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A Comparative Survey on Silicon Based and Surface Acoustic Wave (SAW)-Based RFID Tags: Potentials, Challenges, and Future Directions

KASYAP SURESH[1], (Student Member, IEEE), VARUN JEOTI[1], (Senior Member, IEEE), SOCHEATRA SOEUNG[1], (Member, IEEE), MICHEAL DRIEBERG[1], (Member, IEEE), MARK GOH[2], AND MUHAMMAD ZUBAIR ASLAM[1]

[1]Department of Electrical and Electronics Engineering, Universiti Teknologi PETRONAS (UTP), Seri Iskandar 32610, Malaysia
[2]NUS Business School and The Logistics Institute-Asia–Pacific, National University of Singapore (NUS), Singapore 119245

Corresponding author: Kasyap Suresh (kasyap_suresh@yahoo.com)

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ABSTRACT Many Automatic Identification (Auto–ID) technologies such as bar codes, magnetic stripes, Optical Character Recognition (OCR) and Electronic Article Surveillance (EAS) security tags are in existence. However, they are limited by a variety of constraints on them such as limited object rate of scan, need for Line-of-Sight (LOS) operation, very small interrogation range and poor accuracy in complex environments. Research has accordingly grown rapidly in recent years into the development of robust identification or tracking mechanisms. Radio Frequency Identification (RFID) technology using readers and RFID tags, whether passive, semi-passive or active in nature, has been deemed to be a promising candidate. Silicon based IC tags are quite popular. However, some alternative RFID technologies have also been on the rise. In particular, another special type of tag based on Surface Acoustic Wave (SAW) design also has a great potential for deployment in future identification fields due to its ruggedness against harsh conditions, metallic environments, interference, small and low cost and is being thoroughly reviewed, which is ignored in other survey papers. While other chipless RFID systems based on conductive ink, ink-tattoo and others do exist, negative aspects such as inability to survive in extreme weather, larger tag size and limited data storage capacity have severely impacted the penetration of such tags in the RFID market. Therefore, the scope of this survey article does not include chipless RFID tags. This article instead provides a comparative survey of silicon based IC and SAW based tags, which has attracted much attention from both academia and industry. The underlying characteristics, principles, advantages, and limitations of such tags are thoroughly discussed, and relevant research work followed by frequency of operation and other parameters are elaborated. This article undertakes a thorough investigation into the evolution of RFID technology and comparison into the current trend in silicon based IC and SAW based RFID tags and provides a comparison across many metrics, such as read range, tag size, tag power, availability of tag power, lifespan and more importantly, cost and security. It discusses active and passive tags under silicon based IC and SAW technology. Finally, the article reviews recent advances and provides potentials, open challenges and future research directions in such RFID tags.

INDEX TERMS RFID tracking/identification, surface acoustic wave (SAW), interdigital transducer (IDT), silicon based integrated circuit (IC) RFID tags, near field, far field communication.

I. INTRODUCTION

The last half of the 19th century i.e. the pre 1940's saw many advances in our understanding of electromagnetic energy. By the turn of that century, the works of Faraday, Maxwell, Hertz and other scientists had yielded a set of laws describing their nature. Beginning in 1896, Marconi, Watson and many others had sought to apply these laws in radio communication theory and radar too. The work done in this period form the building blocks upon which many technologies based

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on radio have been built, including RFID [1]. In the year 1945, during the time before RFID had come into existence, a famous Russian and Soviet inventor named Leon Theremin had invented a listening device for the use in Soviet Union which relied on the operating principle as follows. The device, upon excited or activated by Radio Frequency (RF) waves by an external source such as a radio transmitter, retransmitted the RF signal with an additional audio information that can be used by the listeners on the receiver side. The device typically consists of a diaphragm which vibrates due to the beat of sound waves that altered the shape of this diaphragm. This in turn modulated the incident RF signal response. Although this device was more of a covert listening device rather than an identification based tag, it was considered to be a predecessor of RFID technology as it was passive in nature indicating that it gets energized and activated by such incident RF waves that come from an external radio source [2].

Another research work that explored RFID past the year 1945 was on the basis of the work by Harry Stockman in paper [3] during the year 1948 who stated that "considerable research and development has to be carried out before the fundamental problems in the reflected power from such RFID tag devices are completely resolved, and before the field of potential applications or use cases is explored". Similar to covert listening device was another technology called the Identification Friend or Foe (IFF) transponder was introduced by Watson–Watt during the 1950's and was regularly utilized by several allies and in Germany during World War II to identify potential aircrafts either as a friend or foe [4].

The early and late 1960's were a prelude to RFID explosion and that would come later in 1970's. R.F. Harrington conducted a great deal of research in the field of electromagnetic theory as it directly applied to RFID as described in "Field measurements using active scatterers" and "Theory of loaded scatterers". RFID inventors and inventions also began to emerge. Some examples include Robert Richardson's "Remotely activated radio frequency powered devices", Otto Rittenback's "Communication by Radar beams", J.H. Vogelman's "Passive data transmission techniques utilizing radar beams" and J.P. Vinding's "Interrogator–Responder Identification Systems". Some commercial activities began in the late 1960's too. Sensormatic and checkpoint were founded to develop Electronic Article Surveillance (EAS) equipment for anti– theft and security applications (for example, anti–theft gates placed at the doors of department stores). Their systems were simple 1-bit systems, meaning they could only detect the presence of RFID tags rather than identify and range with them. Much later, EAS technology became the first widespread commercial use of RFID.

In 1969, the plan showed potential uses of RFID tags in transportation (automobile vehicle identification, automated toll system, electronic license plate, electronic manifestation and vehicular routing) and banking (electronic credit card) and medical (patient history) [5]. It had also found numerous use cases in banking sectors such as electronic checkbook, electronic credit card, for security such as personnel identification and for medical applications such as identifying patients with memory loss in order to keep track of patient history.

The 1970's witnessed a great deal of growth in the RFID technology. Companies, academic institutions, and government laboratories became increasingly involved in RFID. Notable advances were made in research. The initial device was passive that was powered by an interrogator signal transmitted from a proximity reader was demonstrated in 1971 to the New York port authority and to other potential users. The device consisted of a transponder with a 16 bit memory and found application in road tolls. The patent covers the use of Radio Frequency (RF), sound and light as the fundamental carriers for the information. As a result, for the given configuration, the device had proved to be useful for the purpose of identification because many number of tags, as large as 2^{16} was thought possible and could be used as a unique identifier for several items or pallets and humans too. During the year 1973, a famous American inventor Mario Cardullo patented in the same year on January 23 and was considered the first patented document and a true ancestor of the modern RFID. The patent design was a passive radio transponder that contained memory.

In 1975, Los Alamos Scientific laboratory released a great deal of RFID research to the public in a paper titled "Short- -range radio telemetry for electronic identification using modulated backscatter", written by Alfred Koelle, Steven Depp, and Robert Freyman. An early demonstration of reflected power (electromagnetic backscatter) from RFID tags for both passive (which depends on external energy) and semi passive was performed at Los Alamos National Laboratory that operated at 915 MHz with a 12 bit memory [6]. This technique of identification through Electromagnetic (EM) backscatter is used by the majority of today's UHF and microwave RFID tags. Numerous small companies that focused on RFID technology began to emerge during the late 1970's. By the end of the decade, much of research in RF electronics which are mostly applied to RFID, were complete and the research and development necessary in Information Technology (IT), crucial to the development of RFID host (PC's, laptops), networks and interrogators had also begun, as is provided in the evidence by the early periods of PC and also the ARPANET, the predecessor to the Internet revolution.

The 1980's brought about the first widespread commercial RFID systems for livestock management, keyless entry and personnel access systems. The world's first toll application was implemented in Norway in 1987, followed by Dallas in 1989. The Port Authority of New York and New Jersey implemented a commercial project for buses passing through the Lincoln tunnel. All of the RFID systems implemented in the 1980's were proprietary systems. There was no interoperability between systems and little competition in the RFID industry and as a result, kept the costs high and impeded industry growth.

The 1990's were significant in that RFID finally began to enter the mainstream of business and technology. By the middle of the decade, RFID toll systems could operate at highway speeds, meaning drivers could pass through toll points unimpeded by any barriers. As a result, deployment of RFID toll systems became widespread in the United States. Regional toll agencies took the technology one step further and began to integrate their RFID systems too, enabling drivers to pay multiple tolls through the same account. Texas Instruments began its TIRIS system in the 1990's. This system developed new RFID applications for dispensing fuel, such as ExxonMobil's speed-pass, as well as ski-pass systems and vehicle access systems. In fact, many companies in the United States and Europe became involved in RFID during the 1990's, such as Alcatel and Bosch. Until the 1990's, the RFID systems on the market were proprietary systems. Many in the industry recognized this as a barrier to growth and an effort to standardize the technology began. Several standards organizations started to work on providing guidelines such as the International Standards Organization (ISO). The auto–ID center at MIT was established in 1999 for that purpose also. At present, all of these organizations are working on the standards for RFID technology, particularly applications such as supply chain management and asset management for inventory tracking and control. By the early 2000's, it had become clear that 5-cent tags would be possible, and that the RFID technology could someday replace bar codes and other systems. The implications this had for the product distribution and retail industries, and the dollar figures involved, brought in a lot of attention for the industry. The year 2003 in particular was an eventful one for RFID. Both Walmart and the Department of Defense (DoD), the world's largest retailer and the world's largest supply chain, issued RFID mandates requiring suppliers to begin employing RFID technology by 2005. The total size constituted a huge market for RFID. Sooner, other companies such as Proctor and Gamble and Gillette gained momentum and followed suit. Furthermore, the auto-ID center was merged into EPCglobal, a joint venture with Uniform Product Code (UPC) council, makers of the UPC bar code symbol. As of 2007 and beyond, it is obvious that numerous applications pertaining to RFID across a large number of industries will soon emerge. In the coming years, RFID technology will grow further and further into the mainstream and become another part of everyday life where identification will become possible through such tags [1]. With such development in RFID technology, on a fundamental level, RFID tags can now be classified into three sub-categories namely the passive, active and semi-passive tags. Passive tags do not contain an internal battery except IC microchip and depend entirely on the energy from the RFID reader. Active tags on the other hand contain an internal battery followed by other additional features such as security modules and do not depend on the energy from the reader. Semi-passive tags also contain an internal battery but is used only to power the IC microchip while being dependent on the energy from RFID reader to retransmit the signal. These tags also possess the ability to harvest the energy using various sources such as solar cells apart from an internal battery-like design. While these come under silicon-based IC technologies, Surface Acoustic Wave (SAW) based RFID tags are another special case of passive tags which do not contain any silicon based microchip. Instead, they make use of the principle of piezoelectricity to generate acoustic waves which, upon reflection from strategically located reflectors give rise to unique signatures. Travelling as they do on elastic materials, these reflected signals are slow to reach the reader compared to instantaneous and other multipath reflections. SAW tags are able to work even in metallic environment unlike their silicon based counterparts. A more detailed description of SAW tags will be provided in the RFID tag technology section. Other auto-ID techniques [7] such as bar codes, EAS and magnetic stripes do exist but they are constrained by several factors such as Line-of-Sight (LOS) requirement between the scanner and the object to be read, close contact (very short read range), inability to survive in harsh weather and, very limited number of object reads per second. On the other hand, RFID technologies are free from all such constraints and hence more favorable than bar code and others. Many RFID tag technologies have evolved since the introduction of RFID technology found a plethora of applications as mentioned in the preceding paragraphs. Several work has been carried out in the RFID domain using such types of tags. To name a few, in paper [8], authors have explained a brief history of RFID technology followed by the operating principle, while focusing primarily on privacy concerns of RFID tags and readers. Paper [9] described a multi tag scenario in which multiple tags are being deployed in a given environment. The economics of such RFID systems were explored and argued that benefits of multi tags will continue to outweigh the costs in many identification based applications. Papers [10] and [11] explained the rules and regulations of deploying and using the RFID system and an application scenario in school buses where passive silicon based IC tags were deployed in the school children's bags, with the objective to enhance the safety. Paper [7] briefly explains the usage of passive and active silicon based IC tags for two different Indoor propagation models namely the Dual One Slope Model (DOSM) and Dual One Slope with Second Order Polynomial Model (DOSSOM) and showed that the accuracy had improved by around 5 cm when using the DOSSOM model. On the other hand, many review papers have also been published in the domain of RFID so far.

Among the review papers on RFID, paper [12] explains the introduction of RFID technology, applications and limitations of barcodes and emergence of RFID as an enabling technology followed by classification, architecture and reader design. Papers [13] and [14] explained the different types of RFID tags and tag antenna issues in the UHF band. Paper [15] reviewed the antenna designs of RFID tags. In paper [16], the authors have reviewed different types of tags. Paper [17] discusses the application of RFID tags in the library along with its advantages and issues. In paper [18], the authors had provided a very brief review on RFID transponders where they have classified the readers into different types followed by the potentiality of each of them in different fields. In paper [19], the authors have provided the explanation for the adoption of RFID tags and readers in large-scale organization followed by various challenges and solutions. Papers [20] and [21] provided a brief review on RFID tag antenna and reviewed tag anti–collision algorithms for RFID. Papers [22] and [23] reviewed the privacy issues of RFID tags during implementation and also discussed chipless RFID tag technology. Paper [24] discussed the evolution of RFID tags in terms of security and privacy. In paper [25], the authors have provided a case based analysis for the potentiality of RFID projects. The paper had provided close to 13 case studies on the use of RFID in green products and which reveals its potential as not only to enhance the environmental sustainability but also to minimize the effective cost and generate higher revenue by creating new commercial opportunities. As such, RFID technology has found a lot of interest and yet a significant amount of research has been carried out and is still underway to build tags that should be commercialized at low cost, longer read range, ability to simultaneously detect multiple tags, highly secure and, maintains robustness in harsh environmental conditions such as under extreme temperature and pressure, humidity, radiation and during high mass loading. Papers [26] and [27] provided an overview of RFID technology principles and a general review on chipless RFID tags.

The review carried out herein, however, is different from the previous survey articles [13]–[28] in several ways. Comparing with the articles from [13] to [25], our paper provides a comparative survey on both the established RFID tag technologies which are silicon based and Surface Acoustic Wave (SAW) based. While paper [28] discusses chipless RFID tags, it neither covered all chipless RFID technologies nor provided detailed insights on important aspects such as privacy and security. Papers [7] and [26] focused only on silicon based IC active and passive tags and a general description on silicon based IC tags, without a detailed comparison addressing all performance metrics that affect tag performance metrics such as read range, cost, security and privacy and longevity. Although paper [27] does cover almost all kinds of chipless RFID tags and includes performance metrics such as read range, the paper still lacks a detailed explanation of different designs in SAW RFID tags and a quantitative comparison across crucial parameters such as cost and security across such tags which also strongly determines the ability of them to penetrate the RFID market. Although chipless RFID tags based on conductive ink and others do exist, they present three main drawbacks compared to silicon based IC tags: 1) a large tag size, 2) limited data storage capacity, and 3) shorter read ranges. Furthermore, the conductive ink properties tends to degrade if the ink is exposed to extreme conditions. Despite being attractive in terms of cheaper cost, those other negative aspects have severely impacted the penetration of chipless RFID tags in the market [28]. Hence, the chipless RFID tags are ignored in this review. SAW RFID tags, on the other hand, are considered superior in those aspects and are therefore included in the review although bringing down the cost of SAW tags is still a challenge [28]. When possible, we also offer a quantitative comparison of these RFID tags across these performance metrics to provide a quick overview. Accordingly, in this paper, we seek to present both a comprehensive and a quantitative comparison study on various silicon based IC and SAW based RFID tags across various design technologies that exist and which are quite established and popular, and compare such tags across various performance metrics such as the interrogation read range, tag size, availability of tag power, lifespan and, more importantly, cost and security which lacks in other review papers. This paper will be further organized as follows. Section II will provide a detailed explanation into the reader technology, silicon based IC and SAW based RFID tags along with their working principles. Performance metrics for various RFID tags are explained in Section III. Section IV explains the performance description, potentials on deployment and challenges of such RFID tags. Finally, Section V and VI concludes the paper and provides possible future directions for the research on such RFID tags.

