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Advances in the Design Techniques and Applications of Chipless RFIDs

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ABSTRACT The recent emergence of Radio Frequency Identification (RFID) applications have attracted the attention of all the stakeholders, namely developers, manufacturers, and end-users. In essence, RFID has permeated the broad spectrum of item tracking, identification, and sensing. Alternatively, it is safe to say that RFID has revolutionized item tracking, sensing, and monitoring mechanisms. However, RFID's proliferation often faces a roadblock due to its associated cost due to silicon-based integrated circuits. This aspect can be addressed by the emerging design techniques and performance enhancement approach adopted for the realization of Chipless RFIDs. This has catapulted the Chipless RFIDs at the forefront in recent years. The chipless RFID tag uses electromagnetic properties to store the information and eliminate memory chips. It is anticipated that the usage of Chipless RFIDs will increase by leaps and bounds in the coming years. Therefore, this paper discusses some of the critical applications that can be directly served by Chipless RFIDs. This paper also elaborates on the associated constraints which limit the mass deployment of the Chipless RFIDs. Furthermore, this paper throws some light on some of the exciting research directions for future development.

INDEX TERMS Chipless RFID, frequency domain, IoT, localization, green technology.

I. INTRODUCTION

Radio Frequency Identification (RFID), an automatic ID system, is a well-known technique where information is communicated between the transponder and the identification device using radio frequencies. This concept was first introduced during World War 2 to track and control enemy warplanes [1]. H.Stockman first proposed RFID in his paper "Communication using Reflected Power" [2]. Since then, RFID has permeated across a wide variety of applications and has evolved as a key component of supply chain management and tracking. The decreasing cost of electronics on Moore's law pattern since 1960 [3] made the use of RFID feasible. Its advantages include high reading range, non-line-of-sight (NLOS) reading, power requirements, and automated identification over traditional technology like barcode, Wireless Fidelity (WiFi), Wireless Sensor Network (WSN), Bluetooth Low Energy(BLE).

With advancements in associated technologies and applications regime, the RFID has become a key component in the retail and health sectors management [4]. Some of the most commonly known RFID applications include road toll systems, object tracking, automated payment system, pallet identification, blood bank management system, etc. A typical RFID system consists of mainly three distinct components, namely reader, tag, and application software. The primary communication in the RFID system takes place between the RFID reader (interrogator) and the RFID tag (transponder). The application software performs the processing and analysis of the received signal by the reader. The readers are responsible for reading the information from tags and come in a variety of configurations [5]. On the other hand, the tags broadly fall within three categories, namely active tags, the passive tags, and the Chipless RFID tags [6]–[8].

In any application, the RFID tags are primarily chosen based on tags' parameters such as sensitivity, reading range, cost-effectiveness, and bit encoding capacity. In this context, conventional passive RFID tags are very cost-effective. They

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are frequently used in automatic tracking, identification, and sensing applications [9]–[13]. However, the passive chip-based RFID tags suffer from a limited reading range and narrow bandwidth. These issues can be readily overcome by employing active RFID tags. However, the cost of active tags is significantly higher due to the semiconductor chips. Furthermore, the RF circuitry employed in these designs have the potential of failure in extreme environments such as extremely low temperatures, harsh environmental conditions, and space applications.

Therefore, alternative Chipless RFID tags [14], [15] are attracting researchers, manufacturers, and end-users, considering that it can provide excellent trade-offs between various aspects such as cost, reading range, and bit density. In the extraction of information in the passive chip-based tag, the delay and noise in the signal occur due to the memory element of the RFID tag, and it suffers a lower reading range [16]. Chipless RFID has a more extended reading range as compared to silicon-based RFID [17]–[19]. Its cost is significantly less compared to conventional RFID due to the absence of a memory chip. The response delay introduced in chip-based RFID due to memory element is absent in the Chipless RFID, so the sensitivity and response time are better than traditional RFID. Also, as the technology progress to 5nm and less, the chip-based RFID tag fabrication cost increases. On the other side chipless RFID can be designed at a substantially lower cost since it can be fabricated to our lab and directly printed on paper or object using low-cost technology instead of semiconductor fabrication techniques [20], [21].

A simple block diagram of the Chipless RFID system is depicted in Fig. 1, which consists of two significant elements, RFID reader and RFID tag. The reader works as a transponder and queries a remotely placed Chipless RFID tag using an RF signal. The Chipless RFID tag acknowledges the queries with the information in the form of encoded data using resonating structures. The encoded information can be disturbed due to the external environment and the object associated with the tag. The algorithms need to apply to the RFID reader's side to deal with the external disturbance and environmental noise [22].

There has been a number of reports about the recent research and development carried out in the domain of Chipless RFID tags to meet the requirements of varied applications [23]–[26]. This paper's main emphasis is to delve into some of the applications of Chipless RFID and analyze their various aspects. In this investigation, particular attention is given to the usefulness of chipless RFID in the advancement of Internet of Things (IoT) by considering the seamless integration with accepted technologies such as sensors and localization in the real-world sectors such as health, food, and agriculture. Subsequently, future aspects are also explored to comprehend the advancing directions of Chipless RFID technology and the possible paradigm shift it may bring. The paper is divided as follows: Section II discusses the background and the types of Chipless RFID technologies available in the literature. Applications and technologies employing Chipless RFID are presented in Section III. Section IV elaborates the potential future work and directions in the area of Chipless RFID, and finally, Section V concludes the paper.

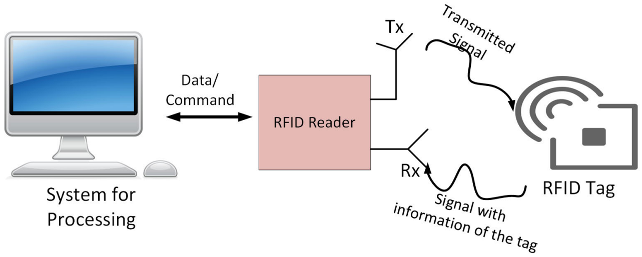


FIGURE 1. **A general RFID and chipless RFID system.**

II. BACKGROUND AND CLASSIFICATION OF CHIPLESS RFID TAG

Based on the encoded signal processing of the Chipless RFID tag signal, Chipless RFID tags can be majorly categorized into two categories: Time-Domain Reflectometry (TDR) Chipless RFID tags, and Frequency Domain Chipless RFID tags. [27], [28]

A. TIME DOMAIN REFLECTOMETRY BASED CHIPLESS RFID TAG

The RFID reader's interrogation signal is reflected after a time delay from the tag in the TDR Chipless RFID system. In the TDR design, these reflections are controlled by impedance modulation, and after that, the circuit is tuned accordingly. The prime example of this technique is 'On-off Keying', [29] where discontinuities are being placed at equal distances to represent '1's and '0's. Another example of TDR-based design is shown in Fig. 2; here, four capacitances have been used as discontinuities that are placed equally apart [30]. This configuration represents 4 bits of information, or equivalently, $2^4 = 16$ IDs.The length of a transmission line is determined by two factors: the pulse width of the signal being sent to the transponder, and the other is the code length, which gives us the number of discontinuities. The length of the transmission line in this experiment can be calculated using (1). In the experiment, the Gaussian interrogation pulse with a pulse width of 2ns and a period of 20ns is sent to the chipless tag. A 20ns period was chosen to get rid of noise caused due to ringing. The bit response appears after 2ns having a period of 2ns. Different experiments are being conducted for multiple bit patterns to analyze the TDR chipless RFID in detail.

$$L = \frac{c}{\sqrt{\varepsilon_r}} * t \tag{1}$$

L is the length of the transmission line, c is the speed of light in free space, ε_r is the substrate's permittivity, and t is the traveling time for wave for each discontinuity.

