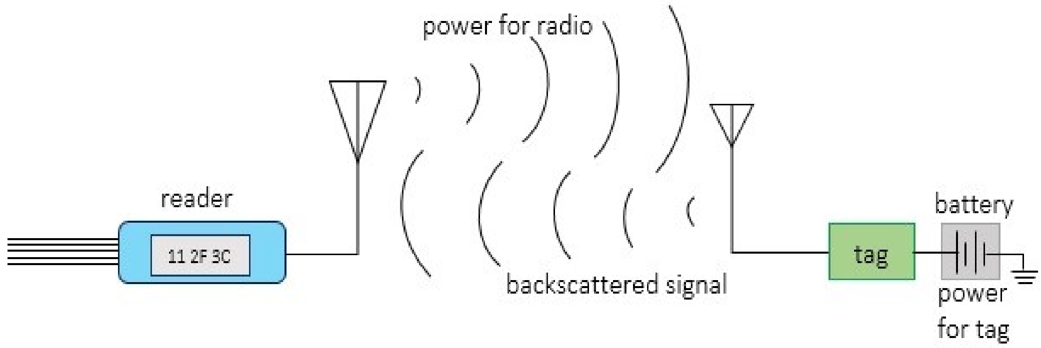

Figure 2.3: *Semi-passive Tag* [1]

Active tags inherent their own power source and transmitter, which allow them to communicate by itself to the reader. As can be seen in Figure 2.4 the tag does not need backscattered signal for communication. Comparatively, these kinds of tags are costly, bigger in size and required maintenance. As a trade-off, they have longer read ranges.

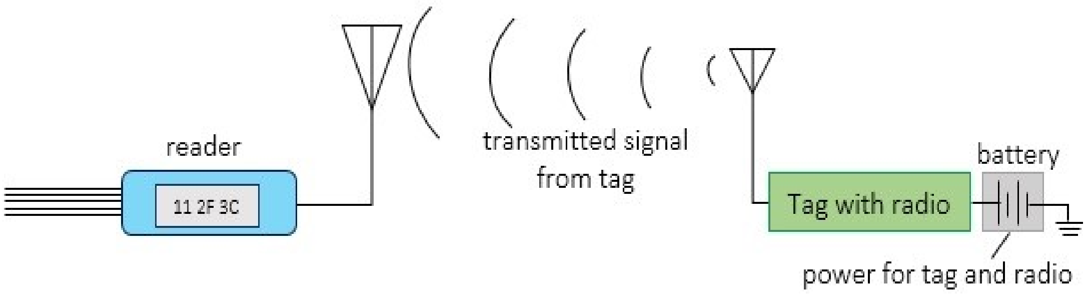

Figure 2.4: *Active Tag* [1]

2.2 Standardization

Standardization is implementing basic technical terms for the interest groups by the authorized body. This is important for any technology in terms of commercial perspectives so that the users do not have to be dependent on any manufacturing company for services or updating the system. This also allows development of the technology and helps to add a wide variety of features to it. The International Organization for Standardization (ISO) together with The International Electrotechnical Commission (IEC) and EPCglobal of GS1 are the main international standardization bodies of Radio Frequency Identification (RFID) [3, 4].

2.2.1 Standards by ISO

ISO is a standardization body, who has members in 163 different countries, which works with other organizations like IEC (International Electrotechnical Commission) and ITU

(International Telecommunication Union) to form International Standards [4]. The recognized standards of RFID by ISO are [5]:

- ISO 11784/11785: These standards define the RFID technology of animals. ISO 11784 states the formation of the identification code and ISO 11785 describes the transmission protocols between tag and reader. The frequency used for these standards is 134.2 kHz.

- ISO/IEC 14443: This standard is for contactless integrated circuit cards, primarily proximity cards. The communication protocols occur at 13.56 MHz frequency between card and reader.

- ISO/IEC 15693: This standard specifies the contactless smart cards, particularly vicinity cards. The communication between card and reader happen at 13.56 MHz.

- ISO/IEC 18000: This standard specifies numbers of common communication protocols for item management each having unique frequency range.

- ISO/IEC 24730: This standard describes the infrastructure of real-time locating systems (RTLS).

The ISO/IEC 18000 series includes the following parts,

- ISO/IEC 18000-1: This specifies the architecture and parameters of ISO/IEC 18000.

- ISO/IEC 18000-2: This defines the parameters of RFID systems that operate below 135 kHz band. Two types of tags have been defined by ISO/IEC 18000-2:

    - Type A, powered by the reader for communication, and
    - Type B, powered by the reader for communication as well, except during uplink.

- ISO/IEC 18000-3: This specifies the parameters of RFID systems that operate at 13.56 MHz band.

- ISO/IEC 18000-4: This defines the parameters of RFID systems that operate at 2.45 GHz band.

- ISO/IEC 18000-6: This specifies the RFID systems that operate in the 860 MHz to 960 MHz bands. This standard is divided into four types based on the physical and logical requirements. They are:

    - ISO/IEC 18000-61: Type A,
    - ISO/IEC 18000-62: Type B,
    - ISO/IEC 18000-63: Type C and
    - ISO/IEC 18000-64: Type D

- ISO/IEC 18000-7: This specifies the parameters of active RFID systems that operate at 433 MHz bands.

2.2.2 Standards by EPCglobal

EPCglobal works for standardization of the Electronic Product Code (EPC), which also includes forming a standard for RFID worldwide. RFID tags can be classified into six classes based on their functional characteristics, which are recognized by EPCglobal. Here is a brief description of them below [6, 7]:

- Class 0: These tags are equipped with the basic passive functionality of RFID, as optional functionality is not required for identification applications. They are preprogrammed read-only tags for a specific task, that uses the backscattered signal for communication with the reader. All other classes are incorporated with additional functionalities and power source, but keeping this class as their base.

- Class 1: This class shares the same functionalities as Class 0, i.e. passive backscattering technology for communication. The only exception to Class 0 is, these Class 1 tags are capable of being written once by the users.

- Class 2: The Class 2 tags protocol is built upon the functionality of Class 1 tag, that is passive backscattering technology. In addition, this class has extended memory, read/write capability, together with encryption and authentication feature.

- Class 3: The functionalities of this class is similar to Class 2 tags, except the addition of power source. These tags are battery-assisted passive or semi-passive, that means these tags are able to support additional functionalities with a power source, such as sensors, while still can communicate as like passive tag when there is a failure of the power source.

- Class 4: These are active tags with a built-in power source, which are capable of communicating with each other and forming a peer-to-peer network. In addition, they are reprogrammable.

- Class 5: These tags are similar to Class 4 tags, nonetheless they are capable of supplying power for passive tags.

2.3 Memory Options for RFID Tags

RFID tags can be differentiated into three different types based on memory options according to their applications [6], such as:

- Read-Only
- Write Once Read Many (WORM), and
- Read/Write

Read-Only tags are preprogrammed, these tags are solely used for identification purpose. They possess a unique code which is stored in the memory, the user is not entitled to rewrite or change the information of the tag.

Write Once Read Many (WORM) tags are analogous to Read-Only tags, except the feature of being written once by the user. The user can add supplementary information beside the unique identification code as per requirement to applications, which cannot be changed afterward.

Read/Write tags can be overwritten and the information in memory can be changed numerous times according to the applications. This kind of tags have large memory space and cost more compared to Read-Only tags.

2.4 RFID Readers

The RFID reader is the fundamental part of an RFID system. An RFID reader's functionalities include reading or writing the information on the tags and communicating with the application software through computer or microcomputer with whom it is connected to. The reader can be attached to either one or multiple antennas, in order to attain considerably large operating range, which collects signals through electromagnetic waves from the tags. According to the specification of the application, the reader can either be installed to a fixed place or used as a portable appliance. In Figure 2.5 an example of RFID reader is presented that is suitable for commercial and industrial environments, additionally, it features 4-ports to attach antennas.

Figure 2.5: *Sample of RFID Reader* [8]

The reader operates as a receiver in active RFID systems that actively listens for the signals transmitted by tags. Anyhow, in terms of passive systems, besides listening for signals from the tags, the reader transmits a continuous wave (CW) signal to provide power for the tags [1, 6].

2.5 Operation Principles of RFID Systems

The communication procedure between RFID tag and reader is dependent upon the intended application, which affects the selection of carrier frequency and antenna design to be used for the system as well. The way the reader and tag interact with each other via electromagnetic waves is known as the coupling mechanism. The coupling mechanism defines the way of transferring energy and sharing information between the tag and reader circuitries. The three main coupling methods that are commonly used:

- Capacitive Coupling,
- Inductive Coupling and
- Backscatter Coupling

The read range of tag and reader is affected by the type of coupling method is used. The capacitive coupling is used for a close range within 1 cm, the inductive coupling is used for the remote distance between 1 cm to 1 m, and the backscatter coupling is used for long-range communication generally more than 1 m [9].

2.5.1 Electromagnetic Waves

To understand the RFID system's mechanism of operation, we should analyze the concept of electromagnetism which leads to the contribution of James Clerk Maxwell (1831-1879). His discovery about ether helped to learn about radio waves, propagation of electric and magnetic fields in space. In his publication "A Dynamical Theory of the Electromagnetic Field", he demonstrated that propagation of electric and magnetic fields through space is approximate to the speed of light, which led to Heinrich Hertz's experimental generation of radio waves [10].

The Maxwell's equations that explain the behavior of electromagnetic waves are the result of the Faraday's law (2.1), Ampere's law (2.2), and Gauss' law (2.3, 2.4). For a homogeneous, isotropic, and linear medium, Maxwell's equations can be expressed as [11],

$$\nabla \times \boldsymbol{E} = -j\omega\mu\boldsymbol{H} - \boldsymbol{M} \tag{2.1}$$

$$\nabla \times \boldsymbol{H} = (\sigma + j\omega\varepsilon)\boldsymbol{E} + \boldsymbol{J_i} \tag{2.2}$$

$$\nabla \cdot \boldsymbol{D} = \rho_e \tag{2.3}$$

$$\nabla \cdot \boldsymbol{B} = \rho_m \tag{2.4}$$

where $\boldsymbol{E}$ is electric field intensity (volts/meter), $\boldsymbol{H}$ is magnetic field intensity (amperes/meter), $\boldsymbol{D}$ is electric flux density (coulombs/square meter), $\boldsymbol{B}$ is magnetic flux density (webers/square meter), $\boldsymbol{M}$ is magnetic current density (volts/square meter), ρ_e is electric charge density (coulombs/cubic meter), ρ_m magnetic charge density (webers/cubic meter), μ is permeability (henries/meter), ε is permittivity (farads/meter), σ is electric conductivity (siemens/meter), and ω is radial frequency (radians/second).