II. TAXONOMY OF READER TECHNOLOGY, SILICON BASED AND SAW BASED RFID TAG TECHNOLOGIES

Although the comparison of various RFID tag technologies that are quite established and popular is the primary focus, an RFID system becomes complete and useful only if it involves an interrogation mechanism, which is usually from an external source. This source is in the form of an RFID reader. An RFID reader interrogates by transmitting any form of a signal, sometimes depending on the type of tag used, to the proximity tags. The technique with which the tags are interrogated depends on many crucial parameters such as frequency of operation, transmit power, gain of the antenna, internal losses in the tag and so on. Hence, the reader technology itself needs to be explained prior to explaining various types of RFID tags.

A. RFID READER TECHNOLOGY

RFID tags can be activated or energized remotely and can retransmit back upon interrogation by an RFID reader. To interrogate the tags, there are techniques with which it can be accomplished, which depends on the design of the tag. This distinguishes the tags which can be interrogated only within a very small distance versus tags that can be read from a distance in the order of several meters.

There are two fundamental methods of interrogating the RFID tag using the reader. They are:

A.1. Inductive Coupling or Near Field Communication
A.2. Electromagnetic Backscatter or Far Field Communication

These two techniques exploit the properties of Electromagnetic (EM) wave that is generated from the RFID tag/reader

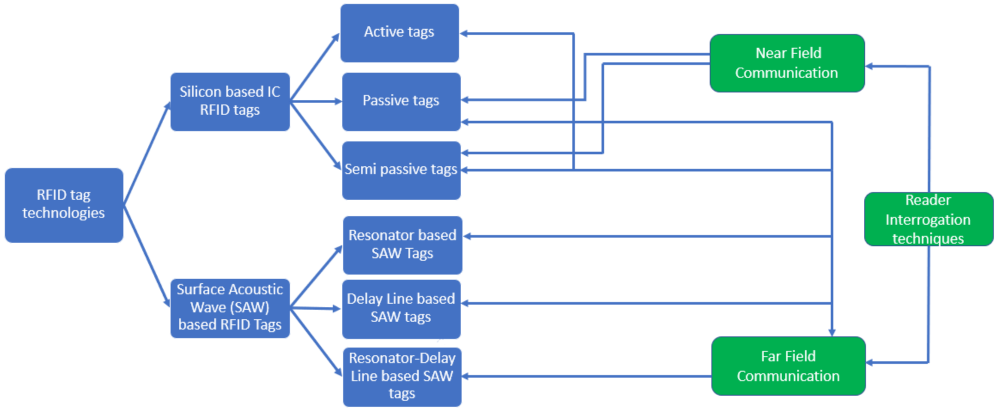

FIGURE 1. **Knowledge Hierarchy of Silicon based IC and SAW based RFID technologies and interrogation mechanisms.**

antenna. While near field interrogation is carried out in the range comparable to or is just a fraction of the wavelength, far field communication range is usually in multiples of the signal wavelength. Hence, the term far field.

The range of power is usually in between 10 μW and 1 mW [26] and depends on the type of tag used which in turn determines the targeted application. This is one of the factors that determine the read range. On a special case, an Intel XScale processor can consume around 500 mW of power and Intel Pentium 4 can consume around 50 W which can be used on the RFID reader side. Through the use of different modulation techniques, both the near–field and far–field communication can assist in the transmission and reception of data [29]. These two techniques differ from each other in terms of the interrogation range from the tag to the reader and vice-versa. This range is usually expressed in terms of the wavelength of the signal transmitted. Depending on the wavelength of the signal, the rate of decay of energy varies accordingly. A detailed overview into the different methods of interrogating the tags via a RFID reader is explained below.

1) INDUCTIVE COUPLING/NEAR FIELD RFID COMMUNICATION

The principle of near field interrogation between RFID reader and tag is based on the principle of Faraday's law of electromagnetic Induction. When the RFID reader induces an alternating current (AC) or AC power in the coil (such as copper) which is used for reading, the reading coil generates a magnetic field in the form of flux lines passing through and away from it. At this time instant, any RFID tag that also possess a magnetic coil wounded around the antenna will receive the power in the form of magnetic flux lines i.e. a field that is being induced in the reading coil induces a similar field in the coil placed near to it. A diagram for the near field mechanism is shown in Fig. 2. The strength of the field that is being drawn by the tag coil depends on the distance between the tag and the RFID reader. The closer it is to the reading coil; more will be the induced voltage across the load of the

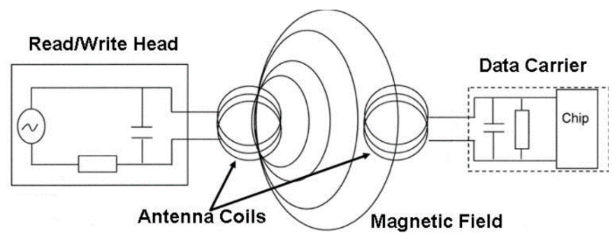

FIGURE 2. **Near field RFID Communication (NFC) scenario [130].**

tag. Appropriate impedance matching should be performed so that the power received to the tag is dependent only on the losses due to the distance between the RFID reader and the RFID tag and not due to the losses occurring from the tag [26].

If the tag is coupled to a static capacitor, a certain amount of charge will start to accumulate in it, which can then be used to charge the chip of the tag. For efficient transmission, tags that employ near field communication uses a technique known as load modulation. The tag is passive and hence it gives rise to only a small magnetic field around it. So, the reader can sense only a small amount of current after the transmission. The current that is now being received is proportional to the load applied to the coil of the tag. Hence, the technique is named as load modulation.

The principle is also being applied to applications such as power transformers that are found in most of the homes, office buildings and almost every closed structure where people stay. Here, the closeness between the primary and the secondary coil is infinitesimally small such that they are very closely wound which appears as though they touch each other. This is to ensure that maximum power transfer is transferred from the source to the load of the transformer. The closeness is usually a fraction of the wavelength of the wave that is transmitted.

However, magnetic field can still extend well beyond this range, as the secondary coil can acquire most of the energy at a given distance which is very similar to the communication between a reader and a tag for as long as the signal strength is within desirable limits to detect its presence. The reader can then reconstruct the alternating current signal by monitoring the change in the magnitude of current passing through the coil of the reader. Apart from load modulation, a variety of modulation based coding techniques can be used and is purely dependent on the number of bits that is required on the tag, the data rate and the redundancy bits placed in the beginning or in the end to remove the bit errors resulting from channel noise and multipath reflections. When using passive RFID system for tagging purpose, near field coupling is the most straightforward approach as the environment is not as complicated as backscatter mechanism or far field RFID communication.

a: READ RANGE ESTIMATION ANALYSIS FOR NEAR FIELD COMMUNICATION

But, near field communication possesses certain physical drawbacks. Since the read range distance R between the reader and the tag is limited to the value which is given by [26],

$$R = \frac{c}{2\pi f} \tag{1}$$

where c is the speed of light which is a constant and is given by, $c = 3 \times 10^8$ m/s and f is the operating frequency of the RFID reader, as the operating frequency of the RFID reader increases, the distance with which the near field RF signal can propagate will also rapidly decrease, which results in a lower read range. Another limitation is that the RF energy available for magnetic induction is actually a function of the distance from the coil of the reader. The magnetic field thus decays with this distance with a factor of $\frac{1}{r^3}$, while electric field decays with a factor of $\frac{1}{r^2}$ where r is the distance of separation between the RFID tag and the reader along the center line which is perpendicular to the plane of the coil and to the plane on which the RFID system is placed [30].

Thus, as applications require a greater number of bits for communication and for locating large number of tags within a short time and over a large distance, tags will then require a higher bit rate and hence a higher operating frequency [26]. Such design constraints have led to the development of new field power transfer techniques such as the far field RFID communication which is elaborately explained in the next sub-section.

2) ELECTROMAGNETIC BACKSCATTER/FAR FIELD RFID COMMUNICATION

Unlike the near field RFID communication between a reader and the RFID tag which uses a special inductive coil on both the reader and the RFID tag to power each other using the magnetic field, far field communication technology does not employ any inductive coil to drive the internal circuitry through magnetic induction and alternating current (AC) power. This technique rather uses RFID tags that are purely based on far field radio emissions that uses electromagnetic (EM) waves that propagate from the dipole antenna of the reader to the RFID tag and vice versa. The RFID tag receives this energy from the dipole antenna as an alternating potential difference that is created between the opposite terminals (that appears across the arms of the dipole antenna). A schematic diagram of the way an RFID reader interrogates with a tag in the far field region is given in Fig. 3.

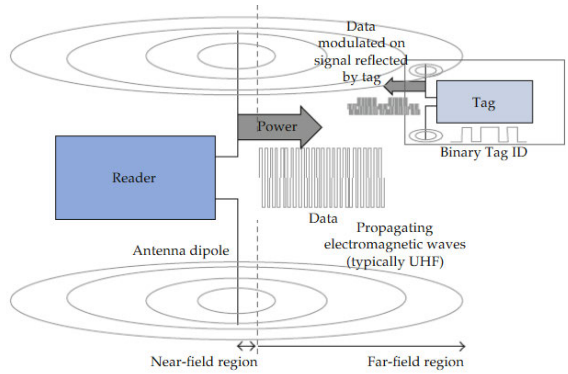

FIGURE 3. Far field RFID communication scenario [131].

Usually, a dipole antenna is the one that can rectify this potential difference created between the two ends and can in turn link this energy to a static capacitor that will result in the accumulation of charge. This charge can then be used by the tag to power up its electronic components such as the IC microchips and will also use the same energy to retransmit the RF signal in a coded fashion. This movement of charge creates a magnetic field around them. The resulting wave now contains both electric and magnetic field components. The technique that the designers typically use for such commercial far field RFID tags and readers is called Electromagnetic Backscattering or shortly EM backscatter.

If the designers use a constructed design layout with precise dimensions, then the RFID tag can be tuned or shifted to a specific operating frequency and will then be able to absorb or reflect most of the RF energy that reaches it at that particular frequency. But there are certain glitches during this time of occurrence. When there is a mismatch in impedance of the RFID tag at this frequency, the tag antenna will reflect back only a certain fraction of the total energy towards the RFID reader.

But this change in energy can be detected using a sensitive radio receiver, as long as the receiver sensitivity is lower than the instantaneous received signal power.

The tag antenna usually backscatters a coded waveform at different times or in other words, as different RF pulses that is incident on the reader's antenna at different times. Therefore, by altering the impedance of the RFID tag at different times for a continuum duration of time, the tag can actually reflect off the incoming RF signal according to a binary pattern that is encoded in the tag's ID which determines a unique signature of the tag.

In practical applications, one can also untune or detune the RFID tag's antenna for this purpose by placing a transistor that can act in a switched mode. This transistor can be inserted or placed across the dipole antenna across its ends and by switching the transistor between the ON and OFF state, a coded binary waveform pattern tends to appear at the reader antenna in the form of a positively polarized pulse and a zero potential pulse, indicating a series of 1's and 0's in the received RF response.

The RFID tags that employ far field communication protocol typically operate at an operating frequency much greater than 100 MHz, usually in the Ultra High Frequency (UHF) RFID frequency band which is in between 860-960 MHz, or the 433 MHz band or the 2.45 GHz band as mentioned in the RFID tags section of section II. Other operating frequency bands are also used for far field applications such as 2.4 GHz. The far field range is usually in multiples of signal wavelength or more than a wavelength.

a: READ RANGE ESTIMATION ANALYSIS FOR FAR FIELD COMMUNICATION

A far field communication system's range is constrained to two main factors namely:

1) To the amount of RF energy that is received by the tag antenna from the RFID reader,
2) And how sensitive the RFID reader's radio receiver module is to the RF reflected pulse.

Thus, the actual return energy or the total received energy of the RF signal is smaller because the RF signal decays off as a result of two phases of attenuation, each is entirely based on the inverse square law of emitted RF wave [26]:

1) One, the first attenuation that occurs as these EM waves propagate from the reader to the tag, and,
2) Secondly, when the coded waveforms from the tag antenna propagates/backscatters from the tag to the reader.

The remaining RF energy that is being received at the RFID reader antenna is proportional to twice the distance and $\frac{1}{r^1}$, where r is the distance of separation between the RFID reader and the RFID tag indicating a greater range coverage compared to the near field distance [30]. Such designs of RFID tags are attributed to the Moore's law, and the ability to shrink the RFID tag to a much smaller form factor or size, the RF energy that is required to power up the tag at any given operating frequency still continues to decrease rapidly to as low as in the order of a few milliwatts or microwatts. This shrinkage is also attributed to the increase in the operating frequency of the RFID tag which in turn reduces the antenna wavelength to an order smaller than Low Frequency (LF) or High Frequency (HF) tags.

As described in the previous sections, since the form factor of the RFID tag is dependent on the frequency at which the tag is operating [7], a reduced wavelength will require a very small size tag which will be compact, compatible and highly suitable for many applications such as human tracking. Thus, with such modern RFID tag designs, it is possible to design more such tags with unique ID's that can also be

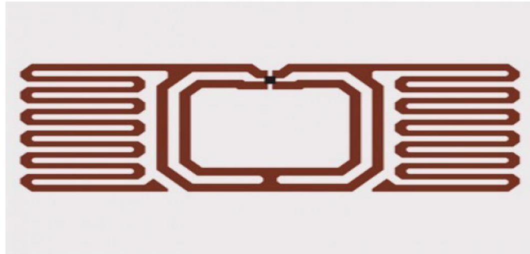

FIGURE 4. A typical passive silicon based IC RFID tag patch [132].

read at an increasingly greater distances than were thought to be possible using magnetic induction coupling between the reader and the tag many years ago. As a result, more such cheap radio transponders have been under development in certain RFID manufacturing companies such as RFID Inc., and have also developed with a much improved sensitivity such that these can detect RF pulses at a reasonable cost and even at much lower power levels in the order of -100 dBm, at an operating frequency of 2.4 GHz, which is a band used by the WiFi technology too.

A typical far field RFID reader range can be determined using a combination of several parameters such as transmitted power, gain of the transmitter, pulse width or conversely, the transmitted bandwidth of the RF signal, gain of the tag, sensitivity and the tag loss incurred. The pulse width determines the bandwidth of the coded pulse. A higher bandwidth is mostly preferred because of its ability to provide a very high resolution in time and range. This characteristic will be useful for combating effects such as multipath and tag interference that are common in far field regions. With the discussion of reader technology complete, the subsequent section will discuss the different types of RFID tags followed by the relevant parameters of interest for determining the performance of the tag.