Most commonly TDR based Chipless RFID tags operate around a single resonant frequency [30]–[36].

The time-domain reflectometry term comes from the time delays in the information/data pulse sent by the RFID reader are interpreted as the tag's data. These time delays are introduced by the wave reflectors present on the Chipless RFID tag. The reflectors are placed at a certain point to introduce a certain time delay. Such an encoding technique of a Chipless RFID tag is known as Pulse Position Modulation (PPM) [37].

The length of the transmission line embedded in these tags depends on two factors, i.e., pulse width and code length, which implies the number of discontinuities. The major problem in these designs is to control the ringing reflections, which carry no additional information and appear as noise and interference to the system. Other disadvantages in the TDR design are the signal's attenuation after passing each discontinuity and the tag's large area due to a long transmission line. In other examples of the TDR concept, the Surface Acoustic Wave (SAW) based Chipless RFID tags [38]–[40] boasts some of the highest bit capacity of Chipless RFID tags, as reported through academic research and commercial deployments. SAW-based Chipless RFID tags' disadvantages exist in terms of price and technological complexity [41]–[43].

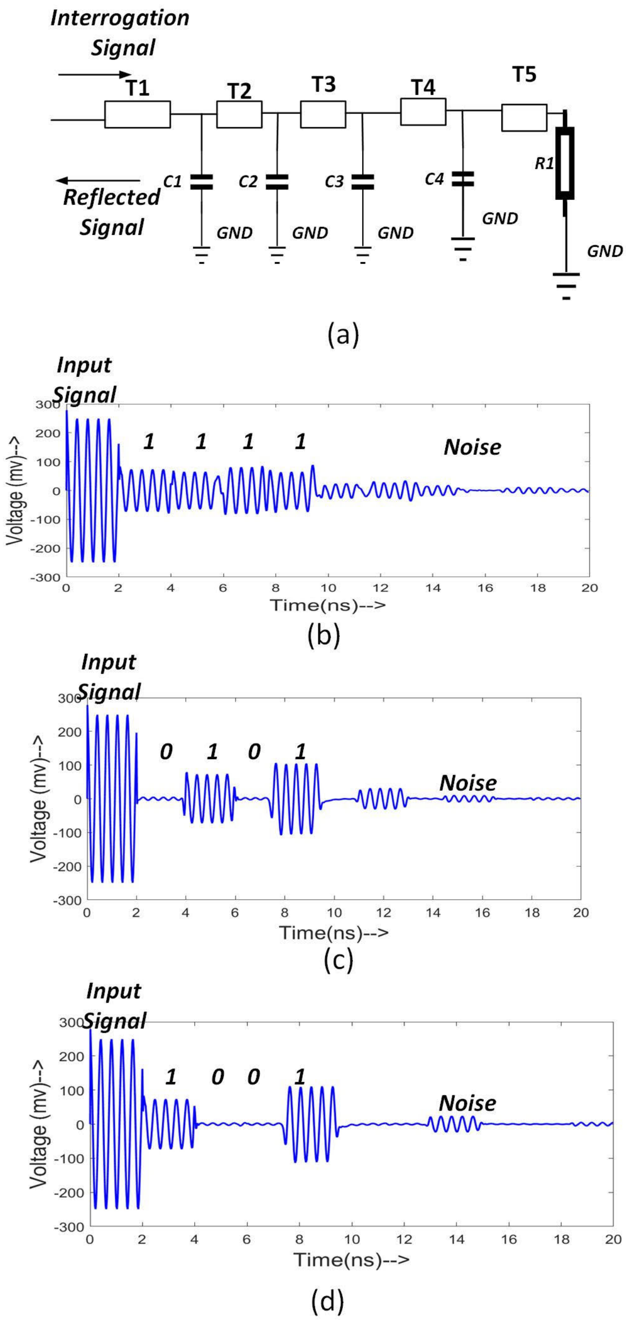
The reader for TDR chipless RFID uses an Ulta Wide Band (UWB) impulse radio (IR) transceiver [44]. In this technique, the reader uses a very short pulse in the UWB range for interrogation. It will improve the reading speed and range of the chipless reader. The backscattered response is sampled by the Analog to digital converter (ADC) using time sampling or filter bank-based methods in the reader's receiving path.

B. FREQUENCY DOMAIN CHIPLESS RFID TAG

Frequency domain Chipless RFID tag uses resonators on a substrate designed to produce different resonant frequencies. In the frequency domain reflectometry (FDR) based Chipless RFID tag design, resonators are used to scatter the interrogation signal. Based on the scatter signal's spectral response, the tag's identification is decoded by the reader. The frequency band in FDR designs is divided, corresponding to the bit associated with the tag. Each resonator is associated with one or more bit as per the design. The '0' and '1' bits are assigned to the absence and presence of the resonance frequency.

In the FDR chipless RFID, the reading process is done using continuous wave (CW) signals at different frequencies. A voltage-controlled oscillator generates interrogation CW signals. The receiver path of the FDR reader is similar to a homodyne or heterodyne receiver.

There are two significant classes of frequency domain Chipless RFID tags named backscattering and retransmission based. The underlying principle of both types of tags is similar, albeit with a few differences. The retransmission-based Chipless RFID tags employ two external antennas to receive and transmit data to and from the tag [45]. The antennas' presence allows retransmission-based tags to transmit data at higher distances than backscattering tags, although it increases the overall tag size. The cross-polarized antennas are used to avoid interference between the transmitting and receiving antennas. These antennas increase the tag size, weight, and overall cost of the Chipless RFID tag and the associated object. The reading process of an L-resonator based retransmission Chipless RFID tag employing microstrip transmission line [46] is given in Fig. 3. The presented Chipless RFID tag has a difference of 15dB in the bits' absence and presence that allow easy encoding and detection of the bits. The open-loop resonator-based



(a)

(b)

(c)

(d)

FIGURE 2. (a) Schematic of 4-bit chipless RFID tag, time response of bit code (b) '1111' (c)'0101' (d) '1001'.