The permeability and permittivity of the medium in equation (2.1) and (2.2) are normally expressed as [10],

$$\mu = \mu_0 \mu_r \tag{2.5}$$

$$\varepsilon = \varepsilon_0 \varepsilon_r \tag{2.6}$$

where $\mu_0 = 4\pi \times 10^{-7}$ [H/m] and $\varepsilon_0 = \frac{1}{c^2 \mu_0} = 8.854 \times 10^{-12}$ [F/m] in free space, c is the speed of light, μ_r and ε_r are relative values in free space.

The Electromagnetic waves are the formation of energy which is emitted from electrically charged particles by oscillating electric and magnetic fields. Both fields propagate perpendicular to each other at the speed of light (2.99792458 x 10^8 ms^{-1}) through a vacuum.

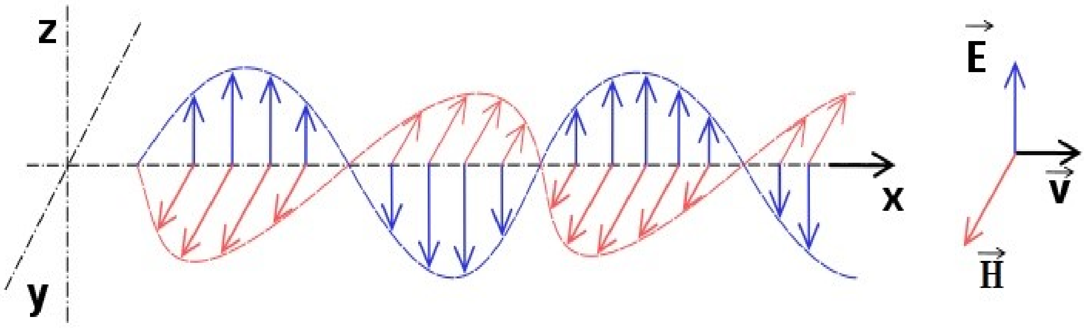

Figure 2.6: *Propagation of Electromagnetic Waves* [12]

In Figure 2.6, the electromagnetic wave is propagating from left to right, the electric field E is oscillating in the vertical direction, the magnetic field H is oscillating in the horizontal direction and both are perpendicular to the each other.

2.5.2 Capacitive Coupling

Capacitive coupling is the transmission of energy by creating a mutual capacitance between tag and reader. Instead of using antennas or coils, electrodes are used for coupling. While the reader generates AC signal, the conductive patches of the reader and tag form a capacitor between them when both held side by side, through this created capacitance the circuitry of the tag power-up and data is transmitted from tag to reader. As Figure 2.7 depicts, the circuits of reader and tag are connected through a capacitor and a common ground is shared by them. This coupling is used for short ranges where the close coupling is required, such as to read smart cards [9].

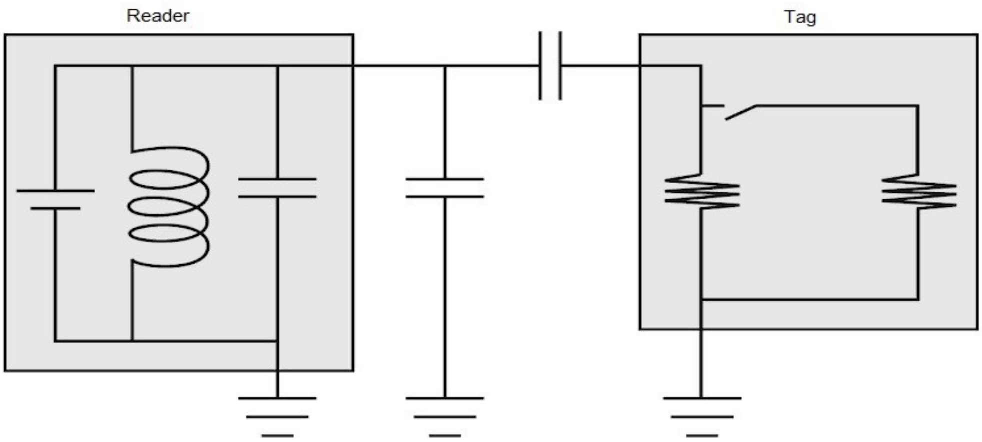

Figure 2.7: *Capacitive Coupling* [9]

2.5.3 Inductive Coupling

Inductive coupling is the phenomenon of transmitting energy by generating a magnetic field between tag and reader. The coupling elements i.e. coil antenna and capacitor, of reader and tag are used to induce current via communication signal. When the tag held close to the reader, the flowing electrical current through the reader coil induces a current in the tag that provides power for the tag circuitry. The phenomenon is illustrated in Figure 2.8, which shows the creation of a magnetic field when the reader and tag come close enough to each other. The energy from the reader antenna falls away while the tag starts moving off. As a result, inductive coupling is suitable for near field communication, and low frequencies (LF) are used for conduction [9, 10].

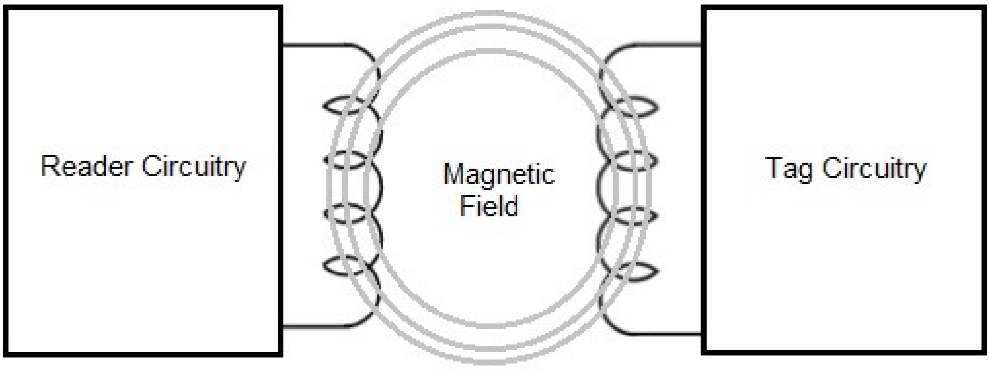

Figure 2.8: *Inductive Coupling* [10]

2.5.4 Backscatter Coupling

Backscatter coupling is typically used by the passive RFID tags that use scattered RF waves to communicate with the reader. As passive tags don't inherent a transmitter, they use backscatter modulation to talk back to RFID reader. The electromagnetic waves transmitted by reader antenna is received by the tag antenna and induces current on the receiving end only if the antenna is attached to load. The induced current results in radiation, which eventually gets back to the transmitting antenna of the reader and gets decoded afterward. The signal that makes it back to the reader is known as a backscattered signal.

On the contrary, if the antenna of the tag is not attached to load or connected load has substantial impedance value, no current or negligible amount of current will be induced on the receiving end, thus, no radiation or negligible radiation will happen. The stages of the operation are illustrated in Figure 2.9.

The way of communication between reader and tag is full-duplex, which means, the reader keeps transmitting continuous wave while the receiver observes for a signal from the tag. However, only reflected signals can get to the receiver. This phenomenon is normally used on ultra-high frequencies, in order to reach far-field regions [1].

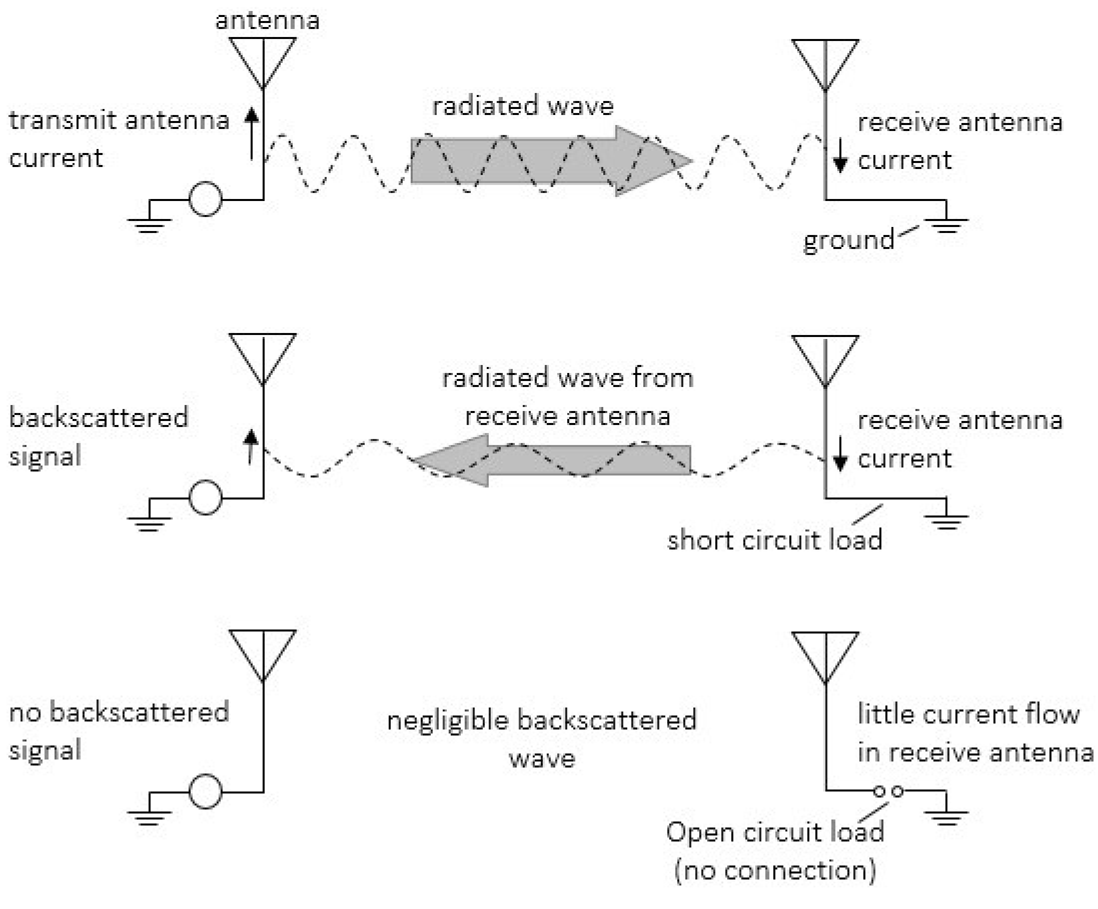

Figure 2.9: *Schematic representation of Backscatter Signaling* [1]

3. INTEGRATED CIRCUIT (IC)

An integrated circuit (IC) or microchip is an essential part of RFID tag. It consists of the logic unit, memory, modulator, envelope detector, rectifier, and capacitors [1].