B. SILICON BASED IC RFID TAGS

1) PASSIVE RFID TAGS

When the concept of RFID started around the late 19-20th century, the passive RFID tags which are silicon based Integrated Circuit (IC) type were the first to be introduced. As discussed earlier, passive RFID tags typically rely on the external power source and is interrogated by an RFID reader from a finite distance away from the tag. These tags generally have a higher longevity and they are also cheaper compared to active tags because of lesser computational circuits and hence the power backscattered to the RFID reader is also minimal.

These tags were the first to be developed and implemented in the aircrafts as IFF transponders during the World War II to differentiate between the aircrafts which were considered friendly and the aircrafts considered to be potentially a threat i.e. a foe.

A general schematic of passive IC tag is shown in Fig. 4. A passive IC tag consists of three components namely the antenna, a silicon based IC microchip as in Fig. 5 for

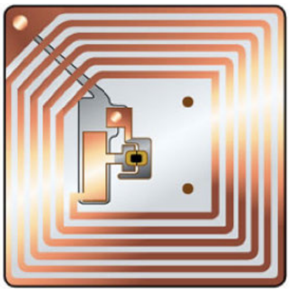

FIGURE 5. A passive IC based RFID tag with circuitry [133].

performing computation or encoding the unique identification number and is coupled to the radiating antenna followed by some form of encapsulation (packaging). The encapsulation acts as an outer protective layer for the passive tag against external turbulence. In paper [31], the authors have designed a UHF based RFID tag that is being covered by a thin superstrate (the protective layer) of epoxy resin. The encapsulation should be performed in such a way that it does not affect the performance of the tag response. Depending on the frequency of operation and other design parameters, the suitable method of interrogation is determined. The typical read range for passive IC based RFID tags lies between 3 feet and up to 15 to 20 feet. Larger UHF passive tags are claimed to be interrogated in the range of 30+ meters, but under ideal conditions and in far field. But this larger form factor will face economic problems such as high cost per tag which is undesirable. Moreover, this form factor may not be suitable for certain applications such as implanting RFID chips to monitor health parameters, livestock management and tracking smaller pallets or items. Passive IC based RFID tags do possess certain advantages and limitations. These tags are not suited for harsh environmental conditions such as bad humid weather, high temperature and pressure environment and extreme radiation conditions. But these tags can be well suited for normal applications such as within a home, inventory control room or in a warehouse for asset tracking where these are located within the above mentioned read range. These tags suffer from electromagnetic interference too as they are instantaneously identified through RF signals. The cost is less compared to their active tag counterparts. In terms of security, since these tags don't contain any inbuilt sophisticated modules such as cryptographic module, privacy could be of concern to the end user when these tags are deployed for many commercial applications where security is important. Hence, robust cryptographic algorithms should be used in the reader side to encrypt the data such that the data cannot be read by a third party reader. Much later, such characteristic features such as security modules were introduced into the tags which led to the introduction and evolution of active IC based tags. A detailed description of them is explained below.

2) ACTIVE RFID TAGS

Active RFID tags are also known as battery powered RFID tags which had come after EM backscatter or Inductive coupling based passive tags had evolved and found usage in a variety of applications, mainly because of longer read range than passive tags.

FIGURE 6. An active RFID Tag (containing an internal battery) [134].

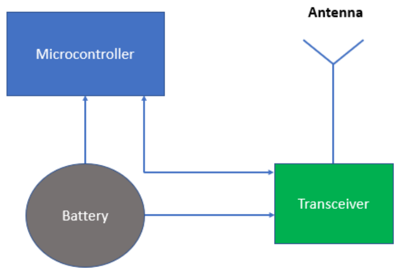

FIGURE 7. Block diagram of an active RFID Tag.

Usually, active RFID tags, as shown in Figs. 6 and 7, consists of an internal power source in the form of a battery. They are either serially connected to an infrastructure that is already powered or it uses the energy stored in a battery that is integrated along with it. Active tags use the energy supplied to both the microcontroller or the micro-chip and to generate the signal on the antenna to be transmitted or backscattered into the medium which could be air, vacuum and so on.

Hence, it is evident that the active tags lifetime is entirely limited to the stored energy or capacity, including the read/write operations carried out until that time at which the battery drains completely. Active tags usually possess the ability to transmit RF signals without utilizing the energy supplied by RFID reader. Such types of devices are called beacons as they exhibit this nature. However, certain active tags do exist which transmit information only when interrogated by the reader. Active RFID tags do not perform EM backscattering by using reader's energy unlike passive RFID tags because they are already built with an internal battery. Hence, the power with which the signal can be transmitted and the read range that is possible from an active RFID tag depends on the capacity of the battery. A more capacity means that more power can be transmitted and hence a longer range can be achieved, compared to passive tags upon filtering and amplification to a certain extent. Hence, active tags belong to the far field communication, indicating that it is beyond the Fresnel region. The read range of an active RFID tag can be anywhere between a meter to tens of meters and is an ideal tag for locating different types of pallets or items and for labeling the product with more such specifications or serving as landmark points for locating other objects that are in the close proximity to the reference active tag. The lifetime of active tags is usually up to a period of five years from the time the operation/usage is started [7]. Like passive IC based tags, active tags also possess certain advantages and limitations. These tags are generally cost intensive compared to passive tags. This is because of the internal battery followed by other features such as a cryptographic module for security, amplification and others.

While the cost is high, it comes with a better range (upto 100 m meters under ideal conditions) and security features added to it. Similar to passive tags, these tags do face electromagnetic interference under either weak or strong electric and magnetic fields generated by other sources and they cannot be used under such complex environmental scenarios also. As mentioned, since battery source is used for a variety of operations within the tag, the longevity of it reduces to only a couple of years, while passive tags have a better longevity than the former as the choice of performing various operations is limited.

Like passive IC tags, these tags are also susceptible to hazardous environmental conditions such as high temperature, temperatures below freezing point, high pressure, humidity and radiation. While these tags are more common and popular, another sub–category of active tags called semi passive tags also exist. These tags rely on a power source which is used only for powering the microchip. There are two methods to power the microchip of a semi-passive tag which will be discussed in the next section. However these tags are not quite popular among researchers from both academia and industry as the objective of RFID is to reduce the cost without using such additional features while still satisfying the primary objectives that promote RFID technology. But this tag will also be reviewed in the subsequent section as it falls under the sub–category of silicon based IC tags.

3) SEMI PASSIVE RFID TAGS

There are two types of semi-passive tags which either contain an internally localized battery or a certain kind of energy harvester such as a solar cell.

The inclusion of a battery in semi–passive tags allows additional features such as sensors, real time tracking and identification and sound notifications to be applied to such tags. The only additional feature that is difficult to locate on a semi passive tag is an on–board transmitter since that is the main attribute that differentiates semi–passive tags from active tags. A typical semi–passive silicon based IC RFID tag is shown in Fig. 8 which contains an in-built energy source. Without an on–board transmitter the read range of these tags is limited, and with the inclusion of a battery, their longevity reduces. The semi passive IC based tags can also be interrogated in the region beyond the Fresnel region (near-field). The primary characteristic that differentiates semi–passive RFID from both active and passive RFID tags is the inclusion of a battery and its lack of an on–board transmitter, which gives these tags the ability to support additional features without increasing the read range. But, additional features such as a battery or an energy harvester typically maximizes the read range of such tags and hence operate beyond the near-field region.

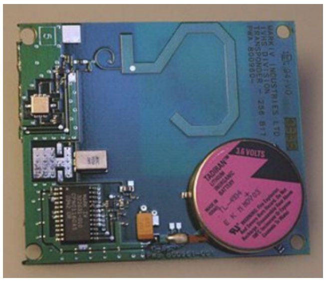

FIGURE 8. A typical semi–passive tag with an internal battery [116].

Because of these features, semi–passive tags are best suited for applications where additional features such as environment monitoring are necessary, and the tagged pallets or items remain within the reader interrogation range [116]. However, modern semi-passive tags derive energy from other sources such as sun and other energy harvesters. While these sources provide an additional power so as to maximize the read range, the process of interfacing them with the RFID increases the form factor of the overall system which in turn increases the net cost. Furthermore, such energy sources require a certain absolute temperature for providing optimum performance. Hence, they cannot be utilized for hazardous applications such as high humidity, temperature, pressure and radiation as they will contribute to a reduction in the performance of such RFID systems.

C. MORE RELATED WORK ON ACTIVE AND PASSIVE SILICON BASED IC TAGS

Silicon based IC active and passive RFID tags have been used in several applications and has been tested and evaluated in many platforms mainly to observe the interoperability, read range distance [27] and improve it further depending on the advantages and limitations they possess for a certain application. A lot of work has been done using such tags and will be explained below.

1) SILICON BASED IC TAGS FOR TRACKING HUMANS

a: ACTIVE AND PASSIVE TAGS FOR SMART TRACKING APPLICATIONS

In project [32], the authors have demonstrated the use of active RFID technology for smart tracking system to enhance the child safety when he or she is driving to school in school bus. They propose that it is better for the children to use school buses to commute from home to school and vice-versa rather than opting for a car where the child ends up being a road traffic casualty. The research utilized the active RFID tracking technology because of its efficient tracking features and longer read range interrogation from a remote location. Experiments showed that using such tags were effective in terms of monitoring the child on a regular basis and take preventive measures and steps before a child becomes vulnerable.

Paper [33] proposed a smart tracking system for bus safety enhancement for school children using passive RFID tag technology. The system consisted of parents in possession of a controller that allows them to find out whether their children reached the school or not. The passive RFID tags were embedded on the school bags. Through a combination of GPS, WiFi and RFID enabled technology devices, parents will receive a message from the school regarding the location of child at any instant of time. Over 95% of the parents found the technology useful and were convinced regarding the safety of school children using the RFID method of identification.

Another similar paper [34] proposed a Real Time Location System (RTLS) to focus and track the location of real time objects in a given vicinity.

b: RFID TAG IDENTIFICATION USING TIME INTERVAL OF ARRIVAL (TIA) FOR USER MOVEMENT

To overcome the limitations of using the Received Signal Strength Indications (RSSI) from GPS, DGPS, active RFID tags have been deployed in the vicinity and can be easily affixed to the objects. The proposed system adopted the Time Interval of Arrival (TIA) instead of RSSI for the purpose of distance evaluation that is useful for minimizing the errors that occur while estimating the read range distance. A 48 MHz PLL RFID reader was used that can store up to 8 bits in the CPU. The proposed system was able to obtain a read range distance with an accuracy of around 3.3 m. They had also used a central server for post-processing (e.g., filtering, equalization etc.,) the RF signal.

Paper [35] provides a description on several aspects of RFID technology. The goal of the paper was to make sure that RFID tags can prove to be the future technology in comparison to other auto–ID techniques such as bar codes and others in applications such as user movement. Several factors such as cost of manufacturing and privacy of silicon based IC tags were discussed. It was concluded that printing tags (such as in paper like bar codes) will be a cost effective solution for many identification and tracking applications such as tracking the user movement.

c: ACTIVE RFID TAGS FOR APPLICATIONS IN HUMAN AND ROBOT TRACKING

Paper [36] presents a study on the way to detect movements of a worker using passive tag. Readers were used to monitor the worker's speed and acceleration. Tags were concluded as cheap compared to its counterpart, active tags. The observation was that the number of responses decreased when the read range and number of tags present had started to rise. By increasing the bandwidth and total energy of the signal transmitted by the reader, the accuracy of read range

FIGURE 9. Golf ball-reader system [135].

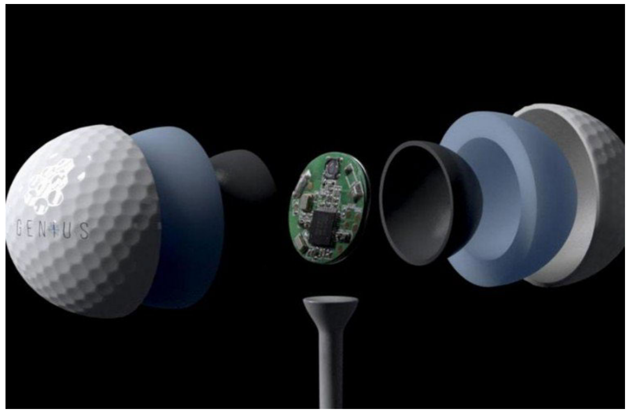

FIGURE 10. An RFID golf ball with an internal structural layout [136].

estimation had improved significantly. Paper [37] was about object mapping using such tags with a 45° orientation with respect to the horizontal plane. Contrary to this paper where robots with 45° orientation of two antennas were located to the left and right of the robot, the other robot was also in motion. They had showed that their Monte Carlo simulation results worked well under highly dynamic environments even when the tags were attached to moving objects.

2) SILICON BASED IC TAGS FOR APPLICATIONS IN SPORTS

a: RFID TAGS FOR APPLICATIONS IN TRACKING A GOLF BALL

Paper [38] had incorporated an active RFID tag into a golf ball as in Figs. 9 and 10. The mobile reader was carried by the golf player in Fig. 8 that indicated the balls identification number and the location in its LCD screen or even through audio feedback. Th read range was estimated to be around 30–100 feet. But the paper did not mention the method used to locate the ball and was proprietary. Paper [39] also explains a scenario where a golf ball has been incorporated into an RFID tag that is used to identify/track the golf ball at every instant of time and also measure several other parameters such as speed, direction and acceleration of the ball.

Paper [40] explained different production methods with which the RFID tags were usually designed. A survey reported that the ideal cost of an RFID tag should cost less than a cent only (or in the order of a hundredth). Current production management typically uses the low cost silicon as the substrate which is then fabricated with microchips on top

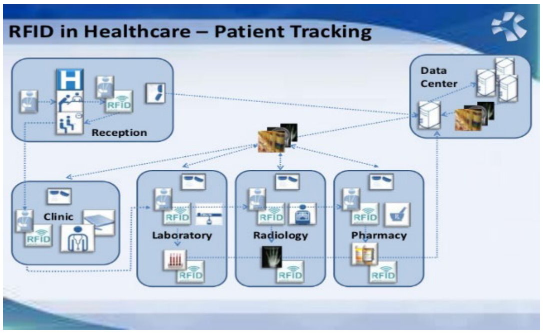

FIGURE 11. Active RFID tags for patient tracking [137].

of it. The resulting device is then coupled to the antenna. They had reported that even with sophisticated techniques such as pick and place and self- assembly of fluid and as reported in the papers [41]–[44], the production cost in addition to the cost per tag still remained high. These issues existed for 13.56 MHz RFID tags and hence did not motivate the researchers to fabricate more such tags despite its good read range. The primary issues were as follows. These tags suffer from the presence of metallic environments and a Non-Line-of-Sight (NLOS) type of environment too, though these tags provide better performance inside fluids, due to greater penetrability (due to longer wavelength). On the other hand, Low Frequency (LF) tags require too large spiral inductors for interrogation for a high transmit power which led to practical difficulties such as high cost of fabrication and limited to specific applications. Such tags were concluded as useful for Line-of-Sight (LOS) applications (for golf ball tracking within the reader's sight). But the progress remains steady towards the development of robust RFID tag and readers.

In paper [45], the authors had discussed the use of a radar enabled golf ball that contains a radio frequency tag. The company uses ball positioning technology, shortly known as BPS that enables a golfer to identify or track the lost golf ball through the use of a Radar Golf Handheld device. This handheld device is nothing but an RFID reader or an interrogator which typically beeps when the pointer in the radar map points in the direction of the ball which is either heading in a particular direction or is stationary. The RFID tag was implanted at the core of the golf ball such that the radiation from the tag is isotropic with respect to the outer structure.