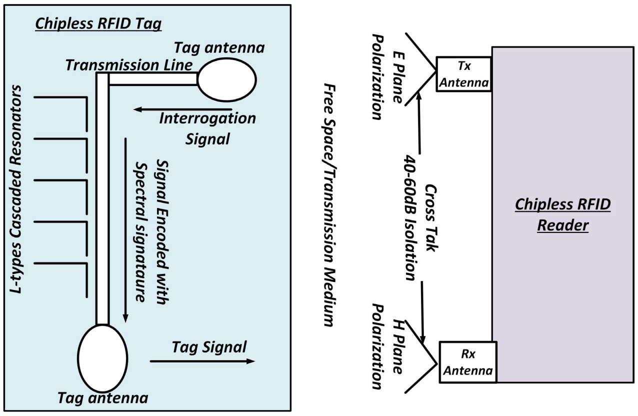


FIGURE 3. **Reading process of retransmission based chipless RFID tag.**

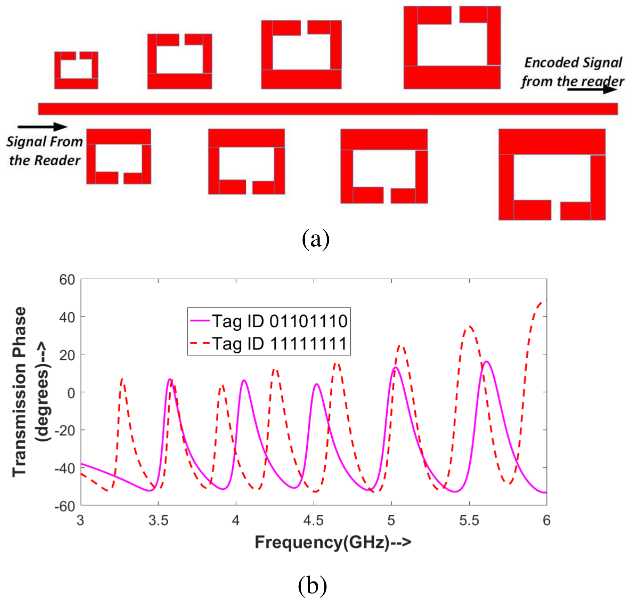


FIGURE 4. **(a) Schematic of open loop resonator based chipless RFID tag and (b) phase response of the chipless tag for tag ID of '01101110' and '11111111'.**

retransmission tag [17] is another example in this tag category, given in Fig. 4, which provides reconfigurability in the system. The tag has been configured for two coding patterns, '01101110' and '11111111', and their measured phase response is shown in Fig. 4(b). The reconfigurability enhances the utilization of tags for different applications.

The backscattering-based tags do not have any antennas and simply backscatter the incoming signal towards the reader. It is similar to a radar system where a signal is sent from the transmit antenna, and an object is discovered by receiving the signal. Two backscattering 8-bit Chipless RFID tags [27] are presented in Fig 5(a). Patch resonators in the L shape are printed on a Rogers substrate. The transmission magnitude response of these tags is shown in Fig. 5(b), which shows eight notches that can be read as binary '1' for the tag's encoding. The absence of antennas in the backscattering tag reduces the overall size and cost of the tag and the object associated with it. These tags can be used on a small object

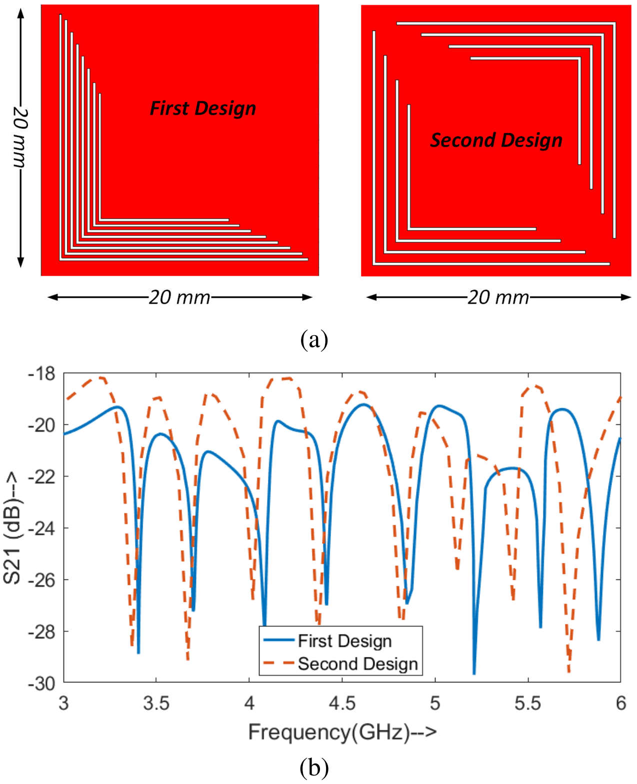


FIGURE 5. **(a) Designs of L-resonators based backscattering chipless tags (b) Measured Response of both the chipless tag designs.**

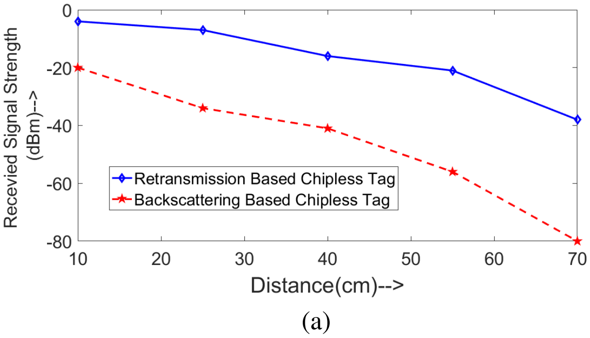
such as a book or a small packaging box for tracking and localization purposes.

A comparison has been shown in Fig. 6 based on received signal strength between open-loop resonator based retransmission chipless tag and L-resonator based backscattering chipless tag. The distance and power level are varied for the experiments. The results clearly show that retransmission-based tags have the upper hand in received signal strength. On the other side, the use of antennas makes retransmission-based tags costlier.

The FDR based reader provides more accurate and sensitive results due to the high-resolution frequency responses. On the other side, FDR faces the issue with the settling time and performance of VCO, which cost the overall reader cost. On another side, TDR based reader uses a short pulse and has a lower reading time. However, it limits the frequency resolution and faces the jitter and noise in the sampling clock and the received response. At higher frequencies, this jitter issue is a dominating factor.