3.1 Available Different ICs

There are various kinds of RFID chips available in the market. Each of them has some specific feature. Some of the chips of UHF bands (860-960 MHz) have been described below with their specifications.

HIGGS 3:

This chip is manufactured by Alien Technology. It conforms with EPC global Class 1 Gen 2 specifications as well as ISO/IEC 18000-63.

It offers 800-bits of Nonvolatile Memory, of which 96-bits of EPC memory (extensible to 480-bits), 512-bits of user memory, 64-bits of Unique tag ID (TID), 32-bits of access and 32-bits of kill password. Data can be retained for 50 years and write endurance is allowed up to 100 kcycles.

Additionally, it features pre-programmed with a unique 64-bit serial number that cannot be altered, which can be considered as unique “fingerprint” to eradicate copying of tags. Locking User Memory with BlockPermalock, as well as password protected read in 64-bit Blocks is also possible, which allows public/private usage of the chip.

Supports Item Level Commands and all Mandatory Commands. Furthermore, Custom Commands can be programmed for high speed, likely 30 tags per second for the 96-Bit EPC number.

It offers operating range up to 10 m, along with read sensitivity of -20 dBm. Besides, the operational requirements of power for read and programming is extremely low [13].

HIGGS 4:

This chip is fabricated by Alien Technology, optimized in terms of read sensitivity and cost, for mass-market and retail applications. It complies with EPC global Class 1 Gen 2 and ISO/IEC 18000-63.

It provides 512-bits of non-volatile memory, of which 128-bits of EPC memory, 128-bits of user memory, 64-bits of unique tag ID (TID), 32-bits of access and 32-bits of kill passwords. Data can be retained for 50 years and write endurance is allowed up to 100 kcycles.

In addition to EPC code, Higgs-4 offers pre-programmed unique 64-bit serial number which cannot be changed. User memory can be locked with BlockPermalock, also read can be password protected in 32 Bit blocks.

It can be programmed to write at high speed using one command, QuickWrite™. Or else, BlastWrite™ command can be used regarding mass-programming, to encode multiple tags concurrently.

Higgs-4 provides Dynamic Authentication™ feature, which can be considered as anti-cloning and anti-counterfeit of the tag.

It operates at extremely low power, yet still offers up to 11 m of operating range and read sensitivity of -20.5 dBm [14].

HIGGS-EC:

This is Alien Technology's next-generation chip with enhanced data quality, meets EPC global Class 1 Gen 2 and ISO/IEC 18000-63.

It comes with 512-bits of nonvolatile memory, of which 128-bits of EPC memory, 128-bits of user memory, 48-bits of unique tag ID (TID), 32-bits of access and 32-bits of kill passwords. Data can be retained for 50 years and write endurance is allowed up to 200 kcycles.

Moreover, it is factory programmed with a unique 64-bit unchangeable serial number, also has the option to block user memory with BlockPermalock and make read password protected in 32-bit blocks.

Like Higgs-4, this also allows QuickWrite™ / BlastWrite™ for writing in high-speed and mass-encoding of multiple tags simultaneously. Dynamic Authentication™ feature is also available to protect the chip from being cloned and counterfeited.

The astonishing feature of Higgs-EC is the self-correcting memory, Sentinel Memory architecture, which detects and fixes the error in such a way, the user of the tag doesn't realize the error happened at all.

The chip requires low power for operational purposes, whilst provides operating range up to 13 m. In addition, offers best in class read sensitivity of -22.5 dBm and write sensitivity of -19 dBm [15].

UCODE HSL:

This passive IC is manufactured by NXP Semiconductors, designed to meet ISO standards 18000-4 and 18000-6 considering long-range operations.

It carries 2048-bits of nonvolatile memory, of which 64-bits of a unique ID (UID), 216-bytes of user memory. It maintains high data integrity with cyclic redundancy check (CRC) value of 16-bits in every message between tag and interrogator. To avoid a collision, the interrogator can run collision-arbitration algorithm among selected tags. Moreover, the data can be retained for 10 consecutive years.

In regard to security issues, the unique serial number is allotted to each device and allows write protection for each byte.

The operational distance is 8.4 m, whereas the write distance is 70% of the read distance along with 100 kcycles of endurance [16].

UCODE G2XM and G2XL:

This passive G2X series is a product of NXP Semiconductors, supports EPC global Class 1 Gen 2.

It comes with 240-bits of EPC memory, 64-bits of tag ID (TID) along with 32-bits of unique serial number, 32-bits of kill password, 32-bits of access password and 512-bits of user memory (only in G2XM). Data can be retained for 50 years and write endurance is allowed up to 100 kcycles.

It features Electronic Article Surveillance (EAS) command that enables applicability of the chip as EAS tag. It is feasible to assess the communication link of the tag-to-reader by Calibrate command, which triggers permanent back-scatter. In addition, an advanced anti-collision aspect provides reliable activity of multiple tags.

Regarding security issues, the entire memory can be read protected from unauthorized reading.

It offers read distance of 7.5 m, whereas write distance is 50% of the read range. Besides, the data rates obtainable in forward link is 40 to 160 kbit/s, and in return link is 40 to 640 kbit/s [17].

UCODE G2iM and G2iM+:

These chips of NXP Semiconductors, conform to the EPC global Class 1 Gen 2.

They possess 256-bits of EPC memory for G2iM / 448-bits of EPC memory for G2iM+, 640-bits of user memory in G2iM+, 96-bits of tag ID (TID) along with 48-bits of unalterable unique serial number, 112-bits of user TID memory, 32-bits of kill password, 32-bits of access password, and 32-bits of user password to authorize access to private user memory. In addition, the data retention period is 20 years.

Built-in Product Status Flag (PSF) enables the applicability of the chip as Electronic Article Surveillance tag. Some other exceptional features, like BlockPermalock, BlockWrite, tag tamper alarm, digital switch, data transfer mode, read range reduction mode, and external supply mode can be configured with a custom command. Additionally, multiple tags can concurrently perform their activity on account of the advanced anti-collision feature.

They provide read and write protection of the memory, to protect the chip from any unauthorized reading and writing.

They offer read sensitivity of -17.5 dBm in passive mode and -27 dBm in batter-assisted mode [18].

UCODE G2iL and G2iL+:

These chips from NXP Semiconductors meet the standard of EPC global Class 1 Gen 2.

They come with 128-bits of EPC memory, 64-bits of Tag ID (TID) along with 32-bits of invariant unique serial number, 32-bits of kill password, and 32-bits of access password. Data can be retained for 20 years and write endurance is allowed up to 1000 cycles.

In the matter of security issues, they provide built-in Product Status Flag (PSF) which facilitates the usage of the chips as EAS tag. Besides, they offer read protection and write locking of memory, to avoid any unauthorized reading or writing of the chip. Moreover, to overcome collisions between tags, they present advance anti-collision mechanism.

G2iL+ outstands G2iL in some features, like built-in tag tamper alarm, digital switch, RF field detection, read range reduction, external power supply mode, and data transfer mode.

They provide read sensitivity of -18 dBm in passive mode, though in case of battery-assisted mode the read and write sensitivity can be achieved up to -27 dBm [19].

UCODE 7xm-1k, 7xm-2k and 7xm+:

These products of NXP Semiconductors comply with EPC global Class 1 Gen 2.

They possess 448-bits of EPC memory along supporting 96-bits of EPC pre-serialization, 96-bits of Tag ID (TID) along with 48-bits of invariant unique serial number, 1-kbit of user memory (in 7xm-1k), 2-kbits of user memory (in 7xm-2k), 2-kbits of user memory (in 7xm+), 384-bits of digital signature (in 7xm+), 32-bits of kill password and 32-bits of access password.

In addition, the chips yield 32-bits per 1.5 milliseconds of encoding speed, 20 years of data retention period and 100 kcycles of write endurance.

Including, untraceable attribute, the chips also provide BlockWrite, BlockPermalock, built-in Product Status Flag which enables the tag's usage as EAS tag, tag power indication that allows the reader to choose the tag with adequate power to be written to, and parallel means of encoding.

They offer read sensitivity of -19 dBm and write sensitivity of -12 dBm. In addition, they get along with single-slit antenna as well [20].

UCODE 7 and 7m:

These chips of NXP Semiconductors meet the standard of EPC global Class 1 Gen 2.

They are available with 128-bits of EPC memory, 96-bits of unalterable unique tag ID (TID) along with 48-bits of the serial number, 32-bits of user memory (only in UCOE 7m), 32-bits of access password and 32-bits of kill password (only in UCODE 7). Data retention period is 20 years and write endurance is allowed up to 100 kcycles.

It is feasible to do parallel encoding of tags at a rate of 100 objects in 60 milliseconds. Moreover, the encoding can be accomplished at the speed of 16-bits per millisecond.

Some other impressive features they offer, such as BlockWrite, tag power indicator to optimize tag localization, and built-in product status flag (PSF) for applications like electronic article surveillance.