3) SILICON BASED IC RFID TAGS WITH APPLICATIONS IN HEALTHCARE MONITORING

In paper [46], the authors discuss about RFID tags that was implanted in VIP members during the Spanish Baja Beach Club ceremony. In this system, the VIP members can get an implant that they can use to easily pay for their drinks they are willing to purchase in the club. The implanted RFID tag was active in nature which had required the company to recharge those tags once every five years. The implanted active RFID tag was a VeriChip. In paper [47], the same RFID company had produced human implantable RFID chips which were mainly designed for healthcare applications such as in bio-signal monitoring of cardiac patients and also to monitor several other parameters such as blood pressure, glucose concentration, hydration level and so on. A schematic representation of the locations where RFID tags were being used is shown in Fig. 11. The papers [48] and [49] proposed physical layer solutions called SecureScatter and a tag named SecureTag to mitigate spoofing attacks from off–body tags and provide authentication mechanism for battery–free communication link between smart Internet–of–Things (IoT) devices with tags. These techniques were designed for healthcare applications to monitor various parameters such as blood pressure, glucose concentration and so on. The motivation behind the exploration was that when active off–body tags transmit a signal to the on–body receivers with a fake data (e.g., causing an electric shock), the resulting effect can be dangerous as the devices are placed on a human being. Because of this, an authentication mechanism was critical for providing a widespread solution. These works used tags and propagation signatures from on–body and off–body tags to analyze the pattern of variations in the Received Signal Strength Indications (RSSI).

The authors explain that the direct and backscatter path signatures from the on–body devices exhibit a high and characteristic correlation in the signal strength as compared to off–body active tags. This factor was useful in eliminating the off-body tag responses. SecureTag feature also functions similar to SecureScatter. These are essentially signal processing techniques to combat malicious attacks. However, the ability to distinguish between on–body and off–body tags become difficult when more such tags are deployed within the identification vicinity. The propagation signatures will also vary with time as the tags become highly mobile. This is also partly due to the reason that the characteristics of the environment keeps changing with time. The detection becomes even more difficult because there are other types of objects present within a room other than the tags. Since these objects also reflect off the signals, it will also become necessary to compensate the multipath effects apart from securing the on–body tag. Such problems are certain in applications like RFID too. While RFID tags possess a unique serial identification number, it will be important for the proximity active readers and servers to make sure that the tags that are present matches the ID's in the database. This information can help to block such malicious tag attackers from intrusion. Passive tags on the other hand cannot be manipulated in general by the tag attackers as they generally cannot be written. Hence, counterfeiting the information contained in such tags is not possible.

4) APPLICATIONS OF SILICON BASED IC TAGS FOR PAYMENT AND VERIFICATION PURPOSES

a: ACTIVE TAGS FOR TOLL COLLECTION

In paper [50], the authors had proposed active RFID tags for automatic toll collection in National Highways in the roads and in other bridges. The tolls are usually thought

FIGURE 12. RFID tags in gas stations [138].

of as checkpoints designed to pay to enter a different city or town or to enter a different country. The tolls or checkpoints act as repeaters after every point until we reach the destination. Active RFID tags have been deployed for this application to test, evaluate and validate the performance and rate of scan. The results showed excellent rate of scan even when it is constrained by factors such as the car is not required to come to a halt at the checkpoint. The toll points will scan all the cars (RFID tags) passing through the toll using their RFID readers and the required money to enter a different region will automatically be deducted from the passenger's bank account.

b: PAYMENTS IN GAS AND FUEL STATIONS

Paper [51] proposed an application where paying at petrol and diesel stations such as Exxon Mobil and other mobile gas stations using RFID systems will be relatively simpler compared to manual payment where the latter approach causes an unnecessary increase in time spent by the customers at the station followed by other inaccuracies due to human errors. They had used RFID tags such that every customer who gets an RFID tag provided to them can login and enter their details into their Exxon Mobil account.

At subsequent times, when they enter the gas station, the station scans their ID serial number that is attached to the car and the money will automatically be withdrawn corresponding to the amount of fuel. Fig. 12 provides a schematic methodology on how a vehicle's payments, volume of fuel fill followed by other parameters will be carried out using an RFID identification system.

c: RFID TAGS FOR PASSPORT PROCESSING AND IN RETAIL STORES

In paper [52], the International Civil Aviation Organization or more popularly called as ICAO had posted guidelines for adopting RFID enabled passports. In an effort to make it easier to process several passports, many countries have implemented RFID in it, despite the security and privacy issues that may arise. Since the time when the break of encryption algorithm on UK chips occurred, researchers have started to clone the passport data while it is being mailed to the corresponding owner in order to ensure that the algorithm becomes difficult or almost impossible to break.

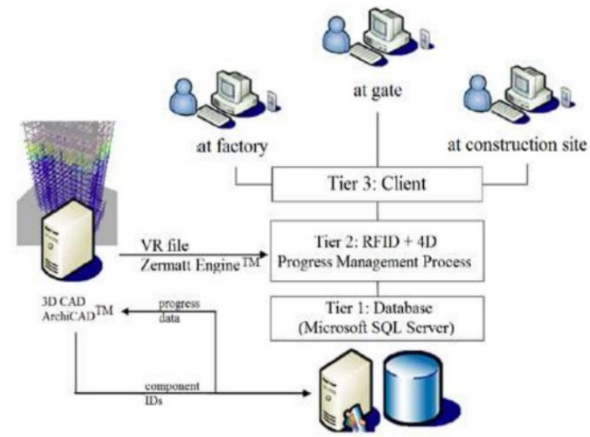

FIGURE 13. RFID tags in factories and construction sites [139].

Paper [53] states that the Colorado State Legislature advocated the use of an aluminum underwear as a misdemeanor because since RFID tags are covered with an external shield to prevent RF signals from passing through it, an aluminum clothing proved to prevent such hassles for shopkeepers to miss any detection of RFID tags labeled in their objects [54].

5) RFID TAGS FOR OTHER APPLICATIONS IN VARIOUS SITES

Paper [55] discusses different factors that influence the popularity of RFID technology and different methods with which both the active and passive RFID tags are designed followed by the methods with which they are coupled with the RFID reader to enable communication between them. The paper also discusses different applications where such RFID tags have been most commonly deployed followed by the international regulatory and standardization of the technology. In paper [56], the authors had discussed the invention of IFF for incorporating RFID tags at many sites such as construction given in Fig. 13. In patents [57] and [58], the authors had discussed the first RFID patent where a base station transmits an interrogation signal to a remote transponder. The tag or transponder then responds with an acknowledgement. The transponder includes a writeable and a rewriteable memory (a field programmable tag). Thus, for every reading cycle the tag is being interrogated by the RFID reader, the tag can replace the existing memory with a new information and can query this new information in the form of EM backscattering to the RFID reader by the use of far field RFID communication. The invention claims that the transponder generates its own operating power from the transmitted interrogation RF pulse in a way that the transponder component is self-contained and self-sustainable for as long as the interrogation power generated by the RFID reader is enough to charge the RFID tag. Patent [58] explains a similar principle as proposed in the patent [57] but as an extended version where the scenario now contains multiple tags in the close vicinity and by the use of modified configuration. The other challenge now is to be able to uniquely identify the tags while all are simultaneously present in the response. This requires the RFID engineer to design tags such that every code is strictly orthogonal to each other. This reduces the inter-tag interference and hence improves the signal detection in applications such as identifying several building materials in factories.

D. WORK ON RFID TAGS WITH A SOFTWARE–DEFINED –HARDWARE INTERFACE

Paper [59] discussed the major contributions made by the auto–ID center at MIT, KAIST and other research institutions that focused on EPC network, EPC global network simulator and integration with existing systems for developing software for RFID tags. These softwares are designed to be software-defined-hardware-compatible which can work together to form a complete RFID system. They bridge the RFID network and end user network such as IT industry, supply chain management, retail stock management and so on. They are designed to provide a meaningful sense of the data captured by the RFID network.

Several hardware manufacturing processes such as RF microchip design, class 2 generation RFID tags and other higher classes of tags, RFID tags with memory, battery, sensors and actuators were also performed at the auto–ID center.

Paper [60] had outlined the history and current trend of active and passive RFID tags. The paper basically focused on how the auto ID technologies developed to how the RFID technology is existing and proliferating now. The paper discussed the limitation of bar codes and a brief technical survey on how active RFID tags can prove to be a significant technological advancement if all the issues such as providing a meaningful sense of the data to the end user and minimizing the cost are resolved.

In terms of obtaining higher interrogation range, active RFID tags can provide a better performance compared to silicon based passive IC tags. But the limitation is that such an increase in range would generally require to add more signal processing functions which would increase the complexity of the internal circuitry. This would in turn increase the operating cost. Moreover, the overall cost will also keep adding up as the battery has to be replaced once every three to five years which may not be attractive for many large scale applications such as inventory stock, warehouses for asset tracking and other medical applications such as in health care to identify and monitor the health status of a patient such as blood pressure, glucose concentration and so on. The lifetime of active tags is also limited to around five years.

While these technologies have already been developed and significant research is still going on in the RFID domain, other novel technologies had arrived in the 21^{st} century which are called chipless RFID tags. However, the review of such tags will not be carried out as negative aspects such as inability to survive in harsh weather due to degradation of conductive ink (substrate) properties, larger tag size and shorter read ranges have limited the penetration of such tags into the RFID market. To summarize, silicon based IC RFID tags possess certain advantages and limitations as follows. The active tags are expensive because there is an internal power supply which needs to be replaced frequently, though they can be interrogated from a distance higher than passive tags. They are expensive because they also contain certain in-built components that can perform other functions such as security module. Passive tags on the other hand suffer from security issues compared to active tags and provides a lower read range primarily due to strong or weak electromagnetic interference and under harsh environmental conditions, which reduces the signal strength further than active tags. Harsh conditions could indicate a high or low temperature and pressure environment, areas susceptible to extreme mechanical vibrations, humidity and radiation. Hence, unbreakable cryptographic algorithms must be available at the reader side for passive tags followed by robustness in passive tags. The average read range for passive tags is between 1-5 m and 30-100 m for active tags (under ideal or normal conditions). Thus, to compensate in terms of cost, read range and environmental effects, another type of RFID tag design was proposed around the very late 90's which did not contain the silicon chip within them, unlike the silicon based IC tags. These are called Surface Acoustic Wave (SAW) based RFID tags and will be the next focus because several work has been carried out and the read range is very high compared to passive IC based RFID tags and almost comparable to active RFID tags even under harsh environmental conditions. These tags can withstand and provide higher read range compared to silicon based tags for applications even under high temperature and pressure and other mentioned effects. SAW based RFID tags are quite popular in both academia and industry because of a variety of features such as robustness, read range, low cost of operation and high degree of interoperability in metallic environments. A detailed explanation into the SAW device followed by SAW as RFID tags will be explained in the subsequent sections.

E. SURFACE ACOUSTIC WAVE (SAW) BASED RFID TAGS

Active RFID and passive RFID tags that are silicon based are used for many applications such as supply chain management, logistics control for maintaining the tracking order of several containers across multiple floors, identification of healthcare patients within private and public hospitals, identifying or tracking a number of animals located within a domestic environment such as farm and other areas. In such applications, where the objects or the livestock need to be identified, it is inevitable that all such tags will encounter electromagnetic interference and multipath reflections which occurs due to interference between electric and magnetic fields generated by such tags since these tags are being instantaneously identified using EM field and also due to the surrounding objects. As a result, the probability of detecting such tags will significantly reduce when there are many of them present in the scenario. In the light of this, active RFID

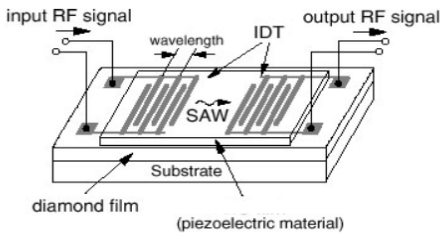

FIGURE 14. A typical surface acoustic wave (SAW) device structure using input IDT, a delay line and output IDT [118].

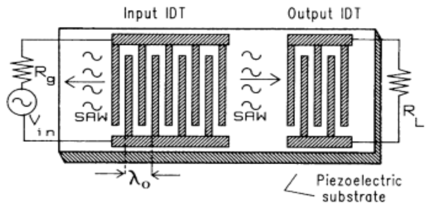

FIGURE 15. SAW structure with an externally connected source and load [118].

tags cannot be a viable alternative as the cost of deploying them is high, followed by frequent replacements of the same once every couple of years which adds up to the production management cost. Passive RFID tags can be a better alternative compared to active RFID but since they are all based on IC microchip, the electromagnetic interference will be an impediment to the complete RFID system which prevents them from achieving an optimum performance. Furthermore, since many of these EM signals face rapid attenuation in the presence of metallic environments, the deployment of such silicon based IC tags for widespread applications will be a debatable issue. A still newer approach and a unique device based on the principle of piezoelectricity has been a topic of interest, called Surface Acoustic Wave (SAW). Surface Acoustic Wave (SAW) devices have been under usage for a variety of applications such as localization and an application where identification using SAW tags at 2.5 GHz have been reported for indoor environment in 2002 [61]. Papers [62] and [63] discuss the principles, developments and applications of SAW RFID tags. Surface Acoustic Wave (SAW) tags could be thought of as a unique method of tagging compared to other IC based tags and the usage of such tags has been there for only a decade. These tags can easily compensate for multipath reflections due to their delay lines separating the IDT's as shown in Fig. 15. They are also robust against EM interference due to their acoustic mode of operation. In general, SAW devices are also being used as sensors, filters, resonators and in many other forms for a variety of applications such as chemical sensing for factories and industries, bio sensing for healthcare applications, for temperature and pressure sensing in many adverse environments, as linear and non-linear FM chirp filters, as reflective array compressors for radar design, bandpass filters for TV video game systems for suppressing interference, acousto-optic filters for spectrum analyzers and as acoustic filters for many high end applications related to deep space communications [64], [65].

A typical Surface Acoustic Wave (SAW) device structure as in Fig. 14 consists of four major components namely the:

1) Input IDT (either bidirectional or unidirectional)
2) A finite delay line
3) Output IDT, and a
4) Piezoelectric substrate (e.g. Quartz)

The schematic of a typical SAW device structure with an externally connected source and load resistance is provided in Fig. 15. The phenomenon of generating surface acoustic waves has been demonstrated at the free surface of an elastic solid in the paper [66].

The generation of such SAW waves can be achieved by applying an electrical voltage to a metal film Interdigital Transducer (IDT) at the input side which is embedded over the surface of a piezoelectric material such as Quartz, Lithium Niobate ($LiNbO_3$) and Lithium Tantalate ($LiTaO_3$). The two IDT's separated by a finite spacing called a delay line is typical for a SAW device configuration as in Fig. 14 and Fig. 15. One of these acts as a transducing device that converts the incoming electrical voltage variations into acoustic waves. These waves propagate through a finite delay line spacing between the input and output IDT over the surface of a piezoelectric material. Hence, the term Surface Acoustic Wave (SAW). This delay line is introduced to provide sufficient time delay between the incident and received electrical signal to ensure that the distinction is made between the transmitted and the received signal from the SAW device [65]. The IDT is deposited on the surface of piezoelectric substrate to exploit piezoelectricity that enables energy conversion from electrical energy to mechanical energy and vice versa.