C. HYBRID CHIPLESS RFID

The requirement for hybrid tags emerges from the need for increased bits density in the Chipless RFID tag domain without increasing the tag area significantly. In a frequency domain, Chipless RFID tags, the number of bits stored on the tag is N, require N number of resonators. In a general design of the frequency domain, each resonator represents individual single resonant frequencies, which creates difficulties



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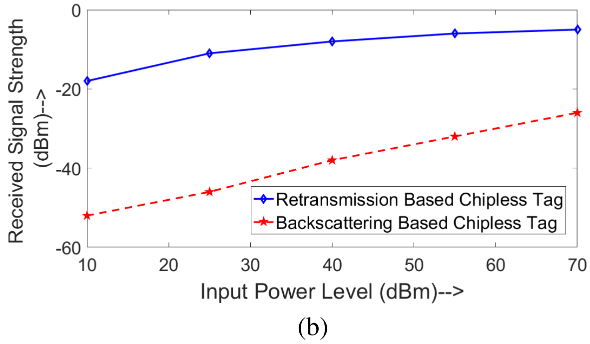


(b)

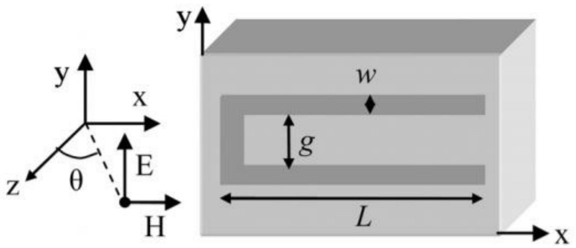
FIGURE 6. **Received signal strength for both types of chipless tags (a) Varying distance at input power level at 10dBm (b) Varying input power level at a distance of 30cm.**

for manipulating the bit density. However, in a hybrid tag concept, the frequency domain technique is build up with other Chipless RFID tag designs to increase the number of bits per resonator.

For example, incorporating frequency domain tags with phase domain makes a 'frequency-phase Chipless RFID systems [47], [48]. The resonators are tuned in such a manner that they produce different results concerning resonant frequency and phase and therefore allow for a higher number of bits to be encoded in the same tag area without increasing the number of resonators.

An example of a Hybrid Chipless RFID tag design, depicted in Fig. 7(a), shows a patch resonator-based tag's design to achieve changes in the resonant frequency and the impinging signal phase [49]. The changes in the resonator's length and the gap between the two sides of the resonator are utilized. Apparently, shifting in the frequency and phase is clearly visible in Fig. 7(b) and Fig. 7(c), the tag's RCS response due to specific changes to the resonator. The hybrid design gives relaxation on the number of resonators' sides for each resonating frequency; however, it increases the complexity of the Chipless RFID tag's analysis.

The other modifications that can be done in hybrid tags is polarization, [51]–[54]. It involves the positioning and polarization of resonators in a certain manner so that it advances the capabilities of the Chipless RFID tag. This polarization concept involves one set of resonators of the tag that responds to a particular set of antennas, and the other set of resonators is responsive to the others. Another example of a hybrid design incorporates three dimensions to increase data capacity [55]. It utilizes dual frequencies, polarization diversity, and frequency division multiplexing.



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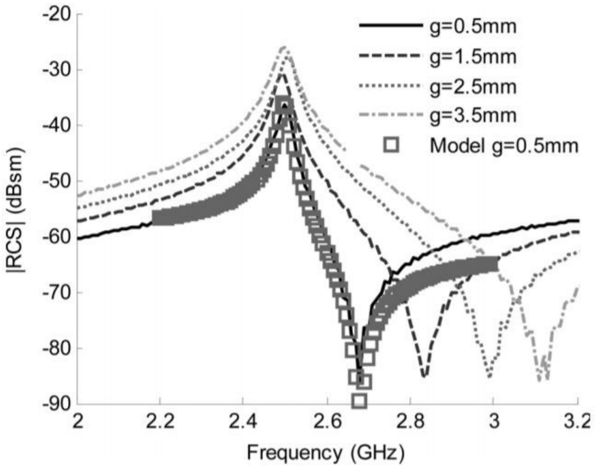

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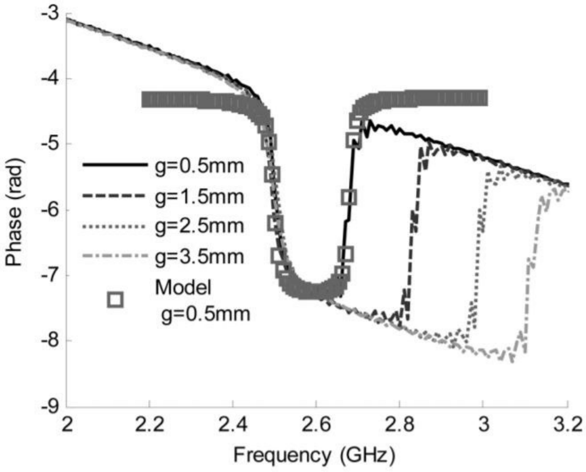


(c)

FIGURE 7. **(a) One bit hybrid resonator layout (b) RCS response (c) Phase response of a One bit resonator [50].**

III. CHIPLESS RFID APPLICATIONS FOR REAL-WORLD SCENARIO

Chipless RFID has several applications in the commercial and industrial sectors. It can be utilized for information collection and characterization of the object. Chipless RFIDs can be used to communicate between two objects and systems, process the data and information, and decision-making in

TABLE 1. Comparison of different wireless sensors.

Type	Reading Range	Cost	Size
Barcode [45]	Very Less	Lowest	Small
Passive Chip Tag [73]	1-10 cm	Meadium	Small
Bluetooth [74]	Meters	High	Medium
Wifi [75]	Meters to KM	Very High	Large
Active RFID Tag [76]	few meters	High	Large
Chipless RFID [77]	10 cm to few meters	Less	Medium

TABLE 2. Chipless RFID sensor applications.

Application	Chipless RFID type	Frequency Bands
Temp. Sensor [93]	II	2.4 - 2.5 GHz
Pipeline Monitoring [94]	I	3.3 - 3.9 GHz
Defect Detection [95]	II	2 - 6 GHz
Permittitivity Sensor [96]	II	3 - 5 GHz
Health Monitoring [97]	II	9 - 11 GHz
Humidity Sensor [98]	II	2 - 8 GHz
Resistor Detection [99]	II	1.72 - 2.62 GHz
Humidity Sensor [100]	II	3 - 7.5 GHz
Humidity Sensor [101]	II	0.12 - 0.3 GHz
Temp. Sensor [88]	II	6 - 7 GHz
Temp. Sensor [80]	T	3.5 GHz
Temp. Sensor [102]	II	4 - 9 GHz
Humidity Sensor [103]	II	3 - 7 GHz
Conc. Measurements [81]	I	3 - 6 GHz
Light Sensors [104]	I	5 to 25 MHz
Temp. Sensor [82]	T	250 MHz
Temp. Sensor [105]	T	922.5 MHz
Aerospace Monitoring [106]	T	315 MHz
Level Detection [107]	II	0.2 - 0.6 GHz
Rotation Monitoring [108]	II	3 - 6 GHz
Quality Monitoring [63]	H	3 - 24 MHz
Conc. Detection [83]	II	2.4 - 2.5 GHz
Fluid Sensing [109]	II	3 - 6.5 GHz
Growth Monitoring [60]	II	1.7 - 2.2 GHz
Biomedical Sensor [110]	II	10 - 20 MHz

real-world applications. Based on the type of information, a Chipless RFID application can broadly divide into three categories, sensors, localization, and high capacity tags for unique identification.