They present read sensitivity of -21 dBm and write sensitivity of -16 dBm. Furthermore, they get along with the single-slit antenna [21, 22].

UCODE 8 and 8m:

These chips from NXP Semiconductors comply with EPC global Class 1 Gen 2, particularly convenient for applications like stock management.

They possess 128-bits (UCODE 8) / 96-bits (UCODE 8m) of EPC memory, 96-bits of factory locked unique tag ID (TID) along with 48-bits of the serial number, 32-bits of user memory (only in UCODE 8m), 32-bits of kill password, and 32-bits of access password. Data can be retained for 20 years and write endurance is allowed up to 100 kcycles.

This series of chip provides, BlockWrite, identification of brand originality, untraceable feature, memory safeguarding which makes sure of data integrity, auto adjustment of chip sensitivity according to the environment, and built-in product status flag (PSF) for electronic article surveillance application.

In addition to, compatibility with single-slit antenna, they offer read sensitivity of -23 dBm and write sensitivity of -18 dBm [23].

UCODE DNA:

This chip from NXP Semiconductors conforms EPC global Class 1 Gen 2 and ISO/IEC 29167-10, as well emphasizes on long read range and security issue.

It possesses 224-bits of EPC memory, 96-bits of unalterable Tag ID (TID) along with 48-bits of unique serial number, up to 3-kbits of user memory with BlockPermalock, 32-bit kill password and 32-bit access password.

The encoding speed can be attained up to 32-bits per 1.5 milliseconds with a minimum write endurance of 100 kcycles and 20 years of data retention period.

In terms of security, it provides an untraceable feature, as well as cryptographic authentication of tag using advanced encryption standard (AES) coprocessor of -18 dBm sensitivity and 128-bit crypto key.

Additionally, this chip also provides tag power indicator for tag localization, built-in product status flag (PSF), and allows parallel encoding at a rate of 100 tags in 60 milliseconds.

It offers read sensitivity of -19 dBm, write sensitivity of -11 dBm and compatibility of the single-slit antenna [24].

UCODE DNA City:

This RAIN RFID chip of NXP Semiconductors complies with EPC global Class 1 Gen 2 and ISO/IEC 29167-10, also unites long-range identification and protection of end-user privacy.

The chip comes with 96-bits of tag ID (TID), 224-bits of EPC memory including 96-bits of EPC factory locked, 1-kbit of user memory, 32-bits of kill password and 32-bits of access password. The encoding can be accomplished at the rate of 32-bits per 1.5 milliseconds with write endurance of 100 kcycles and 20 years of data retention period.

In addition, it provides untraceable feature, tag power indication for tag localization and built-in product status flag, cryptographic authentication of tag with advanced encryption standard (AES) coprocessor using the 128-bit confidential key.

Moreover, simultaneously encoding of stock keeping unit (SKU) is feasible with 100 tags in 60 milliseconds.

It offers read sensitivity of -19 dBm and write sensitivity of -11 dBm [25].

UCODE DNA Track:

This RAIN RFID chip from NXP Semiconductors conforms EPC global Class 1 Gen 2 and ISO/IEC 29167-10, intended for automated tracking to confirm the authenticity of products.

The chip carries 448-bits of EPC memory along with 96-bits of factory locked EPC, 96-bits of tag ID (TID), 256-bits of user memory, 32-bits of kill password and 32-bits of access password. Data can be encoded at the speed of 32-bits per 1.5 milliseconds while write endurance is 100 kcycles and data retention period is 20 years.

Like other UCODE tags, it provides, BlockPermalock, BlockWrite, tag power indication for tag localization, built-in product status flag, untraceable feature, and parallel stock keeping unit (SKU) encoding at the speed of 100 tags per 60 milliseconds.

Furthermore, it features cryptographic tag authentication with advanced encryption standard (AES) coprocessor of -18 dBm sensitivity using the 128-bit confidential key.

It offers read sensitivity of -19 dBm, write sensitivity of -11 dBm and compatibility with the single-slit antenna [26].

MONZA R6:

This RAIN RFID chip from Impinj is, compliant with EPC global Class 1 Gen 2 and ISO/IEC 18000-63, enhanced in terms of serialization of products.

It comes with 96-bits of EPC memory, 96-bits of serialized tag ID (TID) along with 48-bits of the serial number. Data can be encoded in the speed of 32-bits per 1.6 milliseconds and encoding throughput can be obtained up to 9,500 tags per minute by adopting the Impinj STP source tagging. In addition, data can be retained for 50 years and write endurance is allowed up to 100 kcycles.

It ensures data integrity with Integra technology, accordingly maintains performance in different environments with AutoTune technology, and patent-pending Enduro technology provides high-quality tags.

In addition to, BlockWrite, it allows 2 to 3 times faster both the EPC and the TID based inventory by FastID mode, also enables reading weak unread tags by suppressing the already read tags by TagFocus mode.

It offers read sensitivity of -22.1 dBm, as well as robustness to interference and write sensitivity of -18.8 dBm [27].

MONZA R6-P:

This RAIN RFID chip of Impinj with enhanced privacy, conform EPC global Class 1 Gen 2 and ISO 18000-63.

It carries 128-bits of EPC memory, 96-bits of serialized tag ID (TID) along with 48-bits of the serial number, 32-bits of kill password, 32-bits of access password and up to 64-bits of user memory. Memory can be written at the speed of 32 bits per 1.6 milliseconds and encoding throughput can be achieved up to 9,500 tags per minute utilizing the Impinj ItemEncode software. As well, data can be retained for 50 years and write endurance is allowed up to 100 kcycles.

Like MONZA R6, it also ensures data integrity with Integra technology, maintains performance according to different environments with AutoTune technology, and patent-pending Enduro technology provides high-quality tags.

Additionally, it features, BlockWrite, BlockPermalock, a FastID mode which allows 2 to 3 times faster both the EPC and the TID based inventory, TagFocus mode that enables reading weak unread tags by suppressing the already read tags, Short-range mode reduces the read range of chips by 1/10 than normal read range.

It offers -21.1 dBm of read sensitivity with robustness to interference and -17.3 dBm of write sensitivity [28].

MONZA R6-A:

This RAIN RFID chip of Impinj with enhanced privacy, conform EPC global Class 1 Gen 2 and ISO 18000-63.

It carries 96-bits of EPC memory, 96-bits of serialized tag ID (TID) along with 48-bits of the serial number, 32-bits of kill password, and 32-bits of access password. Memory can be written at the speed of 32 bits per 1.6 milliseconds and encoding throughput can be achieved up to 9,500 tags per minute utilizing the Impinj ItemEncode software. As well, data can be retained for 50 years and write endurance is allowed up to 100 kcycles.

Like MONZA R6, this also ensures data integrity with Integra technology, maintain performance according to different environments with AutoTune technology, and patent-pending Enduro technology provides high-quality tags.

Additionally, it features, BlockWrite, FastID mode which allows 2 to 3 times faster both the EPC and the TID based inventory, TagFocus mode that enables reading weak unread tags by suppressing the already read tags, Short-range mode reduces the read range of chips by 1/10 than normal read range, kill password and access password prevent chips from any unauthorized access.

It offers -21.1 dBm of read sensitivity with robustness to interference and -17.3 dBm of write sensitivity [29].

MONZA S6-C:

This RAIN RFID chip from Impinj complies with EPC global Class 1 Gen 2 and ISO 18000-63.

It comes with 96-bits of EPC memory, 96-bits of serialized tag ID (TID) along with 48-bits of the serial number, 32-bits of user memory, 32-bits of kill password and 32-bits of access password.

Memory can be written at the speed of 32-bits per 1.6 milliseconds, and encoding throughput can be attained up to 9,500 tags per minute by utilizing the Impinj ItemEncode software. In addition, it allows write endurance up to 100 kcycles, and data retention period of 50 years.

Moreover, it ensures data integrity with Integra technology, maintains performance according to different environments with AutoTune technology, and patent-pending Enduro technology provides high-quality tags.

Furthermore, it features, BlockWrite, BlockPermalock, fail-safe one-way counter for exploiting applications like ticketing and metering, a FastID mode which allows 2 to 3 times faster both the EPC and the TID based inventory, and TagFocus mode that enables reading weak unread tags by suppressing the already read tags.

It offers read sensitivity of -22.1 dBm, including excellent interference withstanding potentiality and write sensitivity of -17.3 dBm [27].

MONZA 5:

This chip from Impinj compliant with EPC global Class 1 Gen 2 and ISO 18000-63, enhanced in terms of serializing products.

It bears 128-bits of EPC memory, 96-bits of serialized tag ID (TID) along with 48-bits of the serial number, 32-bits of user memory, 32-bits of kill password and 32-bits of access password. In addition to, encoding speed of over 3000 tags per minute, it allows write endurance of 100 kcycles, and data retention period of 50 years.

Furthermore, it features, BlockWrite, a FastID mode which allows 2 to 3 times faster both the EPC and the TID based inventory, and TagFocus mode that enables reading weak unread tags by suppressing the already read tags.

Additionally, patent-pending “repassivation”, makes the production of the tag moderately divergent.

It offers read sensitivity of -20 dBm together with the potentiality to resist interference and write sensitivity of -16 dBm [30].

MONZA 4:

This chip of Impinj complies with EPC global Class 1 Gen 2 and ISO 18000-63. The MONZA 4 family consists of MONZA 4QT, MONZA 4E, MONZA 4D and MONZA 4i.

It carries 96-bits of serialized tag ID (TID) along with 48-bits of the serial number, 32-bits of kill password and 32-bits of access password. Moreover, this chip let's user to choose from its four different available combinations of memory, such as, 512-bits of user memory and 128-bits of EPC memory (in MONZA 4QT), 128-bits of user memory and 496-bits of EPC memory (in MONZA 4E), 32-bits of user memory and 128-bits of EPC memory (in MONZA 4D), 480-bits of user memory and 256-bits of EPC memory (in MONZA 4i).

In addition, memory can be written at the speed of 32-bits per 3.4 milliseconds and encoding throughput can be accomplished up to 1200 tags per minute. Data can be retained for 50 years and write endurance is allowed up to 100 kcycles.