Such energy conversions from electrical to mechanical waves and vice-versa are possible only in conjunction with such piezoelectric substrates. Both the input and output IDT are connected to electromagnetic transmission and backscatter antennas where the principle of reciprocity applies to both IDT's and which states that the voltage and current applied at one source of a branch in the network creates a similar magnitude in the other branch of the network when a similar source is connected to it. However, this theorem is applicable only for networks containing a single voltage or current source and not multiple sources. It indicates that voltages can be applied to either of the two IDT's with the end result being the same magnitude of voltage or current measured from the other IDT.

When the output IDT receives this mechanical SAW wave, it converts this wave into an electrical signal that can be collected by the antenna coupled to it. The antenna then radiates this waveform from the SAW device in the form of an electromagnetic (EM) signal into the free space. Detailed mathematical descriptions regarding SAW wave propagation over a given piezoelectric material is mentioned in numerous texts [64], [65]. The method with which the electrical signal is converted to a mechanical SAW wave is termed as electromechanical coupling. The amount of power that

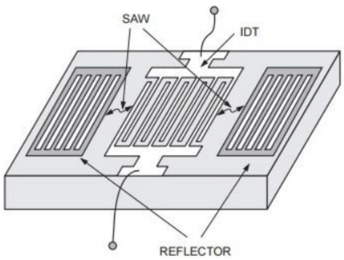

FIGURE 16. A SAW resonator based RFID Tag/Sensor with double sided reflectors.

is converted is determined by the term electromechanical coupling coefficient, denoted by k^2 which is given by the expression (2),

$$\frac{\Delta V}{V_o} = \frac{V_o - V_m}{V_o} \tag{2}$$

where the coupling coefficient term k^2 is given by the ratio $\frac{\Delta V}{V_o}$. The terms V_o and V_m denote the SAW velocity in the free space and metallized region where the thin metallic electrodes of IDT are deposited on the elastic film. Like how SAW devices can be structured in the form of sensors, resonators, filters and so on, the SAW devices can also be fabricated in the form of tags for identification. A typical SAW tag configuration with a single IDT and multiple reflectors spaced by a finite delay line is shown in conjunction with an RFID reader in Fig. 16.

SAW tags are usually designed with multiple reflectors spaced by a finite delay line between the input IDT and also between them to allow a uniquely coded waveform pattern. Many SAW tags and sensors have been designed with coded patterns in conjunction with Time Division Multiplexing (TDM) [64], [65]. While SAW based RFID tags are a unique type of passive tags, these reflectors are fabricated as metal strips (non-silicon) on top of the piezoelectric substrates.

There are many ways to design a code in SAW tags as given in [67] which include Orthogonal Frequency Coding (OFC), Pulse Position Modulation (PPM) or Time Position Encoding (TPE) with many coded waveforms depending on the nature of the code.

1) RESONATOR BASED SAW RFID TAGS/SENSORS

Surface Acoustic Wave (SAW) RFID tags based on resonator design consists of reflectors located on either side of the input IDT. Frequencies are allocated such that the reflectors on either side generate different frequencies (for instance, left track at f_1 and right track at f_2) while the spacing between them remains constant. When the input IDT is excited, it generates an acoustic wave which travels on either side. Reflections are produced at successive and equal intervals but at different frequencies. Hence, SAW tags that are resonator based can be separated only in the frequency domain.

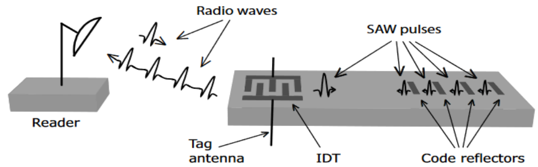

FIGURE 17. A typical SAW RFID reader tag interrogation system based on pulse position modulation (PPM) technique [79].

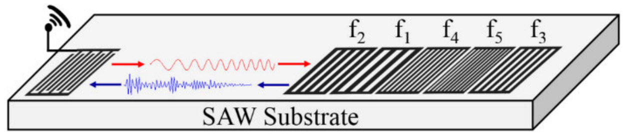

FIGURE 18. A SAW RFID-tag based on an OFC chirped reflector design [140].

2) DELAY LINE BASED SAW RFID TAGS

Other techniques of coding SAW tag reflectors have also been proposed [68]–[70] such as using Time Position Encoding (TPE) and Pulse Position Modulation (PPM) as shown in Fig. 17. The TPE and PPM technique involves fabricating the reflectors at specific locations in the SAW tag such that the reflections occur at different instants of time in the received signal response. Conversely, given the time instants, the physical locations of such reflectors can also be determined. Appropriate locations have to be chosen such that least amount of loss is suffered by the reflections. These designs are such that the tags can be separated only in the time domain with reflected codes of different tags arriving at different times that correspond to unique time signatures.

3) HYBRID DESIGN (RESONATOR AND DELAY LINE) BASED SAW RFID TAGS

Unlike the resonator and delay line based SAW RFID tags where the reflectors are designed either as varying frequency chips or as varying time positioned chips, papers [71]–[75] and patent [76] shows the most famous patented design of SAW RFID tags where a combination of the above is used as shown in Fig. 18 and are called Orthogonal Frequency Coding (OFC) based SAW tags. In this design, the different reflectors deposited on top of the substrate are both designed at different resonant frequencies and spaced at different locations which corresponds to different time instants in the received signal response or as a combination of reflections occurring at different times along with phase information. Here, for a one/two port network, the input IDT and the reflectors resonate at different frequencies (also obeys the above orthogonal frequency conditions). Thus, as far as the general reader interrogation is concerned, the SAW RFID tag can be interrogated as a response containing taps of different resonant frequencies from reflectors, as taps spaced at different time instants or as a combination of both resonator and delay line based design that corresponds to a unique signature code. The most famous patented technology till date is the mixed design of each reflector resonating at different frequency and which is separated by a finite delay distance and in turn corresponds to a unique frequency-time or time-phase response of a particular SAW RFID tag. A mathematical modeling such OFC SAW tags is provided in succeeding paragraphs.

The use of OFC codes for SAW tag embodiment has been previously reported [67] which refers to establishing orthogonality between different chip frequencies. The basic functions that support the construction of OFC chips in a SAW ID tag is presented as necessary conditions for ensuring orthogonality. For instance, consider a time domain response $g_{\mathrm{bit}}(t)$ containing length T_{b} that is defined as the code time-length. The code will be partitioned into a number of chips which is present in the integer subset such that,

$$T_b = j.T_c \tag{3}$$

where the chip interval T_{c} is the time interval required to construct the orthogonal basis set [67], and j is the number of chips present in the SAW tag.

The function for each chip interval is given by (4),

$$g(t, f_{oj}) = a_j.cos(2\pi f_{o,j}t).rect\left(\frac{t}{T_c}\right) \tag{4}$$

The generalized time domain function for each chip is thus given by (5),

$$g_{chip}(t, f_{o,j}, j) = f(t - jt_c, f_{o,j}) \tag{5}$$

Here, each chip that is present in the OFC SAW tag is continuous without causing any overlap. Hence, the complete time domain response for the code is given in paper [67] where $j = 1, 2, \ldots, M$ is the j^{th} chip contained in the code bit and $f_{\mathrm{o,j}}$ is the operating frequency of the j^{th} chip while meeting the conditions in (6),

$$f_n = \frac{n}{T_c} \; and \; f_m = \frac{2m+1}{2T_c} \tag{6}$$

which typically require an integer number of wavelengths at the frequency f_{n} and an integer number of half wavelengths at the frequency f_{m} and n and m are integers. Meeting these conditions will yield a set of orthogonal frequencies for a particular OFC SAW RFID tag. In this design, the tags can be separated and distinguished only in the frequency domain. The frequencies are then shuffled in an order such that multiple SAW tags can be produced to meet certain applications that require identification of multiple assets and packages within a store room.

4) BENEFITS OF SURFACE ACOUSTIC WAVE (SAW) BASED RFID TAGS

Compared to its counterpart technology which are IC based active and passive RFID tags, the SAW tags, though being passive possess a greater advantage that outweigh the active tags to be used for many identification or tracking applications. Such advantages include:

1) SAW devices can be designed to provide various complex signal processing operations within a package. For instance, SAW tags with superior frequency response characteristics can be designed for several radar based applications which may require several thousands of LC circuits in conventional device designs [64], [65].
2) Since the SAW devices can be implemented with a relatively small size, robust, light weight and with highly power efficient modules, such advantages of SAW devices can find potential in various applications such as inventory and logistics identification as passive RFID tags and also in deep space borne communication systems.
3) Though SAW tags are analog in nature, they can also be used in many digital systems for designing Quadrature Amplitude Modulation (QAM) radio systems for efficient transmission.
4) SAW tags can also be fabricated at Gigahertz frequencies and a higher bandwidth can be used to provide a high resolution for applications in pulse compression radars.
5) Since they rely on mechanical waves which create coded waveforms, the design structure is completely different from other conventional silicon based manufacturing of RFID tags. This proves to be very useful in avoiding electromagnetic interference as the acoustic waves do not interfere with neither the electric nor magnetic fields, while silicon based IC tags are instantaneously identified using EM fields.
6) Since SAW tags are passive in nature, they are cheaper compared to active RFID tags. They are also superior to both active and passive RFID tags due to their robustness against EM interference.
7) Also, SAW RFID tags are more robust and can also work under hazardous environmental conditions such as high amounts of dust, higher temperature environment such as in boilers, heat exchangers, high pressure areas such as in physical structures, humidity and radiation. Active and passive IC based RFID tags show poor performance under such conditions. Furthermore, SAW tags also possess the capability to withstand higher temperatures up to 750°C unlike the silicon based IC tags [77].
8) SAW tags can also operate very efficiently in metallic environments with higher accuracy while other IC based tags cannot provide sufficient performance due to rapid and instantaneous absorption of signals by the metallic objects.

Since SAW tags operate in acoustic mode and also consists of a finite delay line that separates the transmitted and received RF pulse in itself, the time delay of SAW tag is usually much larger than the multipath delay. Hence, the response of SAW tag arrives much later than the multipath reflection delay. As a result, SAW tags can easily compensate for any multipath reflections in a given environment. Papers [61] and [78] reported identification and localization using SAW ID tags and Ultra-Wide Band (UWB) SAW RFID tags which were fabricated at 2.5 GHz and 1 GHz respectively. The authors had proposed an RF signal bandwidth of 50 MHz which corresponds to a pulse width of 20 ns duration in time domain. With the proposed system, numerical results show that the estimated accuracy was around 6 cm for a temperature of 20°C and 12 cm for a 40°C temperature raise. SAW tags with good response characteristics can provide a read range of up to 30 m [27]. This will be an ideal system when the RFID reader is assumed to be placed in the middle, the tags can cover 30 m to the left, right, north and south. This can provide a cell coverage area of 60 x 60 m^2 and is useful for many tracking applications. When multiple readers are deployed within the area along with multiple SAW tags, a much larger area comparable to active IC based RFID tags can be easily covered.

5) LIMITATIONS OF SAW BASED RFID TAGS

While SAW tags provide immense benefits as mentioned above, there are certain limitations and features that SAW tags still lack today. While active tags possess the feature of Read/Write operation where the tags can be written (only once), SAW tags do not contain that feature yet. Compared to active tags, SAW tags do not offer a read range of up to 100 m at present. But this can be achieved or even improved further than this through proper reduction in device's insertion (for two-port device) and reflection loss (one-port device) followed by further design optimizations. Finally, in terms of security, SAW tags do not contain such additional features such as cryptographic modules as the active tags. Hence, robust cryptographic algorithms must be developed at the reader side to overcome security and privacy issues in SAW RFID tag-reader systems. And also, while SAW RFID tags do offer competitive advantages compared to silicon based IC and other chipless tags such as conductive ink based, they face a challenge of cost reduction [28]. To solve this problem, an appropriate choice of piezoelectric material in conjunction with a low cost fabrication technique will bring down the cost of manufacturing SAW RFID tags.

III. PERFORMANCE METRICS AND IMPORTANT FACTORS AFFECTING RFID TAG PERFORMANCE AND COMMERCIALIZATION

While many use-cases or applications of such RFID tags are present, a widespread adoption and more research and development is still required and is undertaking at present such as resolving security issues, improving the read range, reducing the cost and ability to simultaneously read many tags at a time. Certain factors pertaining to RFID technology are given which include:

A. PROPER REGULATION & STANDARDIZATION OF RFID TAGS

Although the characteristics of application and the scenario determines the appropriate tag to be used for the same, many standards provide freedom of using communication protocols and the way in which the information has to be stored in the tag. Companies manufacturing and locating various assets may encounter conflicts and need to agree with the standards related to communication protocols such as data rate, type of modulation, packet encoding, frame sequencing and other anti-collision management strategies.

B. COST

The cost of RFID tags depend on the type i.e. the design constraint. Though the 2003 report on "RFID system used for Supply Chain management" [26] claimed a predicted reduction in costs, the results are still insufficient as labor costs and zero tag data generation to other parties also introduce costs which would vary between 5 and 25 cents from common item level tagging to tagging high end products. IC based active RFID tags are expensive and have to be replaced very frequently due to their limited battery life also.

C. COLLISION

While multiple tags transmit their identification code followed by other additional information to the proximity RFID readers, data collision is an inevitable issue and needs to be addressed carefully. To prevent such issues, many anti-collision algorithms for the reader side have been proposed and patented. The cost required to incorporate such protocols and to reduce them is still underway according to papers [7] and [26]. Active IC based RFID tags provide many features such as security, varied data form types and so on which can possess a large memory to maintain sophisticated communication protocols between the reader and tag. Passive RFID tags that are IC based do not contain such features and must be synchronized (e.g., time, frequency) to avoid collision.

D. SECURITY AND PRIVACY ISSUES

One of the most common issues in RFID technology is when unauthorized people read and write or manipulate the information on the tag by introducing a programmable mechanism such as virus and other firmware update mechanisms. Hence it becomes important to prevent such unauthorized personnel from reading or manipulating the information present in the tag. To achieve this, encryption algorithms must be robust against such attackers such that the algorithm cannot be breakable.

E. FAULTY MANUFACTURE OF RFID TAGS

Certain tags have a tendency to be damaged when under usage. Many application challenges need to fulfil through the use of multiple tags, and still none of them which are IC based tags are completely invulnerable. They result in physical damage where the degree of damage varies from one application to another. The end result will cause a lower read range or even a read failure. This leads to a hidden tag problem. This could result in a huge loss in certain business firms such as when identifying the goods, pallets or items, any missing commodity would result in a reduced profit.

F. BLOCKING TAGS VIA SOFTWARE INTRUSION

Many applications in paper [26] had reported on the potential to become vulnerable when the RFID system is connected

TABLE 1. Various frequency bands and corresponding read range.

Band type	Frequency Range (in Hz)	Read Range (in m)
Microwave band	2.45 GHz	Maximum of 2 m
UHF band	300 MHz – 3 GHz	Minimum of 3 m and up to 50 m or 100 m
HF band (Smart cards)	3 – 30 MHz	1.5 m; high end readers
LF band	30 kHz – 300 kHz	At best around 1 m

UHF – Ultra High Frequency
HF – High Frequency
LF – Low Frequency

to a database server. SQL injection attacks could alter the information present in the tag which would convey a different meaning than previously thought. This problem can be resolved by erasing and damaging the tag once the purchase of any commodity has been done. The tag cannot be read again if the item has already been purchased.