A. SENSORS

One of the major applications that have seen increasing use of Chipless RFID is the ubiquitous sensing [56]. The chipless RFID sensor is essentially an passive electronic device that can detect changes in the environment. It is well accepted and established that sensing, detection, and characterization of objects are useful for various applications such as food quality monitoring or humidity and temperature sensing [57]–[67]. A comparison between different wireless sensors on various parameters is given in Table 1. The Chipless RFID can be used as a potential sensor due to its cost-effectiveness and robustness in operation. It can withstand harsh environments such as extreme frozen weather and humid or dry conditions. Hence, chipless RFID can be used as a commercial sensor for retail, health, and other applications [68]–[72].

There has been a lot of research carried in the direction of Chipless RFID sensors; a part of the research is covered in Table 2, Where I and II represent retransmission-based and backscattering-based chipless tags in the frequency domain, respectively. T and H signify the time domain and hybrid tags. In the latest research, the backscattering Chipless RFID tags are readily and frequently preferred over the retransmission-based Chipless RFID tags considering that they do not require additional antennas and benefit from the reduced size and cost. On the other side, the backscattering Chipless RFID tag loses the reading range due to the absence of antennas. Most of the research emphasizes the simplicity of the sensor's design while employing backscattering type tags. It has been accepted that for long-distance sensing, the chipped RFID tags should be preferred [78]. The Chipless RFID tags are, in essence, earmarked for low cost and small distance sensing.

There are primarily two set of bands that are utilized by Chipless RFID technologies. One is the unlicensed bands available worldwide, such as the ISM bands of 2.45 GHz, and the other is UWB. The UWB [79] technology has an extensive operation bandwidth (>7 GHz), which is beneficial to frequency domain Chipless RFID tags since each bit is assigned a unique resonant frequency. Thus, the UWB facilitates large bandwidths required by frequency domain Chipless RFID tags to provide identification and sensing capabilities.

Furthermore, a lot of research in recent literature focuses on temperature [80], humidity [65], liquid, or gas sensors [81]. The temperature and humidity sensors work similarly, i.e., the resonant frequency shifts with temperature or humidity changes [82]. The liquid concentration experiments involve changes in dielectric properties where different solutions are mixed. As an example, a sodium chloride solution and an isopropanol solution are mixed for conducting the dielectric detection experiment. The change in the dielectric constant of the combined liquid solution leads to a shift in the resonant frequency, which can be mapped using Chipless RFID tag information to detect the solution type. A similar pattern of the experiment is used in water level detection. The increase in the water volume changes the effective permittivity for the resonators, and therefore, the system experiences a shift in resonant frequency.

In another Chipless RFID sensor research, the gas sensor [83] utilizes the change in magnitude response of the received signal rather than a shift in resonant frequency. The light sensors require the development of a photosensitive planar resonator to sense changes in the amount of light falling on it. These are mainly appropriate for items that should not be exposed to light. In the same direction of sensors, the planar sensor involves a resonator's coupling using a photosensitive polymer layer [84]. When the planar sensor system is exposed to ambient light, polymerization occurs, which leads to changes in the dielectric constant. This, in turn, brings out a shift in the resonant frequency. This process can be used to create a threshold light sensor that can alert the system to the fact that an item may have been exposed to light. Food quality sensors arise from the need for monitoring the product by observing the temperature, humidity of food in order to provide data on food safety and security [85]. These sensors are needed since many perishable food items require specific conditions to remain fresh.

Chipless RFID sensors can be used in many industries, such as food safety, retail sector management, disaster

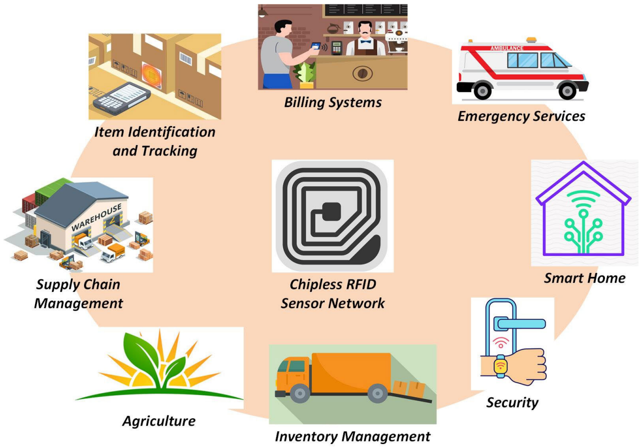


FIGURE 8. **Different applications of chipless RFID sensor network.**

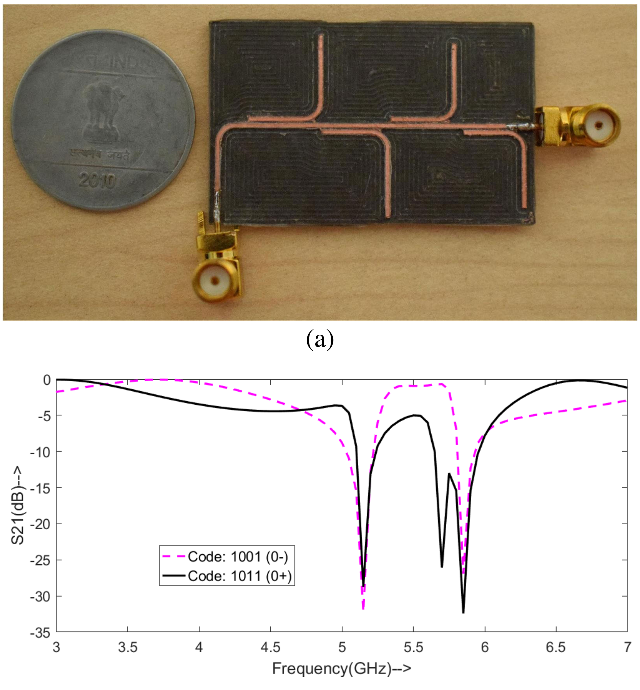
management, smart home, environment monitoring, etc., as depicted in Fig. 8. The research and advancement in the use of Chipless RFID are being carried out in every application field, as mentioned in Fig. 7. The orientation and positioning of the Chipless sensor play a vital role in the outcome of the information. Some of the real-world applications of the Chipless sensors are discussed in the following section.