Again, it features, BlockWrite, a FastID mode which allows 2 to 3 times faster both the EPC and the TID based inventory, TagFocus mode that enables reading weak unread tags by suppressing the already read tags, and BlockPermalock command gives more flexibility in utilizing memory.

Additionally, it provides, True3D antenna technology that enables omnidirectional performance of tags by eliminating blind spots, also QT technology (only in MONZA 4QT) gives the owner the opportunity whether to make information publicly accessible or confidential by private/public profiles and short-range mode.

It offers read sensitivity of -19.5 dBm with the single port operation or -22 dBm with True3D antenna technology and write sensitivity of -16.7 dBm [31].

MONZA 4 DURA:

This chip from Impinj conforms EPC global Class 1 Gen 2 and ISO 18000-63, besides optimized for applications related to the printed circuit board (PCB).

It bears 96-bits of serialized tag ID (TID) along with 48-bits of the serial number, 32-bits of kill password, and 32-bits of access password. It is available in two different memory combinations, one is 512-bits of user memory with 128-bits of EPC memory (in MONZA 4QT Dura), and another is 128-bits of user memory with 496-bits of EPC memory (in MONZA 4E Dura).

Also, memory can be written at the speed of 32-bits per 5 milliseconds and encoding throughout can be attained up to 2500 tags per minute. Moreover, data can be retained for 50 years and write endurance is 100 kcycles.

Additionally, it features, True3D antenna technology that enables omnidirectional performance of tags by eliminating blind spots and BlockPermalock command gives more flexibility in utilizing memory.

It offers read sensitivity of -17.4 dBm (with single port) or -19.9 dBm (with True3D) together with the potentiality to withstand interference, and write sensitivity of -14.6 dBm (with single port) or -17.1 dBm (with True3D) [32].

MONZA X-2K:

This chip of Impinj compliant with EPC global Class 1 Gen 2 and ISO 18000-63, possesses an I^2C (Inter-Integrated Circuit) interface which allows more access to chip than usual.

It carries 2176-bits of nonvolatile memory, 128-bits of EPC memory, 96-bits of tag ID (TID), 32-bits of kill password and 32-bits of access password. Memory can be written at the speed of 32-bits per 4.7 milliseconds and data retention period is provided for 50 years while write endurance is 100 kcycles.

Additionally, it features, BlockWrite, BlockPermalock, wakeup write mode, five one-time programmable (OTP) blocks with BlockPermalock, also QT function that enables short-range mode and states privacy of data.

Furthermore, it provides, I^2C (Inter-Integrated Circuit) slave interface that enables to read and write memory of chip even at powered off state of the electronic device, as well, RF access control over the I^2C interface.

It offers, read sensitivity of -17 dBm in passive mode or -24 dBm in battery-assisted mode, and write sensitivity of -12 dBm in passive mode or -24 dBm in battery-assisted mode [33].

MONZA X-8K:

This chip from Impinj conforms EPC global Class 1 Gen 2 and ISO 18000-63, as well possesses an I^2C (Inter-Integrated Circuit) interface which allows more access to chip than usual.

It carries 8192-bits of nonvolatile memory, 128-bits of EPC memory, 96-bits of tag ID (TID), 32-bits of kill password and 32-bits of access password. Memory can be written at the speed of 32-bits per 4.7 milliseconds and data retention period is offered for 50 years while write endurance is 100 kcycles.

Additionally, it features, BlockWrite, BlockPermalock, wakeup write mode, sixteen one-time programmable (OTP) blocks with BlockPermalock, also QT function that enables short-range mode and states privacy of data.

Moreover, it provides, I^2C (Inter-Integrated Circuit) slave interface that enables to read and write memory of chip even at powered off state of the electronic device, similarly, RF access control over the I^2C interface.

It offers, read sensitivity of -17 dBm in passive mode or -24 dBm in battery-assisted mode, and write sensitivity of -12 dBm in passive mode or -24 dBm in battery-assisted mode [34].

em|echo / EM4423:

This chip from EM Microelectronic compatible with dual frequency devices, which means it is compliant with EPC global Class 1 Gen 2 and ISO 18000-63, as well as ISO/IEC 14443 Type A and NFC Forum™ Type 2.

It comes with 96-bits unalterable unique tag ID (TID), 32-bits kill password, 32-bits access password, in addition to this, it is available in two different memory configurations, such as, 128-bits of EPC memory and 160-bits of user memory for small EPC memory configuration, or 224-bits of EPC memory and 64-bits of user memory for large EPC memory configuration. Data can be retained for 10 years and write endurance is allowed of 100 kcycles.

Additionally, it features untraceable command, BlockWrite command that enables rapid encoding, and BlockPermalock that allows interrogator to change the state of tag's user memory.

Furthermore, the EPC interface has access to Near Field Communication (NFC) memory and vice versa, though their functionalities do not influence one another. The user can read NFC access counter and detect NFC field over EPC interface.

It offers, read sensitivity of -18 dBm and write sensitivity of -13 dBm with dipole antenna [35].

em|aura-C:

This crypto transponder IC from EM Microelectronic conforms EPC global Class 1 Gen 2 and ISO/IEC 18000-63. It is also compliant with Crypto Suites ISO/IEC 29167-10 (AES-128) and ISO/IEC 29167-13 (Grain-128A), which ensure mutual authentication, interrogator authentication, data exchange during authentication including key update, tag authentication and authenticated communication.

It has 3072-bits of non-volatile memory with BlockWrite feature, 32-bits of access and kill passwords, 416-bits for EPC encoding, XTID with 48-bits serialization. As well, it allows user configurable memory options, i.e. 6 crypto keys and 1280 bits of user memory, or 2 crypto keys and 1792 bits of user memory.

It features tamper detection, secure counter mode operation, pseudo-random number generator, and resistance to eavesdropping on the tag-reader communication, cloning attacks, and harvesting.

It offers read sensitivity of -18.5 dBm, write sensitivity of -15.5 dBm and crypto sensitivity of -18 dBm with dipole antenna [36].

em|echo-T:

This chip from EM Microelectronic supports dual frequency on single die, that means it conforms ISO/IEC 14443A-3 and NFC Forum Type 2, as well compliant with RAIN RFID protocols ISO/IEC 18000-63 and EPC global Class 1 Gen 2.

It has 96-bits of unalterable unique identifier (UID), 32-bits of access and kill passwords. It allows BlockWrite for fast encoding, BlockPermalock for user memory, as well as untraceable command to ensure privacy.

It features tamper detection, NFC field detection, electronic article surveillance (EAS), and access counter.

It offers read sensitivity of -18 dBm and write sensitivity of -13 dBm with dipole antenna [37].

EM4124:

This chip of EM Microelectronic conforms EPC global Class 1 Gen 2 and ISO/IEC 18000-63.

It carries 64-bits of factory locked unique Tag ID (TID), 176-bits of non-volatile memory of which 16-bits of protocol control word, 96-bits of EPC code, 32-bits of kill password and 32-bits of access password. Data can be retained for 10 years and write endurance is allowed up to 10 kcycles.

Additionally, it features deactivation function that allows the user to deactivate tag, and temporarily or fully re-activate it again while necessary.

It offers read sensitivity of -19 dBm, which can be achieved up to -21 dBm with dipole antenna and write sensitivity of -8 dBm [38].

EM4126:

This chip from EM Microelectronic complies with EPC global Class 1 Gen 2 and ISO/IEC 18000-63.

It comes with 224-bits of non-volatile memory of which 208-bits of EPC memory and 16-bits of protocol control word, 32-bits of tag ID (TID). Data can be retained for 10 years and write endurance is allowed up to 10 kcycles.

Moreover, it provides data rates of 40 to 160 kbit/s in forward link and 40 to 640 kbit/s in return link. Besides, it supports near-field mode that allows reading through metal or liquid substance, and parallel-inductance matching.

It offers read sensitivity of -19 dBm or -21 dBm with dipole antenna, and write sensitivity of -8 dBm [39].

EM4324:

This chip from EM Microelectronic, compliant with EPC global Class 1 Gen 2 and ISO/IEC 18000-63, available in passive and battery assisted mode.

It carries 720-bits of user memory, 96-bits of EPC memory, 64-bits of factory locked unique tag ID (TID), 32-bits of kill password, and 32-bis of access password.

Moreover, it’s memory can be encoded at the speed of 16-bits per 7.2 milliseconds. It provides data rates of 40 to 160 kbit/s in forward link and 40 to 640 kbit/s in return link. Data can be retained for 10 years and write endurance is allowed up to 10 kcycles.

Additionally, it features, near-field mode that allows reading through metal or liquid substance, tamper detection that detects the low impedance of tag, anti-tearing that prevent the tag from unauthorized unlocking, and parallel-inductance matching.

It offers read sensitivity up to -9 dBm in passive mode and -27 dBm in battery-assisted mode [40].

EM4325:

This chip of EM Microelectronic complies with EPC global Class 1 and Class 3 Gen 2, ISO/IEC 18000-63, and ISO/IEC 18000-64. It operates both in passive mode and battery assisted mode.

It comes with 4096-bits of non-volatile memory, of which 48-bits factory programmed serial number, 352-bits of EPC memory, 3072-bits of user memory/3008-bits for TOTAL data, 128-bits of register file, 32-bits of kill password and 32-bits of access password. Data can be retained for 10 years and write endurance is allowed up to 100 kcycles.

Moreover, it provides data rates of 26.7 to 128 kb/s in forward link and 40 to 640 kb/s in return link. As well, provided data rates for TOTAL are 64, 128, 160, 256, or 320 kb/s.

Additionally, it features, BlockErase and BlockWrite which make memory transactions faster, BlockPermalock for protecting user’s privacy, synchronized Universal Time Clock

(UTC), a built-in programmable temperature sensor for monitoring and alarming along with time stamp, and power source management.

Furthermore, it has 4-bit I/O port that can be configured as 4 discrete signals or serial peripheral interface (SPI) bus, and an auxiliary function programmable as tamper detector or notification for RF events.