G. READ RANGE/INTERROGATING RANGE OF READER–TAG

The interrogating range between the RFID reader and tag does play a vital role in determining which tags are superior in their technological aspects. Generally, a larger read range will be suitable for long range and large scale applications such as in warehouses whereas a longer range may not be necessary for applications such as a small grocery store or within a home. However, a longer read range is one of the primary benefits that RFID technology offers compared to other auto ID approaches such as bar codes, magnetic stripes and others. Though there are certain applications such as access control for a person or a moving car where a longer read range may not be necessary, this characteristic will be useful for other applications such as inventory and asset control. Table 1 contains the plausible read range for various frequencies in the microwave, LF and HF spectrum.

IV. PERFORMANCE EVALUATION AND COMPARISON, POTENTIALS AND CHALLENGES OF SILICON BASED IC AND SAW BASED RFID TAGS

According to the literature survey on active and passive silicon based IC RFID tags, many identification and tracking applications where such tags are used exhaustively provide a strong advocacy for the deployment of such tags for the same. Active based tags that rely on an internal battery powered module can use it to power the microchip as well as to transmit the signal from the tag antenna. Active tags can generate more power due to which increases the read range interrogation between the RFID reader and the tag.

A typical read range distance between the reader and tag when active tags are used is around 30 m or can go up to a maximum of 100 m depending on the nature of the environment and also on the type of tag used. Active tags can also provide other features such as allowing different types of data forms such as ID number, nature of product on which the tag is placed on and cryptography and privacy modules which ensures privacy and authentication with the nearby readers so that the likelihood that an eavesdropper can access or manipulate the information can be prevented. Also, the detection of forged tags can be performed which can save huge losses. But the major challenge is that the encryption algorithms designed for the tag must be robust enough to prevent such eavesdroppers from misusing the RFID devices. Another challenge is that active tags are expensive due to such additional features which limits the potential to be deployed in large numbers such as in healthcare, hospitals and in inventory and asset control and replacing with newer batteries is also a debatable issue for active tags. Active tags also suffer a huge loss in hazardous conditions such as high temperature, high pressure, environments below freezing point, places susceptible to very high mechanical vibrations, humidity, radiation and so on. Hence, the applications of such tags are also limited to only specific scenarios. In particular, certain applications such as transferring healthy organs of a patient require that the pallets or items be stored under extreme pressure and temperature conditions. In such scenarios, active tags does not provide sufficient intensity (reflected power) of identification and an appreciable read range. This example can be applicable to any other similar scenario that pose a stringent requirement regarding the nature of environment.

On the other hand, passive IC based RFID tags are relatively cheaper than their counterpart, active tags, and can be thought of as a tag that can be easily deployed in large numbers for applications such as identification or tracking of millions of data center assets in logistics, identifying containers during shipments and even when they are mobile. But the challenge of such tags is that they cannot operate beyond a certain range. The read range of passive IC tags is also limited to a minimum of 3 m and up to 6 m. Unlike active tags that can provide additional features such as security and privacy modules and others, passive tags do not offer such modules. The primary distinguishing characteristic from active tags stems from the cost of operation, lower read range and without additional feature modules. As such, passive IC based tags are not designed to offer such advantages like active tags which in turn becomes a questionable technology when privacy issue becomes a critical factor. Passive silicon based IC tags also suffer from a huge loss under many hazardous conditions such as those mentioned in the preceding paragraph. Hence, similar consequences are faced by passive IC based tags too. As a result, the deployment of such tags is also limited to very specific applications like active tags. Therefore, a motivation to conduct research and develop SAW based RFID tags is very high among the researchers from both academia and industry as they provide many attractive features which the silicon based IC tags cannot offer. Semi-passive tags are another class of passive tags which rely not only on the reader's power but also on other energy harvestable sources such as organic solar cells. While the latter can be an alternative for flexibility and low

TABLE 2. A comparative summary of various silicon based ic and saw based rfid tag technologies.

Existing literature	Type of RFID tag (Silicon based IC and SAW based)	Average cost per tag (in US Dollars ($))	Average read range (in m)	Security and Privacy	Tag size	Availability of tag power	Lifespan
[93]-[103], [127]	Passive Silicon based IC RFID tags	Cheaper – $0.07 – $0.15	LF: 1 - 10 cm HF: 1 cm – 1 m UHF: Min: 1 m, Max: 5 – 6 m (under normal conditions)	Cryptographic modules are not built inside the tag due to power constraints.	Small	Only in interrogation field of the RFID reader	Very long (up to 20 years)
[95], [104]-[113], [127]	Active Silicon based IC RFID tags	Expensive - $25 and more (depending on the need of additional features)	Up to 100 m (under normal conditions)	Built with cryptographic modules to encrypt the data.	Large	Continuous	Short – Limited to battery source (5- 10 years)
[114]-[117]	Semi-passive Silicon based IC RFID tags	Expensive - $20 and more	Min, range: 5 m Max. range: 60 – 80 m (under normal conditions)	Not built with cryptographic modules.	Large	RFID reader for interrogation, Internal battery/energy harvesters (e.g. solar cell) for powering the microchips	Short – Limited to battery source (2 – 7 years)
[27], [118]-[129]	Passive Surface Acoustic Wave (SAW) based RFID tags	Cheap - ≤ $1 in volume purchase	2 m and up to 30 m (both normal and hazardous/extreme conditions)	They are not built with encryption/decrypti--on modules.	Small	Only when interrogated or excited by RFID reader	Very long (Usually up to 20 years)

fabrication cost, these tags tend to degrade in performance under hazardous conditions. The interfacing of such energy sources with the main RFID module also increases the form factor which in turn raises the operating cost of such tags.

Surface Acoustic Wave (SAW) tags are built with a unique design compared to conventional silicon based RFID tags. These tags exploit the principle of piezoelectricity by utilizing various types of piezoelectric substrates such as Quartz, Lithium Niobate ($LiNbO_3$) and so on. They are also passive like passive tags in silicon based IC type. They are small, rugged and offer superior signal processing functionalities compared to conventional IC based tags. Compared to active tags, SAW tags can also provide a read range of 5 m and up to 30 m as claimed by paper [27], but could also be extended using multiple readers and also by improving the performance of the tag such as minimizing the reflection and insertion loss and maximizing the coding gain. SAW RFID tags can be robust than active and passive silicon based RFID tags even in hazardous and adverse climatic conditions and can provide a much better accuracy than the silicon based tags under the same conditions. While passive tags based on both IC and SAW can be cheaper, SAW tags offer other important characteristics and benefits such as the ability to compensate multipath reflections occurring due to external objects in the environment, robustness under harsh environments, robustness against electric and magnetic fields due to acoustic mode operation, better read range distance of up to 30 m even under extreme conditions, which makes it popular than conventional silicon based tags and reasonable level of security due to impossibility in manipulating the SAW tag via software programs like virus and other firmware updates or counterfeiting. However, issues such as replicating tag information do exist for SAW tags too. In these cases, blocking the tags once the item is purchased can be a good solution so that problems such as reducing the cost in a blank tag using the information present in an expensive item can be avoided.

Because of low radiated power of around 10 mW, SAW tags have a substantially higher order of interference rejection than silicon based IC tags. The reading process of SAW tags permits a direct as well as accurate measurement of various parameters such as temperature, pressure, gas concentration and others. Thus, SAW tags show an inherent capability to operate as sensors too. They can operate in the 2.45 GHz ISM band which is compliant with RF emission rules and regulations throughout the world whereas the use of IC based tags demands specific certifications and licenses. Additionally, SAW RFID tags can also operate in many metallic environments while silicon based IC tags suffer losses from such metallic reflections [79]. On a similar note, SAW tags can be attached on metal objects too. SAW tag systems achieve greater penetration into various pallets that contain metals [80]. Thus, when comparing the SAW technology with the silicon based IC tags, there are certain trade-offs in terms of privacy issues between active and SAW based RFID tags while the read range is far higher than the passive tags which are silicon based IC. This reading range could also be further extended through a large energy. By interrogating with a wideband signal, it provides an accurate estimation of various signal parameters such as Time of Arrival (ToA), Received Signal Strength Indications (RSSI) and so on. Before RFID technology could be deployed, the problems pertaining to it such as read range, security and privacy, collision of tags and high cost of operation should be resolved so that they can be deployed in all applications [81]–[92]. Though these issues still exist for RFID systems, it can be seen that SAW based RFID tags provide many other attractive benefits that makes it a promising candidate for developing robust RFID systems. Certain benefits that are obtainable from SAW based RFID tags are such that they provide a high degree of versatility compared to the conventional silicon based IC tags, given their excellent stability under varying and harsh environmental conditions such as high temperature and pressure, environments prone to extreme mechanical vibrations and others. While all silicon based IC tags face problems such as electromagnetic interference and multipath reflections, SAW tags can greatly compensate such effects and provide outstanding characteristic responses compared to the former. These attributes provide a strong motivation to do extensive research into the development of SAW RFID tags. A detailed comparative summary into the silicon based IC and SAW based RFID tag technologies is provided in the Table II.

V. CONCLUSION

This article presented a detailed review of existing types of RFID tags and technologies namely the active and passive which are based on silicon based IC and SAW technology and critically reviewed the complete RFID reader-tag system for a thorough insight. Many application scenarios based descriptions were explained in section II to emphasize the importance of where and how RFID technology found such numerous applications. Then the major features of active and passive IC based and SAW based, their structure and working principle were thoroughly discussed, including the reader design, the reader interrogation technology such as the near – field and far – field communication protocols, the relevant research work performed in the RFID identification domain and various conclusive results have been made regarding read range, security and privacy, cost and other factors. Then, various benefits and limitations of using active and passive RFID tags have been enlisted to show where one tag is better than the other for certain applications.

Many outlying characteristics, advantages followed by limitations of SAW RFID based tags were discussed and compared with other silicon based IC RFID technologies. As such, according to the existing work on RFID tag designs and their implementation across various testbeds and evaluation, it can be seen that passive SAW based RFID tags can provide immense benefits in terms of cost, read range, robustness against a variety of interference sources such as electromagnetic, hazardous or harsh environments such as high temperature and pressure, humidity and radiation in comparison to silicon based IC tags.

This article is the first one to provide a comprehensive review on all types of RFID tags technologies that are quite established and popular among the researchers from both academia and industry. Furthermore, this article analyzed the characteristics and performance of silicon based IC and SAW based RFID tags and made conclusive remarks on crucial factors such as read range, cost, robustness against external impediments, and more importantly on security and privacy issues. While other kinds of chipless tags based on conductive ink also exist, they are ignored in this review as they are constrained by factors such as large tag size, limited data storage capacity, shorter read ranges and inability to survive in extreme weather which severely impacted the penetration of such tags into the RFID market. Next, this article reviewed potentials, open challenges and provided future directions for the use of SAW based RFID tags in various identification applications. While concerns related to security and privacy should be resolved so that the growth of RFID technology will accelerate quicker than before, SAW based RFID tags appear to provide other attractive benefits that outweigh its limitations in other factors. Though SAW RFID tags do provide competitive advantages compared to other RFID tag technologies, achieving a very low cost followed by addressing the problem of security and privacy of such tags still remains an open challenge for such tags. fixing issues such as cost and security of SAW tags improves the probability to deploy such tags for several tracking applications.

VI. FUTURE DIRECTIONS ON SAW RFID TAGS

Since the silicon based IC tags are already mature as a lot of study and research has been conducted, research and development into such tags is not very popular at present, and partly due to varying limitations across various types of such tags. On the other hand, there is a lot of scope to conduct research in SAW based RFID tags to improve its performance across various dimensions which include 1) Read Range, 2) Manufacturing cost and, 3) Security and privacy. For a given frequency of operation, an appropriate piezoelectric material in conjunction with a low cost fabrication technology would be the direction towards minimizing the cost of manufacturing such tags (to 5 cents) which can eventually find numerous applications for identification. In particular, the focus of SAW devices should be directed towards multilayer piezoelectric material design where more than one material is deposited on top of each other. In the light of this, silicon based multilayer structure which is Complementary Metal Oxide Semiconductor (CMOS) compatible has been on the rise and is found to be attractive due to low cost. A design such as this can bring down the cost to 5 cents when utilized for SAW tags. Furthermore, flexible polymers can be an excellent choice of substrate when designing SAW tags that need to be fixed on any object or item of interest that need to be tracked. SAW based RFID tags, in general, provide an excellent technological competence compared to silicon based IC tags. However, to convert this idea into a large scale business, several scientific and technological challenges should be resolved, and the fabrication cost of such tags as mentioned before should be reduced to an appreciable value. SAW RFID tags should also be improved in terms of privacy and security issues to prevent unauthorized access so that cheaper and secure tags can eventually be a reality. Finally, we hope and expect that this article will promote further research and development and improve the feasibility of deploying passive SAW based RFID tags for various identification based services.