1) HEALTH SECTOR

RFID is now widely used in health sectors, including patient tracking, drug management, medical equipment tracking, and management. Chipless RFID sensors have great potential to enhance the performance of the sensor in the health sector. The Chipless sensor's non-line of sight feature gives the tag reading flexibility, irrespective of its orientation. Chipless RFID sensors can be directly printed on the pills' surface hence, ensuring the drug delivery wirelessly. The patient monitoring and medicine management of the patient can be performed using a Chipless sensor easily. In recent research, a 4-bit Chipless RFID sensor [86], as shown in Fig. 9, is proposed for the blood bank management system. It covers all the blood groups' information and blood verification checks, which ensures the efficient management of blood banks. For example, the measurement responses are shown in Fig. 8(b), which includes two different blood groups (O+ and O−), which depicts the sensor's versatility in blood bank management.

2) FOOD AND AGRICULTURE SECTOR

Chipless sensors can contribute to food safety, such as expiry dates tracking, quality and processing control, and storage and transport management [87]. Chipless sensors can be used to measure the pH, temperature, and humidity of the food and individual items [88], [89]. These can provide critical information about food and related items [63]. These parameters also help in evaluating the expiry dates of the product to ensure the safety of the food [85]. In the agriculture sector, information on soil moisture can help in optimizing water uses in farming. Chipless sensors can be used to track the soil moisture and salinity of the land so that the farming decision can be taken accordingly [33].



(a)

(b)

FIGURE 9. **(a) Chipless RFID for blood bank (b) Measured response for different blood groups.**

Chip based [90], [91] and chipless sensors can be extensively used in emergency services such as disaster management and security. These sensors can track the temperature and humidity data continuously and make emergency decisions accordingly. Chipless sensors are also being used to track the object to ensure the safety of the item. RFID and Chipless RFID technology is considered a stepping stone for IoT and smart cities concept [92].

B. LOCALIZATION

Localization is the concept of identifying the position of an object in 3-D space. One famous example of localization is the use of the Global Positioning System (GPS) that is used by millions of people worldwide to get directions and the location of a place. The RFID has improved on this concept by introducing indoor localization, where GPS signals cannot penetrate [111]. Chipless RFID moves one step further by operating in higher frequencies (GHz to THz) to improve the accuracy of the object's position in question.

In the localization experiment [112], the S-parameter results are recorded for various distances in the positive and negative directions. The magnitude and frequency shifts are observed in the recorded response from the Chipless RFID tag. These shifts in the response can be used to determine the position of the Chipless RFID tag and help localize the object associated with the Chipless RFID tag. A list of recent work

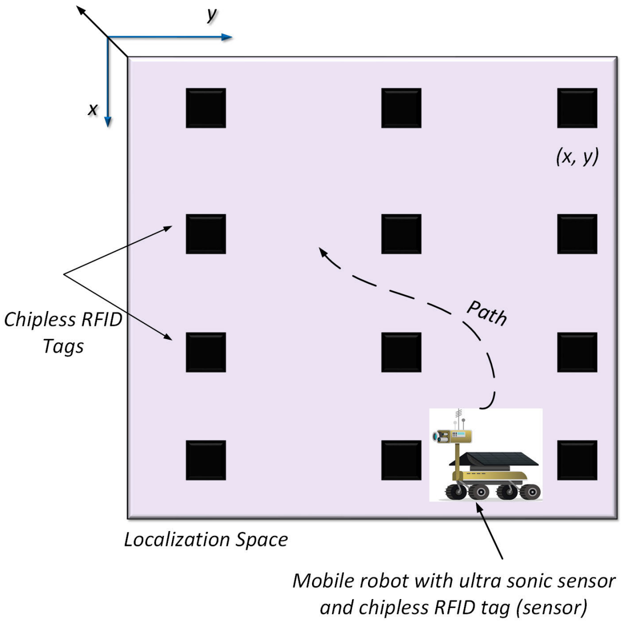


FIGURE 10. A general floor-based localization system using chipless RFID tags.

in the area of localization is presented in Table 3. Again, most recent work tends to utilize backscattering principles for tags due to its economical cost, simplistic design, and easy fabrication. The size of chipless tags in recent literature are also small as compared to traditional localization techniques [113]

The use of service and entertainment robot in real-world applications are increasing. In the robotics field, localization is a fundamental issue for mobile robots [114]. Recognize the robot's position in a different environment can be identified as a localization problem in the robotics field. A general floor-based Chipless RFID localization system is given in Fig. 10, which uses multiple Chipless RFID tags to find the mobile robot's position and path. Different sensors, such as ultrasonic sensors and wheel encoders, are used with Chipless RFID tags in the robotic system to reduce the uncertainty of the localization problem. The Chipless RFID localization system provides a robust and cost-effective approach to locate the robot and object in different environmental conditions.

Another essential point to note is the shift towards high frequencies in the field of localization, such as the THz band, which confers multiple advantages to the system:

1) It reduces the overall size and cost of the Chipless RFID tag.
2) The THz range provides a considerable bandwidth, enabling coding of more number of bits for frequency domain Chipless RFID tags.
3) Higher frequencies allow for accurate position resolution [115]–[117].

C. LARGE CAPACITY TAGS

The current research in the domain of Chipless RFID tags is also focused on enhancing the bit encoding capacity compared to the conventional chip-based RFID tag. The main challenge of the Chipless RFID design is the optimal area density, which embraces the maximum bits in the least area. The frequency coding technique has a higher bits capacity as compared to other design techniques of Chipless RFID [14].

TABLE 3. Research of localization in the domain of chipless RFID.