It offers, read sensitivity up to -8.3 dBm and write sensitivity up to -7 dBm in passive mode, or read and write sensitivity up to -31 dBm in battery-assisted mode [41].

SL900A:

This chip from ams, compliant with EPC global Class 1 and Class 3 Gen 2, operates both in battery-assisted mode and passive mode.

It carries 9-kbits of non-volatile memory, of which 512-bits of system memory, 32-bits of kill password, 32-bits of access password, 144-bits of EPC memory, 80-bits of factory locked unique tag ID (TID), and 8416-bits of user memory.

Moreover, it provides data rates up to 40 to 160 kbit/s in forward link and 5 to 640 kbit/s in return link. Data can be retained for 20 years and write endurance is allowed up to 100 kcycles.

Additionally, it features, energy harvesting from the interrogator, temperature sensor, synchronized real-time clock (RTC) for the time stamp, serial peripheral interface (SPI) bus, built-in dynamic shelf life calculation, analog to digital converter, and data protection.

It offers read sensitivity up to -15 dBm in battery-assisted mode and -7 dBm in passive mode [42].

3.2 Comparison and Summary

The table below states the differences among available ICs.

Table 3.1: *Differences between available RFID integrated circuits.*

Integrated Circuits	Supported Protocols	Read Sensitivity / Distance	User Memory (bits)	BAP mode Sensitivity	Optional Commands	Optional Passwords	Additional Features
HIGGS 3	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-20 dBm	512	-	BlockPermalock, Custom, Access	Kill and Access passwords	-

HIGGS 4	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-20.5 dBm	128	-	BlockPermalock, Access	Kill and Access passwords	QuickWrite, BlastWrite, Dynamic Authentication
HIGGS-EC	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-22.5 dBm	128	-	BlockPermalock,	Kill and Access passwords	QuickWrite, BlastWrite, Dynamic Authentication, Sentinel or Self-correcting Memory
UCODE HSL	ISO 18000-4, 18000-6	8.4 m	216	-	-	-	-
UCODE G2XM	EPCglobal Class 1 Gen 2	7.5 m	512	-	Access	Kill and Access passwords	EAS Alarm, Calibrate Command
UCODE G2XL	EPCglobal Class 1 Gen 2	7.5 m	-	-	Access	Kill and Access passwords	EAS Alarm, Calibrate Command
UCODE G2iM	EPCglobal Class 1 Gen 2	-17.5 dBm	-	-27 dBm	Custom, BlockWrite, BlockPermalock	Kill and Access passwords	EAS Alarm, Tag Tamper Alarm, Digital Switch, Data Transfer Mode, Read Range Reduction Mode
UCODE G2iM+	EPCglobal Class 1 Gen 2	-17.5 dBm	640	-27 dBm	Custom, BlockWrite, BlockPermalock	Kill and Access passwords	EAS Alarm, Tag Tamper Alarm, Digital Switch, Data Transfer Mode, Read Range Reduction Mode
UCODE G2iL	EPCglobal Class 1 Gen 2	-18 dBm	-	-	Access	Kill and Access passwords	EAS Alarm

UCODE G2iL+	EPCglobal Class 1 Gen 2	-18 dBm	-	-27 dBm	Access	Kill and Access passwords	EAS Alarm, Tag Tamper Alarm, Digital Switch, RF Field Detection, Read Range Reduction, External Power Supply, Data Transfer Mode
UCODE 7xm-1k	EPCglobal Class 1 Gen 2	-19 dBm	1024	-	Access, BlockWrite, BlockPermalock	Kill and Access passwords	Tag Power Indicator, Parallel Encoding, EAS Alarm, Compatible with Single-Slit Antenna
UCODE 7xm-2k	EPCglobal Class 1 Gen 2	-19 dBm	2048	-	Access, BlockWrite, BlockPermalock	Kill and Access passwords	Tag Power Indicator, Parallel Encoding, EAS Alarm, Compatible with Single-Slit Antenna
UCODE 7xm+	EPCglobal Class 1 Gen 2	-19 dBm	2048	-	Access, BlockWrite, BlockPermalock	Kill and Access passwords	Digital Signature, Tag Power Indicator, Parallel Encoding, EAS Alarm, Compatible with Single-Slit Antenna
UCODE 7	EPCglobal Class 1 Gen 2	-21 dBm	-	-	Access, BlockWrite	Kill and Access passwords	EAS Alarm, Tag Power Indicator, Parallel Encoding, Compatible with Single-Slit Antenna

UCODE 7m	EPCglobal Class 1 Gen 2	-21 dBm	32	-	Access, BlockWrite	Access password	EAS Alarm, Tag Power Indicator, Parallel Encoding, Compatible with Single-Slit Antenna
UCODE 8	EPCglobal Class 1 Gen 2	-23 dBm	-	-	Access, BlockWrite	Kill and Access passwords	Memory Safeguard, Self-Adjust, Brand Identifier, EAS Alarm, Compatible with Single-Slit Antenna
UCODE 8m	EPCglobal Class 1 Gen 2	-23 dBm	32	-	Access, BlockWrite	Kill and Access passwords	Memory Safeguard, Self-Adjust, Brand Identifier, EAS Alarm, Compatible with Single-Slit Antenna
UCODE DNA	EPCglobal Class 1 Gen 2, ISO/IEC 29167-10	-19 dBm	3072	-	Access, BlockPermalock	Kill and Access passwords	AES based Cryptographic Security, Tag Power Indicator, EAS Alarm, Parallel Encoding, Compatible with Single-Slit Antenna
UCODE DNA City	EPCglobal Class 1 Gen 2, ISO/IEC 29167-10	-19 dBm	1024	-	Access	Kill and Access passwords	AES based Cryptographic Security, Tag Power Indicator, EAS Alarm, Parallel Encoding

UCODE DNA Track	EPCglobal Class 1 Gen 2, ISO/IEC 29167-10	-19 dBm	256	-	Access, BlockPermalock, BlockWrite,	Kill and Access passwords	AES based Cryptographic Security, Tag Power Indicator, EAS Alarm, Parallel Encoding, Compatible with Single-Slit Antenna
MONZA R6	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-22.1 dBm	-	-	BlockWrite	-	Integra Technology, AutoTune Technology, Enduro Technology, FastID mode, TagFocus mode
MONZA R6-P	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-22.1 dBm	64	-	BlockWrite, BlockPermalock	Kill and Access passwords	Integra Technology, AutoTune Technology, Enduro Technology, FastID mode, TagFocus mode, Short-range mode
MONZA R6-A	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-22.1 dBm	-	-	Access, BlockWrite	Kill and Access passwords	Integra Technology, AutoTune Technology, Enduro Technology, FastID mode, TagFocus mode, Short-range mode

MONZA S6-C	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-22.1 dBm	32	-	BlockWrite, BlockPermalock	Kill and Access passwords	Integra Technology, AutoTune Technology, Enduro Technology, FastID mode, TagFocus mode, Short-range mode, One-way fail-safe counter
MONZA 5	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-20 dBm	32	-	Access, BlockWrite	Kill and Access passwords	FastID mode, TagFocus mode
MONZA 4QT	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-22 dBm	512	-	Access, BlockWrite, BlockPermalock	Kill and Access passwords	QT Technology, Short-range option, True3D Antenna Technology, FastID mode, TagFocus mode
MONZA 4E	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-22 dBm	128	-	Access, BlockWrite	Kill and Access passwords	True3D Antenna Technology, FastID mode, TagFocus mode
MONZA 4D	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-22 dBm	32	-	Access, BlockWrite	Kill and Access passwords	True3D Antenna Technology, FastID mode, TagFocus mode
MONZA 4i	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-22 dBm	480	-	Access, BlockWrite, BlockPermalock	Kill and Access passwords	True3D Antenna Technology, FastID mode, TagFocus mode

MONZA 4 DURA	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-19.9 dBm	512	-	Access, BlockWrite, BlockPermalock	Kill and Access passwords	QT Technology, Short-range option, True3D Antenna Technology, FastID mode, TagFocus mode, applicable for PCB applications,
MONZA X-2K	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-17 dBm	2176	-24 dBm	Access, BlockWrite, BlockPermalock	Kill and Access passwords	I^2C interface, QT Technology, Write Wake-up feature
MONZA X-8K	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-17 dBm	8192	-24 dBm	Access, BlockWrite, BlockPermalock	Kill and Access passwords	I^2C interface, QT Technology, Write Wake-up feature
em|echo / EM4423	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63, ISO/IEC 14443 Type A, NFC Forum™ Type 2	-18 dBm	160	-	Access, BlockWrite, BlockPermalock	Kill and Access passwords	NFC and EPC Technology in one chip
em|aura-C	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63, ISO/IEC 29167-10, ISO/IEC 29167-13	-18.5 dBm	1792	-	BlockWrite	Kill and Access passwords	Crypto Suites, Tamper detection, Secure counter mode operation

em|echo-T	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63, ISO/IEC 14443A-3, NFC Forum™ Type 2	-18 dBm	-	-	BlockWrite, BlockPermalock	Kill and Access passwords	Tamper detection, EAS, NFC field detection, access counter
EM4124	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-19 dBm	-	-	Access, Custom	Kill and Access passwords	Deactivation feature
EM4126	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-19 dBm	-	-	Access, Custom	-	Near-Field mode, Parallel-Inductance Matching
EM4324	EPCglobal Class 1 Gen 2, ISO/IEC 18000-63	-9 dBm	720	-27 dBm	Access, Custom	Kill and Access passwords	Near-Field mode, Parallel-Inductance Matching, Tamper Detection, Anti-Tearing Feature
EM4325	EPCglobal Class 1 and Class 3 Gen 2, ISO/IEC 18000-63, ISO/IEC 18000-64	-8.3 dBm	3072	-31 dBm	Access, Custom, BlockWrite, BlockErase, BlockPermalock	Kill and Access passwords	Built-in Temperature Sensor, Real-Time Clock, I/O port, Power Source Management

SL900A	EPCglobal Class 1 and Class 3 Gen 2	-7 dBm	8416	-15 dBm	Access, Custom, BlockWrite, BlockErase	Kill and Access passwords	Built-in Temperature Sensor, Real-Time Clock, External Sensor Interface, Energy Harvesting Feature, Built-in Shelf Life Calculation, Serial Peripheral Interface

From the above table, we can observe that each chip has its own characteristics, such as some chips support multiple protocols, some have long read ranges, some carry large user memory that can be used for additional purposes, some support battery assisted passive or semi-passive mode, some allow optional commands for memory, some provide privacy by making them password protected, and some have additional features like sensing, calculating, notifying, etc. Correspondingly the cutting edge features offered by the chips are Dynamic Authentication, Self-correcting Memory, EAS Alarm, Tag Tamper Alarm, Read Range Reduction Mode, RF Field Detection, Tag Power Indicator, Parallel Encoding, Digital Signature, Memory Safeguard, Self-Adjustment, Brand Identifier, AES based Cryptographic Security, Integra Technology, AutoTune Technology, Enduro Technology, FastID Mode, TagFocus Mode, Shortrange Mode, QT Technology, True3D Antenna Technology, I^2C interface, I/O port, Serial Peripheral Interface, NFC and EPC Technology in one chip, Crypto Suites, NFC Field Detection, Near-Field Mode, Anti-Tearing Feature, Built-in Temperature Sensor, Real-Time Clock, and Energy Harvesting system. The users can select the one convenient from this diverse list of chips.