REFERENCES

[1] V. Daniel Hunt, A. Puglia, and M. Puglia, *RFID: A Guide to Radio Frequency Identification*. Hoboken, NJ, USA: Wiley, 2007.
[2] Radio Frequency Identification (RFID). *Wikipedia*. Accessed: Oct. 2019. [Online]. Available: https://en.wikipedia.org/wiki/Radio frequency_identification#cite_note-5
[3] H. Stockman, "Communication by means of reflected power," *Proc. IRE*, vol. 36, no. 10, pp. 1196–1204, Oct. 1948.
[4] B. Violino, "The history of RFID technology," *RFID J.*, p. 1, Jan. 2005.
[5] M. Cardullo, "Genesis of the versatile RFID tag," *RFID J.*, p. 1, Sep. 2013.
[6] J. Landt, "Shrouds of time: The history of RFID," ver. 1.0, AIM, Inc., Cranberry Township, PA, USA, Tech. Rep. 1.0, 2001, pp. 1–11.
[7] E. Hatem, E. Colin, S. Abou-Chakra, B. El-Hassan, and J.-M. Laheurte, "New empirical indoor path loss model using active UHF-RFID tags for localization purposes," in *Proc. IEEE Int. Conf. RFID Technol. Appl. (RFID-TA)*, Sep. 2018, pp. 1–6.
[8] C. Jechlitschek, "A survey paper on radio frequency identification (RFID) trends," Tech. Rep. 1.0, 2006, pp. 1–13.
[9] L. Bolotnyy and G. Robins, "Multi-tag RFID systems," *International Journal of Internet Protocol Technology*, vol. 2, nos. 3–4, pp. 218–231, 2007.
[10] "The state of RFID implementation and its policy implications: An IEEE-USA White Paper," IEEE USA, Washington, DC, USA, Apr. 2009, pp. 1–27.
[11] GAO RFID Inc., A Member of GAO Group. *Applying RFID to School Bus Transportation*. Accessed: Oct. 2019. [Online]. Available: https://gaorfid.com/school-bus-transportation-rfid-systems/
[12] N. C. Karmakar, *RFID Readers—Review and Design*. Hoboken, NJ, USA: Wiley, 2011.
[13] S. Preradovic and N. C. Karmakar, "RFID transponders—A review," in *Proc. Int. Conf. Elect. Comput. Eng.*, Dhaka, Bangladesh, Dec. 2006, pp. 19–21.
[14] B. Lee, "Review of RFID tag antenna issues at UHF band," in *Proc. Asia–Pacific Microw. Conf.*, Dec. 2008, pp. 1–4.
[15] K. V. S. Rao, P. V. Nikitin, and S. F. Lam, "Antenna design for UHF RFID tags: A review and a practical application," *IEEE Trans. Antennas Propag.*, vol. 53, no. 12, pp. 3870–3876, Dec. 2006.
[16] S. Preradovic, C. N. Karmakar, and I. Balbin, "RFID transponders," *IEEE Microw. Mag.*, vol. 9, no. 5, pp. 90–103, Sep. 2008.
[17] N. Ojha, "Radio frequency identification (RFID) technology in library: Advantages and issues," in *Proc. 2nd Int. Conf. Inventive Syst. Control (ICISC)*, Jan. 2018, pp. 1206–1213.
[18] S. Preradovic and C. N. Karmakar, "RFID readers—A review," in *Proc. 4th Int. Conf. Electr. Comput. Eng. (ICECE)*, Dhaka, Bangladesh, Dec. 2006, pp. 100–103.
[19] A. Badru and N. Ajayi, "Adoption of RFID in large-scale organisation—A review of challenges and solutions," in *Proc. IST-Africa Conf. Paul Cunningham Miriam Cunningham (Eds) IIMC Int. Inf. Manage. Corp.*, 2017.
[20] P. Y. Lau, C. Qingxin, and W. Yueshan, "Review on UHF RFID antennas," in *Proc. Int. Workshop Electromagn., Appl. Student Innov. Competition*, May 2017.
[21] F. Shuo, G. Fei, X. Yanming, and L. Heng, "Review of studies of tag anticollision algorithm in RFID," in *Proc. Int. Conf. Wireless Netw. Inf. Syst.*, 2009, pp. 121–124.
[22] M. F. Mubarak, J.-L.-A. Manan, and S. Yahya, "A critical review on RFID system towards security, trust, and privacy (STP)," in *Proc. IEEE 7th Int. Colloq. Signal Process. its Appl.*, Mar. 2011, pp. 39–44.
[23] L. Roselli, C. Mariotti, P. Mezzanotte, F. Alimenti, G. Orecchini, M. Virili, and N. B. Carvalho, "Review of the present technologies concurrently contributing to the implementation of the Internet of Things (IoT) paradigm: RFID, green electronics, WPT and energy harvesting," in *Proc. IEEE Topical Conf. Wireless Sensors Sensor Netw. (WiSNet)*, Jan. 2015, pp. 1–3.
[24] R. K. Pateriya and S. Sharma, "The evolution of RFID security and privacy: A research survey," in *Proc. Int. Conf. Commun. Syst. Netw. Technol.*, Jun. 2011, pp. 115–119.
[25] I. Bose and S. Yan, "The green potential of RFID projects: A case–Based analysis," *IEEE Comput. Soc.*, no. 1, pp. 41–47, 2011.
[26] M. Kaur, M. Sandhu, N. Mohan, and S. Parvinder Sandhu, "RFID technology principles, advantages, limitations & its applications," *Int. J. Comput. Elect. Eng.*, vol. 3, no. 1, pp. 1793–8163, Feb. 2011.
[27] A. Hashemi, A. H. Sarhaddi, and H. Emami, "A review on chipless RFID tag design," *Majlesi J. Elect. Eng.*, vol. 7, no. 2, pp. 68–75, Jun. 2013.
[28] C. Herrojo, M. Moras, F. Paredes, A. Nunez, J. Mata-Contreras, E. Ramon, and F. Martin, "Time-Domain-Signature chipless RFID tags: Near-field chipless-RFID systems with high data capacity," *IEEE Microw. Mag.*, vol. 20, no. 12, pp. 87–101, Dec. 2019.
[29] K. Finkelzeller, *The RFID Handbook*, 2nd ed. Hoboken, NJ, USA: Wiley, 2003.
[30] Near and Far Field Communication. *Wikipedia*. Accessed: Oct. 2019. [Online]. Available: https://en.wikipedia.org/wiki/Near_and_far_field
[31] A. Michel, V. Franchina, P. Nepa, and A. Salvatore, "A UHF RFID tag embeddable in small metal cavities," *IEEE Trans. Antennas Propag.*, vol. 67, no. 2, pp. 1374–1379, Feb. 2019.
[32] "Bus safety system for school children transportation safety enhancement," Tech. Rep., Apr. 2017, pp. 1–69.
[33] K. Shaaban, A. Bekkali, E. B. Hamida, and A. Kadri, "Smart tracking system for school buses using passive RFID technology to enhance child safety," *J. Traffic Logistics Eng.*, vol. 1, no. 2, pp. 191–196, Dec. 2013.
[34] S. Behera and C. Maity, "Active RFID tag in real time location system," in *Proc. 5th Int. Multi-Conf. Syst., Signals Devices*, 2008, pp. 1–7.
[35] K. Bonsor and W. Fenlon, "How RFID works," HowStuffWorks, 2007.
[36] W. Dongjian and Z. Ling, "A low-power passive RFID tag for UHF," in *Proc. Int. Conf. Elect. Control Eng.*, Wuhan, China, Jun. 2010.
[37] D. Hahnel, "Mapping and localization with RFID technology," in *Proc. IEEE Conf. Robot. Automat.*, vol. 1, no. 1. Berlin, Germany: IEEE, 2004, pp. 1015–1020.
[38] RF-Golf Unique Ball Location Finder. *The Ultimate Ball Finder*. [Online]. Available: https://www.rf-golf.com
[39] R. Luciano, W. White, and D. Grieshaber, "Golf ball with encapsulated RFID chip," U.S. Patent 9 539 471, Jan. 10, 2017.
[40] *UAE Ministry of Interior pilot project for RFID-based School/Bus Student Tracking System*, Essen RFID, SN-ESSEN, Mumbai, India, 2005.
[41] B. Nath, F. Reynolds, and R. Want, "RFID technology and applications," *IEEE Pervasive Comput.*, vol. 5, no. 1, pp. 22–24, Feb. 2006.
[42] N. Gazda, K. Hansen, K. E. Forbis, and A. Santora, "Current and future applications for RFID technology," *Drug Verification Products*, vol. 15, no. 4, p. 6, Apr. 2018.
[43] S. R. Dalal, "Chipping away at the constitution: The increasing use of RFID chips could lead to an erosion of privacy rights," Boston Univ. Lab., Boston, MA, USA, Tech. Rep. 86, Apr. 2006, p. 485.
[44] E. W. T. Ngai, T. C. E. Chang, S. Au, and K.-H. Lai, "Mobile commerce integrated with RFID technology in a container depot," *Decis. Support Syst.*, vol. 43, no. 1, pp. 62–76, 2007.
[45] RadarGolf.com. *A Company Producing a Ball Positioning System*. Accessed: Oct. 2019. [Online]. Available: http://www.radargolf.com
[46] K. Michael and M. G. Michael, "The diffusion of RFID implants for access control and epayments: A case study on Baja Beach Club in Barcelona," in *Proc. IEEE Int. Symp. Technol. Soc.* Australia: IEEE, 2010, pp. 242–252.
[47] "Company that produces human implantable RFID chips," Verichip, Delray Beach, FL, USA, 2010.
[48] Z. Luo, W. Wang, J. Xiao, Q. Huang, T. Jiang, and Q. Zhang, "Authenticating on-body backscatter by exploiting propagation signatures," *Proc. ACM Interact., Mobile, Wearable Ubiquitous Technol.*, vol. 2, no. 3, pp. 1–22, Sep. 2018.
[49] W. Wang, L. Yang, Q. Zhang, and T. Jiang, "Securing on-body IoT devices by exploiting creeping wave propagation," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 4, pp. 696–703, Apr. 2018.
[50] *Electronic Toll Collection for Toll Roads and Bridges*. Accessed: Oct. 2019. [Online]. Available: http://www.e-zpassiag.com
[51] *Paying at Exxon and Mobile Gas Stations With RFID Tags*. Accessed: Oct. 2019. [Online]. Available: https://www.speedpass.com/forms/frmHowItWorks.aspx?pPg=howTech.htm&pgHeader=how

[52] *[ICAO] International Civil Aviation Organization: Guidelines for RFID Enabled Passports*. Accessed: Oct. 2019. [Online]. Available: http://www.icao.int
[53] *[ColoradoLaw] Colorado State Legislature: Colorado State Legislature Makes Aluminum Underwear a Misdemeanor*. Accessed: Oct. 2019. [Online]. Available: http://www.state.co.us/gov_dir/leg_dir/olls/sl2001/sl.162.html
[54] *[InformationWeek] Article on RFID Enhanced Golf Balls*. Accessed: Oct. 2019. [Online]. Available: http://www.informationweek.com/story/showArticle.jhtml?articleID=57703713
[55] *High Performance Passive RFID Tags*, Omni-ID Inc., Rochester, NY, USA.
[56] *[Wizard Wars] the Invention of IFF in WWII*. Accessed: Oct. 2019. [Online]. Available: http://www.vectorsite.net/ttwiz1.html
[57] *[U.S. Patent 3,713,148] the Probably First RFID Patent*. Accessed: Oct. 2019. [Online]. Available: http://patft.uspto.gov/netacgi/nph-Parser?patentnumber=3,713,148
[58] *[U.S. Patent Office]*. Accessed: Oct. 2019. [Online]. Available: http://www.uspto.gov/
[59] *[Auto ID Center]*. Accessed: Oct. 2019. [Online]. Available: http://www.autoidcenter.org/
[60] *Shrouds of Time, Outlines History and Present of RFID*. Accessed: Oct. 2019. [Online]. Available: http://www.aimglobal.org/technologies/rfid/resources/shrouds_of_time.pdf
[61] T. F. Bechteler and H. Yenigun, "2-D localization and identification based on SAW ID-tags at 2.5 GHz," *IEEE Trans. Microw. Theory Techn.*, vol. 51, no. 5, pp. 1584–1590, May 2003.
[62] S. Harma and V. P. Plessky, *Surface Acoustic Wave RFID Tags, Development and Implementation of RFID Technology*, C. Turcu, Ed. Rijeka, Croatia: InTech, 2009.
[63] V. Plessky and L. Reindl, "Review on SAW RFID tags," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 57, no. 3, pp. 654–668, Mar. 2010.
[64] L. Rayleigh, "On waves propagated along the plane surface of an elastic solid," *Proc. London Math. Soc.*, vol. 7, pp. 4–11, Nov. 1885.
[65] R. C. Williamson, "Case studies of successful surface-acoustic-wave devices," in *Proc. Ultrason. Symp.*, Phoenix, AZ, USA, Oct. 1977, pp. 460–468.
[66] W. R. Smith, "Basics of the SAW interdigital transducer," in *Computer-aided Design of Surface Acoustic Wave Devices*, J. H. Collins and L. Masotti, Eds. New York, NY, USA: Elsevier, 1976, pp. 25–63.
[67] D. Puccio, D. C. Malocha, D. Gallagher, and J. Hines, "SAW sensors using orthogonal frequency coding," in *Proc. IEEE 50th Anniversary Conf. Int. Ultrason., Ferroelectr., Freq. Control Joint*, Aug. 2004, pp. 307–310.
[68] L. Reindl and W. Ruile, "Programmable reflectors for SAW-ID-tags," in *Proc. IEEE Ultrason. Symp.*, Oct. 1993, pp. 125–130.
[69] S. Harma, V. P. Plessky, X. Li, and P. Hartogh, "Feasibility of ultra-wideband SAW RFID tags meeting FCC rules," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 56, no. 4, pp. 812–820, Apr. 2009.
[70] D. Malocha, N. Kozlovski, B. Santos, J. Pavlina, M. A. Belkerdid, and T. Mears, "Ultra wide band surface acoustic wave (SAW) RFID tag and sensor," in *Proc. MILCOM IEEE Mil. Commun. Conf.*, Boston, MA, USA, Oct. 2009, pp. 1–7.
[71] M. Forouzandeh and N. C. Karmakar, "Chipless RFID tags and sensors: A review on time-domain techniques," *Wireless Power Transf.*, vol. 2, no. 2, pp. 62–77, Oct. 2015.
[72] D. Malocha, M. Gallagher, B. Fisher, J. Humphries, D. Gallagher, and N. Kozlovski, "A passive wireless multi-sensor SAW technology device and system perspectives," *Sensors*, vol. 13, no. 5, pp. 5897–5922, May 2013.
[73] S. Harma, W. G. Arthur, C. S. Hartmann, R. G. Maev, and V. P. Plessky, "Inline SAW RFID tag using time position and phase encoding," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 55, no. 8, pp. 1840–1846, Aug. 2008.
[74] C. S. Hartmann, P. Brown, and J. Bellamy, "Design of global SAW RFID tag devices," in *Proc. 2nd Int. Symp. Acoustic Wave Devices Future Mobile Commun. Syst.*, 2004, pp. 15–19.
[75] M. Tavakoli, H. Hajghassem, M. Dousti, and M. Fathipour, "Design and implementation of high data capacity RFID tag using eight-phase encoding," *Int. J. Electron.*, vol. 101, no. 1, pp. 113–120, 2014.
[76] C. S. Hartmann and L. T. Claiborne, "Anti-collision interrogation pulse focusing system for use with multiple surface acoustic wave identification tags and method of operation thereof," U.S. Patent 7 084 768, Aug. 1, 2003.
[77] *SAW Sensor and Sensor—Tag Developments at ASR&D*, Appl. Sensor Res., Develop. Corp., Arnold, MD, USA, Jul. 2011.
[78] S. K. Harma, "Surface acoustic wave RFID tags: Ideas, developments, and experiments," Dept. Appl. Phys., TKK Diss., Helsinki Univ. Technol., Espoo, Finland, 2009, pp. 1–74.
[79] V. P. Plessky, "Review on SAW RFID tags," in *Proc. IEEE Int. Freq. Control Symp. Joint 22nd Eur. Freq. Time Forum*, Besançon, France, May 2009, pp. 14–23.
[80] RFSAW, Inc. (2004). *The Global SAW Tag—A new technical approach to RFID*. [Online]. Available: http://www.rfsaw.com/pdfs/SAW%20RFID%20Whitepaper.pdf
[81] A. Fikri, E. M. Zrihni, and Y. Salih Alj, "A smartphone-based system for traffic congestion control using RFID tags," in *Proc. Int. Conf. Electr. Inf. Technol. (ICEIT)*, Mar. 2015, pp. 410–413.
[82] L. Vojtech, M. Nerada, J. Hrad, and R. Bortel, "Outdoor localization technique using active RFID technology aimed for security and disaster management applications," in *Proc. 16th Int. Carpathian Control Conf. (ICCC)*, May 2015, pp. 586–589.
[83] E. Colin, A. Moretto, and M. Hayoz, "Improving indoor localization within corridors by UHF active tags placement analysis," in *Proc. IEEE RFID Technol. Appl. Conf. (RFID-TA)*, Sep. 2014, pp. 181–186.
[84] J. C. Nelson, T. Santala, J. Lenchner, R. Calio, M. Frissora, and J. E. Miller, "Locating and tracking data center assets using active RFID tags and a mobile robot," in *Proc. 10th Int. Conf. Expo Emerg. Technol. Smarter World (CEWIT)*, Oct. 2013, pp. 1–6.
[85] F. Tlili, N. Hamdi, and A. Belghith, "Accurate 3D localization scheme based on active RFID tags for indoor environment," in *Proc. IEEE Int. Conf. RFID-Technol. Appl. (RFID-TA)*, Nov. 2012, pp. 378–382.
[86] E. Nilsson, B. Nilsson, L. Bengtsson, B. Svensson, P.-A. Wiberg, and U. Bilstrup, "A low power-long range active RFID-system consisting of active RFID backscatter transponders," in *Proc. IEEE Int. Conf. RFID-Technol. Appl.*, Guangzhou, China, Jun. 2010, pp. 26–30.
[87] J.-M. Lin and Z.-Q. Hou, "Bio-sensing and monitor system design with micro array probes on an active RFID tag," in *Proc. 3rd Int. Nanoelectron. Conf. (INEC)*, Jan. 2010, pp. 346–347.
[88] S. Oyarhossein and S. Mohammadi, "Cryptography and authentication processing framework on RFID active tags for carpet products," in *Proc. IEEE Int. Conf. Commun. Technol. Appl.*, Oct. 2009, pp. 26–31.
[89] A. Ammu, L. Mapa, and A. H. Jayatissa, "Effect of factors on RFID tag readability-statistical analysis," in *Proc. IEEE Int. Conf. Electro/Inf. Technol.*, Jun. 2009, pp. 355–358.
[90] J.-H. Lin and Y.-H. Kao, "Wireless temperature sensing using a passive RFID tag with film bulk acoustic resonator," in *Proc. IEEE Ultrason. Symp.*, Nov. 2008, pp. 2209–2212.
[91] S. behera and C. Maity, "Active RFID tagin real time location system," in *Proc. 5th Int. Multi-Conf. Syst., Signals Devices*, 2008, pp. 1–7.
[92] M. Buckner, R. Crutcher, R. M. Moore, and B. Whitus, "MICLOG RFID tag program enables total asset visibility," to be published.
[93] M. Yeoman, *RFID Tag Read Range and Antenna Optimization*, COMSOL Multi Phys., Oct. 2014.
[94] *Read Range of an RFID Tag—Factor Which Affect Read Range for RFID*, SAGE DATA.
[95] "What is an RFID reader's maximum range?" *RFID J.*, Feb. 2014.
[96] "Active RFID vs. passive RFID: What's the difference?" Suzanne Smiley, RFID Insider, Mar. 2016.
[97] "Read range calculation for a passive RFID tag," *RFID J.*, Aug. 2013.
[98] S. S. Srikant and R. P. Mahapatra, "Read range of UHF passive RFID," *Int. J. Comput. Theory Eng.*, pp. 323–325, Jun. 2010.
[99] "Radio frequency identification (RFID) technology and their cost of operation," *RFID J.*
[100] Advanced Mobile Group. (Sep. 1, 2016). *The Shocking Price of RFID Tags*. [Online]. Available: https://www.advancedmobilegroup.com/blog/the-true-price-of-rfid-tags
[101] B. Ray. (Feb. 13, 2018). *A Breakdown of 7 RFID Costs, From Hardware to Implementation, RTLS Technologies, AirFinder*. [Online]. Available: https://www.airfinder.com/blog/rfid-cost
[102] L. Bolotnyy and G. Robins, "The case for multi-tag RFID systems," in *Proc. Int. Conf. Wireless Algorithms, Syst. Appl. (WASA)*, 2007, pp. 174–186.
[103] S. Kim, Y. Kawahara, A. Georgiadis, A. Collado, and M. M. Tentzeris, "Low-cost inkjet-printed fully passive RFID tags for calibration-free capacitive/haptic sensor applications," *IEEE Sensors J.*, vol. 15, no. 6, pp. 3135–3145, Jun. 2015.
[104] J. Chang and S. Quan, "Design of long range RFID tag in X-band based on modulated scattering technique," in *Proc. IEEE Int. Conf. Ubiquitous Wireless Broadband (ICUWB)*, Nanjing, China, Oct. 2016, pp. 1–4.