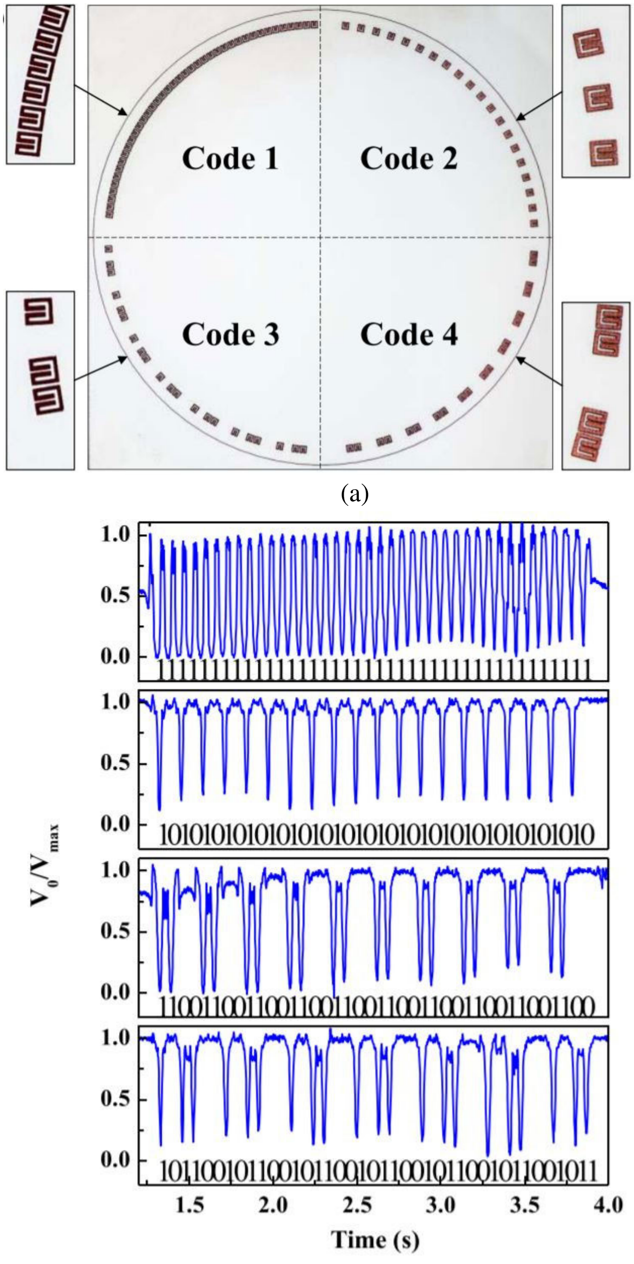
Research	Size of tag(cm)	Chipless RFID type	Frequency(GHz)
[113]	12 x 1.3	T	5.75
[118]	4.5 x 5.5	II	4 - 11
[119]	3.8 x 3.8	II	4 - 7
[120]	0.3	II	100-200
[121]	4.2 x 4.3	II	4 - 7
[122]	1.5 x 2.5	II	5 - 10
[123]	2 x 2.6	II	6.5 - 10
[124]	3 x 3	II	70 - 110
[125]	3 x 3	II	8 - 12
[126]	1.0 x 1.17	II	75-110

The increase in no of bits allows the formation of a higher number of unique IDs. It allows the Chipless RFID tag to process more information about the object associated with the tag. High-capacity tags require larger bandwidth to hold the bits without overlapping each other. The other challenge with the high bit density Chipless RFID tag is the mutual coupling between the resonators. The mutual coupling creates the resonate frequency shifts, enhancing the bandwidth of the Chipless RFID tag response. The frequency shift allows the lesser no. of bits in the allowed spectrum. The reader's sensitivity for high bit density tags should be high enough to detect the bits at a difference of 100 MHz or less.

An example of a high capacity Chipless RFID tag using TDR-based design encodes 40 bits using multiple split-ring resonators shown in Fig. 11(a). This tag operates at a center frequency of 4 GHz by sending a carrier signal to the tag and extracting its envelope output. An example of detecting the different configuration responses of the Chipless RFID tag is shown in Fig. 11(b), with all 40 bits.

The frequency signature under different polarizations is the favored method [128] to get a high number of bits in the limited area. The resonators are used in horizontal and vertical polarization, as presented in Fig. 12, to double the encoded bits with the same no. of resonators. Horizontally polarized resonators will not respond to vertically polarized plane waves and vice versa. The dual-polarization technique gives the flexibility to read the tag irrespective of its orientation. Additionally, dual-polarization solves the limited bandwidth issue using the same frequency bandwidth for horizontal and vertical polarization.

A list of recent literature about improving the encoding capacity of Chipless RFID tags are provided in Table 4. The major research carried in the Time domain based tags and backscattering Chipless RFID tags for high capacity tags. The Time domain based tags are taken into consideration because their reading process is sequentially over a time frame and therefore do not require a larger frequency bandwidth. The backscattering type Chipless RFID tags are more feasible to design and fabricate but require larger frequency bandwidths to encode many bits, which entails a shift towards higher



(a)

(b)

FIGURE 11. **(a) Chipless RFID tag having 40 bits (b) Response for different configuration [127].**

frequencies. Furthermore, the larger frequency also helps in the reduction of the overall size of the Chipless RFID tag, which opens up to multiple applications where the size of the tag can be a constraint, such as aerospace or biomedical applications.

IV. FUTURE DIRECTIONS

Chipless RFID technology bridge the gap between digital data and the physical product. It meets the requirements of the retail sector and other related companies and is being deployed promisingly in all tracking applications. It is imperative to note that Chipless RFID has already permeated in a broad range of applications. The research work is still going on for requisite performance and capacity enhancement for tag encoding. However, several applications may benefit from advancing the tools and techniques related to Chipless RFID technology. This section briefly touches upon some of the futuristic work in this domain.

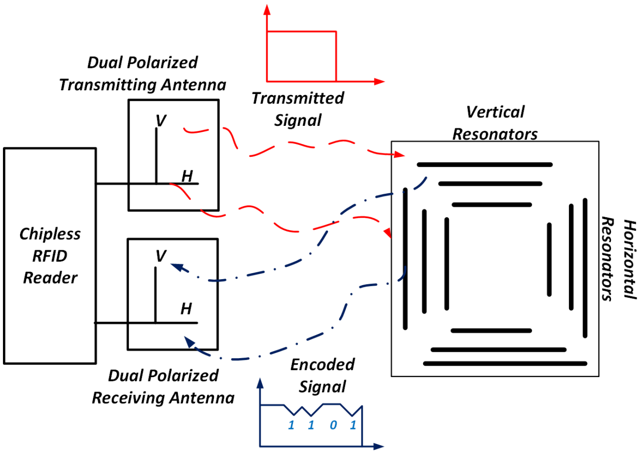


FIGURE 12. **Dual Polarization chipless RFID tag for high bit capacity applications.**

A. SPATIAL DOMAIN CHIPLESS RFID

Spatial domain Chipless RFID, also known as image-based Chipless RFID, is a newer technology that is gaining the attraction of researchers. It scans the small section of the tag and gathers the EM image of the particular area, which is different from the prevailing Chipless RFID techniques. The spatial technique is significantly different from a time domain or frequency domain, a Chipless RFID tag, illuminating the entire tag. An example [138] is comprehended in Fig. 13, which describes the difference between a spatial Chipless RFID tag reading technique and a frequency-based Chipless RFID tag reading technique.

To have a specific beam to interrogate a tag in the spatial domain, one requires the tag and reader to operate in mmWave or higher frequency range. The spatially based tags are advantageous over their conventional counterparts in the following aspects:

1) Time-domain SAW-based systems are costly and require a larger area for encoding more amounts of data.
2) The lower quality substrates and printing errors can reduce the resonators' quality factor present on the Chipless tag, and the spectral signatures may be hard to detect for the reader.
3) The spatial technique can be used with low grade to low sensitivity tag material and is useful in health sectors and human tracking, where a Chipless RFID tag is used inside the body part.