RFID technology is emerging to our daily activities unquestionably, in order to ensure the privacy of data, some measures should be taken when it comes to private information about individuals. For instance, RFID technology used in personal identification, passports, bank cards, and such confidential objects can be considered a threat to information security if the data can be decoded by a third party.

Here is a practical example where all the credentials of individuals have merged into a single unit. Emirates national ID card holds resident's passport, driving license, labor card, and health insurance details within one card [43, 44]. Besides, it features E-wallet which allows residents to do financial transactions with the same card.

Taking aforementioned scenario into consideration the regulatory bodies should take necessary steps to make public awareness and protect privacy.

4. APPLICATION OF THE RFID IC CHIPS

The application field of RFID is enormous nowadays, for instance, it is applicable in agriculture, medical purpose, shopping malls, stock house, sensing, library, tracking, authorizing, identifying, and so forth. Depending on the usage, the formation of chips can be different. In this chapter, diverse ways of fabricating RFID tags have been discussed.

4.1 Printed Tags

Printing or painting processes are popular techniques for fabricating RFID tags, which are developing constantly in need of efficiency and finding cost-effective ways. There are different forms of printing methods that can be used to manufacture RFID tags, such as flexography, gravure, inkjet printing, screen printing, brush painting, 3D printing. Some of the popular ones are discussed below.

4.1.1 Inkjet Printed Tags

Inkjet printing is a contactless non-impact digital printing method by means of propelling ink droplets, where usually silver conductive nanoparticle ink is used to print on the substrate. In two ways inkjet printing can be performed, drop-on-demand (DOD) method, where only required ink droplets are produced, and continuous inkjet (CIJ) printing method, which is a constant stream of droplets. Depending on the substrate, the printing process may be repeated multiple times to ensure the adequate level of thickness of the antennas, as well considering the fact of ink being absorbed to some extent. Afterward, the sintering process is carried out by means of heat, so that the nanoparticles cohere and form a conductive surface. The temperature of sintering process depends on the material of the substrate. Subsequently, the RFID IC is attached to the substrate with a conductive adhesive and the tag is optimized by using high-frequency structure simulator (HFSS) software [45].

As consistently Internet-of-Things (IoT) is becoming widespread, fabricating tags on renewable materials, for instance, paper, wood, cardboard, plywood is getting attention for development, in favor of increasing the use of sustainable materials. The passive tags directly inkjet printed on renewable materials exhibits reliable performance in [46, 47]. In fact, the tags printed on wood attained 7 to 8 meters of read ranges, the tags on cardboard reached 4 to 7 meters of read ranges, and the tags on paper obtained 2 to 7 meters of read ranges [46]. As well, passive tags inkjet printed on veneer and embedded inside 2-millimeter thick plywood for identification purpose in [47], exhibited read ranges from 7.9 to 10.3 meters.

In addition, inkjet printing method has shown remarkable outcomes for passive humidity sensors that have been printed on durable polyimide film Kapton HN substrate, with the intention of enclosing them inside walls for a longer period [48]. The sensor has exhibited read ranges up to 8 meters at various levels of humidity. Another passive humidity sensor inkjet printed on photo paper has been presented in [49], that includes write-once-read-many-times memory functionality and changes resistance permanently after being exposed to high humidity.

Another application of inkjet-printed tag presented in [50], a chemical gas detector based on reduced graphene oxide (rGO) printed on photo paper that changes backscattered signal when it comes in contact to any noxious gas. In a similar manner, a potential harmonic RFID gas sensor based on carbon nanotube has been inkjet printed on the paper substrate in order to detect the level of ammonia in the atmosphere [51].

Furthermore, the tattoo paper tags can also be inkjet-printed, which has been experimented in [52]. The experiment shows that by placing ink on specific areas, the read range of tag can be increased, thus the usage of ink can be reduced.

In the matter of optimizing the fabrication process for inkjet-printed tags, the experiment has been carried out in [53, 54], it has been observed that the read range of the tag is significantly dependent on the number of layers used for printing, the material of the substrate and the ink.

4.1.2 Screen Printed Tags

Screen printing is a stencil method, where a screen consists of nylon threads is used to print the tag. The conductive ink is forced through a stencil by a squeegee to the substrate. When the screen is uplifted, the remaining ink adheres to the substrate. Then sintering process is carried out applying heat, for a period of time depending on the substrate material. Afterward, the assembly of IC takes place with conductive adhesive. Finally, the curing of conductive adhesive is performed by means of heat [45].

Screen printing can be used for fabricating wearable tags on fabric substrates, presented in [55], which is indeed an innovative way that opens door to numerous medical applications. Since the clothes need to be washed after several wearings in order to keep them clean, an experimented data shows the printed tags showed 1.3 m of read distances after several times of washing, despite the inimical impact of detergents. Otherwise, the screen-printed tag on fabric showed 11.2 m of read range in [56].

This printing technique can also be used in renewable paper-based products for different applications, e.g. passive screen-printed tag on cardboard package presented in [57], allows multiple sensing features, i.e. applied force on the package, the opening of the package, and temperature.

In terms of effectiveness of the screen-printed tags, the thickness of conductive ink layer has a significant effect on the tag performance. It has been presented in [58] that the performance gradually worsens when the ink layer is reduced for fabricating the screen-printed tags.

4.1.3 Brush Painted Tags

Brush painting is the simplest among these fabrication process of printed tags with fewer process steps. The antenna area is painted directly on the substrate using a brush with conductive ink material, consequently which minimizes the usage of inks unnecessarily. Afterward the sintering process is carried out by applying heat.

Brush-painting has been successfully applied on substrates, like fabric and wood. The passive brush painted tags on wood substrates experimented in [59], exhibited 3 m to 5 m of read ranges consisting single layer of paint. For the straightforward method, brush painting can be considered as the fabrication process.

4.1.4 3D Printed Tags

The three-dimensional Computer-Aided Design (3D CAD) printing system is also known as additive manufacturing (AM). 3D printers use layer-based approach to print the 3D antennas of multiple layers, where each layer has a finite thickness. There are several ways of fabricating 3D objects, which includes selective laser sintering (SLS), stereolithography (SLA), and fused deposition modeling (FDM). SLS is used to manufacture metal objects, however, SLA and FDM methods are used for manufacturing objects made out of plastic materials [60].

Generally, the computer-aided design (CAD) model of the chosen antenna pattern is printed in 3D at first. The conductive paste is dispensed on the surface of the 3D-printed substrate using direct write method to fabricate the tag. The electrical properties, such as dielectric relative permittivity and loss tangent values, of the substrate, are needed to be measured to analyze the antenna model and use these parameters in EM simulation. Followingly, the sintering process is carried out for a time period depending on the material used for fabrication. Then the IC is fixed to the tag with conductive adhesive and again the interconnection goes under sintering process.

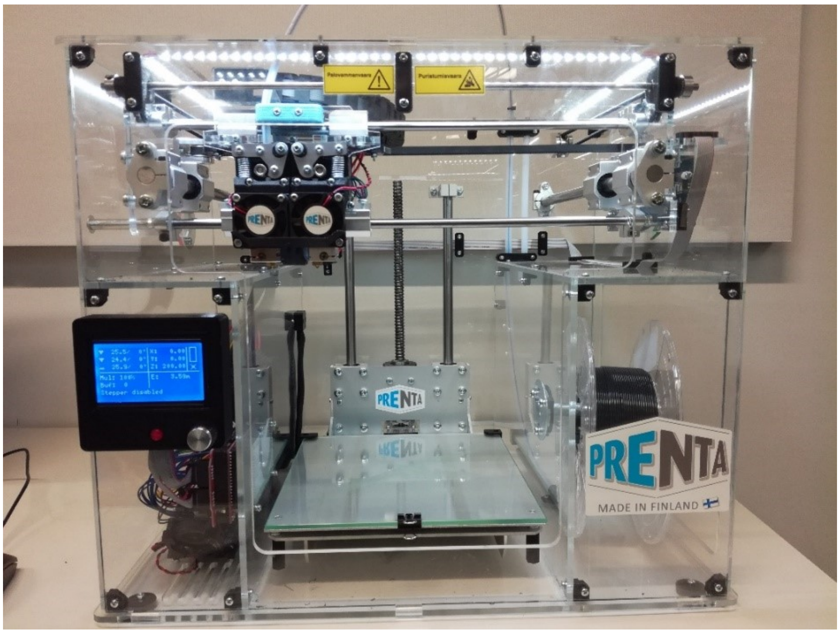

Figure 4.1: *Example of a 3D printer*

By using 3D printing technique, a miniaturized passive UHF RFID tag has been printed on wooden cube [61], that showed 2 m of read ranges around the tag in every direction. If the exhibited read range is compared to the dimension of the tag, then it turns out to be approximately 100 times.