[105] E. Nilsson, B. Nilsson, L. Bengtsson, B. Svensson, P.-A. Wiberg, and U. Bilstrup, "A low power-long range active RFID-system consisting of active RFID backscatter transponders," in *Proc. IEEE Int. Conf. RFID-Technol. Appl.*, Guangzhou, China, Jun. 2010, pp. 26–30.
[106] B. Ray. (Mar. 14, 2018). *The Complete Active RFID Overview, AirFinder*. [Online]. Available: https://www.airfinder.com/blog/active-rfid
[107] Atlas RFID Store. *Active RFID Tags and Technologies*. Accessed: Jan. 2020. [Online]. Available: https://www.atlasrfidstore.com/active-rfid/
[108] A. Dua. *Applications for Active and Passive RFID, RFID Blogs*. Accessed: Jan. 2020. [Online]. Available: https://rfid4u.com/applications-for-active-and-passive-rfid/
[109] T. Watson. (Oct. 29, 2013). *Simple Cost Analysis for RFID Options, 15 AMI Asset Track*. [Online]. Available: https://www.amitracks.com/2013/10/simple-cost-analysis-for-rfid-options/
[110] The Evolution of Active RFID. *Omni ID, Industrial RFID Tagging Solutions Provider*. Accessed: Jan. 2020. [Online]. Available: https://www.omni-id.com/active-rfid-tags/
[111] H. R. Tags. *Overview of RFID Technology*. [Online]. Available: https://www.hidglobal.com/products/rfid-tags#whatdotagscost
[112] Active RFID Tags. *Learning Centre/RFID/Active Tags*. Accessed: Jan. 2020. [Online]. Available: https://www.sagedata.com/learning-centre/active-rfid-tags.html
[113] *RFID Tag Considerations, WiFi Location—Based Services 4.1 Design Guide*, Cisco Syst., San Jose, CA, USA, 2008, ch. 6.
[114] A. Zavvari and A. Patel, "Critical evaluation of RFID security protocols," *Int. J. Inf. Secur. Privacy*, vol. 6, no. 3, pp. 56–74, Jul./Sep. 2012.
[115] E. H. Neto, R. Soares, E. Conrad, J. Costa, and M. Ramaswami, "A semi-passive UHF RFID tag compliant with Brazilian national automated vehicle identification system (SINIAV)," in *Proc. IEEE Int. Conf. RFID-Technol. Appl. (RFID-TA)*, Nice, France, Nov. 2012, pp. 117–121.
[116] A. Athalye, V. Savic, M. Bolic, and P. M. Djuric, "Novel semi-passive RFID system for indoor localization," *IEEE Sensors J.*, vol. 13, no. 2, pp. 528–537, Feb. 2013.
[117] L. Guong Jang, S.-F. Yang, T.-S. Ho, L.-Y. Lai, and C.-C. Nien, "Logistics information monitoring by means of RFID sensor tag," in *Proc. Int. Conf. Inf. Manage., Innov. Manage. Ind. Eng.*, Sanya, China, Oct. 2012, pp. 86–89.
[118] C. Campbell, *Surface acoustic wave devices and their Signal Processing Applications*. New York, NY, USA: Academic, 1989.
[119] R. Fachberger, G. Bruckner, J. Bardong, and L. Reindl, "High temperature RFID system using passive SAW transponders," in *Proc. Eur. Microw. Assoc.*, vol. 4, 2007, pp. 194–288.
[120] V. Plessky and Y. S. Shmaliy, "Code reading error probability estimation for SAW tag systems with pulse position coding," *Electron. Lett.*, vol. 46, no. 21, pp. 1415–1416, 2010.
[121] L. Reindl, G. Scholl, T. Ostertag, H. Scherr, U. Wolff, and F. Schmidt, "Theory and application of passive SAW radio transponders as sensors," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 45, no. 5, pp. 1281–1292, Sep. 1998.
[122] G. Bruckner and R. Fachberger, "SAW ID tag for industrial application with large data capacity and anticollision capability," in *Proc. IEEE Ultrason. Symp.*, Nov. 2008, pp. 300–303.
[123] G. Bruckner, J. Bardong, C. Gruber, and V. Plessky, "A wireless, passive ID tag and temperature sensor for a wide range of operation," *Procedia Eng.*, vol. 47, pp. 132–135, 2012.
[124] V. Plessky, "Surface acoustic wave RFID tags," in *Development and Implementation of RFID Technology*. Espoo, Finland: Helsinki Univ. of Technology, Jan. 2009, ch. 8.
[125] V. Plessky, *Passive Remotely Controlled SAW (Surface Acoustic Waves) Sensors and SAW RFID Tags*. Gorgier, Switzerland: Tutorial II, Mar. 2018.
[126] C. Hartmann and L. Claiborne, "Fundamental limitations on reading range of passive IC-based RFID and SAW-based RFID," in *Proc. IEEE Int. Conf. RFID*, Grapevine, TX, USA, Mar. 2007, pp. 41–48.
[127] F. Nawaz and V. Jeoti, "SAW sensor read range limitations and perspectives," *Wireless Netw.*, vol. 20, no. 8, pp. 2581–2587, Jun. 2014.
[128] K.-Y. Hashimoto, *Introduction to Surface Acoustic Wave (SAW) Devices*. Chiba, Japan: Chiba Univ., Apr. 2019.
[129] A. P. Gnadinger, "Vibration analysis based on surface acoustic wave sensors," in *Proc. MATEC Web Conf.*, 2015, Art. no. 02002.
[130] M. Sippel. (Aug. 2, 2010). *Choosing RFID For Industrial Applications; Part 3*. [Online]. Available: https://rfidspec.wordpress.com/2010/08/02/choosing-rfid-for-industrial-applications-part-3/
[131] B.-Y. Shih, C.-W. Chen, C.-Y. Chen, and T.-W. Lo, "Merged search algorithms for radio frequency identification anticollision," *Math. Problems Eng.*, vol. 2012, pp. 1–20, Apr. 2012.
[132] Silver Passive RFID Tag. *Packaging Type: 10,000 PCS/Carton*. Accessed: Jan. 2020. [Online]. Available: https://www.indiamart.com/proddetail/passive-rfid-tag-18462578548.html
[133] (2018). *How Does RFID Reader Reads a Passive RFID Tag, Electrical Engineering, SCM Wiki*. [Online]. Available: https://scmwiki2012.wordpress.com/r-2/radio-frequency-identification-rfid/
[134] *Active Tag Expansion Kit*. Accessed: Jan. 2020. [Online]. Available: https://www.digikey.ca/product-detail/en/ams/ACTIVE-TAG-EXPANSION-KIT/ACTIVETAGEXPANSIONKIT-ND/3828229
[135] G. Dave, "Prazza golf ball finder-review," *Trust Digest MyGolfSpy*, Jul. 2011.
[136] E. Matuszewski. (Oct. 10, 2017). *Forget a Smart Golf Ball You Can't Lose; OnCore Has 'Genius Ball' That Runs $50 Per Sleeve*. [Online]. Available: https://www.forbes.com/sites/erikmatuszewski/2017/10/10/forget-a-smart-golf-ball-you-cant-lose-oncore-has-genius-ball-that-runs-50-per-sleeve/#3579f57c306c
[137] A. N. Khan. (Feb. 22, 2011). *RFID Applications in Healthcare, Exponent Consulting Group, RFID Applications*. [Online]. Available: https://www.slideshare.net/asamnkhan/healthcare-presentation-pilot
[138] Scientific Control Instruments. (Mar. 31, 2016). *Case Study: Fuel Management for Transportation Company in Mexico*. [Online]. Available: https://sciww.com/fuel-management-in-mexico/
[139] C. Arjun Babu. (Sep. 2, 2016). *RFID in Construction*. [Online]. Available: https://www.slideshare.net/ArjunCBabu/rfid-in-construction
[140] J. Humphries, J. Figuroa, M. Gallagher, D. Gallagher, A. Weeks, and D. Malocha, "Interrogating Passive Wireless SAW Sensors with the USRP," *Ettus Research*, May 2016.

KASYAP SURESH (Student Member, IEEE) received the B.Eng. degree in electronics and communication engineering from Anna University, India. He is currently pursuing the M.S. degree in electrical and electronics engineering with Universiti Teknologi PETRONAS (UTP), Perak, Malaysia, where he conducts research in the Communications Lab. He is also affiliated with the Communications Group, UTP. His research interests include radio frequency identification (RFID), wireless network dynamics, surface acoustic wave (SAW) devices, array signal processing, various applications of signal processing and communications, ultrawide band (UWB) pulse compression radars, intelligent vehicles, energy harvesting communications, and indoor localization.

VARUN JEOTI (Senior Member, IEEE) received the Ph.D. degree from IIT Delhi, India, in 1992. He is currently a Professor with the Department of Electrical and Electronic Engineering, Universiti Teknologi PETRONAS (UTP), Malaysia. He has over 29 years of teaching experience in leading Indian and Malaysian universities by teaching students from various social and cultural backgrounds and conducting frontier research for over 38 years in the areas of signal processing and wireless communications. Starting his studies in 1980 from IIT Delhi soon after his graduation, he worked on defense sponsored projects developing surface acoustic wave (SAW) pulse compression filters and underwater optical receivers at IIT Madras. He was a Visiting Faculty Member with the Department of Electronics Engineering, Madras Institute of Technology, for about a year, from 1989 to 1990, and he was with IIT Delhi for the next five years, until 1995. He moved to the School of Electrical and Electronic Engineering, Universiti Sains Malaysia (USM), in 1995, and later moved to the Department of Electrical and Electronic Engineering, UTP, in 2001. His research interests include various applications in the areas of signal processing, wireless communications, and surface acoustic wave (SAW) devices.

SOCHEATRA SOEUNG (Member, IEEE) was born in Phnom Penh, Cambodia, in 1986. He received the B.Eng. degree (Hons.) in electrical and electronics engineering, majoring in computer system architecture, from Universiti Teknologi PETRONAS (UTP), Malaysia, in 2010, and the M.Sc. degree in research on PCB testing based on Eddy current from UTP, in 2013, where he is currently pursuing the Ph.D. degree in RF microwave engineering. His research interests include lossy filter design, passive microwave filter design, and multiband filter design. He currently holds a faculty position at the Department of Electrical and Electronics Engineering, UTP, an MTT Member, and a Committee Member of the IEEE ED/MTT/SSC Penang Chapter, Malaysia.

MICHEAL DRIEBERG (Member, IEEE) received the B.Eng. degree from Universiti Sains Malaysia (USM), in 2001, the M.Sc degree from Universiti Teknologi PETRONAS (UTP), Seri Iskandar, Malaysia, in 2005, and the Ph.D. degree from Victoria University, Melbourne, VIC, Australia, in 2011, all in electrical and electronics engineering. He is currently a Senior Lecturer with the Department of Electrical and Electronics Engineering, UTP. He has authored or coauthored several IEEE journals and conferences. His research interests include radio resource management, medium access control protocols, energy harvesting communications, and performance analysis for wireless and sensor networks. He served as a Reviewer for IEEE journals and conferences. He has also made several contributions to the IEEE 802.16d Task Group.

MARK GOH received the Ph.D. degree in applied mathematics from the University of Adelaide, Australia, in 1987. He is the Director (Industry Research) of The Logistics Institute-Asia–Pacific, National University of Singapore (NUS), Singapore, and a Professor with the NUS Business School. His current research interests include buyer-seller relationships, performance measurement, and supply chain strategy. He also served as an Associate Editor for the *Asia–Pacific Journal of Operational Research*, and has authored over 300 technical articles in internationally refereed journals and conferences.

MUHAMMAD ZUBAIR ASLAM received the B.S. degree in computer engineering from COMSATS, Pakistan, in 2011, and the M.S. degree in electrical and electronics engineering from Universiti Teknologi PETRONAS (UTP), Malaysia, in 2014. He is currently pursuing the Ph.D. degree in electrical engineering with UTP. His research interests include analysis and designing of capacitive sensing elements, surface acoustic wave (SAW) sensors based on single and multilayer structure, and investigation into the behaviors of different piezoelectric materials for SAW sensors.