The important application of spatial technique includes a non-line of sight-reading or tag hiding, high conductive object tagging, and use of Chipless with bent material and object.

TABLE 4. High capacity chipless tags for unique ID.

Research	Max. No. of bits	Operating Freq.(GHz)
[127]	40	4
[129]	20	2.2 to 3.5
[130]	31	4.4 to 8
[131]	16	4.63
[132]	40	4
[133]	800	77.5
[134]	16	7 to 11
[135]	100	2 to 5
[136]	4.6	2.4 to 2.48
[137]	30	3.1 to 11.7

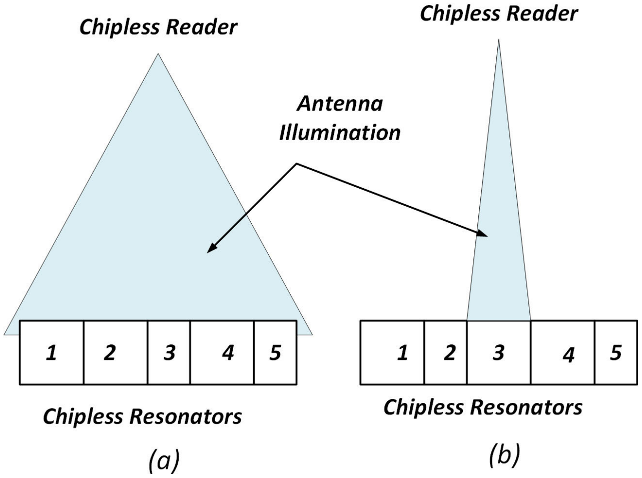


FIGURE 13. (a) Conventional RFID tag interrogation (b) Spatial interrogation.

The work on the spatial domain is still in its infancy, but there are a few works by Dong Huu Nguyen *et al.* [139] and M. Zomoroddi *et al.* [140] in this area.

B. CHIPLESS RFID IN SUPREME ENVIRONMENTS

Multiple industries, including industrial equipment manufacturing, oil, chemical, and gas processing, mining, and life sciences, face harsh environmental conditions in their daily routine. RFID is widely used in harsh environmental industries to automate manufacturing, management, research facilities, exploration, and aftermarket services. Chipless RFID will further enhance RFID's uses due to its cost-effectiveness and robustness towards a harsh environment.

The recent research work in Chipless RFID mainly focuses on moderate temperatures required applications. However, Chipless RFID could work towards customization of the technologies for use in extreme and harsh environments in the future. It can be similar to conventional RFID work in tagging biological samples like cells, tissues, or sperm, which are kept at temperatures below −310 degree Fahrenheit or threshold sensors for cold storage applications [141]. This work could shift towards utilizing a Chipless system with no worries about the electronics or RF circuitry not working at those temperatures. Another research direction for Chipless RFID is to use it as a sensor in a real outside environment. Chipless RFID is more equipped to handle the extreme environment than conventional chipped-based RFID since there is no microchip or other electronics onboard the Chipless RFID tag that could be disfigured by cosmic and ultraviolet radiation [142].

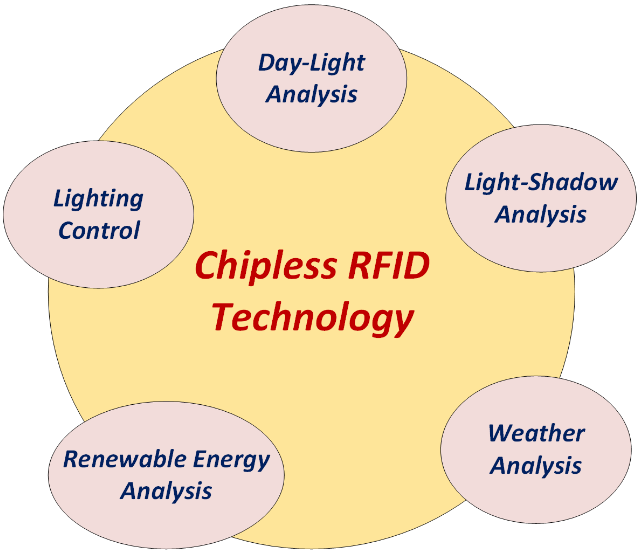


FIGURE 14. Chipless RFID application for green technology.

C. CHIPLESS RFID FOR GREEN PROJECTS

RFID technology plays an important role in delivering green technology and reducing carbon footprint [143], [144]. Chipless RFID technology presents new directions in many industrial applications due to the tags' integration with sensor applications. Chipless RFID tags can be used in the retail sector's supply chains to reduce CO_2 emissions, optimization of goods flow, room temperature control for spoilage reduction and quality improvement, and delivery efficiency increment, enhance waste management, and improving production and management efficiency. Chipless RFID technology can also provide an environmentally friendly solution for various hazardous problems [145].

The future of green technology research has many attributes, including daylight simulation, weather analysis, lighting control, and renewable energy like sun, water, and wind analysis, as presented in Fig. 14. Chipless RFID can perform data collection and analysis efficiently in the different fields of green technology. There are a few challenges in the adoption of Chipless RFID in the direction of greener technology. A Chipless RFID tag material composition and its performance are some of the crucial challenges in this direction. Paper or cloth printed and wearable Chipless RFID tag designs are receiving considerable attention in the environment-friendly mission. Finally, a better understanding of tagged objects and substrates' material characteristics will improve readability. It will offer efficient solutions for new technology and applications. As the future moves towards an eco-friendly and silicon-free world, chipless RFID could provide a better solution for green and eco-friendly projects.

The energy harvesting using Chipless RFID can be a significant step in energy-efficient technology. Printed RFID antennas into solar cells [146] is an excellent example where the antenna harvests RF energy and simultaneously communicates with the reader. Finally, the biodegradable and recyclable Chipless RFID tag will be a significant aspect of future research.

V. CONCLUSION

This paper briefly discussed and summarized the increasing use of Chipless RFID. Firstly, various Chipless RFID technologies' operational mechanism is presented through various examples showing how the time domain, frequency domain, and hybrid tags operate. It looked at the recent literature that helps understand significant applications that have cropped up in the domain and are explored in detail.

Finally, future research directions of Chipless RFID are explored, which diverts our attention from the traditional reading mechanism. Green Chipless RFID applications show advancements on multiple fronts, including flexible tag designs, energy harvesting, power management algorithms, and environmentally friendly material. This survey's key observations are that the Chipless RFID research has moved towards higher frequencies and smaller tag sizes, which finds applications in sensing, localization, and higher capacity encoding. The development of Chipless RFID technology on a global scale will require new reading mechanisms that adapt all types of reading techniques.

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