Figure 4.1 represents a 3D printer from the Library of Tampere University of Technology (TUT). The 3D printing system seems to be a compelling way of printing flexible tags. The fabricated stretchable 3D printed passive UHF RFID tag in [62] showed 10.6 m of read range at the beginning and regardless of being stretched after 100 times still exhibited 7.4 m of read range.

4.2 Energy Harvesting Systems

Energy harvesting is an innovative technique to supply power in RFID tags. It can be applicable in many aspects, for instance, to increase the read range, to run multiple applications. Energy can be harvested by different means, e.g. exploiting the power of the harmonic signal, dissipated heat from the human body, sound from our surroundings, solar energy etc.

The experimental results show that harmonic signals can be successfully applied for enhancing tag performance. In [63], the harmonic signals have been exploited to enhance the sensitivity of passive RFID tag by integrating an electromagnetic energy harvesting unit to the tag, which resulted in 24% improvement of the performance when the energy harvesting unit operated simultaneously with RFID tag, consequently that yields 7.2 dB enhancement of tag sensitivity. In an analogous manner, electromagnetic harmonic harvester has been integrated with commercial RFID chip in [64], that results in enhancement of 2.5 m read range.

Similarly, a commercial temperature sensor has been demonstrated in [65] that utilizes the energy carried by the third harmonic signal of passive RFID chip. The system has achieved to harvest 39 μW of dc power from the third harmonic signal of the chip.

In order to utilize the Wi-Fi signal efficiently, RFID harmonic signals can be combined with it to get better performance, which has been demonstrated in [66]. The experimental results exhibited an increase in power efficiency while the third harmonic signal combined with Wi-Fi signal.

A tremendous way of utilizing the dissipated heat from neck to measure human body temperature is presented in [67]. The sensor tag has been placed on patient's arm to measure skin temperature. The measurement results show that power harvesting unit has influenced tag performance, hence the communication range has improved by 100% when the read span set to 750 ms and 75% when the read span set to 1 s.

4.3 On-Body Tags

Nowadays placing tags on the body, either on the skin or on garments, is favored in terms of allowing access, tracking, and medical applications, such as monitoring heartbeat, temperature, blood pressure etc. These tags are fabricated either by screen printing, inkjet printing or etching.

By using etching method, a passive transfer tattoo tag based on slotted patch topology has been implemented in [68], that can be directly placed on the human skin. The tag exhibited 80 cm of read ranges when placed on the forearm, but the read ranges enhanced to 120 cm when placed on the chest. In order to increase the read range of tag and reduce the cost of fabrication, the inkjet-printing method would be the ideal choice, which has been demonstrated in [52]. The presented inkjet-printed passive transfer tattoo tag outweighs the read distances of screen printed and etched tags.

Another influential characteristic to read range is dielectric properties of human skin. In [69] it has shown that the body tissue has a strong correlation with read range, and the composition of body tissue varies from person to person. In that case, it might be essential to fabricate tags for individuals.

Apart from tattoo tags, there are applicable wearable tags that can be sewed, embroidered, or printed on clothes. Since Wireless Body Area Networks (WBANs) is progressively becoming prominent, this kind of tags is given more heed for development. In [70], a passive electro-textile tag has been fabricated based on slotted patch topology and sewed with conductive metal plated thread. Two different kinds of tags have experimented, built upon copper conductor and e-textile, which have exhibited read ranges 6 to 7 meters and

3 to 4 meters, respectively. During the fabrication process, some key points are needed to be considered for the betterment of tag performance, such as flexibility, operability near the human body, and durability of the tag.

Similarly, a laboratory-scale fabricated embroidered tag is presented in [71], where the conductive thread is used for sewing on the fabric substrate. The fabricated tag achieved 4 m read range. In terms of embroidered tags, the geometry of antenna pattern, thread density, and sewing pattern play a vital role in the achievement of high read range. Additionally, high-permittivity tissues of human body influence the tag performance badly. The fabricated embroidered tag in [72] achieved 1.5 m read range on the bare human arm, but, when the tag is separated by 1 mm with cotton fabric from the body, it attained 2.5 m read range.

In addition, moisture and washing cycles effect tags read range, that has been demonstrated in [55, 73, 74]. The experimental results show that the performance of wet tag did not drop significantly, it achieved its original performance again when dried. But, the washing repetitions resulted in a permanent drop of tag read range. For this reason, the protective coating is required to combat wear and for sustainable operation of electro-textile tags. The experimented tags, based on copper and silver fabric, in [74] has achieved 10.8 m and 6 m of read ranges in the first place, respectively. The noncoated copper fabric tag became dysfunctional after four washing cycles and the noncoated silver fabric tag exhibited 2 m read range after 10 washing cycles. The glue-coated copper and silver fabric tags managed to achieve 5 m and 4 m of read ranges after 10 washing cycles, respectively.

4.4 On High-Permittivity Substrate for Metallic Surfaces

The electromagnetic properties of tag substrate or the material attached to, have a considerable impact on RFID tags. The ultra high frequency (UHF) passive transponder in close proximity to metallic substance suffer greatly, in terms of reflecting and detuning of the signal from RFID readers [75, 76]. As a consequence, the performance of the RFID system degrades and the read range decreases.

In order to combat these characteristics of metal, a passive tag fabricated on a flexible polymer-ceramic composite substrate of 1.5 mm thickness, is presented in [77]. The high-permittivity substrate makes the tag metal mountable by increasing the isolation between tag antenna and metallic surface of the object.

Utilizing this phenomenon of correlation, between substrate's dielectric properties and tag sensitivity, a fragmented-type tag is fabricated in [78] to ensure security and avoid misuse of the tag. Hence, slight changes in substrate's permittivity led to degradation of tag's readability.

4.5 Graphene-Based

Graphene is hexagonally bonded thin layer of carbon. It is the modern ecologically friendly semi-metal substance which is considered to be the lightest and the strongest material discovered, as well as best conductor of heat and electricity [79]. There are still ongoing researches on this substance and a lot of applications has already been developed. The characteristics of graphene make it a potential substance for RFID applications.

In [80], utilizing graphene substance a passive textile tag has been demonstrated, where graphene ink is placed directly on the cotton fabric substrate. The tag exhibited a rapid increase in read range in high-humidity condition, which returned to the original state when dried. Additionally, it has shown substantial resistance in terms of harsh bending. In an analogous manner, a graphene-based passive tag fabricated directly on cardboard in [81] for experimenting the tag performance in high-humidity condition. The measurement results show that initially, the read distance was 2.7 m, which has increased to 3.2 m in high-humidity condition and turned back to normal state when dried.

Figure 4.2: *Edible toast etched with laser-induced graphene* [82]

Edible electronics is the new discovery of graphene, which is presented in [83]. Here multiple pulsed-laser scribing methods have been applied to cloth, wood, paper, potatoes, coconut shells, and toast, which turns the target surface into laser-induced graphene (LIG). This technique enables the use of the material itself as a tag, which can be applied for implementing new thoughts and making things more informative, such as, wearable electronics, and biodegradable sensors that detects Escherichia coli (E. coli) or another microscopic organism by which food may be contaminated. Figure 4.2 represents an image of an owl on a toast that has been etched with laser-induced graphene (LIG).

4.6 Using RF only Passive Tags

Space and cost are inevitable concerning factors of RFID chips. These two elements are the key constraints that limit widespread of RFID tags. For this reason, the researcher pays attention to making chip smaller and cheaper during fabrication phase.

Generally, passive RFID tags run on DC voltage, which is converted by rectifier from AC signal of the interrogator and stored in capacitor [1]. In order to reduce the size and the cost, a rectifier free chip is demonstrated in [84] that operates on AC signal of the interrogator. Everything comes at a price, in this case, the price has been paid by eliminating the non-volatile memory and compromising on the low sensitivity of the chip.

5. CONCLUSIONS

RFID is a flourishing technology, that is already impacting peoples’ life with numerous applications on their day-to-day activities. In pursuance of making RFID technology widespread and convenient for the commercial purpose, the cost and the manufacturing process should have considerable attention to make it more efficient. In this paper, the features of RFID chips and their fabrication process have been analyzed.

There are several methods of fabricating RFID tags, such as inkjet printing, screen printing, etching, brush painting, and 3D printing. The inkjet-printed method is a non-contact and drop-on-demand printing; thus, it has no wastage of inks. However, the cost of silver nanoparticle ink and heat sintering time can be considered as the limiting factors of this method. On the other hand, screen printing requires contact with stencil, and usage of excessive conductive inks.

The etching process includes multiple phases and use of chemicals. The eliminated metal from the substrate produces waste and effects the cost. Hence, fabricating tags in this method is not environment-friendly.

Brush painting is the straightforward hassle-free technique among all these fabrication methods. Not to mention, direct printing on the object that is to be identified would eradicate the usage of substrates, and ultimately this will reduce the cost as well.

Although 3D printing is free from producing waste, following this method will produce one tag individually. In terms of mass production, the 3D printing method is certainly going to be questionable.

Regarding RFID chips, the security is a concerning issue for some applications. A precedent case of Emirates national ID card, that has been described in chapter 3, can be considered as a threat to public security. RFID chips should have considerable resistance to fight against these kinds of possibilities.

In order to manage multiple applications smoothly, the efficient power supply is essential. It is quite demanding for passive tags to meet the power requirements as they don’t own any external power source to assist the operation of the tag. The advantage of energy harvesting systems can be considered to overcome this hurdle. There are diverse ways of collecting energy from our surroundings, for instance, by utilizing human body, harmonic signals, external signal, sound, solar etc.

The interest of wearable and on body tags are going to increase substantially in the future according to analysis. Hence, to feed the growing demand a few developments are yet to be accomplished in terms of body-centric communication and attaining long read range by utilizing energy harvesting systems.

Regarding e-textile tags, the tag’s antenna starts to decay due to the repetition of washing cycles and effect of detergents, as a result, tag’s performance deteriorates, and the read range reduces rapidly. To alleviate this consequence the tag can be sewed inside of a plastic wrapping and attached near to collar, where usually brand label is sewed, or on the opposite side of the collar on shirts, so that, the tag goes through less wear. If the tag is meant to be for pants, then it could be sewed on the waist.

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